An Investigation of Some Aspects
of the Coordination Chemistry of
Synthetic Macroheterocyclic Ligands

Peter Osvath

Submitted for the degree of
Doctor of Philosophy in Chemistry
at the Victoria University of
Wellington
June 1984

Nothing is as easy as it looks
Everything takes longer than you expect
If anything can go wrong - it will
At the worst possible moment

Murphy's Law

Murphy was an Optimist

O'Reilly's Law

Abstract

The preparation of a range of fully saturated, unsubstituted pentaazamacrocycles is described. The macrocycles vary in ring size from fifteen to twenty members, and comprise every possible arrangement of dimethylene and trimethylene linkages between five nitrogens in a monocyclic arrangement. A new linear homologue of tetraethylene pentamine with trimethylene linkages between nitrogens is also reported.

The copper(II) and nickel(II) complexes of these amines have been prepared; the conductivity and spectral properties have been determined in order to investigate their stereochemistry. The nickel(II) complexes of the two largest macrocycles appear to be five-coordinate both in the solid state and in solution. The remainder of the complexes are either five-coordinate (as the perchlorate salts in the solid state or in non-coordinating solvents) or six-coordinate (with a coordinated nitrate).

Cobalt(III) complexes of the fifteen to eighteen membered macrocycles have been prepared with a variety of ligands occupying the sixth coordination site. Ligand field parameters have been derived from the electronic spectra of the complexes. The stereochemistry of the complexes and their behaviour on ligand substitution have been investigated principally by ^{13}C n.m.r. Only a few of the numerous possible isomers of each species were formed. The structures of $[\text{Co}(1,4,7,10,14\text{-pentaazacycloheptadecane})\text{Cl}]\text{Br}_{0.33}\text{Cl}_{1.67}\cdot\text{H}_2\text{O}$ and $[\text{Co}(1,4,7,11,15\text{-pentaazacyclooctadecane})\text{Br}]\text{Br}_2$, which were determined by single-crystal x-ray diffraction studies, are described. The spontaneous aquation rates of the bromo complexes have been investigated semi-quantitatively, and found to span many orders of magnitude. The most labile bromo complex $[\text{Co}(1,4,8,11,15\text{-pentaazacyclooctadecane})\text{Br}]\text{Br}_2$

spontaneously aquates in a matter of seconds at room temperature. The increasing strain and steric crowding caused by successive replacement of five-membered chelate rings by six-membered chelate rings, or by simply altering the sequence of five- and six-membered chelate rings is manifested in a progressive increase in the instability of the complexes. In the case of the nineteen- and twenty-membered macrocycles, this crowding and strain results in the formation of stable five-coordinate cobalt(II) complexes; for these ligands, no stable complexes were formed with the smaller cobalt(III) cation.

The acid-dissociation kinetics of the copper(II) complexes have been examined in nitric acid at 298 K. A variable temperature study has also been performed on the complex of 1,4,7,10,14-pentaazacycloheptadecane in order to determine the activation parameters. The complexes are labile by comparison with most tetraazamacrocyclic complexes. The dissociation reactions are first-order in complex concentration, but the acid-dependence varies. The observed rate constant is second-order in hydrogen ion concentration for the complex of 1,4,7,10,13-pentaazacyclopentadecane, first-order in hydrogen ion concentration for 1,4,7,10,14-pentaazacycloheptadecane and takes the form $k_{\text{obs}} = a[\text{H}^+]^2/(1+b[\text{H}^+]^2)$ for the complex of 1,4,7,10,13-pentaazacyclohexadecane. For the remainder of the complexes, the observed rate constant takes the form $k_{\text{obs}} = (c[\text{H}^+] + d[\text{H}^+]^2)/(e + [\text{H}^+])$. Possible mechanisms that are consistent with the above behaviour are presented.

Acknowledgements

I wish to thank the following people, all of whom have contributed to the completion of this work:

Dr David C. Weatherburn, not only for the help and guidance he has unstintingly given me through the years (never being short of a flash of brilliant inspiration when there seemed to be no answer!) or for his fantastic patience and infectious enthusiasm, but also for being a good friend as well as a supervisor.

Professor Neil Curtis, for many stimulating discussions, and for never letting me down in my belief that if one ever wanted to know anything, and couldn't find it in a book, one could simply "Go and ask Prof Curtis..."

Steven Milgate (who ran a million and one n.m.r. spectra), Ian Crighton (glassblower par excellence) and the rest of the staff (both academic and non-academic) of the Chemistry Department, all of whom appear at some stage to have been involved.

My fellow students, particularly Paul (the "Triazamacrocyclic King"), and also Keith, Dennis, Dave, Stephen, Richard and Barry for the flow of ideas as well as friendship and mutual commiseration over our plight.

Rhyl Singleton, who had the unenviable task of typing this work and whose experience in matters of presentation and format turned a morass of paper into a thesis.

Sarah, for being so loving, patient and supportive through the most difficult part of this work, and for making me laugh when there seemed to be no end to it all.

But above all I wish to thank my Parents (a Drága Szüleim), whose love, help and support have made my life happy and secure. Without their example and inspiration, none of this would ever have been possible.

Table of Contents

Chapter 1 INTRODUCTION

1.1	Introduction	1
1.2	Crown Ethers and Cryptates	3
1.3	Nitrogen Containing Macrocycles	5
1.3.1	Synthetic Methods	5
1.3.1.1	Template Cyclizations	5
1.3.1.2	Non-Template Condensations	12
1.3.1.3	A Versatile General Method	15
1.3.2	Pentaazamacrocyclic Ligands and their Analogues	20
1.4	Properties of Transition Metal Complexes of Macrocyclic Amines	22
1.4.1	Macrocyclic Effect and the Stability of Copper and Nickel Complexes	22
1.4.1.1	Tetraazamacrocycles	22
1.4.1.2	Pentaazamacrocycles	25
1.4.1.3	Hexaazamacrocycles	26
1.4.2	Magnetic, Electronic and Spectral Properties	27
1.4.2.1	Tetraazamacrocyclic Nickel(II) Complexes	29
1.4.2.2	Pentaazamacrocyclic Nickel(II) Complexes	30
1.4.2.3	Tetraazamacrocyclic Nickel(I) and Nickel(III) Complexes	34
1.4.2.4	Pentaazamacrocyclic Nickel(III) Complexes	35
1.4.2.5	Copper Complexes	36
1.4.2.6	Cobalt(III) Complexes of Tetraazamacrocyclic Ligands	40
1.4.2.7	Cobalt(III) Complexes of Linear and Macrocyclic Pentamines	43
1.4.2.8	Cobalt(II) Complexes	44
1.4.3	Kinetics of Formation and Dissociation of Macrocyclic and Linear Complexes with Labile Transition Metals	46
1.4.3.1	Formation Reactions of Copper(II) Complexes	46
1.4.3.2	Dissociation Reactions of Nickel(II) Complexes of Linear Amines	53
1.4.3.3	Dissociation Reactions of Copper(II) Complexes of Linear Amines	58
1.4.3.4	Dissociation Reactions of Copper(II) and Nickel(II) Complexes of Macrocyclic Ligands	60
1.4.3.5	Medium Effects on Stability and Kinetics	72

1.4.4	Macrocyclic Complexes of Cobalt(III)	73
1.4.4.1	Introduction	73
1.4.4.2	Synthetic Methods	74
1.4.4.3	Isomerism of Cobalt(III) Amine Complexes	76
1.4.4.4	Separation Methods	77
1.4.4.5	^{13}C n.m.r. Studies of Cobalt(III) Complexes	81
Chapter 2	EXPERIMENTAL	84
2.1	Instrumentation	84
2.2	Synthesis of Organic Species	86
2.2.1	Synthesis and Purification of Linear Amines	86
2.2.2	Tosylation of Linear Amines	89
2.2.3	Preparation of Disodium Salts	91
2.2.4	Synthesis of Amino Alcohols	92
2.2.5	Tosylation of Amino Alcohols	94
2.2.6	Cyclization Reactions	97
2.2.7	Detosylation Reactions	104
2.2.8	Extraction of Free Amines from Amine Salts	113
2.2.9	Attempted Non-Template Synthesis of Macrocyclic Amines with Glyoxal	121
2.2.10	G.l.c. Analysis of Free Amines	122
2.3	Synthesis of Metal Complexes	125
2.3.1	Copper Complexes	125
2.3.1.1	$\text{CuL}(\text{ClO}_4)_2$	125
2.3.1.2	$\text{CuL}(\text{NO}_3)_2 \cdot x\text{H}_2\text{O}$	127
2.3.2	Nickel Complexes	127
2.3.2.1	$\text{NiL}(\text{ClO}_4)_2$	127
2.3.2.2	$\text{NiL}(\text{NO}_3)_2 \cdot (\text{solvent})$	127
2.3.3	Cobalt Complexes	141
2.3.3.1	Cobalt(III) Complexes of [15]aneN ₅	141
2.3.3.2	Cobalt(III) Complexes of [16]aneN ₅	151
2.3.3.3	Cobalt(III) Complexes of [17A]aneN ₅	157
2.3.3.4	Cobalt(III) Complexes of [17B]aneN ₅	162
2.3.3.5	Cobalt(III) Complexes of [18A]aneN ₅	169
2.3.3.6	Cobalt(III) Complexes of [18B]aneN ₅	173
2.3.3.7	Cobalt(II) and Cobalt(III) Complexes of [19]aneN ₅	178
2.3.3.8	Cobalt Complexes of [20]aneN ₅	181
2.3.3.9	Cobalt(III) Complexes of tetren	182
2.3.3.10	Attempted Synthesis of Cobalt(III) Complexes of tetrpn (3,3,3,3-pent)	184

2.3.4	Rhodium(III) Complexes	186
2.3.4.1	$[\text{Rh}([\text{16}] \text{aneN}_5)\text{Cl}]\text{Cl}_2$	186
2.3.4.2	$[\text{Rh}([\text{20}] \text{aneN}_5)\text{Cl}](\text{ClO}_4)_2$	187
2.4	Chemical, Spectral and Structural Properties of Cobalt Complexes	189
2.4.1	Ligand Substitution Reactions of Cobalt(III) Complexes	189
2.4.1.1	Substitution Reactions of Cobalt(III) Complexes of $[\text{15}] \text{aneN}_5$	189
2.4.1.2	Substitution Reactions of Cobalt(III) Complexes of $[\text{16}] \text{aneN}_5$	193
2.4.1.3	Substitution Reactions of Cobalt(III) Complexes of $[\text{17A}] \text{aneN}_5$	194
2.4.1.4	Substitution Reactions of Cobalt(III) Complexes of $[\text{17B}] \text{aneN}_5$	195
2.4.1.5	Substitution Reactions of Cobalt(III) Complexes of $[\text{18A}] \text{aneN}_5$	200
2.4.1.6	Substitution Reactions of Cobalt(III) Complexes of $[\text{18B}] \text{aneN}_5$	200
2.4.1.7	Substitution Reactions of Cobalt(III) Complexes of tetren	201
2.4.2	Electronic Spectra of Cobalt(II) and Cobalt(III) Complexes	203
2.4.2.1	Cobalt(III) Complexes	203
2.4.2.2	Cobalt(II) Complexes	208
2.4.3	Structural Study of $[\text{Co}([\text{17A}] \text{aneN}_5)\text{Cl}]\text{Br}_{0.33}\text{Cl}_{1.67} \cdot \text{H}_2\text{O}$	213
2.4.3.1	Synthesis	213
2.4.3.2	Crystal Data	213
2.5	Acid-Dissociation Kinetics of Copper Complexes	226
2.5.1	Data Acquisition and Analysis	226
Chapter 3	DISCUSSION OF RESULTS	257
3.1	Synthesis of Macrocyclic Amines	257
3.1.1	Cyclization Reaction	257
3.1.2	Detosylation Reaction	260
3.1.3	Free Macrocyclic Amines	261
3.2	Copper(II) and Nickel(II) Complexes	266
3.2.1	Preparation of Complexes	266
3.2.2	Structure of the Copper(II) and Nickel(II) Complexes	266
3.2.2.1	Infrared Spectra of the Perchlorate Complexes	267

3.2.2.2	Infrared Spectra of the Nitrate Complexes	268
3.2.2.3	Other Infrared Bands	270
3.2.2.4	Conductivity Studies	271
3.2.2.5	Stereochemistry and Spectral Properties of the Copper(II) Complexes	275
3.2.2.6	Stereochemistry and Spectral Properties of the Nickel(II) Complexes	280
3.3	Cobalt(II), Cobalt(III) and Rhodium(III) Complexes	288
3.3.1	Structure and Isomerism of Cobalt(III) Complexes	288
3.3.2	^{13}C n.m.r. Spectra of the Complexes	290
3.3.3	Properties of Cobalt(III) Complexes	293
3.3.3.1	General Synthetic Methods of Cobalt(III) Complexes	293
3.3.3.2	Complexes of tetren	294
3.3.3.3	Complexes of [15]aneN ₅	295
3.3.3.4	Complexes of [16]aneN ₅	307
3.3.3.5	Complexes of [17A]aneN ₅	310
3.3.3.6	Structure of [Co([17A]aneN Cl)Br _{0.33} Cl _{1.67} ·H ₂ O]	312
3.3.3.7	Complexes of [17B]aneN ₅	314
3.3.3.8	Complexes of [18A]aneN ₅	321
3.3.3.9	Complexes of [18B]aneN ₅	324
3.3.3.10	Spontaneous Aquation Reactions	325
3.3.3.11	Complexes of [19]aneN ₅ , [20]aneN ₅ and tetrpn	327
3.3.4	Electronic Spectra of Cobalt(III) Complexes	327
3.3.4.1	Analysis of Spectra	327
3.3.4.2	Ligand Field Parameters of the Halopentamines	331
3.3.4.3	Ligand Field Parameters of the Aquo and Hydroxo Complexes	337
3.3.5	Cobalt(II) Complexes	339
3.3.5.1	Structure and Spectra	339
3.3.6	Rhodium(III) Complexes	341
3.4	Kinetics of Acid Dissociation of Copper Complexes	343
3.4.1	Comparison with other Donor Systems	343
3.4.2	Acid Dissociation Kinetics of [Cu([15]aneN ₅)] ²⁺	348
3.4.3	Acid Dissociation Kinetics of [Cu([16]aneN ₅)] ²⁺	354
3.4.4	Acid Dissociation Kinetics of [Cu([17A]aneN ₅)] ²⁺	356
3.4.5	Acid Dissociation Kinetics of [Cu([17B]aneN ₅)] ²⁺ and [Cu([18-20]aneN ₅)] ²⁺	361
	References	368
	Appendices	390

List of Tables

2.1	Data for Sodium Salts of Tosylated Amines	91
2.2	Retention Times of Amines (G.L.C.)	124
2.3	Preparative and Analytical Data for $\text{CuL}(\text{ClO}_4)_2$ Complexes	126
2.4	Preparative and Analytical Data for $\text{CuL}(\text{NO}_3)_2$ Complexes	128
2.5	Infrared Spectra of $\text{CuL}(\text{ClO}_4)_2$ Complexes	129
2.6	Infrared Spectra of $\text{CuL}(\text{NO}_3)_2$ Complexes	130
2.7	Infrared Spectra of $\text{CuL}(\text{NO}_3)_2$ Complexes (overtone and combination bands of the nitrate ion)	131
2.8	Electronic Spectra of Copper(II) Complexes	132
2.9	Preparative and Analytical Data for $\text{NiL}(\text{ClO}_4)_2$ Complexes	134
2.10	Preparative and Analytical Data for $\text{NiL}(\text{NO}_3)_2$ Complexes	135
2.11	Infrared Spectra of $\text{NiL}(\text{ClO}_2)_2$ Complexes	136
2.12	Infrared Spectra of $\text{NiL}(\text{NO}_3)_2$ Complexes	137
2.13	Infrared Spectra of $\text{NiL}(\text{NO}_3)_2$ Complexes (overtone and combination bands of the nitrate ion)	138
2.14	Electronic Spectra of Nickel(II) Complexes	139
2.15	Molar Conductivities of Metal Complexes	140
2.16	(a) Electronic Spectra of $[\text{CoLBr}]^{2+}$ Complexes	204
2.16	(b) Electronic Spectra of $[\text{CoLCl}]^{2+}$ Complexes	205
2.17	Electronic Spectra of $[\text{CoLOH}]^{2+}$ Complexes	206
2.18	Electronic Spectra of $[\text{CoLH}_2\text{O}]^{3+}$ Complexes	207
2.19	Properties of Cobalt(II) Complexes	212
2.20-2.28	$[\text{Co}([\text{17A}] \text{aneN}_5)\text{Cl}]\text{Br}_{0.33}\text{Cl}_{1.67} \cdot \text{H}_2\text{O}$ Structural Data	217-225
2.20	Interatomic Distances	217
2.21	Bond Angles	218
2.22	Selected Dihedral Angles	219
2.23	Deviations from Selected Planes	220
2.24	Equations of Planes	221
2.25	Atomic Coordinates: Non-Hydrogen Atoms	222
2.26	Thermal Parameters: Non-Hydrogen Atoms	223
2.27	Hydrogen Atom Coordinates and Thermal Parameters	224
2.28	Hydrogen-Bond Contact Distances and Angles	225
2.29	(a) Acid Dissociation Kinetics of $[\text{Cu}([\text{15}] \text{aneN}_5)]^{2+}$	230
2.29	(b) Acid Dissociation Kinetics of $[\text{Cu}([\text{15}] \text{aneN}_5)]^{2+}$ in the Presence of Weak Acid	231

2.30	(a)	Acid Dissociation Kinetics of $[\text{Cu}([\text{16}] \text{aneN}_5)]^{2+}$	234
2.30	(b)	Acid Dissociation Kinetics of $[\text{Cu}([\text{16}] \text{aneN}_5)]^{2+}$ in the Presence of Weak Acid	235
2.31	(a)	Acid Dissociation Kinetics of $[\text{Cu}([\text{17A}] \text{aneN}_5)]^{2+}$	238
2.31	(b)	Acid Dissociation Kinetics of $[\text{Cu}([\text{17A}] \text{aneN}_5)]^{2+}$ in Weak Acid	239
2.32		Rate Constants and Activation Parameters for the Acid Dissociation Kinetics of $[\text{Cu}([\text{17A}] \text{aneN}_5)]^{2+}$	242
2.33		Acid Dissociation Kinetics of $[\text{Cu}([\text{17B}] \text{aneN}_5)]^{2+}$	244
2.34		Acid Dissociation Kinetics of $[\text{Cu}([\text{18A}] \text{aneN}_5)]^{2+}$	246
2.35	(a)	Acid Dissociation Kinetics of $[\text{Cu}([\text{18B}] \text{aneN}_5)]^{2+}$	248
2.35	(b)	Acid Dissociation Kinetics of $[\text{Cu}([\text{18B}] \text{aneN}_5)]^{2+}$ in the Presence of Weak Acid	249
2.36		Acid Dissociation Kinetics of $[\text{Cu}([\text{19}] \text{aneN}_5)]^{2+}$	252
2.37	(a)	Acid Dissociation Kinetics of $[\text{Cu}([\text{20}] \text{aneN}_5)]^{2+}$	254
2.37	(b)	Acid Dissociation Kinetics of $[\text{Cu}([\text{20}] \text{aneN}_5)]^{2+}$ in Acetic Acid	255
3.1		Molar Conductivities of Complexes in Nitromethane	272
3.2		Molar Conductivities of Complexes in Methanol	273
3.3		Ligand Field Parameters of $[\text{CoLOH}]^{2+}$ and $[\text{CoLH}_2\text{O}]^{3+}$ Complexes	332
3.4		Ligand Field Parameters of Cobalt(III) Halopentamines	333
3.5		Chelate Ring Sequence in Cobalt(III) Complexes of Pentamines	335
3.6		Acid Dissociation Constants of Copper(II) Complexes	345
3.7		Activation Parameters of Copper(II) Amine Complexes	360
3.8		Coefficients of the Rate Constant $k_{\text{obs}} = (a[\text{H}^+] + b[\text{H}^+]^2) / (c + [\text{H}^+])$	362
3.9		Acid Dissociation Reactions - Derived Parameters	365

List of Figures

1.1	Correlation between $\log_{10} k_{\text{HnL}}^{\text{Cu}}$ and $\text{pK}_{\text{n+1}}^{\text{H}}$ for Macrocycles	52
2.1	Electronic Spectra of Copper(II) Complexes	133
2.2	Infrared Spectra of $[\text{Co}([\text{15}] \text{aneN}_5)\text{Br}]\text{ZnBr}_4$ and $[\text{Co}([\text{15}] \text{aneN}_5)\text{Cl}]\text{ZnCl}_4 \cdot 0.5\text{H}_2\text{O}$	145
2.3	^{13}C n.m.r. Spectra of Peroxo and Hydroxo Cobalt(III) Complexes of $[\text{15}] \text{aneN}_5$	150
2.4	Infrared Spectra of $[\text{Co}([\text{16}] \text{aneN}_5)\text{X}]\text{ZnX}_4$ ($\text{X}=\text{Cl}^-$, Br^-)	154
2.5	Infrared Spectra of α and γ - $[\text{Co}([\text{17B}] \text{aneN}_5)\text{Br}]\text{ZnBr}_4$	163
2.6	Infrared Spectra of α and γ - $[\text{Co}([\text{17B}] \text{aneN}_5)\text{Cl}]\text{ZnCl}_4$	167
2.7	Infrared Spectrum of $[\text{Co}([\text{18A}] \text{aneN}_5)\text{Br}]\text{Br}$	172
2.8	Solid State and Solution ^{13}C n.m.r. Spectra of $[\text{Co}([\text{18A}] \text{aneN}_5)\text{Br}]\text{Br}_2$	174
2.9	^{13}C n.m.r. Spectra of Complexes of $[\text{16}] \text{aneN}_5$ and $[\text{20}] \text{aneN}$ with Rhodium(III)	188
2.10	Infrared Spectra of $[\text{Co}([\text{18B}] \text{aneN}_5)\text{X}]\text{X}_2$ ($\text{X}=\text{Br}^-$, Cl^-)	202
2.11	Hydrolysis of $[\text{Co}([\text{18A}] \text{aneN}_5)\text{Br}]^{2+}$ in Nitric Acid	209
2.12	Hydrolysis of $[\text{Co}([\text{18A}] \text{aneN}_5)\text{Br}]^{2+}$ in Perchloric Acid	210
2.13	Electronic Spectra of Cobalt(II) Complexes of $[\text{19}] \text{aneN}_5$ and $[\text{20}] \text{aneN}_5$ (Solid State and Solution)	211
2.14	Structure of the $[\text{Co}([\text{17A}] \text{aneN}_5)\text{Cl}]^{2+}$ Complex Cation	216
2.15 (a)	Acid Dissociation Kinetics of $[\text{Cu}([\text{15}] \text{aneN}_5)]^{2+}$	232
2.15 (b)	Acid Dissociation Kinetics of $[\text{Cu}([\text{15}] \text{aneN}_5)]^{2+}$ (including values with $I > 1.0 \text{ M}$)	233
2.16 (a)	Acid Dissociation Kinetics of $[\text{Cu}([\text{16}] \text{aneN}_5)]^{2+}$	236
2.16 (b)	Acid Dissociation Kinetics of $[\text{Cu}([\text{16}] \text{aneN}_5)]^{2+}$	237
2.17 (a)	Acid Dissociation Kinetics of $[\text{Cu}([\text{17A}] \text{aneN}_5)]^{2+}$	240
2.17 (b)	Acid Dissociation Kinetics of $[\text{Cu}([\text{17A}] \text{aneN}_5)]^{2+}$ (including values with $I > 1.0 \text{ M}$)	241
2.18	Arrhenius Plot for the Acid Dissociation Kinetics of $[\text{Cu}([\text{17A}] \text{aneN}_5)]^{2+}$	243
2.19	Acid Dissociation Kinetics of $[\text{Cu}([\text{17B}] \text{aneN}_5)]^{2+}$	245
2.20	Acid Dissociation Kinetics of $[\text{Cu}([\text{18A}] \text{aneN}_5)]^{2+}$	247
2.21 (a)	Acid Dissociation Kinetics of $[\text{Cu}([\text{18B}] \text{aneN}_5)]^{2+}$	250
2.21 (b)	Acid Dissociation Kinetics of $[\text{Cu}([\text{18B}] \text{aneN}_5)]^{2+}$ (including values with $I > 1.0 \text{ M}$)	251

2.22	Acid Dissociation Kinetics of $[\text{Cu}([19]\text{aneN}_5)]^{2+}$	253
2.23	Acid Dissociation Kinetics of $[\text{Cu}([20]\text{aneN}_5)]^{2+}$	256
3.1	Relationship Between Retention Times and Molecular Masses of Amines	265
3.2	Isomerism of Cobalt(III)-Macrocyclic Pentamine Complexes	291
3.3	^{13}C n.m.r. Spectra of Cobalt(III) Complexes of $[15]\text{aneN}_5$	298
3.4	Structure of the $[\text{Co}([18\text{A}]\text{aneN}_5)\text{Br}]^{2+}$ Complex Cation	323
3.5	Energy Levels for the Singlet States of a Tetragonal d^6 Ion	328

CHAPTER 1

1.1 Introduction

Macrocycles may be defined as cyclic molecules containing no fewer than nine atoms in a ring and at least three heteroatoms (N, P, S, O etc)¹. Although naturally occurring macrocyclic molecules and their complexes have been known for a number of decades, interest in their chemistry has expanded rapidly in the last twenty years. Initial investigations focussed on the complexes of porphyrins, corrins and phthalocyanines because of their similarity to biological systems containing macrocyclic frameworks such as chlorophyll, vitamin B12 and cytochromes, and the possible applications of such species as phthalocyanine as dyestuffs and other commercial products.

The fact that these large and complex ring structures occur in nature in such varied roles raises the question of whether the cyclic structure that is common to them confers some special properties. Their remarkable stability is evident in the existence of porphyrins in oil and oil shales as nickel and vanadium complexes² which are thought to have been formed by metal exchange over millions of years, with the basic porphyrin ring remaining intact. The research into such biological compounds and studies of related synthetic models has been extensively reviewed.³ A considerable number of different macrocyclic complexes based on these biological compounds have been synthesised in an effort to discover the way in which the macrocyclic framework affects the properties of the enclosed metal ion. One method involves substitution of the metal in the macrocyclic cavity, as in the replacement of diamagnetic iron(II) in hemoglobin by cobalt(II). Investigation of the

spectral and magnetic properties of the resultant coboglobins can be used to elucidate the electronic and geometric structure, from which conclusions are drawn regarding the likely nature of the environment of iron(II) in the parent compound.⁴ Alternatively, the effect of modifications to the parent organic molecule, as in the case of the so-called "picket-fence porphyrin" of Collman⁵ provide another approach. The investigation of the properties of these naturally occurring products and their analogues has been hindered by the very complexity that their varied functions demand. For instance, investigation of the environment of the metal centre in porphyrins is complicated as the electronic spectra, magnetic properties and redox behaviour are also affected by the delocalized π -electron ring system. The other thrust of the investigations has therefore been directed towards the synthesis of simple analogues of these molecules, with little if any aromatic character, and the macrocyclic ligand in these cases merely models the number and nature of the donor species and the geometric constraints imposed by the cyclic structure.⁶ In fact, the term "model compound" can generally only be applied in the loosest sense, and much of the current investigation centres on properties peculiar to the derived compounds with little, if any, reference to the complex molecules that were being modelled.

There are two broad classes of macrocyclic compounds and they can profitably be dealt with separately. The first is the largely oxygen containing "crown ethers" and their polycyclic derivatives⁷ (such as cryptands⁸) which will only be touched upon; secondly, of considerably greater importance to the present study, macrocycles predominantly containing nitrogen donors (with possibly sulphur, phosphorus or oxygen replacing one or two nitrogen atoms).

1.2 Crown Ethers and Cryptates

A great deal of interest has centred around these compounds since the first reported synthesis of a crown ether (dibenzo-18-crown-6 (I)⁹)

This has principally been due to the remarkable stability of the complexes that they are capable of forming with non-transition metals. A large variety of oxygen containing macrocycles with differing cavity sizes and different numbers of attached aromatic rings have been synthesised. They exhibit enormous variations in the relative stability of their complexes (primarily with alkaline earths and alkali metals.¹⁰) The close similarity of some of these compounds to naturally occurring antibiotics such as valinomycin¹¹ and nonactin¹² have led to their use as model compounds for physiologically important processes (generally involving their ability to complex cations and to transport them across membranes). The role of crown ethers and cryptates in facilitating the dissolution of otherwise insoluble salts in organic solvents,¹³ and their usefulness as organic reagent carriers in "hostile solvent" environments (such as phase-transfer catalysts) has also been well documented.

The work has been extended to cover bi- and polycyclic cryptands with capping nitrogens (II). These molecules define a more rigid cavity

than their monocyclic predecessors and there is a concomitant stability enhancement of several orders of magnitude - e.g. the K^+ complex of [2.2.2] (II) has a stability constant 5 orders of magnitude greater than that of the corresponding crown ether amine with a pendant arm¹³ (III). The selectivity towards different cations is also enhanced, as the cavity size in the cryptands is more rigidly defined than in the more flexible monocyclic crown ethers.^{10,14} Some macropolycyclic cryptands are capable of incorporating more than one cation in the intramolecular cavity.¹⁵ Larger crown ether-amines and cryptands can be used to complex small molecules or cationic/anionic species (e.g. H_2O , NH_4^+ , Cl^- ,^{8,16,17}) and substantial changes in properties such as pK_a are to be expected when species such as the ammonium cation is bound into a cavity of this type. Unusual oxidation states are often stabilized by such species; Na^- , K^- , Rb^- and Cs^- are reported to be stabilized by [2.2.2] cryptand.¹⁸ A considerable variety of 'host-guest' complexes have been synthesised by Cram and coworkers,¹⁹ in which large macrocyclic and cryptate-like structures with molecular weights of the order of hundreds have been engineered to provide specific cavities which are "recognized" by smaller organic molecules, recently host molecules have been synthesised which can recognize chiral 'guest' molecules, in an effort to explain such natural phenomena as enzymatic catalysis.¹⁹

1.3 Nitrogen Containing Macrocycles

The bulk of this work deals with macrocyclic species with only one ring and nitrogen donors, as well as their linear analogues. These form a different category from the crown ethers and cryptands, and are characterized by the diverse reactions with transition metal cations rather than with alkali metals and alkaline earths.

1.3.1 Synthetic Methods

Although the synthetic tetraazamacrocyclic [14]aneN₄ (cyclam) (IV) was reported as long ago as 1936²⁰ it was not investigated further - indeed

its metal complexes with cobalt(III) and nickel(II) were not reported for a further 30 years.^{21,22}

1.3.1.1 Template Cyclizations

The 1960's heralded the start of macrocyclic coordination chemistry in earnest when the reaction of *tris* ethylenediamine nickel(II) perchlorate with acetone was shown to yield the macrocycles (V) and (VI) (Scheme 1).²³

SCHEME 1

The formation of an N_2S_2 macrocycle (VII) was reported soon thereafter²⁴ (Scheme 2)²⁴ and the self-condensation of *o*-aminobenzaldehyde in the

SCHEME 2

presence of nickel(II) was found to produce a mixture of the macrocyclic triamine (VIII) and tetramine (IX) (Scheme 3).²⁵

SCHEME 3

An unusual condensation of this type involves the formation of a macrocyclic complex with five nitrogen donors from phthalonitrile in the presence of uranyl chloride to give a compound trivially known as "superphthalocyanine" (X) (Scheme 4).²⁶ Attempts to replace the

metal with other transition metals however, inevitably leads to ring contraction to form the more usually expected phthalocyanine.²⁷

It was recognized that the cyclization reactions represented by these schemes had in common the directing influence of the transition metal,^{24,28} which was responsible for holding the coordinated ligand in a specific geometric orientation and this could facilitate the reaction with the other part of the potential macrocycle, thereby giving improved yields or leading to otherwise inaccessible products. At the same time the formation of the expected polymeric byproducts is suppressed. (Typically, the yield for preparation of cyclam by the non-template method is ~5%²¹ and using a nickel(II) template is ~20%²⁹). In fact, it has been shown that many of these reactions also proceed in the absence of a metal template in good yield if the appropriate reaction conditions are used³⁰. These template syntheses have been extended to include

a variety of amine-carbonyl condensations in the presence of transition metals, and also to include different heteroatoms, predominantly for systems consisting of four heteroatoms, but also three, five, six and even larger. Thus the nickel(II) complexes of linear triamines, tetramines and bis-diamines can be condensed with acetone to give compounds of the type XI, XII, XIII respectively by simple Schiff's base condensation.^{31,32,33}

XI

XII

XIII

Similarly the reaction of $\text{Ni}_2(\text{trien})_3\text{Cl}_4$ with isopropylaldehyde in the presence of ZnCl_2 yields compound XIV.³⁴

XIV

The Jäger-type macrocycles are formed by the reaction of a bis- β ketoiminato complex XV with the appropriate linear diamine.³⁵ Cyclisation reactions involving condensation of metal complexes of dialdehydes like XVI with diamines have been used to synthesise a wide variety of macrocyclic species with (usually) four donor groups.³⁶⁻³⁹

The imine linkages that are formed in all these amine-carbonyl condensations can in general be reduced with borohydride, cyanoborohydride or hydrogen/platinum²⁹ to the more stable amines. Complexes capable of incorporating two metal atoms have been prepared by the same general methods to study the interaction of the two metal ions held in close proximity.⁴⁰

More recently, Sargeson and co-workers have prepared a series of clathrochelates of the type XVII by condensation of [Co(en)₃]³⁺ and formaldehyde with ammonia⁴¹ or nitromethane⁴². Similar reactions

XVII

XVIII

in which nitroethane,⁴³ methylamine⁴⁴ or other nucleophiles capable of forming only two bridges are used, give complexes of the type XVIII.^{43,44}

Another method that has been widely adopted involves the condensation of 2,6-diacetylpyridine with a wide variety of linear or branched chain⁴⁵ amines or ethers (containing two primary amine groups) in the presence of a transition metal cation to yield macrocyclic Schiff's bases (XIX) with three or more amine donor groups.⁴⁶⁻⁴⁸

$Y =$ linear or branched
chain alkylamine or
ether linkage

XIX

Different ligands may be formed by varying the number and nature of the donor groups, chelate ring "bite" sizes, or the branching in the part of the ligand labelled 'Y'. The pyridine ring and two adjacent

imine linkages require the three nitrogen donors shown to be coplanar. The more flexible cyclic pentamine ($Y = -(\text{CH}_2)_2\text{NH}(\text{CH}_2)_2\text{NH}(\text{CH}_2)_2-$)⁴⁹ and branched pentamines ($Y = -(\text{CH}_2)_3\text{N}(\text{R})(\text{CH}_2)_3-$; $\text{R} = -(\text{CH}_2)_2\text{N}(\text{CH}_3)_2$, $-(\text{CH}_2)_2\text{OH}$)⁵⁰ have been prepared by hydrogenation of the imine groups. Spectral, magnetic and electrochemical studies of the iron(II), cobalt(II), nickel(II) and copper(II) complexes have been performed. The pH dependence of the structure of the branched chain tetramine with the additional coordinating group on the branch has also been investigated.^{50,51} In a further extension of this work a potentially decadentate N_6O_4 -donor set macrocycle (XX) has been synthesised first

XX

as a binuclear lead(II) complex (using all ten donor atoms),⁵² and then as a set of mononuclear complexes, in which only the N_6 donor set is utilized.⁵³

The reaction of glyoxal with $\text{Ni}(\text{trien})^{2+}$, followed by reduction and removal from the metal (with cyanide) (Scheme 5)²⁹ has been extended to a variety of different tetramines.^{29,54}

SCHEME 5

The corresponding cyclisations with 2,3-butanedione have also been effected to yield diimines and tetraimines⁵⁵ (XXI, XXII).

XXI

XXII

1.3.1.2 Non-template condensations

Despite the advantages of such template directed syntheses (selection of a particular product by variation of the metal used,^{26,52} improved yields,^{21,29} shorter reaction times, prevention of polymerization etc) there are often considerable disadvantages. The macrocycle is generally formed around the transition metal, which must be removed if complexes with different metals are required. The orientation of the

reacting groups in the coordinated ligand may preclude cyclisation occurring altogether.

It is sometimes possible to prepare the same ligands in the absence of transition metals. For instance, the first published template synthesis²³ involving $\text{Ni}(\text{en})_3^{2+}$ and acetone takes several days and produces a mixture of isomers that must be separated by fractional crystallization. It is possible to prepare the free ligand more conveniently and in good yield (62-73%) in the absence of the transition metal template by reaction of the monoprotonated ethylenediamine with acetone or mesityl oxide³⁰ and the saturated macrocycles can be obtained by subsequent borohydride reduction. Reactions forming macrocyclic ligands from species containing two terminal aldehydes are also known to proceed in the absence of a metal template^{36,56,57} (alternatively in the presence

of a metal). The reaction of ethylenediamine with benzylidene acetone in the presence of K_2CO_3 has also been shown to produce a macrocycle in good yield in the absence of a template.⁵⁸

Another potentially versatile synthesis apparently not relying on the template directing influence of a metal has been reported.⁵⁹ It involves the condensation of the bisulphite adduct of glyoxal with a linear polyamine in aqueous solution in the presence

of calcium hydroxide. Thus, for example, triethylenetetramine reacts to yield a mixture cis- and trans- isomers of 1,4,7,10-tetraazacyclodec-2-ene([12]-2-eneN₄) (XXIII) in 75% yield (Scheme 7).

SCHEME 7

Likewise, commercial tetraethylene pentamine is reported to give the corresponding cis- and trans-1,4,7,10,13-pentaazacyclopentadec-2-ene ([15]-2-eneN₅) in 68% yield. Hydrogenation of both the tetraaza- and pentaazamacrocycles was reported to yield the saturated macrocyclic amines [12]aneN₄ and [15]aneN₅ respectively. The condensation of triethylenetetramine with glyoxal in the absence of calcium hydroxide has been reported to yield compound XXIV, and similar polycyclic products were obtained with other linear tetramines.⁶⁰

XXIV

Attempts to prepare the macrocyclic amines in our laboratories by the former method have been unsuccessful, although good yields of pure polycyclic amines such as XXIV are produced by the reactions even in the presence of calcium hydroxide (see Experimental). In the absence of any later reports on this method or its utilization it must remain somewhat suspect, particularly in light of the fact that commercial tetraethylene pentamine (as used in the reported synthesis) has been shown to be only 15% pure,^{61,62} yet a 68% yield is reported!

1.3.1.3 A Versatile General Method

Quite different approaches are required to produce fully saturated unsubstituted macrocyclic amines. The previously listed methods all produce either macrocyclic complexes or ligands containing aromatic groups, methyl substituents or sites of unsaturation. The first methods used for the synthesis of the "bare-backbone" macrocycles involved the use of high dilution techniques in which a variety of tetraazamacrocycles were prepared by reaction of linear diamines with diacylhalides⁶³ to give the diamides (XXV) (Scheme 8). These were

$$m, n = 2, 3 \text{ or } m = 6, 12 \text{ } n = 3$$

reduced with lithium aluminium hydride to produce the corresponding cyclic amines. Likewise cyclam (IV) can be prepared in low yield by condensing 1,9-diamino-3,7-diazanonane (2,3,2-tet) with 1,3-dibromopropane in alcoholic potassium hydroxide under conditions of high dilution.²¹ Triazamacrocycles of ring size 10-12 were prepared similarly by reacting tosylated linear amines with 1,3-dibromopropane in dimethylformamide/potassium carbonate under conditions of high dilution followed by hydrolysis of the tosyl groups.⁶⁴

A major improvement in this technique occurred in 1974 when Richman and Atkins reported a general synthetic method⁶⁵ that did not involve the use of high dilution techniques, gave good yields and was generally applicable to nitrogen and oxygen containing macrocycles containing three to seven heteroatoms, and various bite sizes between donor atoms. The method involves the condensation of two halves of the target macrocycle in a dipolar aprotic solvent (Scheme 9). One half has the sodium salts of sulphonamides as the two terminal groups and the other has two terminal sulphonate ester leaving groups. Unlike the terminal dihalides used by Stetter and Roos,⁶⁶ the sulphonate esters

$\text{X} = \text{OTs}, \text{OMs}^{65}, \text{halide}^{66}$

$\text{Y}, \text{Z} = \text{tosylated alkylamine or ether linkages}$

SCHEME 9

do not require high dilution techniques to produce the macrocycle. A later report elaborated on the method, reporting yields for a range of 36 oxygen and nitrogen-containing N-tosylated macrocycles containing up to eight nitrogen atoms.⁶⁷ A comparison of yields for $\text{Ts}_4\text{-[12]aneN}_4$ using a variety of leaving groups (X in scheme 9) highlights the superiority of the method, with quoted yields for -OTs (80%), -OMs (66%), -Cl (42%), -Br (40%) and -I (25%).⁶⁷

The method has been utilized in the synthesis of a variety of macrocyclic ligands. The entire range of triazamacrocycles $\text{a,b,c-[N}_3\text{]}$ (XXVI) has been synthesised;⁶⁸ likewise with the same

$\text{a,b} = 2,3$
 $\text{c} = 2-6$

XXVI

notation the tetraazamacrocycles ($\text{a,b,c,d} = 2,3$; $\text{a,b,c} = 2$, $\text{d} = 4,5,6$; $\text{a,c} = 2$, $\text{b} = 3$, $\text{d} = 4,5$)^{65,67,69,70,91}, pentaazamacrocycles ($\text{a,b,c,d,e} = 2,3$; $\text{a,b,c,d} = 2$, $\text{e} = 4,5,6$)^{65,67,71,72,91} and several hexaazamacrocycles ([18]aneN_6 , [21]aneN_6 , TC-[18]aneN_6 ^{†73}; [24]aneN_6 ⁷⁴) have been synthesised, and there have even been reports of a heptaazamacrocycle ([21]aneN_7)^{65,67} and an octaazamacrocycle ([32]aneN_8).⁷⁴

[†] See appendix

Another route to hexaazamacrocycles was reported as the byproduct of an attempted synthesis of a triazamacrocycle. Thus the complex $\text{Ni}([20]\text{aneN}_6)(\text{ClO}_4)_2$ was prepared from the product of a reaction designed to produce $[10]\text{aneN}_3$.⁷⁵ Further reports revealed that not only was the cyclic hexamine formed in the reaction, but also a linear hexamine, presumably the result of a 2+2 condensation reaction.⁷⁶ This is in accord with the original observation of the formation of significant amounts of the 2+2 cyclization products in the preparation of $\text{Ts}_3\text{-}[12]\text{ane-1,4,7-N}_3$ and $\text{Ts}_3\text{-}[13]\text{ane-1,4,7-N}_3$.⁶⁵

Richman and Atkins' method has recently been used to prepare selectively protected tri- and hexamines (by protection of the non-terminal aza-groups of the reactants with benzoyl rather than tosyl groups, and subsequent selective hydrolysis),⁷⁷ and for the preparation of hexaazamacrocycles with larger bite sizes between two sets of N_3 -donor groups,⁷⁸ (XXVII) with the intention of investigating binuclear transition metal complexes. The two large bite sizes would be expected to render

XXVII

n = 3-5

the normal octahedral coordination of these ligands around a single transition metal less favourable with respect to a bis-triaza coordination pattern involving separate metal cations, held in close proximity.

A variety of C-methylated derivatives of macrocyclic triamines has been prepared by this method: (Me[9]aneN₃),⁷⁹ Ts₃-2,2-Me₂[9]aneN₃, Ts₃-2-Me[10]aneN₃, Ts₃-3-Me[10]aneN₃, Ts₃-2-Me[11]ane-1,4,8-N₃, Ts₃-2,2-Me₂[11]ane-1,4,8-N₃, Ts₃-2,3-Me₂[11]ane-1,4,8-N₃^{80,81} and the synthesis of methylated triazamacrocycles using different coupling schemes to prepare the same target macrocycles has been extensively investigated.

The greatest disadvantage of the method is the inefficiency of removal of the protecting tosyl groups and subsequent isolation of the free amines. Prolonged heating of the toluenesulphonamides with 97% sulphuric acid has been used to effect the cleavage,⁶⁷ or alternatively refluxing with 40% hydrogen bromide in glacial acetic acid,⁸² either in the presence or absence of phenol, acting as a bromine scavenger. Both methods can have disadvantages (variable yields, prolonged reaction time, difficulty of workup) and a variety of other methods are available. Electrochemical methods,⁸³ dissolving metal reductions (lithium in propylamine,⁸⁴ sodium in liquid ammonia,^{85,86} alkali metals in hexamethyl phosphorustriamide,⁸⁷ sodium/naphthalene in 1,2-dimethoxyethane⁸⁸) and reductions involving sodium dihydrobis(2-methoxyethoxo)aluminate (SMAH-Na[AlH₂(OCH₂CH₂OCH₃)₂]⁸⁹ in organic solvents, have all been reported as methods of detosylation.

1.3.2 Pentaazamacrocyclic Ligands and Their Analogues

The paucity of reports on pentaazamacrocyclic ligands is apparent from the previous sections. At the commencement of this work, only superphthalocyanine²⁶ (X), the 2,6-diacetylpyridine derivatives (XXVIII, XXIX),^{47,49} [15]aneN₅ (XXX, n=2)⁶⁵ and very few others had been reported. Since then, reports of the ligands [16]aneN₅ (XXX, n=3)⁶⁷ and [17B]aneN₅ (XXXI)⁹⁰ have appeared. A recent paper⁹¹ reports the

synthesis of 17-, 18- and 19-membered macrocycles (XXX, n=4,5,6).

There has been a report of a planar quinquedentate condensation product of 2,6-diacetylpyridine with 2,9 di-(1-methylhydrazino)1,10-phenanthroline (XXXII) and the bipyridyl analogue.⁹² A branched macrocyclic tetramine with one pendant amino group (XXXIII)^{45,50} and a macrocyclic triamine with two pendant amino groups (XXXIV)⁹³ have also been reported.

a

XXXIII

b

XXXIV

Even the linear pentamines have received scant attention. Only tetraethylenepentamine (tetren) (XXXV), its branched chain isomer 'trenen' (XXXVI),⁹⁴ the heptamethylated tetren analogue Me₇-tetren (XXXVII),⁹⁵ a series of bis-imidazolyl polyamines (XXXVIII),⁹⁶ bis-pyridyl amines (XXXIX)⁹⁷ and a branched pyridine derivative of ethylenediamine (XL)⁹⁸ have been reported.

XXXV

XXXVI

XXXVII

n=2,3

XXXVIII

n=2,3

XXXIX

XL

1.4 Properties of Transition Metal Complexes of Macrocyclic Amines

The properties of transition metal complexes of macrocyclic amines differ considerably from those of their straight chain analogues and much of the work reported in the literature concerns their unusually high stability and attempts to relate this to structural constraints, kinetic, spectroscopic, magnetic and electrochemical properties.

1.4.1 Macrocyclic Effect and the Stability of Copper and Nickel Complexes

1.4.1.1 Tetraazamacrocycles

The extreme stability of the red form of the copper(II) complex of tet a (meso) when compared with straight chain analogues was noted by Cabiness and Margerum, and led them to coin the term "macrocyclic effect"⁹⁹ by analogy with the well known chelate effect.¹⁰⁰ The 10^4 fold stability enhancement relative to $[\text{Cu}(2,3,2\text{-tet})]^{2+}$ could not be explained merely by the presence of an extra chelate ring and the concomitant increase in translational entropy. In the absence of reliable enthalpy and entropy data, it was tentatively attributed to differences in the configuration and solvation of the free ligand compared with its linear counterpart. The situation was further complicated when crucial enthalpy data for various macrocycles based on temperature dependence of the equilibrium constants obtained from different laboratories could not be reconciled. In the $[\text{Ni}(\text{cyclam})]^{2+}$ system (which is six orders of magnitude more stable than the $[\text{Ni}(2,3,2\text{-tet})]^{2+}$ analogue) it was shown from spectroscopic determination of the stability constant that a favourable enthalpy term was almost solely responsible for the macrocyclic effect with only a small possible configurational entropy term contributing.¹⁰¹ As the nickel-amine

bond strengths are not significantly different, the differences in enthalpy were assigned to decreased ligand solvation of the macrocycle, as there are less amine-hydrogen-bonded water molecules to be displaced in the complexation reaction. Conversely, polarographic determination of the temperature dependent equilibrium constant of $[\text{Cu}(\text{cyclen})]^{2+}$ (cyclen = [12]aneN₄) suggested that the macrocyclic effect was governed entirely by a more favourable entropy term¹⁰². This confusion led to the investigation of a large range of macrocyclic complexes (mainly tetraaza, but also some tri- and pentaaza) by both microcalorimetric¹⁰³ and polarographic¹⁰⁴ methods.

A redetermination of the original values obtained by Hinz and Margerum using microcalorimetric techniques¹⁰⁵ led to a substantially lower $\Delta H_f^\ominus$ for the $[\text{Ni}(\text{cyclam})]^{2+}$, and thus apparently removed the inconsistency between the copper(II) and nickel(II) results. The macrocyclic effect for these complexes was postulated to include a favourable entropy term (due to the fact that the free ligand is already in an entropically favoured state for coordination) and an enthalpy term that varies mainly with the match between the cation size and the size of the macrocyclic cavity.¹⁰⁵ Some doubt has also been cast on the validity of the polarographic studies by disagreements noted with calorimetrically determined thermodynamic data.¹⁰⁶ The standard enthalpies of formation of 2,3,2-tet and [14]ane-1,4,8,11-N₄ have been determined from the standard enthalpies of sublimation and vapourization,¹⁰⁷ and these support the original conclusion reached by Hinz and Margerum¹⁰¹ that for this system at least, the macrocyclic enthalpy is almost entirely due to the difference in hydration enthalpy of the uncoordinated ligand.

The stability constants of the nickel(II) complexes of [14]ane-1,4,7,10-N₄, [15]ane-1,4,8,12-N₄ and [16]ane-1,5,9,13-N₄ have been potentiometrically determined,¹⁰⁸ and the standard thermodynamic parameters have been derived. The results show that it is not possible to assign the macrocyclic effect to either enthalpic or entropic contributions exclusively. The nickel(II) complexes in the study all exhibit a macrocyclic effect resulting from a favourable entropy term, whereas [Ni(cyclam)]²⁺ apparently derives its macrocyclic effect from both the favourable entropy term and a large favourable enthalpy term.

Stability Structure Correlations. Variations in $\Delta H_f^\ominus$ for copper(II) and nickel(II) complexes as a function of macrocyclic ring size have been examined for the range of 12-16 membered tetraaza-macrocycles.^{103,105,106,109-115} The corresponding optimum cavity sizes have been determined from strain energy minimization calculations, and confirm that the cavity in the 14-membered tetraaza macrocycle is the favoured one for cobalt(III) and nickel(II).¹¹⁶

However, smaller apertures can also accommodate the metal by displacement of the metal out of the plane of the nitrogen donors, or by "folding" the macrocycle;¹¹⁷ but this also leads to a decreased $\Delta H_f^\ominus$.¹¹¹ For example the ideal M-N distance for a metal in the cavity of [12]aneN₄ (cyclen) is 1.83 Å¹¹⁶ which is too small to accommodate the copper(II) ion. The crystal structure of [Cu([12]aneN₄)](NO₃)₂ has shown the copper(II) ion to be displaced 0.51 Å above the plane of the four nitrogen donors of the macrocycle, which form square pyramidal arrangement with the fifth site occupied by a NO₃⁻ ion, thus bringing the Cu-N bond lengths (Cu-N 2.00, 2.02 Å) back within the normally observed range.¹¹⁸ (Average 2.01 Å for copper polyamines).¹¹⁹

Larger rings are accommodated not by lengthening of the Cu-N bonds (with consequent weakening) but by distortion of the carbon skeleton (which leads to a decrease in the heat evolved during complexation, and therefore the stability of the complex), as shown from the crystal structure determination of $[\text{Cu}([15]\text{aneN}_4)](\text{ClO}_4)_2$ which shows significant tetragonal distortion of the four donor nitrogens, and the "middle" six-membered ring has an unfavourable "flattened sofa" conformation.¹²⁰

The sequence of chelate rings has also been shown to have considerable bearing on the stability and structure of complexes - for $[14]\text{aneN}_4$, the two different isomers $[14]\text{ane-1,4,8,11-N}_4$ (cyclam) and $[14]\text{ane-1,4,7,11-N}_4$ (isocyclam) have been investigated. The ΔH_f° of the copper(II) complex with the less symmetrical isomer is considerably smaller ($-27.8 \text{ kcal mol}^{-1}$) than that of its symmetrical counterpart ($-32.4 \text{ kcal mol}^{-1}$)¹⁰⁶ despite the fact that both macrocycles have the same cavity size. Presumably the two adjacent six-membered chelate rings require a greater distortion of the ligand framework than the isomer with alternate five- and six-membered chelate rings (a similar effect has been reported for complexes of linear amines¹²¹⁻¹²³). A less favourable orientation of the nitrogen donor atoms in $[\text{Ni}(\text{isocyclam})]^{2+}$ (and consequent weaker bonding) is also suggested by the shift of λ_{max} from 503 nm to 550 nm, and by the greater extinction coefficient ($100 \text{ dm}^3 \text{ mol}^{-1} \text{ cm}^{-1}$ for $[\text{Ni}(\text{cyclam})]^{2+}$; $172 \text{ dm}^3 \text{ mol}^{-1} \text{ cm}^{-1}$ for $[\text{Ni}(\text{isocyclam})]^{2+}$) which is indicative of a less symmetrical arrangement of the donor atoms.¹⁰⁶

1.4.1.2 Pentaazamacrocycles

The formation constants and thermodynamic data for the copper complexes $[15]\text{aneN}_5$, $[16]\text{aneN}_5$ and $[17\text{B}]\text{aneN}_5$ have been determined

polarographically,⁹⁰ but in the absence of any confirmatory data should be treated with care in light of the substantial variations between the data obtained polarographically and microcalorimetrically for tetraazamacrocycles. The presence of $[\text{Cu}(\text{OAc})]^{+}$ as a reactant species in the systems that were studied, and the fact that only three relatively closely spaced temperatures were used to construct the Arrhenius plot, limit the reliability of the data. The authors conclude that for these copper complexes the macrocyclic effect is due to a favourable enthalpy term, and that the entropy term is similar for all three complexes (and for tetraethylenepentamine¹²⁴) with little effect on the stability.

1.4.1.3 Hexaazamacrocycles

The stability of the complexes formed by [18]aneN₆ (hexacyclen) and its linear analogue pentaethylenhexamine (2,2,2,2,2-hex) with a variety of cations has been investigated polarographically (for mercury(II)) and potentiometrically (for cobalt(II), nickel(II), copper(II), zinc(II), cadmium(II) and lead(II) as well as potassium, calcium, strontium and lanthanum).¹²⁵ It was not possible to study the copper(II) complexes polarographically as an irreversible reduction wave was observed. Furthermore, the titration curve could only be resolved for pH 2.8-3.7 by invoking the existence of CuHL^{3+} and $\text{CuH}_2\text{L}^{4+}$. It was presumed that at higher pH the CuL^{2+} species occurred, but this could not be established potentiometrically, presumably because of the magnitude of K_{ML} . The stability constants observed for these two species were $\log K_{\text{MHL}^{3+}} = 21.6$ and $\log K_{\text{MH}_2\text{L}^{4+}} = 16.1$ by contrast with pentaethylenhexamine ($\log K_{\text{ML}} = 25.1$).¹²⁶

Although the data is rather scanty, it would appear that the macrocyclic effect is not as significant as among the lower homologues, and this is attributed to the greater flexibility of the larger macrocycle. Interestingly, the ions K^+ , Ca^{2+} , Sr^{2+} and La^{3+} (more usually thought of as forming stable complexes with crown ethers) form complexes with [18]aneN₆ that are more stable than would normally be expected for amine complexes of non-polarizable ions, matching the stability of their complexes with the analogous 18-crown-6.^{1,125}

1.4.2 Magnetic, Electronic and Spectral Properties of Macrocyclic Complexes

Insight into the electronic configuration, stability and structure of macrocyclic complexes can be obtained by investigation of their ligand field spectra, magnetic properties, esr and nmr spectra and E_h values. There are certain properties that make macrocycles particularly valuable from this point of view. The ligand field around a metal ion can be systematically changed in small steps simply by varying the macrocyclic ring size, chelate bite sizes or sequences, and the substituents on the macrocyclic ring.

The planar stereochemistry and stability peculiar to the tetraazamacrocycles has been used to provide a constant equatorial environment while investigating the effect of various axial ligands on the ligand field parameters.¹²⁷ The stronger ligand field that is usually produced by a macrocyclic ligand (electroconstrictive effect) can lead to unusual ground state electron configurations, different spin states etc.

It is also possible to force a strained or normally inaccessible coordination geometry on the metal cation by synthesising a ligand with unusual steric requirements. For example, in the case of systems with extensive aromatic or olefinic character planar coordination of five donor groups may lead to pentagonal bipyramidal⁹² or pentagonal pyramidal¹²⁹ coordination. Steric crowding by the methyl substituents on the triazamacrocycle 2,4,4-Me₃-[12]-1-ene-1,5,9-N₃ on the other hand leads to the formation of five coordinate complexes both in the solid state and in aqueous solution.³¹

One of the more interesting properties of macrocycles is their ability to enhance the stability of oxidation states that would normally be unstable or unattainable for the solvated metal cation or in complexes with non-cyclic ligands.¹²⁷ The strong field of the in-plane metal-nitrogen bonds tends to increase the energy of the antibonding orbitals (which are essentially metallic in character) from which an electron must be removed to increase the oxidation state. The metal cation so formed would then normally be a strongly oxidising species, but the cyclic ligand effectively shields it from the solvent or other reducible species in solution. As a consequence of this protection, these redox changes are often reversible or quasi-reversible and thus cyclic voltammetry can be used to investigate the stability or accessibility of these higher oxidation states. In extreme cases, these complexes may be isolable for further investigation. In certain circumstances the metal complex may be stable in an unusually low oxidation state (e.g. [Co(N₅)]²⁺, [Ni(N₄)]⁺) and again the transition metal in an unusual state may be shielded from an environment in which it would not normally be stable.¹³⁰

1.4.2.1 Tetraazamacrocyclic Nickel(II) Complexes

By far the majority of the work has been done on the macrocyclic complexes containing a planar N_4 donor set. A considerable body of results has been brought together in a paper by Busch,¹³¹ discussing a wide variety of complexes of varying ring sizes, chelate ring sequences, substitution patterns, degrees of unsaturation and different axial donor groups. The in-plane ligand field splitting parameter Dq^{xy} is shown to be very strongly dependent on ring size, and is attributed to ring strain energy in the macrocycle. The effect of ring strain is exemplified by the $[Ni([13]aneN_4)]^{2+}$ system. The macrocycle is equatorially coordinated in the low-spin complex, but in the high-spin complex, where the metal ion is effectively larger, the ligand adopts the folded configuration to relieve the strain with the two additional donor ligands oriented cis-octahedrally. The degree of unsaturation is also shown to affect Dq^{xy} as expected, whereas the degree of C-methyl substitution, which also affects the ring strain, has been reported to have little effect, although this has since been questioned.¹ The Dq^z parameter, which is related to the axial field strength, is of considerable interest, as in the case of pentaazamacrocycles if all five nitrogens are coordinated and the metal retains its octahedral geometry, this term will relate to the fifth nitrogen. Dq^z is shown to affect Dq^{xy} linearly but weakly, though is itself rather more strongly affected by variations in Dq^{xy} . It is also decreased by the presence of axial methyl groups on the ligand, and out-of-plane ring strain in the part of the macrocyclic ring connected to the axial nitrogen may well have the same effect.^{1,131}

1.4.2.2 Pentaazamacrocyclic Nickel(II) Complexes

The nickel complex of pyaneN₅ (XLI) has been reported.⁴⁹

XLI

Unlike the parent di-imine complexes in which the planarity of the pyridine ring and adjacent imine linkages leads to planar pentagonal coordination of the ligand (for silver(I), cadmium(II), mercury(II), iron(III) and manganese(II) complexes),¹²⁸ the greater flexibility of this ligand permits octahedral coordination. The in-plane ligand field strength of the $[\text{Ni}(\text{pyaneN}_5)(\text{NH}_3)]^{2+}$ complex ($Dq^{xy} = 1124 \text{ cm}^{-1}$) is comparable with that of complexes of unstrained tetradentate macrocycles^{116,131} or with other $\text{Ni}^{\text{II}}\text{N}_6$ systems ($[\text{Ni}(\text{NH}_3)_6]^{2+}$ 1075 cm^{-1} ; $[\text{Ni}(\text{en})_3]^{2+}$ 1120 cm^{-1})¹³² suggesting that the size and flexibility of the macrocyclic ring are sufficient to ensure relatively strain-free coordination of the equatorial donor atoms. Conductivity measurements (in DMF, CH_3CN and CH_3NO_2) are consistent with the coordination of one additional donor ligand, and the room temperature magnetic moment (3.05–3.15 BM) falls in the range expected for high-spin distorted octahedral d^8 configuration. It is postulated that the pyridyl nitrogen, the two adjacent amines and one other form the equatorial

donor set, while the fifth nitrogen of the ligand and one monodentate ligand complete the coordination sphere.⁴⁹

The nickel complexes of tetraazamacrocycles with a fifth pendant nitrogen donor (either primary or tertiary amine or amide group) have also been synthesised (XXXIII, XLII, XLIII).^{45,50,133}

XLII

XLIII

It is proposed that the nickel(II) complex (XLII) is square pyramidal rather than trigonal bipyramidal on the basis of the reflectance spectrum.⁴⁵ (No solution spectra are recorded). For the nickel(II) complex with a tertiary amine donor group on the side chain (XXXIIIb) a pH dependent spectral change occurs.^{50,51} The complex can be square planar or octahedral (with a coordinated solvent molecule), depending on whether the pendant donor group is coordinated or not. The nickel(II) complexes with ligand of type XLIII have quite different spectra from those of the complex with the parent amine ($R=R'=\text{H}$),¹³³ but the authors are in doubt regarding the nature of the coordination geometry.

The nickel(II) complex of the tetrasubstituted cyclam derivative (XLIV) has been shown to have high-spin 5-coordinate geometry.¹⁵⁹

XLIV

It is postulated that the four tertiary amine groups and one pendant primary amine group are coordinated, irrespective of the nature of the anion. (The visible spectrum is characteristic five coordination, and remains unchanged even in the presence of strongly coordinating anions). The terminal primary amine groups can be selectively protonated in ethanol without destroying the complex, and this stabilizes the coordination of weak donor anions (perchlorate, tetrafluoroborate, bisulphate) to the axial coordination site, producing diamagnetic complexes that have electronic spectra consistent with five coordination (bands at 400 nm and 556 nm). Crossover from low-spin to high-spin is observed to depend on the ligand field strength of the axial group, indicative of square pyramidal geometry.

The nickel(II) complexes of [15]aneN₅, [16]aneN₅ and [17B]aneN₅ have been prepared,¹³⁴ but their structures have not been determined. The electronic spectra have been determined in aqueous solution and are consistent with distorted octahedral geometry. No protonated species of the complexes were observed, nor was there any evidence of low-spin four coordinate complexes, even at high ionic strength, so it is probable that all five nitrogen donors are coordinated. Five and

seven-coordinate geometry can be ruled out on spectral grounds. The ligand is thought to be folded in the complexes with four adjacent nitrogens providing the equatorial donor set, and the fifth together with a water molecule, occupying the axial coordination sites. The observed values of $\Delta H_f^\oplus$ for the nickel macrocyclic complexes are no greater than the values measured or predicted for the linear analogues (in fact the nickel(II) complex with tetren has a substantially higher $\Delta H_f^\oplus$ than that of the cyclic [15]aneN₅). It is pointed out that these macrocycles are more closely related to the linear tetradentate ligands appropriately modified than to the cyclic tetramines. The spectral characteristics are more similar to those of NiL₂X₂ (L = NN'-dialkyl 1,2 diaminoethane) than to the cyclic NiL'X₂ (L' = tetraazamacrocycles). Clearly the characteristics of the four nitrogens in the axial donor set are strongly affected by the lack of the fourth alkylene linkage which leads to a closed equatorial ring system in the macrocyclic tetramines. The similarity of the electronic spectra of [Ni([16]aneN₅)H₂O]²⁺, and [Ni([17B]aneN₅)H₂O]²⁺ to that of [Ni(tetren)(H₂O)]²⁺ also supports the view that these two macrocycles bear a strong resemblance to the linear amines.

Based on the $\Delta H_f^\oplus$ values, it is proposed that the equatorial N₄ donor set in [Ni([16]aneN₅)H₂O]²⁺ contains the six-membered chelate ring. (This is consistent with the known structure of [Co([16]aneN₅)Cl](ClO₄)₂¹³⁵). The equatorial field strength of the complexes of nickel(II) with [16]aneN₅ and [17B]aneN₅ are almost identical, and it is concluded that they both contain the same five- and six-membered chelate ring sequence in the equatorial plane. If this is the case, then the other six-membered chelate ring in the nickel(II) complex of [17B]aneN₅ must be linked to the apical nitrogen.

The axial field strength of this complex is greater than that of $[\text{Ni}([\text{16}] \text{aneN}_5)(\text{H}_2\text{O})]^{2+}$ and the authors claim that this is consistent with the diminution in ring strain that they expect to occur in the presence of an out-of-plane six-membered chelate ring. This suggested structure is the same as that postulated for the unsymmetrical cobalt(III) complex of $[\text{17B}] \text{aneN}_5$; however, for the cobalt(III) complexes the symmetrical isomer appears to be more stable (*vide infra*).

The anomalously high extinction coefficient, and the splitting of the first d-d band ($\sim 12 \text{ kK}$) in the electronic spectrum of $[\text{Ni}([\text{15}] \text{aneN}_5) \text{H}_2\text{O}]^{2+}$ is taken as evidence for considerable distortion from regular octahedral geometry, presumably resulting from the cumulative ring strain caused by successive linked five-membered chelate rings. Its spectrum is compared to that of the rhombically distorted $\text{Ni}(\text{N,N-dimethyl-ethylenediamine})_2(\text{Cl}_3\text{CCOO}^-)_2$.¹³⁶ All three nickel(II) complexes fit the linear correlation between $\Delta H_{\text{aq}}^\oplus$ and $n\nu_1$ (n = number of nitrogen donors) developed by Lever et al.¹²³ reasonably well.

1.4.2.3 Tetraazamacrocyclic Nickel(I) and Nickel(III) Complexes

Reports of nickel(I) complexes of macrocycles must be treated with caution. Magnetic susceptibility data alone is insufficient to assign oxidation states. For example, changes in the formal oxidation state of $[\text{Ni}(\text{Me}_4\text{-}[\text{14}]\text{-hexaenatoN}_4)]^{n+}$ ($n=0,1,2$) have been shown by e.s.r. to be related to changes in the ligand and not the metal.¹³⁷ Several fully saturated tetraazamacrocyclic nickel(I) complexes have been prepared, and the lack of π electrons, together with polarographic evidence led to the conclusion that a genuine metal-reduction was being observed.^{138,139}

The nickel(III) state is far better documented. A wide variety of tetraazamacrocyclic nickel(III) complexes have been prepared, both electrolytically¹³⁸⁻¹⁴⁰ and by chemical means (oxidation with HNO_3 ,¹⁴¹ NOBF_4 ,¹⁴² and $(\text{NH}_4)_2\text{S}_2\text{O}_8$ ¹⁴³). The simplicity of the electron transfer process has been demonstrated by cyclic voltammetry (in acetonitrile), and the e.s.r. spectra are consistent with low spin d^7 nickel(III) in an octahedral environment with two equivalent axially coordinated CH_3CN molecules.^{138,139} The ease of oxidation of the complexes from $\text{Ni(II)} \rightarrow \text{Ni(III)}$ increases with increasing ring size, whereas ease of reduction from $\text{Ni(II)} \rightarrow \text{Ni(I)}$ increases as the macrocyclic ring size decreases. This is thought to be due to the different "ideal" metal-donor atom distances that each oxidation state requires.¹³⁹ A plot of $E_{1/2}^{\text{oxid}^n}$ vs $E_{1/2}^{\text{red}^n}$ for a wide range of tetraaza macrocycles showed a good linear correlation (slope = -1, intercept = 2.42 volts),¹⁴⁴ and this has been proposed as a method for confirming the existence of authentic nickel(I) and nickel(III) oxidation states in novel tetraazamacrocycles (as nickel(I) complexes in which the electron is delocalized over the ligand framework do not lie on the straight line). A good correlation was also shown to exist between $E_{1/2}(\text{Ni}^{2+}/\text{Ni}^{3+})$ and D_q^{xy} for high-spin nickel(II) complexes of saturated tetraazamacrocycles and a linear tetramine¹⁴⁵ by analogy with that observed for low-spin nickel(II) tetrapeptides in aqueous solution¹⁴⁰ and a range of cobalt(III) complexes.¹⁴⁶

1.4.2.4 Pentaazamacrocyclic Nickel(III) Complexes

The electrochemical oxidation of $[\text{Ni}(\text{pyaneN}_5)(\text{CH}_3\text{CN})]^{2+}$ shows a reversible process at 0.78 v (vs Ag/Ag^+ [0.1 M])⁴⁹ which is near the lower limit observed for tetraazamacrocyclic complexes of nickel(II).¹³⁹

Attempted oxidation with nitric acid led to dechelation, but $(\text{NH}_4)_2\text{S}_2\text{O}_8$ oxidation resulted in a light green solution of $[\text{Ni}(\text{pyaneN}_5) \text{H}_2\text{O}]^{2+}$, which was characterized by its low-temperature e.s.r. spectrum in methanol. The electron is reported to be in an orbital of primarily dz^2 character on the basis of the insensitivity of the e.s.r. spectrum to the lack of symmetry in the N_4 donor plane.

The electrochemical properties of the nickel(II) complexes of [15]aneN₅, [16]aneN₅ and [17B]aneN₅ have also been reported.^{71,147} They show a reversible one-electron oxidation in acetonitrile^{147,148}, and the e.s.r. spectra are consistent with d^7 nickel(III) in a low-spin octahedral⁴⁹ environment. The $E_{1/2}$ values are lower than those of most of the tetraazamacrocyclic complexes of nickel(II); they are also rather insensitive to ring size, in marked contrast to the tetraaza-analogues which display a strong dependence of $E_{1/2}$ on ring size. It is concluded that while addition of a fifth (apical) nitrogen donor enhances the stability of the nickel(III) state, the corresponding absence of the completed equatorial ring system of the N_4 donor macrocycles leads to a weakening of the axial stabilization, and thus reduces the stability of the nickel(III) state. (The removal of this axial bridge also reduces the strong dependence of $E_{1/2}$ on the macrocyclic ring size). The continuation of these two opposing trends is evident in the compressed octahedral $[\text{Ni}([\text{18}] \text{aneN}_6)]^{2+}$ system,⁷¹ for which the $E_{1/2}$ value is intermediate between those of the N_4 and N_5 donor systems.

1.4.2.5 Copper Complexes

As a consequence of the Jahn-Teller effect, the coordination geometry of copper(II) is severely distorted from normal octahedral or tetrahedral symmetry.¹⁴⁹ Thus elongation of two trans bonds

may occur for six-coordination, and in the limiting case this is indistinguishable from square planar or distorted tetrahedral geometry. Five-coordination is also important and may take the form of trigonal-bipyramidal or square-pyramidal coordination. The interpretation of spectral data is complicated even though the d^9 configuration can be treated analogously with the one electron (d^1) system.^{149,150} The visible spectrum usually comprises a broad asymmetric envelope corresponding to several d-d transitions, but it is generally not possible to resolve these. (More information may be obtained by measuring the polarized single-crystal spectra, but experimentally this is considerably more involved). Correlations of spectral characteristics with structure and stability are thus far less well established than for nickel(II). Although a correlation between $\lambda_{\max}$ and $\Delta H_f^\ominus$ has been found to hold for a considerable number of copper(II) complexes of linear amines,^{122,151,152} the relationship appears not to hold for the tetraaza- and pentaaza-macrocyclic complexes.

The spectroscopic and electrochemical properties have been determined for a range of copper complexes of saturated macrocyclic ligands with N_4 , N_5 , N_6 , N_4S and N_4O donor sets.⁶ In each case an equatorial N_4 donor set is presumed to be present. Good correlation was observed between $E_{1/2}$ and ν_{d-d} and $E_{1/2}$ and g_{11} for those ligands containing only nitrogen donors. Changing the fifth (axial) donor atom from N to O to S has no effect on $\lambda_{\max}$ or g_{11} , but strongly affects $E_{1/2}$, leading to progressively greater stabilization of the copper(I) state.

There is an additional peak at ~800 nm in the pentaazamacrocyclic complexes which is indicative of axial coordination in a five-coordinate system.¹⁴⁹ (This is of particular interest in the $[Cu([15]aneN_5)]^{2+}$ species, for which the physicochemical data are reported to closely

resemble those of the (bleomycin)-copper(II) complex¹⁵³ as the coordinated primary amino group has been implicated in the molecule's anti-tumour activity). It is proposed that the 13- and 14-membered tetraazamacrocyclic complexes adopt square planar geometry, whereas axial coordination of a fifth donor group, or coordination of the smaller (12-membered) N_4 macrocycle results in off-planar distortion to square pyramidal geometry. The marked shift in λ_{max} for the $[\text{Cu}([18]\text{aneN}_6)]^{2+}$ is postulated to be the result of distorted octahedral coordination.

Two structural determinations of copper(II) pentaazamacrocyclic complexes have been reported. One involves the 15-membered pyaneN₅ ligand,¹⁵⁴ and the other a 20-membered dibenzo-diimine ligand.¹⁵⁵ The geometry of the cations is shown below. Both form distorted five-coordinate

XLV

XLVI

complexes in the solid state. Structure (XLV) is intermediate between square pyramidal and trigonal-bipyramidal geometry, with no Cu-N bond significantly longer than any other. Structure (XLVI) is distorted square-pyramidal with the Cu-N apical bond appreciably longer than the

other four ($2.22 \text{ \AA}$ vs $2.01 \text{ \AA}$ average for the other four). However, both structures are subject to steric restraints caused by aromaticity, so it is difficult to draw conclusions regarding the structural characteristics of saturated pentaazamacrocyclic complexes with copper(II).

A series of copper(II) complexes of tetraazamacrocycles with a pendant amide group (XLVII) have been synthesised.¹³³ Their electronic spectra are quite different from those of the copper(II) complex with the parent amine [14]ane-1,4,7,11- N_4 (isocyclam) which has only a single peak in the visible region of the spectrum. The pendant complexes all contain a further peak between 750 nm and 800 nm, and there is a shift in λ_{max} to longer wavelengths with increasing pH. This is consistent with a change from O-coordination to N-coordination of the amide group in the apical position^{149,156} although no structural data is available for confirmation. A preliminary report of the copper(II) complex

XLVII

XLVIII

XLIX

or

XLVIII has appeared.⁴⁵ The electronic spectrum contains a single peak in the visible region of the spectrum ($\nu_{d-d} = 620 \text{ nm}$) and the authors postulate that the complex has square pyramidal geometry (although no mention is made of the shoulder that would be expected at $\geq 800 \text{ nm}$ if this is indeed the case). The $[\text{Cu}(\text{pyaneN}_5)]^{2+}$ species has the expected spectral characteristics⁴⁹ (bands at 870 nm and 600 nm) for its geometry. The copper(II) complex of the related ligand XLIX has also been synthesised,⁵⁰ and the reflectance spectrum shows only one band at 572 nm. In acetone, this band shifts to 590 nm. The presence of a single band together with the analytical figures (which suggest that the complex is triperchlorate) would indicate that only four nitrogen donors are coordinated. Conceivably the terminal $-\text{NMe}_2$ is not coordinated, and this is supported by the pH dependence observed for the corresponding nickel(II) complex.^{50,157}

1.4.2.6 Cobalt(III) Complexes of Tetraazamacrocyclic Ligands

The majority of cobalt complexes of linear and macrocyclic amines involve d^6 low-spin (diamagnetic) octahedral geometry and lend themselves to reliable interpretation of the electronic spectra.¹⁵⁸ Busch and co-workers have investigated a wide range of tetraazamacrocyclic complexes of cobalt(III) varying not only the macrocyclic ring size¹⁶⁰ but also the degree and position of ligand unsaturation and substitution.¹⁴⁶ The average ligand field strengths of $\text{cis-}[\text{Co}([\text{12-16}] \text{aneN}_4)\text{CO}_3]^+$ ^{160,161} and $\text{cis-}[\text{Co}([\text{12-14}] \text{aneN}_4)\text{Cl}_2]^+$ ¹⁶⁰⁻¹⁶² have been determined from

$$Dq^{\text{av}} = \frac{1}{10}(\nu_1 T_1 + 1 A_1 + 3800) \text{ cm}^{-1} \quad 160 \quad 1.1$$

They all lie within a narrow range, and show no systematic trend,¹⁶³ suggesting that in the folded configuration the average ligand field strength is largely unaffected by macrocyclic ring size. The trans

complexes on the other hand can be fully analysed using a D_{4h} approximation^{158,160} as the ${}^1T_1 \leftarrow {}^1A_1$ transition is clearly split into bands corresponding to ${}^1A_2 \leftarrow {}^1A_1$ and ${}^1E^a \leftarrow {}^1A_1$. The ligand field strength in the axial plane containing the macrocyclic amine donors (Dq^{xy}) varies significantly with macrocyclic ring size, following the order $[13]aneN_4 \gg [14]aneN_4 > [15]aneN_4 > [16]aneN_4$.

This order correlates well with the size mismatch between the metal ion radius and the ideal M-N distance calculated for each macrocycle, rather than with the total strain energy associated with coordination.¹⁶⁰ Furthermore, there are two different configurational isomers observed for both $trans[Co([15]aneN_4)Cl_2]^+$ and $trans-[Co([16]aneN_4)Cl_2]^+$. In each case both isomers have different ideal cavity sizes, and the respective size mismatches correlate well with the Dq^{xy} values obtained.

On the other hand, the half wave potential for the Co^{2+}/Co^{3+} couple correlates well with calculated minimised strain energy for the trans-dichloro complexes, rather than with Dq^{xy} or Dq^z (it has previously been shown that the potential for the Co^{3+}/Co^{2+} couple is not sensitive to small variations in Dq^{xy} but quite sensitive to variations in the axial ligand field strength).^{146,164} This suggests that the strain energy is largely relieved on reduction. The relief of strain would presumably follow a different mechanism for those systems where the ring is undersized and those where it is oversized in relation to the size of the metal ion.

The tendency to form cis- and trans- complexes also reflects the steric requirements of the macrocycle. Thus the smallest ring $[12]aneN_4$ forms only cis-octahedral cobalt(III) complexes, $[13]aneN_4$ and $[14]aneN_4$ (which has the "ideal" cavity size for cobalt(III)) form both cis- and trans-complexes, while $[15]aneN_4$ and $[16]aneN_4$, which

could conceivably encounter steric crowding and can most readily spread equatorially around the transition metal form only trans-complexes unless forced to adopt a folded configuration by a bidentate ligand already cis-octahedrally coordinated. A correlation between the rate of hydrolysis of the trans dichloro cobalt complexes^{165,166} and their strain energy is postulated to be the result of relief from strain in a square pyramidal intermediate where the cobalt(III) ion is no longer constrained to occupy a site that is nearly coplanar with the four nitrogen donors.¹⁶⁶ A range of 14-membered tetraazamacrocyclic ligands have been used to investigate the effects of unsaturation and substitution in the absence of substantial ring size effects.¹⁶¹ Although increasing unsaturation results in increasing Dq^{xy} , it appears not to be as a result of π back-bonding (conjugated and non-conjugated diimines and tetraimines show the same effect) or effective ring size so it is postulated that the character of the metal-nitrogen σ bond is responsible for the enhanced ligand field strengths that are observed. The variations in the Co^{3+}/Co^{2+} reduction potential are comparatively small and appear to be unrelated to Dq^{xy} , consistent with the insertion of the electron into the dz^2 orbital. (This is in marked contrast with the Co^{2+}/Co^+ reduction potentials, which correlate with Dq^{xy} (of the cobalt(III) complex), and are unaffected by the nature of the axial ligands.¹⁶⁴ This is thought to be the result of a weakening of the cobalt-axial donor bonds with the consequence that the dz^2 orbital is no longer the lowest unoccupied orbital).

1.4.2.7 Cobalt(III) Complexes of Linear and Macrocyclic Pentamines

The $[\text{Co}(\text{pyaneN}_5)\text{X}]^{2+}$ ($\text{X} = \text{Cl}^-, \text{Br}^-, \text{NCS}^-, \text{N}_3^-, \text{NO}_2^-, \text{I}^-$) ($\text{pyaneN}_5 = \text{XLI}$) complexes and their electronic spectra have been reported.⁴⁹ The Dq^{av} values calculated for the three complexes with an N_6 -donor set ($\text{X} = \text{NCS}^-, \text{N}_3^-, \text{NO}_2^-$) and the Dq^{Z} and Dt values derived for the halo-complexes are similar to the corresponding values observed for $[\text{Co}(\text{NH}_3)_5\text{X}]^{2+}$ ($\text{X} = \text{Cl}^-, \text{Br}^-$), suggesting that there is little strain associated with coordination. (This is confirmed by a preliminary report of the crystal structure of $[\text{Co}(\text{pyaneN}_5)\text{Cl}](\text{ClO}_4)_2$ which shows undistorted pseudooctahedral coordination¹⁵⁴). The electronic spectra of $[\text{Co}([15]\text{aneN}_5)\text{Cl}]^{2+}$ and $[\text{Co}([15]\text{aneN}_5)\text{H}_2\text{O}]^{3+}$ have been reported,¹⁶⁷ but ligand field parameters were not calculated. The bands corresponding to the (${}^1\text{A}_2 + {}^1\text{A}_1$) and (${}^1\text{E}^a + {}^1\text{A}_1$) transitions in the spectra are not resolved so only Dq^{av} values can be derived. The spectral maxima are similar to those of the cis-carbonato complexes of the macrocyclic tetramines in which the amine is in a folded configuration.¹⁶⁰ The peaks are quite different from those obtained for the same complexes in this work (see experimental section) and from those of $[\text{Co}(\text{NH}_3)_5(\text{H}_2\text{O})]^{3+}$ ¹⁵⁸ and $[\text{Co}(\text{tetren})\text{Cl}]^{2+}$, which has also been the subject of ligand field analysis.⁹⁷

A range of chloro- and μ -peroxo-cobalt(III) complexes of various linear pentamines has been synthesised and values of Dq^{av} (the average ligand field strength) have been determined from their electronic spectra (the ${}^1\text{T}_1$ band is not split for these complexes so it is not possible to resolve Dq^{xy} and Dq^{Z}). A value for $\text{Dq}^{\text{ligand}}$ has been determined by subtracting the contribution of the sixth (chloro) donor group.⁹⁷

1.4.2.8 Cobalt(II) Complexes

A large variety of low spin cobalt(II) complexes with macrocyclic amines have been prepared, and most have been shown to be five-coordinate. The tetraazamacrocycles Me₂-pyo-[14]-trieneN₄ (LI)¹⁶⁸ and 5,7,7,12,14,14-Me₆[14]-1,4,8,11-tetraeneN₄ (LII)¹⁶⁹ form low-spin five-coordinate cobalt(II) complexes, and their electronic spectra have been interpreted in terms of trigonal bipyramidal and square planar geometry respectively. The macrocyclic ligand

1,4,8,11-Me₄[14]ane-1,4,8,11-N₄ (LIII) apparently forms a high-spin five-coordinate cobalt(II) complex,¹⁷⁰ but no attempt is made to relate the electronic spectral details to a specific geometry. The observed shifting of the absorption maxima in different solvents is thought to arise from axial coordination of a solvent molecule.

The cobalt(II) complex of the related ligand

1,4,8,11,13,13-Me₆[13]ane-1,4,8,11-N₄ (LIV) has been prepared in solution but not isolated.¹⁷¹ On the basis of a pH titration experiment, and its visible spectrum, it is assigned five-coordinate

structure (with a water molecule occupying the fifth coordination site), but few details are given. Both this complex and the previous one are stable in air, and do not undergo the oxygen uptake reaction normally associated with cobalt(II) polyamine complexes. The cobalt(II) complexes with [16]ane-1,4,7,10-N₄ and [16]ane-1,4,8,11-N₄ have been shown to be insensitive to oxygenation, but no structural or spectral data is given.⁹¹ Spectral and magnetic data for a series of complexes with saturated unsubstituted triazamacrocycles indicate that air stable high-spin five-coordinate cobalt(II) complexes are formed when the sixth coordination site is blocked by the backbone polymethylene groups.¹⁷²

A series of high-spin cobalt(II) complexes of the pentaaza-macrocyclic ligand LV containing a planar quinquedentate N₅-donor set

and two additional axial substituents have been prepared in good yield by template condensation.⁹² However, neither spectral data nor the oxidation reaction are investigated, although a stable cobalt(I) reduction product can be prepared.

No fully saturated air stable pentaazamacrocyclic complexes of cobalt(II) have previously been reported, although those of the linear pentamine Me₇-tetren (LVI) are known.⁹⁵ The diiodide and

LVI

diperchlorate are high-spin (d^7) and five coordinate in the solid state, and solution (methanol:acetone) spectra are consistent with distorted trigonal bipyramidal geometry with five coordinated amine groups. Although the mono-thiocyanato complex also has an electronic spectrum consistent with trigonal bipyramidal geometry, the infrared spectrum and conductivity measurements indicated that the anion is coordinated in place of one of the terminal tertiary amine groups.

1.4.3 Kinetics of Formation and Dissociation of Macrocyclic and Linear Complexes with Labile Transition Metals

1.4.3.1 Formation Reactions of Copper(II) Complexes

Considerable attention has been focussed on the formation rates of copper(II), nickel(II) and to a lesser extent cobalt(II) and zinc(II) complexes of triaza-,^{173,174} tetraaza-,^{102,174-188} and a few pentaaza-^{90,177} macrocycles. Formation rates have been determined for some copper(II) complexes in strongly basic aqueous solution¹⁷⁶

($[\text{OH}^-] \sim 0.1\text{--}2.0 \text{ M}$). Under these conditions of pH the amines are all present in their unprotonated form, and aqueous solutions of copper(II) contain predominantly $\text{Cu}(\text{OH})_3^-$ and $\text{Cu}(\text{OH})_4^{2-}$ species.¹⁸⁹ The resolved complexation rates of [14]ane-1,4,8,11- N_4 (LVII) and a linear analogue with only secondary amine donors (LVIII) are very similar, but are

LVII

LVIII

LIX

less than those of 2,3,2-tet (LIX) which contains two terminal primary amino groups.¹⁷⁶

The presence of methyl substituents on the alkyl backbone of the macrocycle was also shown to lead to decreased formation rates but cyclization itself appeared to have little effect.^{175,176} The observed formation rates are all less than would be expected on the basis of the Eigen-Wilkins mechanism,¹⁹⁰ so water loss is not rate determining. It was proposed that for complexation reactions with $\text{Cu}(\text{OH})_3^-$, Jahn-Teller inversion following first metal-nitrogen bond formation is rate determining.¹⁷⁶ For complexation with $\text{Cu}(\text{OH})_4^{2-}$ the rate determining step shifts to second bond formation for the macrocyclic ligands and the more sterically hindered linear amines.

In the pH region where $[\text{Cu}(\text{H}_2\text{O})_6]^{2+}$ is the predominant solvated species, the problem of ligand protonation has been circumvented by studying a series of polythiaether macrocycles and their linear analogues.¹⁹¹ The complexation kinetics with copper(II) were studied in aqueous methanol^{192,193} because of the limited solubility of the ligands in water but it was established that the only reactive solvated copper(II) species was $[\text{Cu}(\text{H}_2\text{O})_6]^{2+}$ over a wide range of solvent composition.¹⁹³ The rates were independent of acid concentration at constant ionic strength, as expected for a complexation involving only solvated copper(II) and an unprotonated ligand. The k_f values for the reaction of copper(II) with the linear thiaethers and [14]ane-1,4,8-N₃-11-S (LX) for which first bond formation would be

LX

the likely rate determining step¹⁹⁴ are larger than those for the cyclic thiaether complexation reactions, and are consistent with the values predicted¹⁹³ for rate determining first bond formation. Structural information¹⁹⁵ suggests that the uncomplexed cyclic thiaethers adopt the exo-conformation with ease, thus the first bond formation should be subject to little steric restraint. The smaller k_f values determined for the cyclic species should therefore correspond to a shift of the rate determining step to the point of second bond formation (i.e. ring closure). Variations in k_f for the different

cyclic ligands are presumed to reflect the relative ease of closure of five- and six-membered rings¹⁹⁶ and the degree of total ligand flexibility. The situation is quite different for amine ligands in the pH range where $[\text{Cu}(\text{H}_2\text{O})_6]^{2+}$ is the predominant solvated species. Various protonated forms of the ligand are present, and the reaction of the unprotonated species may well make a negligible contribution to the rate of reaction because of its extremely low concentration. Fully protonated ligands are totally unreactive but large variations in reaction rate are observed for different ligands with differing degrees of partial protonation. The pK_a values for macrocyclic amines may be substantially different from those of the corresponding linear amines of similar chain length.¹⁹⁷ The first protonation equilibrium of the macrocyclic amine may be enhanced through multiple hydrogen bonding. Subsequent protons experience greater repulsion in the macrocyclic amine as the centres of protonation are closer together than for the linear analogue.²¹

Two factors need to be considered in studying the formation rates. One is the relationship between complexation rates of a single ligand with differing degrees of protonation; the other is the relative rates of formation of linear and cyclic ligands exhibiting the same degree of protonation.

The ratio of complexation rates of H_nL and $\text{H}_{(n-1)}\text{L}$ can be divided into two categories.¹⁹⁸

(i)	$k_{\text{H}_{(n-1)}\text{L}}/k_{\text{H}_n\text{L}}$	$\sim 10-500$	1.2
(ii)	$k_{\text{H}_{(n-1)}\text{L}}/k_{\text{H}_n\text{L}}$	> 1000	1.3

If the rate determining step occurs early in the coordination of a multidentate ligand, and the protonation site is well removed from the initial coordination site, the effect of protonation is small, and

category (i) behaviour is observed as for the complexation of nickel(II) or copper(II) with linear tetramines and pentamines.^{199,200} For cyclic tetramines the relative rates generally correspond to category (ii).¹⁷⁸⁻¹⁸⁷

Margerum noted that the reaction of $[\text{Cu}(\text{H}_2\text{O})_6]^{2+}$ with $\text{H}_2(\text{tet a})^{2+}$ (tet a = meso-5,7,7,12,14,14-Me₆[14]ane-1,4,8,11-N₄) was exceedingly slow compared with that of $\text{H}(\text{tet a})^+$ ¹⁷⁵ ($k_{\text{HL}}/k_{\text{H}_2\text{L}} > 10^8$), and proposed that this was a result of the same strong electrostatic repulsion that made addition of a proton to $\text{H}_2(\text{tet a})^{2+}$ so thermodynamically unfavourable ($\text{pK}_2 = 10.4$, $\text{pK}_3 = 0.8$).⁹⁹ A systematic investigation of the series of tetraazamacrocycles [12]aneN₄ to [16]aneN₄¹⁸³ has shown that the complexation rate of the HL^+ species is independent of ring size, whereas that of H_2L^{2+} (at least for copper(II)) is strongly affected both by macrocyclic ring size and the arrangement of five- and six-membered chelate rings. A good correlation exists between pK_3 and $\log k_{\text{H}_2\text{L}}^{\text{Cu}}$ ¹⁸³ (even including both the isomeric 14-membered tetraazamacrocycles) suggesting that the same electrostatic repulsion is again experienced in both protonation and complexation. There is little variation (and no apparent correlation) for pK_2 and $\log k_{\text{HL}}^{\text{Cu}}$. The addition of a second proton (or $[\text{Cu}(\text{H}_2\text{O})_6]^{2+}$) to the monoprotonated ligand can take place at a site remote from the first proton, so electrostatic effects appear relatively unimportant. The formation rates of copper(II) complexes of triazamacrocycles appear to be anomalous¹⁷³ (k_f decreases with increasing ring size, and there appears to be no correlation between pK_a and k_f) hence electrostatic effects do not dominate. However, these ligands are known to coordinate facially,^{201,202} so conformational effects may predominate.

The formation rates of copper(II) complexes of [15]aneN₅, [16]aneN₅ and [17B]aneN₅ have been determined⁹⁰ in acetate buffered solution ($[\text{Cu}(\text{OAc})]^+$ being the reactive species) and at higher pH in unbuffered solution. The relationship between $k_{\text{H}_3\text{L}}^{\text{Cu}}$ and pK_4 for [16]aneN₅ and [17B]aneN₅ correlates well with that between $\log k_{\text{H}_2\text{L}}^{\text{Cu}}$ and pK_3 for the tetraazamacrocycles,¹⁸³ (see fig.1.1) suggesting that the same electrostatic effects may again be important. There is a lack of correlation between pK_3 and $\log k_{\text{H}_2\text{L}}^{\text{Cu}}$ (as with pK_2 and $\log k_{\text{HL}}^{\text{Cu}}$ for the tetraazamacrocycles) and the formation rate constant ratios fall into category(ii), consistent with the considerably smaller electrostatic repulsion present between the diprotonated pentamine and the copper(II) ion. A lack of rate enhancement for complexation with $[\text{Cu}(\text{OAc})]^+$ over $[\text{Cu}(\text{H}_2\text{O})_6]^{2+}$ is noted for monoprotonated tetraazamacrocycles¹⁷⁴ and diprotonated pentaazamacrocycles;⁹⁰ for diprotonated tetraazamacrocycles and triprotonated pentaazamacrocycles a marked (>hundredfold) enhancement is observed, indicating that the Lewis base may be involved in proton abstraction from the more highly proton congested macrocycle. The rates of formation of copper and nickel complexes with partially protonated macrocycles are generally three to four orders of magnitude slower than those of the corresponding linear amines.^{175,184}

Although the degree of N-alkylation of monodentate²⁰³ and bidentate^{204,205} amines has been shown to profoundly affect the complexation rate with nickel(II) (because of steric hindrance and variations in nitrogen basicity which affects the degree of internal conjugate base formation), the same effect is not observed for complexation rate of copper(II) and nickel(II) with tetraazamacrocycles. Thus for [14]ane-1,4,8,11-N₄, successive methylation of the nitrogen

Correlation Between $\log_{10} k_{H_n L}^{Cu}$ and pK_{n+1}^H

fig 1.1

donors does not give the reduction in formation rates expected from statistical considerations¹⁸⁰ if first bond formation were rate determining. Furthermore, for a series of N- and C-methylated derivatives of [13]aneN₄, the presence of even two methyl groups on the carbon β- to the nitrogen donors in the trimethylene bridge has been shown to have little effect on the complexation rate,¹⁷¹ whereas the presence of α-methyl groups has a profound retarding effect, lending further support to the hypothesis that the rate determining step has shifted away from the point of first bond formation.

1.4.3.2 Dissociation Reactions of Nickel(II) Complexes of Linear Amines

The kinetics of acid dissociation of metal complexes of linear polyamines have received scant attention since the original work by Wilkins showed that complex stepwise "unwrapping" of the ligand from the metal was involved.^{199,206} Studies on the nickel(II) complexes of diamines²⁰⁷⁻²¹⁰ and subsequent investigation of the reactions of [Ni(en)]²⁺ and [Ni(en)₃]²⁺ at higher acid concentrations^{211,212} has led to a good understanding of the dissociation mechanism over a wide range of acid concentration. A mechanism consistent with the entire measured pH-rate profile for [Ni(en)]²⁺²¹¹ is shown overleaf (Scheme 10).

SCHEME 10

The pathway represented by (I $\rightarrow$ II $\rightarrow$ III) is the acid-independent pathway which occurs even in the absence of acid. The acid-dependence that is observed from pH 7.3 to pH 4 corresponds to the pathway (I $\rightarrow$ II $\rightarrow$ IV $\rightarrow$ V) where protonation of the non-coordinated nitrogen assists the dissociation. From pH 4 to pH 1.5, where acid-independence is also observed, the chelate ring opening step I $\rightarrow$ II has become rate-determining. At the highest acid concentrations investigated, the acid-dependent pathway (I $\rightarrow$ I(B) $\rightarrow$ IV) becomes operative. This pathway involves proton attack on a loosely coordinated nitrogen or on a non-bonded nitrogen that has not yet been replaced by a solvent molecule in the inner coordination sphere (species IB). If the acid can coordinate to the metal complex, this pathway can contribute significantly to the dissociation rate even at pH 6.²¹³

Investigation of the stepwise dissociation observed for some multi-dentate ligands together with a comparison of different ligand systems has been used to elucidate the relative importance of different effects on the rate of chelate ring opening.¹⁹⁸ However, such comparisons must be made with considerable caution, as variations in rate constants can seldom be attributed to one factor alone, and comparisons need to be made over as wide a variety of complexes as possible. Furthermore, even for comparisons made at the same pH it is possible that for complexes with different ligands, different steps in the proposed mechanism may be rate-determining.

The labilizing effect of ring strain is shown clearly by the relative rate constants for first bond rupture of $[\text{Ni}(2,2,2\text{-tet})]^{2+}$ and $[\text{Ni}(2,3,2\text{-tet})]^{2+}$ (15 sec^{-1} ²⁰⁶ and 0.38 sec^{-1} ¹⁹⁸ respectively in $0.5 \text{ M } [\text{H}^+]$). The latter complex has been shown to be considerably more stable than the former because of the relief of the considerable cumulative ring strain effected by insertion of an extra methylene link in the middle chelate ring of the ligand.¹²¹ Other nitrogen donors attached to the metal have a labilizing effect. The first bond rupture rate constants for $[\text{Ni}(\text{en})]^{2+}$, $[\text{Ni}(\text{en})_2]^{2+}$ and $[\text{Ni}(\text{en})_3]^{2+}$ (0.15 sec^{-1} , 5.2 sec^{-1} , 86.6 sec^{-1} respectively in $0.2 \text{ M } [\text{H}^+]$),²⁰⁸ as well as those of the analogous rac-2,3-diaminobutane nickel(II) complexes (10^{-3} sec^{-1} in $1.08 \text{ M } [\text{H}^+]$,²⁰⁹ 0.26 sec^{-1} and 8.25 sec^{-1} in $0.2 \text{ M } [\text{H}^+]$ ²¹⁰) illustrate this effect. The presence of a positive charge on a group near the chelate ring of interest has an accelerating effect, as shown by the relative rate constants for ring opening in $[\text{Ni}(\text{N-propyl-ethylenediamine})]^{2+}$ and $[\text{Ni}(\text{H-2,2-tri})]^{3+}$ (0.32 sec^{-1} in $0.5 \text{ M } [\text{H}^+]$ and 3.0 sec^{-1} in $0.5 \text{ M } [\text{H}^+]$ ²⁰⁶). The effect of the proximity of the positive charge can be seen in the comparison of $[\text{Ni}(\text{H-tren})]^{3+}$ and

$[\text{Ni}(\text{H}-2,2,2\text{-tet})]^{3+}$ ring opening rate constants (0.22 sec^{-1} and 4.0 sec^{-1} in $0.5 \text{ M } [\text{H}^+]$).²⁰⁶ There are six bonds between the protonated species and the Ni-N bond of interest in $[\text{Ni}(\text{H-tren})]^{3+}$ but only three in $[\text{Ni}(\text{H}-2,2,2\text{-tet})]^{3+}$. Positive charges that are remote from the Ni-N bond do not affect the ring-opening rate. This is borne out by the similarity of the rate constants for ring-opening in $[\text{Ni}(\text{H}_2-2,2,2\text{-tet})]^{4+}$, $[\text{Ni}(\text{H}-2,2,2\text{-tet})]^{3+}$ and $[\text{Ni}(\text{H}-2,2\text{-tri})]^{3+}$ (2.1 sec^{-1} in $0.5 \text{ M } [\text{H}^+]$, 4.0 sec^{-1} in $0.5 \text{ M } [\text{H}^+]$ and 3.0 sec^{-1} in $0.5 \text{ M } [\text{H}^+]$).²⁰⁶ The effective distance between the remote protonated amine group and the Ni-N bond is too large in $[\text{Ni}(\text{H}_2-2,2,2\text{-tet})]^{4+}$ to affect the rate of ring-opening, so all three rate constants reflect the effect of a single proximal protonated amine site. The accelerating effect of a second proximal amine is apparent in $[\text{Ni}(\text{H}_2\text{-tren})]^{4+}$, where the third ring-opening is so rapid that only two ring-opening steps are observed.²⁰⁶ Perhaps surprising is the apparent insensitivity of the rate of rupture of chelate rings to ring size (at least for five- and six-membered chelate rings). This is shown by the ring-opening rate constants for $[\text{Ni}(\text{en})]^{2+}$ and $[\text{Ni}(\text{tn})]^{2+}$ ($6.3 \times 10^{-3} \text{ sec}^{-1}$ and $9.2 \times 10^{-3} \text{ sec}^{-1}$ at 0.3°C respectively),²¹¹ as well as by the ring-opening rate constants for $[\text{Ni}(2,2\text{-tri})]^{2+}$ and $[\text{Ni}(3,3\text{-tri})]^{2+}$. (First ring-opening 14 sec^{-1} and 11 sec^{-1} respectively; second ring-opening 2.8 sec^{-1} and 1.7 sec^{-1} in $0.2 \text{ M } [\text{H}^+]$).²⁰⁶ In the latter example, however, acid-dependence of the rates has not been investigated, and it is possible that the observed rates do not simply correspond to ring opening. Direct acid attack ($\text{I} \rightarrow \text{I(B)} \rightarrow \text{IV}$ in Scheme 10) may also contribute to the observed rate constants.

The question then arises, if the ring-opening is not simply sterically controlled, why is the ring-opening rate 50 to 100 times

slower than the rate of loss of monodentate ligands.¹⁹⁸ It is not caused by differences in metal-nitrogen bond strength, as the metal-amine bonds in chelate rings have been shown to be no stronger than metal-monodentate amine bonds.²¹⁴ It has been suggested that there is steric resistance to rotation of the uncoordinated nitrogen away from the metal centre after ring-opening compared with the linear translation that is possible for monodentate amines. The ring-opening rate of $[\text{Ni}(\text{en})]^{2+}$ is greater than that of $[\text{Ni}(\text{rac-bn})]^{2+}$ ²⁰⁹ and this has been attributed to steric hindrance to rotation caused by the presence of two methyl groups in the latter ligand. The same effect is observed for the series of complexes $[\text{Ni}(\text{en})_2]^{2+}$,²⁰⁸ $[\text{Ni}(\text{rac-bn})_2]^{2+}$ ²¹⁰ and $[\text{Ni}(\text{C-Me}_4\text{-en})_2]^{2+}$ ²¹⁵ (the latter complex has four methyl groups on the alkyl backbone of the five-membered chelate rings) as well as for $[\text{Ni}(\text{en})_3]^{2+}$ ²⁰⁸ and $[\text{Ni}(\text{rac-bn})_3]^{2+}$ ²¹⁰. This trend is even more marked in the case of the copper(II) complexes of these ligands.²¹⁵ The same reservation must be expressed as before regarding the possibility that direct proton attack is contributing to the observed rate constant at the relatively high acid concentrations used in the experiments. On the other hand, methylation of the β -carbon atom in six-membered chelate rings appears to have only a small effect on the rate of chelate ring-opening. (The dissociation rate constants for $[\text{Ni}(\text{tn})]^{2+}$ and $[\text{Ni}(2,2\text{-Me}_2\text{tn})]^{2+}$ are $9.2 \times 10^{-3} \text{ sec}^{-1}$ and $5.2 \times 10^{-3} \text{ sec}^{-1}$ respectively).^{209,211}

However, some nickel(II) complexes with bidentate amines do not show the expected retardation of reaction rates at low pH that would be expected as a result of steric hindrance. For example, the complexes $[\text{Ni}(\text{en})]^{2+}$, $[\text{Ni}(\text{meso-bn})]^{2+}$ and $[\text{Ni}(\text{cis-1,2-diaminocyclohexane})]^{2+}$ all have similar ring-opening rate constants ($6.3 \times 10^{-3} \text{ sec}^{-1}$, $6.0 \times 10^{-3} \text{ sec}^{-1}$

and $5.6 \times 10^{-3} \text{ sec}^{-1}$ respectively^{209,211}). Furthermore, the activation energy for the dissociation reactions of some nickel(II) complexes with sterically hindered bidentate amines are close to the value found for $[\text{Ni}(\text{en})]^{2+}$ and this is seen as evidence for the existence of a species such as I(B) in scheme 10, in which angular expansion of the chelate ring and lengthening of one nickel-nitrogen bond has occurred.¹⁹⁸

1.4.3.3 Dissociation Reactions of Copper(II) Complexes of Linear Amines

Until recently the acid dissociation reaction of copper(II) complexes of amines had been virtually ignored. Among the linear amines, the few studies which had been done were generally for single hydrogen ion concentrations¹⁹⁸ with the exception of the acid dissociation of $[\text{Cu}(\text{Me}_6\text{-tren})]^{2+}$,²¹⁶ which was shown to have an acid-independent rate constant in the range $0.025 \text{ M} < [\text{H}^+] < 1.0 \text{ M}$. The only other pH-rate constant profiles that had been obtained were for macrocyclic complexes, although the mechanisms of their (presumably) simpler analogues remained essentially uninvestigated.

The dissociation kinetics of a wide range of copper(II) complexes of linear amines have recently been studied, both as a function of hydrogen ion concentration (to investigate their acid-dependence), and at various temperatures (to determine the activation parameters).²¹⁷ Unlike the nickel systems, where multiple reactions have been observed,^{206,212} all but one of the complexes appeared to undergo only one reaction, suggesting that in general the rate determining step is likely to be the rupture of the first Cu-N bond. It was proposed that the mechanism formulated by Read and Margerum for the dissociation of $[\text{Ni}(\text{en})]^{2+}$ ²¹¹ (Scheme 10) is also applicable to the dissociation of these copper(II) complexes but that different pathways assume different degrees of

relative importance.

In contrast to the nickel(II) system, the dissociation rates depend on chelate-ring size, as shown by the ring-opening rate constants of $[\text{Cu(en)}]^{2+}$ and $[\text{Cu(tn)}]^{2+}$ (150 sec^{-1} and 73 sec^{-1} respectively). The rate determining step for complexes with five-membered chelate rings was found to be acid-dependent, but those complexes containing only six-membered chelate rings react at a rate that is independent of acid concentration over the range of hydrogen ion concentration that was investigated ($0.025 \text{ M} < [\text{H}^+] < 0.5 \text{ M}$). The rate expression

$$k_{\text{obs}} = \frac{k_{24}k_{12}[\text{H}^+]}{k_{21}+k_{24}[\text{H}^+]} \quad 1.4$$

is derived. Under the conditions where acid-dependent rates are observed, the intercept and slope of a plot of $[k_{\text{obs}}]^{-1}$ versus $[\text{H}^+]^{-1}$ yield values for k_{12} and $k_{21}/(k_{12}k_{24})$ respectively. When $k_{21} \ll k_{24}[\text{H}^+]$ the rate expression reduces to

$$k_{\text{obs}} = k_{12} \quad 1.5$$

which corresponds to the acid-independent reaction pathway. The magnitude of k_{24} is expected to be largely independent of the nature of the metal cation, hence the pH at which acid-independent kinetic behaviour is observed will be determined mainly by k_{21} . It is well established that for metal complexes of polyamines containing five-membered chelate rings, k_{21} is about four orders of magnitude greater for copper(II) than for nickel(II),¹⁹⁸ so the hydrogen ion concentration at which acid-independent kinetics is observed for a copper complex will be about four pH units lower than for the corresponding nickel(II) complex (e.g. $[\text{Ni(en)}]^{2+}$ displays acid-independence at $\text{pH} \leq 4$ whereas at

0.5 M $[H^+]$ $[Cu(en)]^{2+}$ still does not). As ring-closure is slower for six-membered chelate rings than for five-membered chelate rings the condition $k_{21} \ll k_{24}$ $[H^+]$ will be met at lower hydrogen ion concentrations, and acid-independent behaviour for copper(II) complexes with six-membered chelate rings will be expected at even lower hydrogen ion concentration. The direct acid attack pathway ($I \rightarrow IB \rightarrow IV \rightarrow V$) in scheme 10 which is observed for $[Ni(en)]^{2+}$ appears to play little part in the dissociation of the copper(II) complexes of the linear polyamines. No deviation from the expected rates is observed, even at high hydrogen ion concentration. Furthermore the $[Cu(en)]^{2+}$, $[Cu(tn)]^{2+}$ and $[Cu(3,22,3-tet)]^{2+}$ (3,22,3-tet = NN'-di-(3-aminopropyl)-piperazine) complexes show no evidence of general-acid catalysis,²¹⁸ thus the rate determining step must occur before proton transfer takes place.

1.4.3.4 Dissociation Reactions of Copper(II) and Nickel(II) Complexes of Macrocyclic Ligands

As a direct consequence of the great stability of metal complexes of many macrocyclic amines, the dissociation rate constants in the absence of acid are remarkably low for metals that are conventionally classified as labile.¹⁷⁷

This is analogous with the smaller k_d values observed for metal chelate complexes and their correspondingly enhanced stability (chelate effect)¹⁰⁰ when compared with monodentate ligands. The separate steps involved in the dissociation of a chelate or macrocyclic ligand are not necessarily

slow but unless the free donor groups can be protonated or coordinated to another metal, the reverse reaction dominates, and the resultant rate constant for a series of successive steps will be small.

However, even in the presence of acid the dissociation rate for certain metal complexes of macrocycles is remarkably slow. The $[\text{Ni}([\text{14}] \text{ane-1,4,8,11-N}_4)]^{2+}$ ion shows no evidence of dissociation over two days at 60°C in 6 M perchloric acid.^{22,54} Margerum also noted that the red form of $[\text{Cu}(\text{tet a})]^{2+}$ has a half-life of 22 days in 6.1 M hydrochloric acid at 25°C in contrast to $[\text{Cu}(2,3,2\text{-tet})]^{2+}$ for which the half-life under the same conditions is only 0.2 seconds.¹⁷⁵ Similarly the blue form of $[\text{Cu}(\text{tet b})]^{2+}$ (tet b = rac-5,7,7,12,14,14-Me₆[14]ane-1,4,8,11-N₄) has been shown to dissociate very slowly in acid.²¹⁹

The acid-dissociation rate of $[\text{Cu}([\text{14}] \text{ane-1,4,8,11-N}_4)]^{2+}$ has not been measured as it is so slow. The rates have been determined for the dissociation of $[\text{Cu}([\text{12}] \text{aneN}_4)]^{2+}$,¹⁸⁴ $[\text{Cu}([\text{13}] \text{aneN}_4)]^{2+}$ ¹⁸⁵ and $[\text{Cu}([\text{15}] \text{aneN}_4)]^{2+}$ ¹⁸⁷ in acetate medium from polarographically determined formation rates and equilibrium constants. They demonstrate the extreme sluggishness of the dissociation reactions of such systems, but cannot be compared with other results because they represent overall dissociation rates which are influenced by the presence of acetate ions. In an effort to shift the dissociation rates onto a more accessible time-scale Lindoy has synthesised a range of 14-17 membered tetradentate N₂O₂ macrocycles (LXI), studied the dissociation of their nickel(II) complexes

LXI

in a variety of acids,²²⁰ and established that they exhibit acid-independent behaviour over the range $0.1 \text{ M} < [\text{H}^+] < 1.0 \text{ M}$. It is proposed that rupture of one nickel-oxygen bond is rate-determining, and that the rates directly mirror the goodness of fit of the metal in the macrocyclic cavity. The N- and C-methylated derivatives exhibit decreased dissociation rates, and this is thought to be due to the steric hindrance to folding of the macrocycle that is required to move a nitrogen from the coordination sphere.²⁰⁵ This is similar to the behaviour shown by the N-methylated derivatives of $[\text{Ni}([14]\text{ane-1,4,8,11-N}_4)]^{2+}$ ⁵⁴ although complexes are also known in which N-methylation enhances the rate of acid-dissociation.²²¹ There is also a rate enhancement in the presence of acetic acid or acetate ions, but not in the presence of other anions. The enhancement appears to be dependent on the acetate ion concentration, and is therefore not a result of general acid catalysis. (Similar enhancement of the dissociation rate of $[\text{Cu}(2,3,2\text{-tet})]^{2+}$ and $[\text{Cu}(\text{tet a})]^{2+}$ by chloride ion has also been reported²²²). On the basis of these results, a mechanism in which the complex dissociates without acid assistance (the acid merely acting as an amine scavenger) is proposed. The acetate ion dependence is shown in the possible rate-determining step:

or alternatively by the formation of a $[\text{Ni}(\text{L})\text{OAc}]^{+}$ preequilibrium species. Kaden has studied the kinetics of the N_2S_2 donor macrocyclic system (LXII).²²³ The nickel(II) complex dissociates even in neutral solution

LXII

and the rate is acid-independent over the range $3.8 < \text{pH} < 7.0$. Furthermore, the metal exchange process with copper(II) is independent of $[\text{Cu}^{2+}]$ and has the same activation parameters as the nickel dissociation. The reaction is therefore simply described by the equation

although it is possible that at higher hydrogen ion concentrations than those investigated, acid-dependent kinetic behaviour may occur. The dissociation of the copper(II) complex is dependent on the concentration of the complex (CuL^{2+}) and is acid-dependent, with a limiting rate at low pH, producing a linear relationship between k^{-1} and $[\text{H}^+]^{-1}$. Kaden invokes the mechanism given below

but this gives rise to the same form for the rate law as the dissociation pathway (I $\rightarrow$ II $\rightarrow$ IV $\rightarrow$ V) of the mechanism in Scheme 10.

Another approach involves synthesis of macrocyclic amines that form more labile complexes due to the presence of destabilizing alkyl-groups or strained chelate rings. The first reported isomer (R,S,R,S) of $[\text{Ni}(1,4,8,11\text{-Me}_4\text{-[14]ane-1,4,8,11-N}_4)]^{2+}$ (which shows a propensity towards five-coordination) dissociates comparatively rapidly in dilute mineral acid, and an unfavourable stereochemical arrangement of the tertiary amine donor groups of the macrocycle around the metal is postulated to be the cause of the enhanced lability. Kaden has studied the acid dissociation kinetics in detail.¹⁸¹ The mechanism involving reaction pathways (I $\rightarrow$ II $\rightarrow$ III) and (I $\rightarrow$ II $\rightarrow$ IV $\rightarrow$ V) in scheme 10 leads to an expression for the rate constant

$$k_{\text{obs}} = \frac{k_{12}}{k_{21}} (k_{23} + k_{24} [\text{H}^+]) \quad 1.6$$

which is consistent with the observed kinetic behaviour. For the nickel(II) complex, acid-independence was observed at above pH 3.5 in the presence of copper(II) acting as a scavenger for the ligand. This corresponds to the reaction pathway (I $\rightarrow$ II $\rightarrow$ III) in scheme 10. At higher acid concentrations, the pathway (I $\rightarrow$ II $\rightarrow$ IV $\xrightarrow{\text{fast}}$ V) is operative. The reaction was studied up to 2.5 M [HNO₃] with no indication that a limiting rate was being approached. The rate law for the copper(II) complex on the other hand does not contain an acid-independent term (although the reaction was not studied above pH 2). A second-order dependence on the hydrogen ion concentration was noted, but no attempt was made to explain the observed behaviour, or to derive a mechanism consistent with the rate law.

The kinetics of acid dissociation of the copper(II) complex of 1,4,8,11-(2-cyanoethyl)₄-[14]ane-1,4,8,11-N₄ has been investigated up to 1 M hydrogen ion concentration.²²⁴ The complex is markedly labile compared with other 14-membered tetraazamacrocyclic derivatives. The observed rate constant contains an acid-independent term at zero acid concentration as well as a linear dependence on hydrogen ion concentration. This behaviour is related to that noted for the copper(II) complexes of a range of triazamacrocycles²²⁵ and of some linear amines.²¹⁷ The proposed mechanism involves a non acid-catalysed dissociation pathway as well as an acid-catalysed pathway comprising a rapid pre-equilibrium protonation followed by a rate-determining dissociation step.

The observed rate constant then takes the form

$$k_{\text{obs}} = k_d + \frac{k_H K [\text{H}^+]}{(1 + K [\text{H}^+])} \quad 1.7$$

which together with the condition ($K[\text{H}^+] \ll 1$) leads to a rate law consistent with the results obtained.

The full form of the above rate expression is required to describe the observed behaviour of the nickel(II) and copper(II) complexes of trans-Me₆[18]dieneN₄ (LXIII)²²⁶ as the dissociation reactions show an

LXIII

LXIV

acid-independent rate, pseudo-linear hydrogen ion dependence, and limiting acid kinetics, all in the range $0 < [\text{H}^+] < 1.0 \text{ M}$. Hay also noted a kinetic isotope effect on substituting D₂O/DCl for H₂O/HCl in the dissociation studies of the copper(II) complex, and suggests that slow proton transfer is involved in the rate determining step, at least at low hydrogen ion concentration. The rate constant was also found to be dependent on the nature of the anion at constant ionic strength, with dissociation taking place more rapidly in hydrochloric acid than in nitric acid (see section 1.4.3.5). The [Cu(cis-Me₆[18]dieneN₄)]²⁺ (LXIV) complex dissociates considerably more rapidly than the trans-isomer

(in fact even faster than $[\text{Cu}(2,3,2\text{-tet})]^{2+}$) and consequently the kinetics were studied at higher pH (in acetate buffer). The dissociation rate is linearly dependent on hydrogen ion concentration (in the range $4 < \text{pH} < 5$) and is also subject to general acid catalysis, thus establishing that the proton transfer step is rate determining. The considerable differences between the dissociation rates of the two isomers is explained in terms of their different structures. The cis-isomer which has the N-meso configuration is considerably more strained than the near planar N-racemic configuration present in the trans-isomer.²²⁷

The considerable difference in the acid dissociation rates of $[\text{Cu}(\text{tet a})]^{2+}$ (red) and $[\text{Cu}(\text{tet a})]^{2+}$ (blue) is similarly rationalized in terms of the more stable ligand configuration present in the red form of the complex.²²⁸ The acid-dissociation kinetics of $[\text{Cu}(\text{tet a})(\text{blue})]^{2+}$ has been studied over the range $1.0 \text{ M} < [\text{HNO}_3] < 5.0 \text{ M}$.²²⁹ The first equilibrium protonation is the only acid-dependent step in the proposed dissociation mechanism, and is followed by rate determining rupture of a second copper-amine bond. This is in marked contrast to copper(II) complexes of linear amines where rupture of the first copper-nitrogen bond is generally rate determining, and indicates the greater difficulty in removing the uncoordinated nitrogen from the inner coordination sphere to permit solvation of the metal ion in complexes with macrocyclic ligands.

In contrast to the comparatively inert equatorially coordinated tetraazamacrocycles, the metal complexes of macrocyclic triamines are rather more labile. Dissociation rates for the copper(II) complexes of $[9]\text{aneN}_3$, $[10]\text{aneN}_3$, $[11]\text{ane-1,4,8-N}_3$ and $\text{Me}[9]\text{aneN}_3$ all show linear acid dependence ($0 < [\text{H}^+] < 0.5 \text{ M}$) with intercepts that are experimentally

indistinguishable from zero.^{80,225} All the complexes are expected to show a finite acid-independent dissociation rate (k_d) at zero hydrogen ion concentration, corresponding to the reaction pathway (I $\rightarrow$ II $\rightarrow$ III) in Scheme 10. Attempts to determine k_d using buffered solutions were unsuccessful because general acid catalysis occurred. The copper(II) complex of 2,2,4-Me₃[12]aneN₃ dissociates considerably more slowly, and shows a linear dependence on hydrogen ion concentration with a finite intercept at zero hydrogen ion concentration, which is the expected acid-independent dissociation rate.^{80,225} This is similar to the behaviour reported for the nickel(II) complexes of [9]aneN₃, [12]aneN₃²³⁰ and cis,cis-1,3,5-triaminocyclohexane [cis,cis-tach]²³¹ which, although not a macrocycle within the terms of the definition given, displays many of the attributes of a macrocyclic ligand because the amine groups are attached to a relatively rigid carbon skeleton. All three complexes exhibit linear dependence on hydrogen ion concentration over a wide range ($0.4 \text{ M} < [\text{H}^+] < 5.0 \text{ M}$) as well as a finite intercept corresponding to the acid-independent dissociation. Although the $[\text{Ni}([9]\text{aneN}_3)]^{2+}$ complex is five orders of magnitude more stable than $[\text{Ni}([12]\text{aneN}_3)]^{2+}$, the latter complex dissociates considerably more slowly.²³⁰ The complex with the smaller macrocyclic ring shows considerable trigonal distortion from normal octahedral geometry²⁰² (c.f. $[\text{Ni}([10]\text{aneN}_3)]^{2+}$ ²³²) whereas spectral data for $[\text{Ni}([12]\text{aneN}_3)]^{2+}$ is consistent with undistorted octahedral geometry.²³³ It is proposed that the relative dissociation rates are a function of this trigonal strain in the coordinated macrocycle rather than of stability.

Dissociation of the copper(II) complexes of [11]ane-1,4,7-N₃, [12]ane-1,4,7-N₃, [12]ane-1,5,9-N₃, [13]ane-1,5,9-N₃, [14]ane-1,5,9-N₃ and cis,cis-tach show non-linear acid dependence which tends to a limiting

rate at high hydrogen ion concentrations.⁸⁰ (The dissociation of $[\text{Cu}(\text{[12]ane-1,5,9-N}_3)]^{2+}$ was earlier reported to be linearly dependent on hydrogen ion concentration,¹⁷³ as the pH region in which limiting kinetic behaviour occurs was not investigated). A general mechanism (Scheme 11) has been proposed to account for the variety of kinetic

SCHEME 11

behaviour observed among the triazamacrocyclic complexes.²²⁵ It is proposed that the acid-independent rate corresponds to $(\text{I} \rightarrow \text{II} \rightarrow \text{III} \rightarrow \text{V} \rightarrow \text{products})$ with the copper-nitrogen bond rupture (k_{23}) as the rate determining step and that the acid-dependent behaviour corresponds to $(\text{I} \rightarrow \text{II} \rightarrow \text{IV} \rightarrow \text{V} \rightarrow \text{products})$, with the protonation k_{24} representing the rate determining step. The limiting rate observed at high hydrogen ion concentration is reached when k_{45} becomes rate determining. This limiting rate was only observed for the complexes containing the larger macrocyclic systems. The CuHL^{3+} species (IV) is stabilized by the

comparatively greater separation of the protonated nitrogen and the copper(II) than is possible in the smaller ring systems, although calculated values of K_{CuHL} suggest that the protonated nitrogen is still closer to the copper than is the case for complexes of linear polyamines. There appears to be no other obvious correlation of rate with ring size or stability and subtle steric effects within each complex are postulated to account for the observed variations. The concept of "ideal cavity size" is not as relevant for these facially coordinated complexes as for the equatorially coordinated tetraazamacrocycles. Large differences in $\Delta H^\ddagger$ and $\Delta S^\ddagger$ of the dissociation reactions are reported between the nickel(II) and copper(II) complexes. The larger copper-apical nitrogen bond distance^{201,202} compared with the nickel-nitrogen bond lengths and the correspondingly greater ease of protonation is cited as the cause of the differences in $\Delta H^\ddagger$ (and the consequently greater reaction rates). The differences in $\Delta S^\ddagger$ on the other hand are attributed to the ability of the nickel(II) complexes to achieve six-coordination in solution in contrast to the continued five-coordination of the copper(II) complexes. However, a series of nickel(II) complexes of N_2O_2 -donor macrocycles which are apparently all six-coordinate in solution have also been reported to show large variations in $\Delta S^\ddagger$ ²²⁰ so it is possible that factors other than coordination number are responsible for the differences.

The acid dissociation kinetics of the nickel(II) and copper(II) complexes of [15]aneN₅ (L_1) have also been reported.¹⁶⁷ Both reactions are rapid compared with the tetraazamacrocyclic complexes and show a second-order dependence on hydrogen ion concentration. The mechanism proposed is shown in Scheme 12 and is similar to the pathway (I $\rightarrow$ II $\rightarrow$ IV $\rightarrow$ V $\rightarrow$ products) in the previous scheme. The monoprotonated

SCHEME 12

species I is thought to result from protonation of an apical nitrogen atom as the axial copper-nitrogen bond is expected to be weaker than the other four because of Jahn-Teller distortion. On the basis of the three steps

a rate law

$$\text{Rate} = \frac{k_1 K_1 K_2 [\text{CuL}_1^{2+}] [\text{H}^+]^2}{1 + K_1 [\text{H}^+] + K_1 K_2 [\text{H}^+]^2} \quad 1.8$$

is derived. The observed second-order dependence on hydrogen ion concentration is observed when

$$(K_1 [\text{H}^+] + K_1 K_2 [\text{H}^+]^2) \ll 1 \quad 1.9$$

in which case the measured rate constant (k_{obs}) can be expressed as

$$k_{\text{obs}} = k_1 K_1 K_2 \quad 1.10$$

The second-order dependence on hydrogen ion concentration would be expected to break down when the above inequality was no longer valid, and a limiting rate would be observed, corresponding to the rate determining rupture of the third metal-nitrogen bond. No comment is made on the unexpected observation that nickel(II) complex reacts approximately 15 times as fast as the copper(II) complex.

($k_{2\text{H}^+}^{\text{CuL}_1} = 4.9 \times 10^{-2} \text{ dm}^6 \text{ mol}^{-2} \text{ sec}^{-1}$, $k_{2\text{H}^+}^{\text{NiL}_1} = 0.63 \text{ dm}^6 \text{ mol}^{-2} \text{ sec}^{-1}$ at 25°C in $1.0 \text{ M } [\text{ClO}_4^-]$).

A preliminary report²³⁴ on the copper(II) and nickel(II) complexes of [18]aneN₆ (L₂) noted that both complexes are labile in mineral acid, in marked contrast to the tetraazamacrocyclic complexes. A later study¹⁶⁷ established that the dissociation of the nickel(II) complex was third order in hydrogen ion concentration (over the range $1.3 < \text{pH} < 2.0$). A mechanism similar to that in Scheme 12, but including further equilibrium protonation step (K_3) before the final dissociation step, was proposed, leading to the rate law

$$\text{Rate} = \frac{k_1 K_1 K_2 K_3 [\text{NiL}_2^{2+}] [\text{H}^+]^3}{1 + K_1 [\text{H}^+] + K_1 K_2 [\text{H}^+]^2 + K_1 K_2 K_3 [\text{H}^+]^3} \quad 1.11$$

and a measured rate constant

$$k_{\text{obs}} = k_1 K_1 K_2 K_3 \quad 1.12$$

when the condition

$$(K_1 [\text{H}^+] + K_1 K_2 [\text{H}^+]^2 + K_1 K_2 K_3 [\text{H}^+]^3) \ll 1 \quad 1.13$$

is met.

1.4.3.5 Medium Effects on Stability and Kinetics

It is possible to observe considerable variations in the kinetic and thermodynamic parameters of acid dissociation reactions carried out in different media (e.g. different counter anions, different ionic strengths). For example, with linear and macrocyclic polythiaether ligands containing more than three donor groups, Rorabacher noted that the stability of the copper(II) complexes appeared to increase with increasing concentration of "inert" anions such as perchlorate, tetrafluoroborate, and trifluoromethanesulphonate (triflate). Kinetic studies have shown that the dissociation rate constants undergo a corresponding decrease, while the formation rate constants undergo a slight increase.²³⁶ The formation of a tight ion pair or ternary complex with perchlorate enhances the apparent stability of $[\text{Cu}([14]\text{aneS}_4)]^{2+}$. Thermodynamic parameters have been obtained ($K_{25^\circ\text{C}}, 24 \text{ M}^{-1} \text{ dm}^3$; $\Delta H^\circ, -8.8 \text{ kJ mol}^{-1}$; $\Delta S^\circ, -0.7 \text{ e.u.}$ ²³⁵). The lack of any change in the visible absorption and resonance Raman spectra as the perchlorate ion concentration is increased suggests that the copper-sulphur bond distances and angles are not appreciably altered by the perchlorate association. However, the spectra do not rule out the possibility of inner sphere coordination of the perchlorate ion to an axial site, nor the possibility that some form of outer sphere complex is formed. The dissociation rate could be resolved into anion-dependent and anion-independent terms. However, such effects are difficult to separate from ionic strength effects (as it is not possible in such cases to keep the ionic strength constant by using an "inert" medium!) In reactions where protonation occurs, complications may arise because of variations of pK_a with ionic strength. Such medium dependence must also cast serious doubts on the validity of $\Delta H^\ddagger$ and $\Delta S^\ddagger$

determinations from temperature variation studies of rates. Results for acid-dissociation rates of $[\text{Cu}([15]\text{aneN}_5)]^{2+}$ in different media have been shown to vary significantly (vide supra).

1.4.4 Macrocyclic Complexes of Cobalt(III)

1.4.4.1 Introduction

Although in the absence of nitrogen donors the labile (d^7) $[\text{Co}(\text{H}_2\text{O})_6]^{2+}$ species is quite stable to oxidation ($E_{1/2}$, 1.84 v²³⁷), the presence of nitrogen donors in the coordination sphere lowers the oxidation potential dramatically ($[\text{Co}(\text{NH}_3)_6]^{2+}$ $E_{1/2}$, 0.1 v²³⁷), and the inert (d^6) cobalt(III) species becomes more accessible. Considerable attention has been devoted to cobalt(III) complexes of amines for a variety of reasons. Apart from their historical significance in the field of coordination chemistry²³⁸ and their biological importance in such species as vitamin B₁₂²³⁹, their well defined octahedral structure and inertness make them ideal candidates for stereochemical investigation. As a result of their inertness, stereo- and geometrical isomers can be separated chemically or chromatographically. The nature of their electronic spectra makes them amenable to C.D. and O.R.D. analyses. More recently the diamagnetic character of most d^6 cobalt(III) complexes has been utilized in the investigation of the groups coordinated to the metal using ^1H and ^{13}C n.m.r. spectroscopy. The comparatively slow reaction rates of cobalt(III) complexes can simplify the determination of kinetic parameters. Consequently they are valuable probes for investigating the stereochemistry and mechanism of octahedral substitution reactions.

1.4.4.2 Synthetic Methods

Many of the synthetic techniques date back to the time of Werner. A thorough review covers the synthetic methods up to 1970.²⁴⁰ Methods involve either reaction of a cobalt(II) salt with the ligand of choice and subsequent oxidation of the complex that is formed, or reaction between the ligand and a cobalt(III) complex containing relatively labile coordinated groups.

Oxidation of cobalt(II) complexes. The conditions of formation of the cobalt(II) complexes are generally similar to those for other labile first row transition metals. Variations have tended to focus on the choice of oxidising agents for the subsequent oxidation to cobalt(III). Aerial oxidation is often used, but can involve prolonged reaction times. The addition of activated charcoal²⁴¹ to increase the rate of reactions is well established. This may however, lead to the formation of different products, or at least to differences in the relative proportions of the products.²⁴² Alternatively hydrogen peroxide (either with or without activated charcoal catalyst)²⁴³ can be used, and substantially shorter reaction times are then required. Both of these methods have the advantage that they do not contaminate the solution with the reduced form of the oxidant. A variety of other oxidising agents have been utilized, including lead dioxide, sodium chlorite, chlorine and bromine.²⁴⁴ It should be noted that different oxidants may lead to the formation of different products or isomer compositions.²⁴⁰

Replacement of labile ligands in cobalt(III). A number of cobalt(III) complexes with readily displaced ligands have been used, some containing only labile ligands while others also have inert groups

attached, and these are generally retained in the final product. Although $[\text{Co}(\text{H}_2\text{O})_6]^{3+}$ is too unstable for use, $\text{CoO}(\text{OH})$ (prepared by H_2O_2 oxidation of $\text{Co}(\text{OH})_2$) reacts readily with acidic ligands in aqueous solution, and $[\text{Co}(\text{NH}_2\text{CONH}_2)_6](\text{ClO}_4)_3$ can be used in non-aqueous solvents.²⁴⁵ In acidic solution $\text{Na}_3\text{Co}(\text{CO}_3)_3 \cdot 3\text{H}_2\text{O}$,²⁴⁶ $\text{K}_3\text{Co}(\text{CO}_3)_3 \cdot 3\text{H}_2\text{O}$ ²⁴⁷ and $\text{Na}_3\text{Co}(\text{NO}_2)_6$ ^{62,248} are frequently used, while in the presence of more basic ligands, complexes of cobalt(III) containing up to six ammine groups, with a variety of neutral or anionic ligands completing the octahedral coordination shell have been used. If, however, not all of the coordinated ligands on the cobalt are required to be replaced, a polyamine coordinated to the metal in place of some of the ammine groups will generally not be displaced.^{249,250} The substitution reactions have mainly been performed in aqueous medium, but recently the value of non-aqueous solvents has been recognized,^{244,251} particularly when a relatively reactive group is to be replaced and water could compete with the incoming donor group. Improved yields have also been reported for some reactions performed in anhydrous conditions. The use of different solvent systems may also result in the formation of different isomers.²⁵²

Synthesis of cobalt(III) pentaazamacrocyclic -complexes. The synthesis of $[\text{Co}([15]\text{aneN}_5)\text{Cl}](\text{ClO}_4)_2$ from the ligand hydrochloride and $\text{Na}_3\text{Co}(\text{CO}_3)_3 \cdot 3\text{H}_2\text{O}$ in aqueous solution with sodium perchlorate has been reported to yield a number of isomers.¹⁶⁷ Reaction with silver perchlorate in water, dry DMF and formic acid gave the aquo, dimethylformamido and formato complexes respectively.²⁵³ The hydroxo triperchlorate is reported to be insoluble in perchlorate solution and has been isolated.

Aeration of a basified solution of [16]aneN₅.5HCl and cobalt chloride hexahydrate, followed by treatment with concentrated hydrochloric acid and precipitation with perchlorate afforded a single isomer of [Co([16]aneN₅)Cl](ClO₄)₂¹³⁵ for which the structure has been determined. The complex cation has relatively undistorted octahedral geometry with gross structural features shown below (LXV). The bond lengths and

angles are all indicative of a relatively strain-free system.

The [Co(pyaneN₅)X](ClO₄)₂ complex (X=Cl, Br)⁴⁹ was prepared by a similar method to that used for [Co([16]aneN₅)Cl](ClO₄)₂, and a series of metathetical reactions was used to convert it into the azido, isothiocyanato and nitro complexes.⁴⁹ The structure has previously been discussed (section 1.4.2.7).¹⁵⁴

1.4.4.3 Isomerism of Cobalt(III) Amine Complexes

Nomenclature. As a consequence of the inertness of the cobalt(III) state, it is possible to separate the different possible geometrical, configurational and optical isomers of a complex. Although a well-established system of nomenclature exists for the octahedral

configuration generally found in cobalt(III) complexes and even for specifying the conformations of chelate rings,^{254,255} the presence of multidentate ligands, both linear and cyclic, makes systematic nomenclature somewhat unwieldy. Various authors have extended the system of nomenclature to cover specific requirements²⁵⁶⁻²⁵⁸ or to remove ambiguities that exist in the IUPAC system. (The H $\uparrow$ and H $\downarrow$ nomenclature of House²⁵⁹ will be used in this work whenever the standard nomenclature would lead to ambiguity. The different possible dispositions of the five and six-membered chelate rings around the cobalt(III) in the pentaazamacrocyclic complexes studied in this work are discussed and named later (Section 3.3.1).

1.4.4.4 Separation Methods

Traditionally, separation of different isomers involved fractional crystallization methods, and although solubility differences are still exploited in the resolution of enantiomers (by selective precipitation with an optically active resolving anion) other methods now find considerably more favour for separation of geometrical isomers. The use of sulphoethyl (SE) sulphopropyl (SP) and carboxymethyl (CM) substituted Sephadex is now well established for the separation of cationic complexes.²⁶⁰ Sephadex has a variety of advantages over more conventional ion exchange resins.²⁶¹ In general the 2+ or 3+ complex cations involved bind too strongly to ion exchange resins for easy separation, and require concentrated eluents or excessively long elution times. By contrast, complexes associate considerably more weakly with Sephadex, so more dilute eluents may be used, leading to better separation and selectivity. The fact that Sephadex is colourless

means that it is not difficult to follow the progress of the (coloured) complexes on the column. Although expensive, Sephadex can be repeatedly reused, being stable in most environments (except strong acid). An excellent review²⁶⁰ covers experimental techniques, and gives examples of separation of a wide range of cationic cobalt(III)-amine complexes, as well as some involving oxygen donors and anionic complexes.

Although the technique has not been applied to the separation of the few pentaazamacrocyclic complexes that have been reported, it has been used for complexes of other macrocyclic amines as well as a variety of linear amine systems. Thus five of the nine possible isomers of $[\text{Co}(\text{Me}[9]\text{aneN}_3)_2]^{3+}$ have been separated by successive elution with sodium sulphate (0.2 M) and disodium monohydrogen phosphate (0.2 M).²⁶² Likewise the meso and rac isomers of $[\text{Co}([18]\text{aneN}_6)]^{3+}$ have been isolated²⁶³ (their structures have been established by ^{13}C n.m.r.²⁶³ studies and X-ray crystallography.^{73,264} The cobalt(III) complex of the linear analogue pentaethylenehexamine (2,2,2,2,2-hex) has been separated into its seven possible isomers.²⁶⁵ The order of elution (with phosphate eluent) of $[\text{Co}(\text{N}_6)]^{3+}$ species has been correlated with the number and kind of octahedral faces of the complex on which association with phosphate can occur.²⁶⁶

In a reported synthesis of $[\text{Co}([10]\text{aneN}_3)_2]^{3+}$ from the crude ligand salt and $\text{Co}(\text{NH}_3)_5\text{Br}_3$, the crude reaction product was separated on a Sephadex column. This resulted in the isolation of $[\text{Co}([20]\text{ane-1,4,7,11,14,17-N}_6)]^{3+}$ as well as a linear hexamine complex $[\text{Co}(2,3,2,2,3\text{-hex})]^{3+}$ which were identified by ^{13}C n.m.r. spectroscopy.^{76,267} A number of mixed bis-tridentate $[\text{Co}(\text{N}_6)]^{3+}$ systems have been studied by Searle and coworkers, and they have attempted to rationalize the relative rates of elution in both Sephadex and

Dowex 50-X2 ion exchange resin using different eluents. They concluded (similarly to Yoshikawa) that the degree of ion association between the complex cation and the eluent was more important than the association with the resin.²⁶¹ Another study involved the synthesis of the cobalt(III) complexes of [18]aneN₆, [21]ane-1,4,8,11,15,18-N₆ and TC[18]aneN₆[#] which were prepared by reaction of the ligands with Na₃Co(CO₃)₃·3H₂O.⁷³ The cobalt(III) complex of the 21-membered macrocycle was resolved using an optically active eluent and a Sephadex column. Although no geometrical isomers could be separated, the authors concluded that two geometrical isomers were present, because the structure of the solid material isolated from the solution (as determined crystallographically) was not consistent with the ¹³C n.m.r. spectrum observed for the solution. (The reported ¹³C n.m.r. spectrum also appears to lack a resonance corresponding to the β-carbon atom of the six-membered chelate ring). Attempts to resolve [Co([18]aneN₆)]³⁺ were unsuccessful. The cobalt(III) complex of TC[18]aneN₆ was found to be unstable outside the range 2 < pH < 4. Partial separation of five isomers was achieved but the different bands isomerized over several days to give the original (equilibrium) mixture. Tentative identification of the isomers is discussed on the basis of their CD spectra. The ¹³C spectra are not reported. The authors conclude that the rapid isomerization is the result of simultaneous rupture of two cobalt-nitrogen bonds, although they concede that this is somewhat improbable.

Pentamine Complexes. For cobalt(III) complexes that do not contain an N₆ donor set, an additional problem arises in chromatographic

[#] See Appendix.

separations. The sixth donor group may be susceptible to aquation or base hydrolysis and therefore acidic eluents must be used. Although the $[\text{Co}([\text{15}] \text{aneN}_5)\text{Cl}]^{2+}$ species was reported to be a mixture of isomers no separation was attempted.¹⁶⁷ The cobalt(III) complexes of pyaneN_5 ⁴⁹ and $[\text{16}] \text{aneN}_5$ ¹³⁵ appear to be isomerically pure, so the question of separation does not arise. The synthesis of $[\text{Co}(\text{datn})\text{Cl}]^{2+}$ (datn , 1,3-bis(2-aminoethyl)-[9] aneN_3 , XXXIV) has been reported.⁹³ In an attempt to separate the two possible isomers (meso, LXVI and rac, LXVII) the complex was subjected to chromatography on Dowex 50W-X2,

LXVI

LXVII

SP-Sephadex C25 and Dowex 50W-X2 columns successively but only one isomer was obtained. This was identified as the rac isomer (LXVII) by resolution of the enantiomers (the other isomer (LXVI) is optically inactive).

The cobalt(III) complexes of the linear tetraethylene pentamine (tetren) with a range of donor groups in the sixth coordination site have been prepared^{62,268} using a variety of methods (hydrogen peroxide or chlorate oxidation of the cobalt(II) complexes, reaction of the ligand with cobaltinitrite, cobalticarbonate and trinitrotri-*ammine*),

all of which yield predominantly two of the four possible isomers ($\alpha\beta R$ -LXVIII, and $\alpha\beta S$ -LXIX²⁶⁹) although small amounts of a third isomer ($\alpha\alpha$ -LXX²⁷⁰) are also formed.

LXVIII

LXIX

LXX

1.4.4.4 ¹³C n.m.r. Studies of Cobalt(III) Complexes

One technique that is being increasingly used in probing the structure of cobalt(III) complexes is ¹³C n.m.r. spectroscopy since it was first shown that tris-diamine cobalt(III) complexes in D₂O produce quite distinctive spectra.²⁷¹ ¹³C n.m.r. has the advantage over ¹H n.m.r. that all the peaks are singlets (if C-H coupling is removed). It is relatively easy to distinguish between primary, secondary, tertiary and quaternary carbon atoms using selective decoupling techniques (SFORD, GASPE etc); however as all the macrocyclic ligands under study in this work contain only secondary carbon atoms, no useful information can be derived from this source to help with peak assignment.

The chemical shifts of carbon atoms are also dependent on the nature of the atoms to which they are bonded. Thus the central carbon

atom in a six-membered chelate ring, which is bound to two other carbon atoms are observed to have a chemical shift in the region of 20-30 p.p.m. (relative to TMS) in cobalt(III) complexes.^{160,250,267,271-4} Carbon atoms adjacent to a secondary nitrogen in five- or six-membered chelate rings have reported chemical shifts in the range 46-61 p.p.m.^{160,167,250,263,267,271-5} Unfortunately the chemical shifts appear to be very sensitive to quite subtle differences in the micro-environment of each carbon atom. This is best exemplified by the ^{13}C n.m.r. spectrum of $[\text{Co}([\text{18}] \text{aneN}_6)]^{3+}$ which has resonances from 50-61 p.p.m.²⁶³ although in the free ligand all the carbon atoms are equivalent and the ^{13}C n.m.r. spectrum contains only a single resonance. A study of the trans-diacido linear tetramine complexes of cobalt(III)²⁷³⁻⁴ has led to the interpretation of the changes in chemical shift upon coordination of the ligands in terms of two parameters corresponding to the donation of electron density by the ligand to the metal (resulting in decreased shielding) and the steric effects of coordination (which result in increased shielding). The change in ^{13}C chemical shift on coordination has been shown to correlate with the apparent tetragonal crystal field strength ($\Delta t'$) for carbon atoms adjacent to secondary amine groups in five-membered chelate rings. The bond lengths and angles in coordinated five-membered chelate rings are very close to the 'ideal' values, so it is primarily the electronic effect that affects these chemical shifts. For six-membered chelate rings the ^{13}C resonances of the carbon atoms adjacent to secondary nitrogens appear at equal or higher field than in the free ligand, reflecting the significant strain experienced on coordination. The β -carbon in six-membered chelate rings is expected to show the smallest metal ion shielding (because of its distance), and so would be expected to show the greatest upfield shift on coordination.

In general, workers have not attempted to assign each ^{13}C resonance to a specific carbon atom in a complex except when symmetry arguments or comparison with related systems could be used. Isomer assignments can more readily be made, however. Thus it was possible to identify the meso-isomer of $[\text{Co}([\text{18}] \text{aneN}_6)]^{3+}$ on the basis of the single ^{13}C resonance observed²⁶³ (the chelate rings are believed to be conformationally labile in solution on the n.m.r. timescale), as distinct from the rac-isomer for which ten peaks were observed.²⁶³ The two different isomers of $[\text{Co}([\text{10}] \text{aneN}_3)]^{3+}$ (in which the six-membered chelate rings are cis- and trans- to each other) were also distinguished on the basis of symmetry and the number of resonances observed in the ^{13}C n.m.r. spectra.²⁶⁷

Chapter 2

EXPERIMENTAL

2.1 Instrumentation

The infrared spectra were recorded on a Perkin Elmer 599B, Grubb Parsons GS8 or a Pye Unicam SP3-100 spectrophotometer between 4000 cm^{-1} and 600 cm^{-1} using nujol and hexachlorobutadiene mulls (for solids) and thin films (for liquids or oils) between sodium chloride plates. Each spectrum was calibrated using a polystyrene standard. Diffuse reflectance spectra were recorded on a Unicam SP700 double-beam spectrophotometer operating between 1600 nm and 275 nm using magnesium carbonate as reference. Solution spectra were obtained on a Unicam SP 700 or a Perkin Elmer Model 330 double-beam spectrophotometer between 1400 nm and 200 nm using matched 2 mm or 10 mm silica cells.

Nuclear magnetic resonance spectra were acquired on a Varian FT-80A spectrometer (operating on 79.59 MHz for ^1H and 20.00 MHz for ^{13}C n.m.r.) using tetramethylsilane as an internal standard for organic samples in organic solvents, or a soluble sodium salt in aqueous solution or dioxane ($\delta=67.39$ p.p.m. relative to TMS) as a reference for the ^{13}C nuclear magnetic resonance spectra of solution spectra of the metal complexes. For the solid sample the ^{13}C n.m.r. was obtained on a Varian XL-200 spectrometer.

Low-resolution mass spectra were obtained on a Micromass 12F spectrometer operating in the chemical ionization mode. Gas chromatography of the amines was carried out on a Pye Series 105 chromatograph with a flame ionization detector, coupled to a Metrohm Labograph E478 recorder.

Conductivity studies were carried out at 298 K using a Philips PW 9509/20 Digital Conductivity Meter operating at a frequency of 80 Hz. The solvents used for the conductivity measurements (acetone, methanol or nitromethane) were dried by standard techniques then distilled, and their purity was confirmed by determining their conductance.

Magnetic susceptibilities were measured at 298 K by the Faraday Method, with $\text{HgCo}(\text{CNS})_4$ as calibrant. Effective magnetic moments were calculated by assuming the Curie law, with corrections for diamagnetism made using Pascal's constants ($1 \text{ B.M.} = 0.927 \times 10^{-20} \text{ A m}^2$).

Kinetic data were obtained on a Canterbury SF-3A stopped flow spectrophotometer with a 2 mm path length fitted with a grating monochromator MGL. The photomultiplier output was recorded by a Techtronix D11 single-beam storage oscilloscope.

Melting points were determined on a Reichert hot stage and are uncorrected. Elemental analyses were performed by the University of Otago Microanalytical Service.

2.2 Synthesis of Organic Species

2.2.1 Synthesis and Purification of Linear Amines

N,N'-bis(2-aminoethyl)-1,2-ethanediamine (triethylene tetramine, 2,2,2-tet)

Commercial grade 2,2,2-tet (B.D.H.) was treated with concentrated hydrochloric acid (12 M, 1 equivalent) in ethanol to precipitate the N,N-bis(2-aminoethyl)-1,2-ethanediamine, which is the principal impurity, as the trihydrochloride.²⁷⁶ The 2,2,2-tet was then recrystallized as the dihydrosulphate salt from water. The free amine was recovered by separation from concentrated aqueous sodium hydroxide, dried over sodium sulphate and distilled. b.p. 110-115°C at 1.0-1.5 mm Hg (lit.²³⁷ 157°C at 20 mm Hg).

N,N'-bis(3-aminopropyl)-1,2-ethanediamine (3,2,3-tet)²⁷⁷

To a stirred solution of 1,2-ethanediamine (48 g, 0.8 mol) in ether (200 cm³) was added acrylonitrile (106 cm³, 1.6 mol) at such a rate that the temperature did not exceed 30°C. Stirring was continued overnight, then the solvent was removed by rotary evaporation. One half of the crude N,N'-bis(2-cyanoethyl)-1,2-ethanediamine was dissolved in ethanol (160 cm³), placed in a Parr low-pressure hydrogenation apparatus together with aqueous sodium hydroxide (20% w/v, 4 cm³) and T-1 Raney Nickel catalyst²⁷⁸ (~10 cm³) and hydrogenated at 400 kPa. When the uptake of hydrogen was complete, the catalyst was removed by filtration (caution, pyrophoric!), the ethanol was removed by rotary evaporation and the combined product of two hydrogenations was vacuum distilled.

A forerun (11 g) b.p. 80-82°C at ~0.7 mm Hg was collected, and shown by g.l.c., ^1H and ^{13}C n.m.r. spectroscopy to be 3-aza-1,6-diaminohexane. The desired product (99 g, 71%) was collected, b.p. 124-125°C at 0.7 mm Hg. (lit.²⁷⁷ 138°C at 3 mm Hg, 118°C at 0.2 mm Hg). ^1H n.m.r. $\delta(\text{CDCl}_3)$, 1.16 (s, 6H, $-\text{NH}_2$, disappears in D_2O), 1.61 (quintet, J 7 Hz, 4H, $\text{C}-\text{CH}_2-\text{C}$), 2.71 (t, J 7 Hz; t, J 3.5 Hz, 12H, $\text{N}-\text{CH}_2$). ^{13}C n.m.r. $\delta(\text{CDCl}_3)$ 33.58, 40.06, 47.35, 49.16.

N,N'-bis(3-aminopropyl)-1,3-propanediamine (3,3,3-tet)

A solution of 1,3-propanediamine (37 g, 0.5 mol) in ether (125 cm³) was treated with acrylonitrile (66 cm³, 1.0 mol) as in the previous synthesis. The crude dinitrile (obtained essentially quantitatively) was hydrogenated as before, and the resultant amine was vacuum distilled (50 g, 53%) b.p. 150-152°C at ~3 mm Hg (lit.²⁷⁷ 137-140°C at 2.5 mm Hg). ^1H n.m.r. $\delta(\text{CDCl}_3)$, 1.47 (s, 6H, $-\text{NH}_2$, disappears in D_2O), 1.61, 1.66 (2 quintets, J 7 Hz, 6H, $\text{C}-\text{CH}_2-\text{C}$), 2.65, 2.74 (2t, J 7 Hz, 12H, $\text{N}-\text{CH}_2$). ^{13}C n.m.r. $\delta(\text{CDCl}_3)$ 30.24, 33.75, 40.41, 47.82, 48.54 (the peak at 30.24 p.p.m. is approximately half the size of the others).

N-(3-aminopropyl)-N'[3-[(3-aminopropyl)amino]propyl]-1,3-propanediamine (tetrapn, 3,3,3,3-pent)

A solution of N-(3-aminopropyl)-1,3-propanediamine (dpt, 65.6 g, 0.5 mol) in ether (125 cm³) was treated with acrylonitrile (66 cm³, 1.0 mol) as in the previous synthesis. A trial distillation of a small portion of the crude dinitrile led to considerable decomposition. Sixty grams of the undistilled product was dissolved in ethanol (100 cm³) and aqueous sodium hydroxide (20% w/v, 3 cm³), concentrated ammonia (5 cm³) and T-1 Raney Nickel catalyst²⁷⁸ (5 g) was added. Hydrogenation was carried out

at 400 kPa for 100 hours. The catalyst was filtered off, the solvent was removed by rotary evaporation and the crude amine was vacuum distilled, b.p. 179-181°C at 0.5 mm Hg. The procedure was repeated and the combined fractions were redistilled to yield the pure product (47.8 g, 39%), b.p. 150-154°C at 0.2 mm Hg. ^1H n.m.r. $\delta(\text{CDCl}_3)$, 1.20 (s, 7H, $-\text{NH}_2$, disappears in D_2O), 1.60, 1.64 (2 quintets, J 7 Hz, 8H, $\text{C}-\text{CH}_2-\text{C}$), 2.65, 2.74 (2t, J 7 Hz, 16H, $\text{N}-\text{CH}_2$). ^{13}C n.m.r. $\delta(\text{CDCl}_3)$ 30.11, 33.64, 40.21, 47.62, 48.28². m/e, 248.2, 15%, $(\text{M}+3\text{H})^{++}$; 247.2, 100% $(\text{M}+2\text{H})^{++}$.

N-(2-aminoethyl)-N'[2-[(2-aminoethyl)amino]ethyl]-1,2-ethanediamine
(tetraethylenepentamine, 2,2,2,2-pent)²⁷⁹

A sample of commercial 2,2,2,2-pent (Riedel de Haën) was vacuum distilled, and the fraction between 320°C and 330°C was collected. The pentahydrochloride salt of the amine was made, and recrystallized several times from aqueous ethanol. The free ligand was recovered by separation from concentrated aqueous sodium hydroxide, dried over sodium sulphate and redistilled, to yield the pure amine (8 g, 24% of the first distillation product), b.p. 138-143°C at 0.5 mm Hg (lit.²³⁷ 340°C at 760 mm Hg, 186-192°C at 14 mm Hg). ^1H n.m.r. $\delta(\text{CDCl}_3)$ 1.48 (s, 7H, NH_2 , disappears in D_2O), 2.72 (s and t, J 5 Hz, 16H, $\text{N}-\text{CH}_2$). ^{13}C n.m.r. $\delta(\text{CDCl}_3)$ 41.69, 49.23, 49.34, 52.42. $\delta(1\text{ M HNO}_3)$ 36.61, 44.41, 44.48, 45.84.

2.2.2 Tosylation of Linear Amines

N,N'-1,2-ethanediylbis[4-methyl-N-[2-[[4-methylphenyl]sulphonyl]amino]-ethyl]benzenesulphonamide (Ts₄-2,2,2-tet)

To a solution of 2,2,2-tet (86 g, 0.59 mol) and sodium hydroxide (95 g, 4 equivalents) in distilled water (475 cm³) was added a solution of p-toluenesulphonyl chloride (562 g, 5 equivalents) in ether (2.5 dm³) with vigorous mechanical stirring over 90 minutes. Stirring was continued overnight to produce a cream coloured microcrystalline product from the waxy product that initially separated. The solid was filtered, washed with copious ether, warm water and then dried at 110°C. It was pulverized, digested with refluxing methanol (1 dm³) and filtered to give a white product and a yellow solution. The product was dried at 110°C overnight. Yield 350 g (78%). A sample was recrystallized from chloroform/ethanol. m.p. 216-217°C. Found: C, 53.44, H, 5.74; N, 7.38. C₃₄H₄₂N₄O₈S₄ requires C, 53.52; H, 5.55; N, 7.34%. I.r. (nujol): 3274 (m, sp, $\nu_{\text{N-H}}$), 1158 (i, sp, $\nu_{\text{S=O}}$) cm⁻¹. ¹H n.m.r. δ (d₆-DMSO), 2.39 (s, 12H, Ar-CH₃), 2.70-3.25 (br m, 12H, N-CH₂), 3.33 (s, 2H, -NH, disappears in D₂O), 7.40 (d, J 8 Hz, 8H, Ar), 7.65, 7.71 (2d, J 8.2 Hz, 8H, Ar).

N,N'-1,2-ethanediylbis[4-methyl-N-[3-[[4-methylphenyl]sulphonyl]amino]-propyl]benzenesulphonamide (Ts₄-3,2,3-tet)

To a solution of 3,2,3-tet (44.1 g, 0.253 mol) and sodium hydroxide (40.5 g, 4 equivalents) in distilled water (200 cm³) was added a solution of p-toluenesulphonyl chloride (231.5 g, 4.8 equivalents) in ether (250 cm³) with vigorous mechanical stirring over two hours. Stirring was continued for a further hour, the product was then filtered, washed with copious ether, warm distilled water and oven dried at 110°C. The product was

recrystallized from chloroform/ethanol. Yield 148.8 g (80%). A small sample was also satisfactorily recrystallized from methanol.

m.p. 140-141°C. Found: C, 54.76; H, 5.83; N, 7.24; $C_{36}H_{46}N_4S_4O_8$ requires C, 54.66; H, 5.86; N, 7.08%. I.r. (nujol): 3305 (m, sp, ν_{N-H}), 1159 (i, sp, $\nu_{S=O}$) cm^{-1} . 1H n.m.r. $\delta(CDCl_3)$, 1.77 (quintet, J 6 Hz, 4H, C- $\underline{CH_2}$ -C), 2.40, 2.43 (2s, 12H, Ar- $\underline{CH_3}$), 2.86-3.21 (m, 12H, N- $\underline{CH_2}$), 5.39 (t, J 6Hz, 2H, - $\underline{NH}$, disappears in D_2O), 7.28, 7.31 (2d, J 8.5 Hz, 8H, Ar), 7.67, 7.72 (2d, J 8.4 Hz, 8H, Ar). ^{13}C n.m.r. $\delta(CDCl_3)$ 21.49 (Ar- $\underline{CH_3}$), 29.07 (C- $\underline{CH_2}$ -C), 40.23 (HN(Ts)- $\underline{CH_2}$), 47.31, 48.86 (C-N(Ts)- $\underline{CH_2}$), 127.11, 127.33, 129.79, 130.03, 135.55, 137.12, 143.41, 143.90 (Ar).

N,N'-1,3-propanediylbis[4-methyl-N-[3[[4-methylphenyl)sulphonyl]amino]-propyl]benzenesulphonamide (Ts₄-3,3,3-tet)

To a solution of 3,3,3-tet (94.2 g, 0.5 mol) and sodium hydroxide (80 g, 4 equivalents) in distilled water (400 cm^3) was added a solution of p-toluenesulphonyl chloride (381.3 g, 4 equivalents) in ether (1 dm^3) with vigorous mechanical stirring over two hours. Stirring was continued for 2 days until the product solidified. It was filtered, pulverized, stirred mechanically in water/ether (1:1, 400 cm^3), filtered again, washed with copious ether, then warm distilled water, and finally oven dried at 110°C. Yield 385 g (94%). The product was recrystallized from absolute ethanol. Yield 328 g (80%). m.p. 129-131°C (lit.⁶⁹ 126-127°C). Found: C, 55.50; H, 6.01; N, 7.13. $C_{37}H_{48}N_4O_8S_4$ requires C, 55.20; H, 6.01; N, 6.96%. I.r. (nujol) 3355, 3303 (m, sp, ν_{N-H}), 1155 (i, sp, $\nu_{S=O}$) cm^{-1} . 1H n.m.r. $\delta(CDCl_3)$ 1.7-1.9 (m, 6H, C- $\underline{CH_2}$ -C), 2.38 (s, 12H, Ar- $\underline{CH_3}$), 2.8-3.2 (m, 12H, N- $\underline{CH_2}$), 5.52 (t, J 6 Hz, - $\underline{NH}$, disappears in D_2O), 7.25 (d, J 8.2 Hz, 8H, Ar), 7.61, 7.71 (2d, J 8.3 Hz, 8H, Ar).

^{13}C n.m.r. $\delta(\text{CDCl}_3)$ 21.45 ($\text{Ar}-\underline{\text{CH}_3}$), 28.55, 29.24 ($\text{C}-\underline{\text{CH}_2}-\text{C}$), 40.39 ($\text{HN}(\text{Ts})-\underline{\text{CH}_2}$), 46.41, 47.07 ($\text{C}-\text{N}(\text{Ts})-\underline{\text{CH}_2}$) 127.07, 127.16, 129.76, 129.88, 136.04, 137.18, 143.31, 143.57 (Ar).

2.2.3 Preparation of Disodium Salts

The appropriate tosylated amine was slurried in absolute ethanol (approximately 0.15-0.30 mol of tosylated amine to 1 dm^3 ethanol), and heated with stirring to 78°C . A solution of sodium ethoxide in absolute ethanol (2.2 equivalents of $\sim 2 \text{ mol dm}^{-3}$) was added, and stirring was continued until dissolution was complete. The solution was filtered if necessary, and the solvent evaporated until precipitation commenced in the boiling solution. After cooling, the product was filtered and dried by heating in a vacuum. The absence of the $\nu_{(\text{N-H})}$ peak in the infrared spectrum confirmed that the product was not contaminated by unreacted starting material, and in each case the singlet $\nu_{(\text{S=O})}$ at $\sim 1155 \text{ cm}^{-1}$ that was present in the spectrum of the parent tosylated amine was split into several strong sharp peaks in the spectrum of the disodium salt (see table 2.1).

Table 2.1 Data for Sodium Salts of Tosylated Amines

	(Ts_4 -2,2,2-tet) Na_2	(Ts_4 -3,2,3-tet) Na_2	(Ts_4 -3,3,3-tet) Na_2
Yield (%)	93	89	91
m.p. ($^\circ\text{C}$)	313-315	-	-
$\nu_{\text{S=O}}$ (cm^{-1})	1116, 1137, 1150 1170, 1183, 1212	1158, 1175 1190, 1199	1157, 1177 1190, 1201

2.2.4 Synthesis of Amino Alcohols

N-(2-hydroxyethyl)-2-aminoethanol (diethanolamine) Purification

Commercial diethanolamine (B.D.H.) was fractionally distilled, b.p. 137-138°C at ~15 mm Hg, to give pure diethanolamine m.p. 27.5-28°C (lit.²³⁷ 28°C).

N-(2-hydroxyethyl)-3-aminopropan-1-ol (2,3-diol) Method A²⁸⁰

To 3-aminopropanol (30 g, 0.4 mol) was added 2-chloroethanol (16.1 g, 0.2 mol) dropwise over 20 minutes with stirring at 40-50°C. The mixture was then stirred at 60°C for 1 hour. Sodium hydroxide (8.0 g, 1 equivalent) was added, and stirring was continued overnight. Precipitated sodium chloride was removed by filtration, and the reaction mixture was vacuum distilled. A forerun of unreacted 3-aminopropanol was collected, b.p. 60-62°C at ~0.5 mm Hg, followed by the desired product (10.8 g, 45%), b.p. 133-135°C at ~1.5 mm Hg (lit.²⁸⁰ 120-128°C at 2 mm Hg). ¹H n.m.r. δ (CDCl₃) 1.71 (quintet, J 6 Hz, 2H, C-CH₂-C), 2.70, 2.77 (2t, J 6 Hz, 4H, N-CH₂), 3.65, 3.68 (2t, J 6 Hz, 4H, O-CH₂), 4.17 (s, 3H, -NH and -OH, disappears in D₂O). ¹³C n.m.r. δ (CDCl₃) 31.79 (C-CH₂-C), 47.52, 51.47 (O-CH₂) 60.41, 61.23 (N-CH₂).

A further, higher boiling fraction remained. The ¹H n.m.r. spectrum was consistent with that expected for the tertiary amino alcohol, HO(CH₂)₃N(CH₂CH₂OH)₂, which would form on addition of two 2-hydroxyethyl groups to 3-aminopropanol. ¹H n.m.r. δ (CDCl₃) 1.70 (quintet, J 5.8 Hz, 2H, C-CH₂-C) 2.62, 2.68 (2t, J 5.8 Hz, 6H, N-CH₂), 3.63, 3.73 (2t J 5.5 Hz, 6H, O-CH₂), 4.62 (s, 3H, -OH, disappears in D₂O).

N-(2-hydroxyethyl)-3-aminopropan-1-ol (2,3-diol) Method B

To a stirred solution of 3-aminopropanol (150 g, 2 mol) in absolute ethanol (200 cm³) was added ethylene oxide (58.3 g, 1.3 mol) in absolute alcohol (200 cm³) at 0°C over 1 hour. Stirring was continued at room temperature overnight, the solvent was removed by rotary evaporation and the reaction mixture was fractionated to yield a forerun of 3-aminopropanol (76.5 g, 1 mol), b.p. 60-65°C at 0.5 mm Hg, followed by the desired product (75 g, 63%), b.p. 115-122°C at 0.5 mm Hg, as well as a higher boiling product which had the same ¹H n.m.r. spectrum as the corresponding fraction in method A. (These products together accounted for 97% of the starting materials). The product was redistilled, b.p. 116-118°C at ~0.5 mm Hg. Various other ratios of reactants were tried, both neat and in solution, but the yield was lower in each case. More 3-aminopropanol was recovered if a larger excess was used, and if the proportion of ethylene oxide was raised a larger amount of the higher boiling product was obtained.²⁸¹

N-(3-hydroxypropyl)-3-aminopropan-1-ol (3,3-diol) Method A

To 3-aminopropanol (190 g, 2.53 mol) was added 3-chloropropanol (76.4 g, 0.81 mol) at 40°C with stirring over 2 hours. The mixture was stirred at 60°C for a further two hours and sodium hydroxide (33 g, 0.825 mol) in methanol was then added. Stirring was continued overnight, the precipitated sodium chloride was filtered off, the methanol was removed by rotary evaporation and the mixture was fractionated. A forerun of unreacted 3-aminopropanol (126 g, 1.68 mol), b.p. 80-81°C at 8 mm Hg was collected followed by the desired product (78 g, 72%), b.p. 163-165°C at ~8 mm Hg. ¹H n.m.r. δ (CDCl₃) 1.70 (quintet, J 6.2 Hz, 4H, C-CH₂-C),

2.76 (t, J 6.3 Hz, 4H, N-CH₂), 3.67 (t, J 5.9 Hz, 4H, O-CH₂),
 4.04 (s, 3H, -NH and -OH, disappears in D₂O). m/e 134.0, 2%, (M+H)⁺;
 88.8, 31% (M+H-[CH₂CH₂OH])⁺

A small amount (1.66 g) of a higher boiling product, b.p. 250-260°C
 at ~1 mm Hg, was also obtained. The ¹H and ¹³C n.m.r. spectra were
 consistent with the formation of N(CH₂CH₂CH₂OH)₃ resulting from the
 addition of two 3-aminopropyl groups to 3-aminopropanol. ¹H n.m.r.
 δ(CDCl₃), 1.71 (quintet, J 6.2 Hz, 6H, C-CH₂-C), 2.58 (t, J 6.7 Hz, 6H,
 N-CH₂), 3.66 (t, J 5.9 Hz, 6H, O-CH₂), 4.77 (s, 3H, -OH, disappears in D₂O).
¹³C n.m.r. δ(CDCl₃) 28.90 (C-CH₂-C), 51.98 (N-CH₂), 61.44 (O-CH₂).
 m/e 194.2, 1%, (M+3H)⁺; 193.2, 8% (M+2H)⁺; 135.1, 27% (M+3H-
 [CH₂CH₂CHOH])⁺; 134.1, 3%, (M+2H-[CH₂CH₂CH₂OH])⁺; 133.1, 5%,
 (M+H-[CH₂CH₂CH₂OH])⁺

(The three products were characterized by mass spectroscopy.)

(500 cm³), washed with hydrochloric acid (2 M, 2×500 cm³) and water (2×500 cm³). The chloroform solution was dried over sodium sulphate, filtered and absolute ethanol (1 dm³) was added. The product was filtered, desiccated and further recrystallized twice from chloroform/ethanol to produce a white crystalline product. Yield (after two recrystallizations) 151 g (79%). m.p. 94.5-95.5°C (lit.²⁸³ 93-95°C). Found: C, 52.69; H, 5.25; N, 2.47. C₂₅H₂₉NO₈S₃ requires C, 52.89; H, 5.15; N, 2.47%. I.r. (nujol): 1159, 1178, 1191 (i, sp, $\nu_{S=O}$) cm⁻¹. ¹H n.m.r. δ (CDCl₃) 2.41, 2.44 (2s, 9H, Ar-CH₃), 3.36 (t, J 5.9 Hz, 4H, N-CH₂), 4.11 (t, J 5.9 Hz, O-CH₂), 7.21-7.39, 7.55-7.80 (2m, 12H, Ar). ¹³C n.m.r. (CDCl₃), 21.47, 21.60 (Ar-CH₃), 48.44 (N-CH₂), 68.25 (O-CH₂), 127.29, 127.95, 130.02, 130.06, 132.80, 135.63, 144.12, 145.19 (Ar).

The same method was also used for tosylation of the two other amino alcohols studied, but problems were encountered with oiling of the product upon precipitation from the pyridine reaction mixture and low, variable yields were obtained. The best yields obtained by this method were N,O,O'-Ts₃-N(2-hydroxyethyl)-3-aminopropan-1-ol: 59% (crude), 42% (recrystallized). N,O,O'-Ts₃-N(3-hydroxypropyl)-3-aminopropan-1-ol: 61% (crude), 42% (recrystallized).

N-(2-hydroxyethyl)-3-aminopropan-1-ol Tosylation (N,O,O'-Ts₃-2,3-diol)

Method B

To a stirred solution of N-(2-hydroxyethyl)-3-aminopropan-1-ol (43.7 g, 0.376 mol) and triethylamine (200 cm³, dried over calcium hydride, distilled), in dichloromethane (800 cm³, dried over lithium aluminium hydride, distilled) at 5°C, under nitrogen, was added freshly recrystallized solid p-toluene sulphonyl chloride²⁸² (227 g, 1.19 mol, 6% excess) over 10 minutes. The solution was stirred overnight, then washed with

hydrochloric acid (2 M, 2×250 cm³) and water (3×500 cm³) to remove the triethylamine as the hydrochloride. The dichloromethane solution was dried over sodium sulphate, filtered and taken to dryness by rotary evaporation. Absolute ethanol (1 dm³) was added to the colourless oil that remained, and on vigorous stirring, the product solidified. After refrigeration the colourless crystalline product was filtered, washed with propan-2-ol and vacuum desiccated. The product was recrystallized from chloroform/ethanol. Yield 166.7 g (76%) m.p. 73-74°C.

Found: C, 53.66; H, 5.43, N, 2.38. C₂₆H₃₁NO₈S₃ requires C, 53.68; H, 5.37; N, 2.41%. I.r. (nujol): 1160, 1173, 1187 (i, sp, $\nu_{S=O}$) cm⁻¹. ¹H n.m.r. δ (CDCl₃) 1.86 (quintet, J 6 Hz, 2H, C-CH₂-C), 2.41, 2.43 (2s, 9H, Ar-CH₃), 3.12, 3.29 (2t, J 6 Hz, 4H, N-CH₂), 4.01, 4.11 (2t, 4H, J 6 Hz, O-CH₂), 7.22-7.39, 7.55-7.82 (2m, 12H, Ar). ¹³C n.m.r. δ (CDCl₃) 21.48, 21.61 (Ar-CH₃), 28.41 (C-CH₂-C), 46.55, 47.86 (N-CH₂), 67.70, 68.59 (O-CH₂), 127.23, 127.88, 129.96, 130.05, 132.55, 132.89, 135.42, 143.93, 144.96, 145.25 (Ar).

N-(3-hydroxypropyl)-3-aminopropan-1-ol Tosylation (N,O,O'-Ts₃-dipropanolamine) Method B

A solution of N-(3-hydroxypropyl)-3-aminopropan-1-ol (46 g, 0.345 mol) and dried triethylamine (170 g, 1.68 mol) in dried dichloromethane (1 dm³) was treated with freshly recrystallized p-toluenesulphonylchloride²⁸² (214 g, 1.122 mol) as in the previous reaction. A similar workup afforded (after one recrystallization) the desired white microcrystalline product. Yield 153 g (74%). m.p. 78.5-79.5°C.

Found: C, 54.20; H, 5.67; N, 2.37. C₂₇H₃₃NO₈S₃ requires C, 54.43; H, 5.58; N, 2.35%. I.r. (nujol): 1152, 1159, 1180, 1189 (i, sp, $\nu_{S=O}$) cm⁻¹. ¹H n.m.r. δ (CDCl₃) 1.85 (quintet, J 6 Hz, C-CH₂-C), 2.43 (s, 9H, Ar-CH₃),

3.08 (t, J 7 Hz, 4H, N-CH₂), 4.02 (t, J 6 Hz, 4H, O-CH₂), 7.22-7.39, 7.55-7.82 (2m, 12H, Ar). ¹³C n.m.r. δ(CDCl₃) 21.62 (Ar-CH₃), 28.71 (C-CH₂-C), 45.80 (N-CH₂), 67.82 (O-CH₂), 127.21, 127.90, 130.01, 132.99, 135.67, 143.76, 145.05 (Ar).

2.2.6 Cyclization Reactions

1,4,7,10,13-Pentakis[(4-methylphenyl)sulphonyl]-1,4,7,10,13-pentaaza-
cyclopentadecane (Ts₅-[15]aneN₅)

To a stirred solution of (Ts₄-2,2,2-tet)Na₂ (102.4 g, 0.127 mol) in dry DMF (375 cm³) at 100°C was added a solution of N,O,O'-Ts₃-diethanolamine (72.0 g, 1 equivalent) in dry DMF (200 cm³) over 90 minutes under dry nitrogen (to exclude moisture). Heating was continued for a further 2½ hours. The DMF was removed by low pressure distillation at 80°C (water pump) until the final reaction volume was ~250 cm³ and precipitation was just commencing. Ethanol (600 cm³) was added and the mixture was heated at reflux temperature. The pale oil gradually dissolved, and a pale solid precipitated. The solution was cooled, the product was filtered, washed with ethanol, then water and dried at 120°C. Yield 108.5 g (87%). The absence of starting material was confirmed by the presence of a single spot on the t.l.c. (1:1 petroleum ether/ethyl acetate R_f = 0.49) and the absence of a ν_(N-H) peak in the infrared spectrum. A sample was recrystallized for analysis from acetone/methanol. m.p. 279-280°C [lit.⁶⁵ 278-280°C]. Found: C, 54.99; H, 5.63; N, 7.13. C₄₅H₅₅N₅O₁₀S₅ requires C, 54.80; H, 5.62; N, 7.10%. I.r. (nujol): 1158 cm⁻¹ (i, sp, ν_{S=O}). ¹H n.m.r. δ((CD₃)₂CO) 2.46 (s, 15H, Ar-CH₃), 3.28 (s, 20H, N-CH₂), 7.45, 7.69 (2d, J 8.2 Hz, 20H, Ar). ¹³C n.m.r. 21.43 (Ar-CH₃), 48.82 (N-CH₂), 127.98, 130.84, 137.73, 144.68 (Ar).

1,4,7,10,13-Pentakis[(4-methylphenyl)sulphonyl]-1,4,7,10,13-pentaaza-
cyclohexadecane [Ts₅-[16]aneN₅]

To a stirred solution of (Ts₄-2,2,2-tet)Na₂ (81.8 g, 0.10 mol) in dry DMF (300 cm³) at 110°C was added a solution of N,C,O'-Ts₃-2,3-diol (59 g, 0.1 mol) in dry DMF (160 cm³) over 90 minutes. Heating was continued for 16 hours, the DMF was removed by distillation (47°C, water pump) until precipitation commenced. Absolute ethanol (500 cm³) was added, and the mixture was stirred and heated at reflux temperature for one hour. After cooling the product was filtered, washed with ethanol (500 cm³) then hot distilled water (1 dm³) and dried at 110°C. Yield of crude product 94.2 g (93%). The absence of a $\nu_{(N-H)}$ peak in the infrared spectrum together with a single spot observed in the t.l.c. (1:1 petroleum ether/ethyl acetate $R_f = 0.41$) confirmed the absence of unreacted starting material. The product was recrystallized from chloroform/methanol. m.p. 222.5-223°C. Found: C, 54.99; H, 5.81; N, 7.11. C₄₆H₅₇N₅O₁₀S₅ requires C, 55.23; H, 5.74; N, 7.00%. I.r. (nujol): 1155, 1158 (i, sp, $\nu_{S=O}$) cm⁻¹. ¹H n.m.r. δ (CDCl₃) 1.5-2.2 (br m, 2H, C-CH₂-C), 2.40 (s, 15H, Ar-CH₃), 2.9-3.4 (br m, 20H, N-CH₂), 7.3 (d, J 8.3 Hz, 10H, Ar), 7.65, 7.69 (2d, J 8 Hz, 10H, Ar). ¹³C n.m.r. δ (CDCl₃) 21.45 (Ar-CH₃), 28.94 (C-CH₂-C), 48.04, 48.89, 49.09, 49.25, 50.02 (N-CH₂), 127.37, 129.92, 134.81, 135.70, 135.88, 143.82 (Ar).

A sample was recrystallized twice from ethyl acetate to give a compound containing two moles of ethyl acetate of crystallization per mole of macrocycle. m.p. 114-115°C. Found: C, 55.02; H, 6.23; N, 5.84. C₅₆H₇₇N₅O₁₄S₅ requires C, 55.13; H, 6.25; N, 5.95%.

1,4,7,10,14-Pentakis[(4-methylphenyl)sulphonyl]-1,4,7,10,14-pentaaza-
cycloheptadecane (Ts₅-[17A]aneN₅)

To a stirred solution of (Ts₄-2,2,2-tet)Na₂ (72.7 g, 0.09 mol) in dry DMF (270 cm³) at 110°C was added a solution of N,O,O'-Ts₃-dipropanolamine (53.89 g, 0.09 mol) in dry DMF (150 cm³) over 1 hour. The reaction mixture was left at 110°C for 16 hours and subjected to the same workup as that used for Ts₅-[16]aneN₅. A solution of the crude product in chloroform was washed with water (2×250 cm³), dried over sodium sulphate and filtered. Ethanol (1 dm³) was added and the chloroform was removed by distillation. On overnight refrigeration (after addition of a small seed crystal of the crude product) the product crystallized and was filtered, washed with ethanol, then ether and dried at 120°C. Yield (after recrystallization) 75 g (82%). The absence of a $\nu_{(N-H)}$ peak in the infrared spectrum and the sharp singlet at 1161 cm⁻¹, $\nu_{(S=O)}$ confirmed that the product was not contaminated by unreacted starting materials. m.p. 214-215°C. Found: C, 55.69; H, 5.85; N, 7.04.

C₄₇H₅₉N₅O₁₀S₅ requires C, 55.65; H, 5.89; N, 6.91%.

¹H n.m.r. δ (CDCl₃), 1.7-2.2 (br m, 4H, C-CH₂-C), 2.41 (s, 15H, Ar-CH₃), 2.9-3.4 (br m, 20H, N-CH₂), 7.30 (d, J 8.1 Hz, 10H, Ar), 7.67, 7.69 (2d, J 8 Hz, 10H Ar). ¹³C n.m.r. δ (CDCl₃), 21.48 (Ar-CH₃), 29.89 (C-CH₂-C), 48.06, 48.31, 48.71, 50.06, 50.14 (N-CH₂), 127.25, 127.47, 129.91, 135.34, 135.48, 143.60, 143.72, 143.86 (Ar).

1,4,7,11,14-Pentakis[(4-methylphenyl)sulphonyl]-1,4,7,11,14-pentaazacyclo-
heptadecane (Ts₅-[17B]aneN₅)

To a stirred solution of (Ts₄-3,2,3-tet)Na₂ (99.4 g, 0.119 mol) in dry DMF (350 cm³) at 110-115°C was added a solution of N,O,O'-Ts₃-2,3-diol (67.57 g, 0.119 mol) in dry DMF (175 cm³) over 90 minutes. The solution

was heated at 115°C for 3½ hours and the DMF was then removed by distillation (50°C, water pump). Absolute ethanol (500 cm³) was added and after 5 minutes precipitation commenced. The mixture was cooled, the product was filtered, washed with ethanol (1 dm³), ether (2×250 cm³), then hot distilled water (1½ dm³) and dried at 120°C. Yield 72 g (60%). The product was recrystallized from chloroform/ethanol. The t.l.c. showed a single spot (1:1 petroleum ether/ethyl acetate $R_f=0.6$) and the infrared spectrum contained the characteristic sharp peak at 1158 cm⁻¹ $\nu_{(S=O)}$ and no peak corresponding to $\nu_{(N-H)}$ confirming the absence of unreacted starting material. m.p. 219-220°C (form A). Found: C, 55.33; H, 6.04; N, 6.72. C₄₇H₅₉N₅O₁₀S₅ requires C, 55.65; H, 5.86; N, 6.91%.

¹H n.m.r. δ (CDCl₃) 1.8-2.2 (br m, 4H, C-CH₂-C), 2.41 (s, 15H, Ar-CH₃), 2.9-3.5 (br m, 20H, N-CH₂), 7.29, 7.31 (2d, J 8.2 Hz, 10H, Ar), 7.66, 7.68 (2d, J 8.2 Hz, 10H, Ar). ¹³C n.m.r. δ (CDCl₃) 21.46 (Ar-CH₃), 28.78 (C-CH₂-C), 47.94, 48.64², 49.90, 50.29 (N-CH₂), 127.43, 129.89, 134.54, 134.98, 136.00, 143.70 (Ar).

A sample was melted under vacuum (0.1 mm Hg) and allowed to solidify. A different crystalline form appeared to be produced. m.p. 110-111°C (form B). Found: C, 55.55; H, 5.97; N, 6.86. C₄₇H₅₉N₅O₁₀S₅ requires C, 55.65; H, 5.86; N, 6.91%.

The fingerprint region of the infrared spectrum was quite different for the two samples. The principal differences are listed.

Form A; ν (nujol) 980, 960, 943, 917, 817, 747, 741, 730, 723, 716, 655 (all medium intensity, sharp) cm⁻¹.

Form B; ν (nujol) 1039, 1015(m,sp), 965(m,br), 814(i,sp), 738, 717, 714(i,br), 694(m,sp), 655(i,sp) cm⁻¹.

1,4,7,11,15-Pentakis[(4-methylphenyl)sulphonyl]-1,4,7,11,15-pentaaza-
cyclooctadecane [Ts₅-[18A]aneN₅]

To a stirred solution of (Ts₄-3,3,3-tet)Na₂ (115.9 g, 0.137 mol) in dry DMF at 110°C was added a solution of N,O,O'-Ts₃-diethanolamine (77.5 g, 0.137 mol) in dry DMF (200 cm³) with stirring over 70 minutes. The reaction mixture was heated at 100°C for a further 2 hours and then the DMF was removed by distillation (60°C, water pump). Absolute ethanol (1 dm³) was added, and the mixture was heated to reflux temperature and stirred to dissolve the resultant oil. The solid that formed was filtered after cooling, washed with copious ethanol and dried. The crude product was taken up in chloroform, the solution was washed with distilled water (2×500 cm³) dried over sodium sulphate, and the chloroform was removed by rotary evaporation.

The infrared spectrum contained a peak at ~1680 cm⁻¹ indicating the presence of DMF. A sample was melted and degassed under vacuum to remove the DMF. On the basis of the weight loss, it was estimated that the sample contained approximately 1.66 equivalents of DMF per mole of macrocycle. Yield of crude product 119.9 g (75% based on the formulation Ts₅-[18A]aneN₅·(DMF)_{5/3}). The degassed product was recrystallized from chloroform/methanol or alternatively from ethanol. m.p. 101-103°C. Found: C, 55.88; H, 6.18; N, 6.91. C₄₈H₆₁N₅O₁₀S₅ requires C, 56.06; H, 5.98; N, 6.81%. ¹H n.m.r. δ(CDCl₃): 1.7-2.2 (br m, 6H, C-CH₂-C), 2.41 (s, 15H, Ar-CH₃), 3.11 (quintet, J 7 Hz), 3.34(s) (overlapping, 20H, N-CH₂), 7.30 (d, J 7.3 Hz, 10H, Ar), 7.64, 7.70 (2d, J 8.1 Hz, 10H, Ar). ¹³C n.m.r. δ(CDCl₃), 21.47 (Ar-CH₃), 29.05, 30.70 (C-CH₂-C), 47.65, 48.06, 48.32, 49.61, 50.77 (N-CH₂), 127.16, 127.42, 129.84, 134.65, 134.90, 135.34, 143.49, 143.69, 143.92 (Ar).

1,4,8,11,15-Pentakis[(4-methylphenyl) sulphonyl]-1,4,8,11,15-pentaazacyclo-octadecane [Ts₅-[18B]aneN₅)

To a stirred solution of (Ts₄-3,2,3-tet)Na₂ (103.77 g, 0.124 mol) in dry DMF (370 cm³) at 100°C was added a solution of N,O,O'-Ts₃-2,3-diol (72.29 g, 0.124 mol) in dry DMF (185 cm³) over 45 minutes. Heating was continued for 4½ hours, the DMF was then removed by distillation (60°C, water pump) and absolute ethanol (800 cm³) was added. The reaction mixture was stirred and heated at reflux temperature to digest the pale yellow oil, which was gradually replaced by a solid product. The mixture was cooled, the product was filtered and washed with ethanol then hot distilled water to give a white microcrystalline solid, which was vacuum desiccated. The t.l.c. showed that only one compound was present, and the infrared spectrum showed a sharp band at 1156 cm⁻¹ $\nu_{(S=O)}$ and no $\nu_{(N-H)}$ band, indicating the absence of unreacted starting materials. A small peak at 1680 cm⁻¹ was taken as evidence for the presence of DMF in the crystalline product. (This peak remained even after three recrystallizations from chloroform/ethanol). On the basis of the weight loss of a sample melted under vacuum, it was estimated that there was approximately ½ mole of DMF per mole of macrocycle. Yield 112.9 g (87% based on Ts₅-[18B]aneN₅.(DMF)_{0.5}). m.p. 100-103°C. The product, after stripping of DMF was recrystallized from chloroform/ethanol. m.p. 165-166.5°C. Found: C, 56.31; H, 6.33; N, 6.84. C₄₈H₆₁N₅O₁₀S₅ requires C, 56.06; H, 5.98; N, 6.81%. ¹H n.m.r. δ (CDCl₃) 1.8-2.2 (br m, 6H, C-CH₂-C), 2.40 (s, 15H, Ar-CH₃), 2.8-3.4 (2 br m, 20H, N-CH₂), 7.30 (d, J 8 Hz, 10H, Ar), 7.66, 7.70 (2d, J 8 Hz, 10H, Ar). (The original sample also showed a peak at 2.14 p.p.m. corresponding to DMF). ¹³C n.m.r. δ (CDCl₃) 21.53 (Ar-CH₃), 28.87, 30.09 (C-CH₂-C), 48.00, 48.55, 48.80, 49.78² (N-CH₂), 127.28, 127.54, 129.92, 134.53, 134.95, 135.50, 143.73 (Ar).

A recrystallized sample was melted under vacuum to strip the DMF and then allowed to solidify, but the peaks in the infrared spectrum were considerably broadened compared with the sharp peaks in the sample recrystallized after being stripped of DMF.

1,4,8,12,16-Pentakis[(4-methylphenyl)sulphonyl]-1,4,8,12,16-pentaaza-
cyclononadecane (Ts₅-[19]aneN₅)

To a rapidly stirred solution of (Ts₄-3,3,3-tet)Na₂ (102.18 g, 0.12 mol) in dry DMF (360 cm³) at 90°C was added a solution of N,O,O'-Ts₃-2,3-diol (70 g, 0.12 mol) in dry DMF (180 cm³) over 15 minutes. The reaction mixture was heated at 100-110°C for a further 2½ hours and then DMF was removed by distillation (60°C, water pump) until precipitation commenced. Ethanol (1 dm³) was added and an oil separated, but it did not solidify on heating the mixture. It was separated, and distilled water was added to the filtrate to precipitate a white solid, which was filtered, washed with water and vacuum desiccated. The two products were combined, digested with ethanol (1 dm³) and petroleum ether was added. The pale brown solid product was filtered, washed with petroleum ether and dried at 110°C. Yield 105.5 g (84%). The product was recrystallized by dissolving it in a minimum amount of hot acetone and adding aqueous ethanol (1:1 proportion) to induce precipitation. The t.l.c. showed only a single spot (1:1 petroleum ether/ethyl acetate R_f = 0.37) and the infrared spectrum showed the characteristic sharp singlet at 1059 cm⁻¹ $\nu_{(S=O)}$ and no $\nu_{(N-H)}$ band. m.p. 194-195°C. Found: C, 56.59; H, 6.13; N, 6.82. C₄₉H₆₃N₅O₁₀S₅ requires C, 56.46; H, 6.09; N, 6.72%. ¹H n.m.r. δ (CDCl₃) 1.7-2.3 (br m, 10H, C-CH₂-C), 2.39 (s, 15H, Ar-CH₃), 2.85-3.45 (2br m, 20H, N-CH₂), 7.26 (d, J 7.7 Hz, 10H, Ar), 7.64, 7.69 (2d, J 7.5 Hz, 10H, Ar). ¹³C n.m.r. δ (CDCl₃) 21.49 (Ar-CH₃), 29.53, 29.93 (C-CH₂-C), 47.21, 47.88², 48.68, 49.80 (N-CH₂), 127.25, 127.48, 129.88, 134.78, 135.42, 136.01, 143.55, 143.74 (Ar).

1,5,9,13,17-Pentakis[(4-methylphenyl)sulphonyl]-1,5,9,13,17-pentaaza-
cycloeicosane (Ts₅-[20]aneN₅)

To a stirred solution of (Ts₄-3,3,3-tet)Na₂ (109.7 g, 0.13 mol) in dry DMF (1 dm³) at 130°C was added a solution of N,O,O'-Ts₃-dipropanolamine (77.6 g, 0.13 mol) in dry DMF (500 cm³) over 4 hours. The mixture was kept at 130°C for a further 2 hours. DMF (~1.25 dm³) was removed by distillation (60°C, water pump) and aqueous ethanol (1:1, 300 cm³) was slowly added with vigorous stirring. Further water (600 cm³) was added and the white crystalline product was separated by filtration, washed with water and dried at 110°C. Yield 119.8 g (88%).

The product was recrystallized twice from chloroform/methanol. A single spot on the t.l.c. (1:1 petroleum ether/ethyl acetate, R_f = 0.34), together with the strong sharp, $\nu_{(S=O)}$ peak at 1155 cm⁻¹ and the absence of a $\nu_{(N-H)}$ peak in the infrared spectrum confirmed the purity of the product. m.p. 211-212°C. Found: C, 56.30; H, 6.13; N, 6.54. C₅₀H₆₅N₅O₁₀S₅ requires C, 56.85; H, 6.20; N, 6.63%. ¹H n.m.r. δ (CDCl₃) 1.7-2.1 (br m, 10H, C-CH₂-C), 2.40 (s, 15H, Ar-CH₃), 3.16 (br t, J 6 Hz, 20H, N-CH₂), 7.29, 7.66 (2d, J 8 Hz, 20H, Ar). ¹³C n.m.r. δ (CDCl₃) 21.47 (Ar-CH₃), 29.64 (C-CH₂-C), 47.55 (N-CH₂), 127.24, 129.82, 135.59, 143.44 (Ar).

2.2.7 Detosylation Reactions

1,4,7,10,13-Pentaazacyclopentadecane pentahydrobromide trihydrate
([15]aneN₅(HBr)₅·3H₂O)

Four sealed Carius tubes each containing Ts₅-[15]aneN₅ (12.8 g, 13 mmol), phenol (4.3 g, 46 mmol) and hydrogen bromide in glacial acetic acid (40% w/v, 66 cm³) were heated in a Carius oven for eight hours

at 120°C. After approximately 90 minutes all the macrocyclic compound had dissolved, and subsequently precipitation occurred together with darkening of the solution. The combined contents of the tubes was added to distilled water (800 cm³). The resulting solution and some solid material was shaken with toluene (3×300 cm³) and then ether (2×150 cm³) giving a clear, pale gold solution. The volume of the aqueous solution was reduced by rotary evaporation to 250 cm³ and propan-2-ol (1 dm³) was added. The fine dense pale precipitate which formed was digested at reflux temperature for two hours then filtered and washed with copious propan-2-ol. After further digestion at reflux temperature with acetone (1 dm³) the solid was filtered and dried at 120°C. The product was recrystallized from aqueous hydrobromic acid. Yield 21.68 g (61%) (based on analysis as the trihydrate). m.p. 251-254°C (dec.).

Found: C, 18.18; H, 5.33; N, 10.65; Br 58.51. C₁₀H₃₆N₅Br₅O₃ requires C, 17.82; H, 5.38; N, 10.39; Br, 59.28%. I.r. (HCBd): 3450-3300 (i, br, several peaks, $\nu_{\text{O-H}}$), 2850-2400 (i, br, several peaks, $\nu_{\text{N-H}}$) cm⁻¹; I.r. (nujol): 1615, 1585, 1550 (m, sp, $\delta_{\text{NH}_2^+}$) cm⁻¹.

The infrared spectrum is consistent with the formation of a hydrated amine salt, and the absence of the characteristic peak at 1155 cm⁻¹ $\nu_{(\text{S=O})}$ suggest that no tosylated contaminants are present.

¹H n.m.r. δ (DCl) 3.92 (s, C-H), 5.49 (s, N-H, O-H). ¹³C n.m.r. δ (D₂O/DCl) 45.06 (N-CH).

Further product containing partially detosylated Ts-[15]aneN₅.(HBr)₄ could be isolated from the filtrate remaining after the original precipitation. The $\nu_{(\text{S=O})}$ peak at 1156 cm⁻¹ and a pair of sharp peaks at 696 cm⁻¹ and 708 cm⁻¹ were diagnostic for the presence of the partially detosylated product. ¹H n.m.r. δ (DCl) 2.50 (s, Ar-CH₃), 3.44, 3.65, 3.77 (N-CH₂), 7.57, 7.91 (2d, J 8 Hz, Ar). An appreciable amount of the

completely detosylated product was present in the sample, as shown by the integrations of the different peaks. The partially detosylated residues of several preparations were combined and subjected to a further treatment with hydrogen bromide and glacial acetic acid to increase the yield of the desired product.

1,4,7,10,13-Pentaazacyclohexadecane pentahydrobromide dihydrate
([16]aneN₅.(HBr)₅.2H₂O)

Four sealed Carius tubes each containing Ts₅-[16]aneN₅ (12.5 g, 12.7 mmol) hydrogen bromide in glacial acetic acid (44% w/v, 66 cm³) and phenol (5 g, 53 mmol) were heated for nine hours at 115-120°C. The combined contents of the tubes was dissolved in distilled water (800 cm³) and washed with toluene (4×200 cm³). The aqueous layer was filtered through glass fibre filter paper, washed with ether (3×200 cm³) and the volume reduced by rotary evaporation to 250 cm³. Propan-2-ol (1 dm³) was added, and the white microcrystalline product together with the orange solution was heated at reflux temperature for 1 hour. The product was filtered, washed with copious propan-2-ol acetone and finally ether, then dried at 120°C. Yield 28.52 g (85% based on the dihydrate). m.p. 250-252°C (dec.). Found: C, 19.80; H, 5.44; N, 10.25. C₁₁H₃₆N₅Br₅O₂ requires C, 19.72; H, 5.42; N, 10.48%. I.r. (HCBd): 3380 (m, br, $\nu_{\text{O-H}}$), 2900-2300 (i, br, several peaks, $\nu_{\text{N}^+-\text{H}}$) cm⁻¹. I.r. (nujol): 1570 (m, several peaks, δ_{NH_2}) cm⁻¹. The characteristic $\nu_{\text{(S=O)}}$ peak at 1155 cm⁻¹ and the aromatic peaks at 1602 and 655 cm⁻¹ were absent from the infrared spectrum, confirming the absence of tosylated contaminants in the hydrated amine hydrobromide. ¹H n.m.r. δ (DCl) 1.5-1.9 (br quintet, 2H, C-CH₂-C), 2.7-2.9 (br m, 20H, N-CH₂), 4.78 (s, -NH, HOD). ¹³C n.m.r. δ (DCl) 21.60 (C-CH₂-C), 42.16, 43.00, 43.24², 44.45 (N-CH₂).

Workup of the residues (evaporation of the filtrate and precipitation with ether) afforded further product that was shown to contain tosylated material. A strong doublet at 1180 cm^{-1} and 1220 cm^{-1} , together with peaks at 710 cm^{-1} and 680 cm^{-1} in the infrared spectrum are characteristic of the monotosylated tetrahydrobromide salt. ^1H n.m.r. $\delta(\text{DCI})$ 2.32, 2.45 (br m, overlapping, $\text{C-CH}_2\text{-C}$, Ar-CH_3), 3.54-3.70, 3.86-3.92 (2m, N-CH_2), 7.52, 7.82 (2d, J 8 Hz, Ar).

Shorter periods of heating produced less amine hydrobromide and more of the partially detosylated material.

1,4,7,10,14-pentaazacycloheptadecane pentahydrobromide hemihydrate
([17A]aneN₅.(HBr)₅.0.5H₂O)

Four sealed Carius tubes each containing Ts₅[17A]aneN₅ (11 g, 10.8 mmol) and hydrogen bromide in glacial acetic acid (40% w/v, 60 cm³) were heated at 115°C for 3½ hours. The solid contents of the tubes dissolved on heating, but subsequent precipitation of a pale material from the dark orange solution occurred. The combined contents of the tubes was dissolved in distilled water (600 cm³) and the solution was washed with toluene (3×200 cm³) and ether (3×200 cm³) leading to substantial decolourization. The volume of the aqueous solution was reduced by rotary evaporation to a total volume of approximately 75 cm³, and propan-2-ol (500 cm³) was added. The white precipitate and pale orange solution were heated at reflux temperature for ½ hour, filtered hot, and the precipitate was washed with propan-2-ol (2×200 cm³), acetone, finally ether and dried overnight in a vacuum desiccator. Yield 26.88 g (94% based on the hemihydrate). The product was recrystallized from aqueous hydrobromic acid/methanol to provide an analytically pure sample.

m.p. 250–254°C (dec.). Found: C, 22.06; H, 5.35; N, 10.82; Br, 60.68.

$C_{12}H_{35}N_5Br_5O_{1/2}$ requires C, 21.94; H, 5.37; N, 10.66; Br, 60.81%.

I.r. (HCBd): 3520–3450 (w, br, ν_{O-H}), 3050–2400 (i, br, several peaks, ν_{N^+-H}) cm^{-1} . I.r. (nujol): 1560, 1540 (m, $\delta_{NH_2^+}$) cm^{-1} .

(No peaks at 1602, 1155 or 655 cm^{-1} , confirming absence of tosyl groups).

1H n.m.r. δ (DCl), 2.32 (quintet, J 7.4 Hz, 4H, C- $\underline{CH_2}$ -C), 3.29–3.75 (m, 20H, N- $\underline{CH_2}$), 4.73 (s, -NH, $\underline{HOD}$). ^{13}C n.m.r. δ (DCl) 23.35 (C- $\underline{CH_2}$ -C) 44.16, 44.80, 45.02, 45.65, 46.53 (N- $\underline{CH_2}$).

1,4,7,11,14-Pentaazacycloheptadecane pentahydrobromide

([17B]aneN₅.(HBr)₅)

Four sealed Carius tubes, each containing Ts₅-[17B]aneN₅ (12.1 g, 11.9 mmol) and hydrogen bromide in glacial acetic acid (40% w/v, 60 cm³) were treated in the same fashion as the isomeric Ts₅-[17A]aneN₅. Yield 28.9 g (93%).

A sample was recrystallized for analytical purposes from aqueous hydrobromic acid. m.p. 251–254°C (dec.). Found: C, 22.38; H, 5.59; N, 10.95. $C_{12}H_{34}N_5Br_5$ requires C, 22.24; H, 5.29; N, 10.81%.

I.r. (HCBd): 3000–2400 (i, br, several peaks, ν_{N^+-H}) cm^{-1} .

I.r. (nujol): 1600, 1580, 1540 (m, sp, $\delta_{NH_2^+}$) cm^{-1} . (No peaks at 1155 or 655 cm^{-1} , confirms absence of tosyl contaminants).

1H n.m.r. δ (DCl) 1.71 (quintet, J 6 Hz, 4H, C- $\underline{CH_2}$ -C), 2.90–3.23 (m, 20H, N- $\underline{CH_2}$), 5.66 (s, -NH, $\underline{HOD}$). ^{13}C n.m.r. δ (DCl) 23.26 (C- $\underline{CH_2}$ -C), 44.56, 44.67, 45.25², 45.58 (N- $\underline{CH_2}$).

1,4,7,11,15-Pentaazacyclooctadecane pentahydrobromide sesquihydrate
([18A]aneN₅.(HBr)₅.1.5 H₂O)

Using the same procedure as that described for the detosylation of Ts₅[17A]aneN₅ a sample of Ts₅[18A]aneN₅ (52.45 g, 51 mmol) was detosylated in four sealed Carius tubes and the hydrobromide salt isolated. Yield 32.83 g (93% based on the sesquihydrate). A sample was recrystallized from aqueous hydrobromic acid/propan-2-ol for analysis. m.p. 250-253°C (dec.). Found: C, 22.55; H, 5.91; N, 10.13; Br, 57.63. C₁₃H₃₉N₅Br₅O_{1.5} requires C, 22.66; H, 5.71; N, 10.17; Br, 57.98%. I.r. (HCBd): 3420, 3360 (i, br, ν_{O-H}), 3000-2400 (i, br, several peaks, ν_{N⁺-H}) cm⁻¹. I.r. (nujol): 1618, 1580, 1560, 1540 (m, δ_{NH₂⁺}) cm⁻¹. (The absence of peaks at 1602, 1155 or 655 cm⁻¹, confirms that no tosyl contaminants are present. ¹H n.m.r. δ(DCl) 2.30 (quintet, J 6 Hz, 6H, C-CH₂-C), 3.36-3.77 (m, 20H, N-CH₂), 5.26 (s, -NH and HOD). ¹³C n.m.r. δ(DCl) 22.68, 23.26 (C-CH₂-C), 44.33², 44.78, 44.91, 45.25 (N-CH₂).

1,4,8,11,15-Pentaazacyclooctadecane pentahydrobromide hemihydrate
([18B]aneN₅.(HBr)₅.0.5H₂O)

A sample of Ts₅-[18B]aneN₅ (46.8 g, 46 mmol) was detosylated in four Carius tubes each containing hydrogen bromide in glacial acetic acid (40% w/v, 70 cm³) for 3 hours, and the hydrobromide was isolated as a white microcrystalline product using the procedure described for the isolation of [17A]aneN₅.(HBr)₅.0.5H₂O. Yield 28.96 g (95% based on the hemihydrate).

A sample was recrystallized from aqueous hydrobromic acid/methanol for analysis. m.p. 258-261.5°C (dec.). Found: C, 23.34; H, 5.48; N, 10.65; Br, 59.24. C₁₃H₃₇N₅Br₅O_{0.5} requires C, 23.27; H, 5.56,

N, 10.44; Br, 59.54%. I.r. (HCBd): 3429 (m, br, $\nu_{\text{O-H}}$), 3000-2300 (i, br, several peaks, $\nu_{\text{N-H}}$) cm^{-1} . I.r. (nujol): 1574, 1560, 1550, 1542 (m, δ_{NH_2}) cm^{-1} . (The absence of peaks at 1602, 1155 and 655 cm^{-1} confirms that no tosyl contaminants are present). ^1H n.m.r. δ (DCI) 2.32 (quintet, J 6.5 Hz, 6H, C- CH_2 -C), 3.37-3.72 (m, 20H, N- CH_2), 4.86 (s, -NH, HOD). ^{13}C n.m.r. δ (DCI) 24.41², 25.02 (C- CH_2 -C), 45.69, 45.89, 46.50, 47.14² (N- CH_2).

1,4,8,12,16-Pentaazacyclononadecane pentahydrobromide sesquihydrate
([19]aneN₅.(HBr)₅.1.5H₂O).

Four sealed Carius tubes each containing Ts₅-[19]aneN₅ (11.2 g, 10.7 mmol), hydrogen bromide in glacial acetic acid (40% w/v, 65 cm^3) and phenol (5 g, 53 mmol, 5 equiv.) were heated at 110°C for 3 hours. The combined contents were dissolved in distilled water (700 cm^3) and washed with toluene (3x250 cm^3). Problems were encountered with emulsification and it was better to omit the washings with ether that were used in similar detosylation reactions of other macrocycles. The aqueous solution was rotary evaporated to near dryness, propan-2-ol (800 cm^3) was added and the mixture was heated at reflux temperature for $\frac{1}{2}$ hour. The product was filtered hot and the resulting solid was digested with acetone (1 dm^3) at reflux temperature for 1 hour. The pale creamy precipitate was again filtered and dried overnight in a vacuum desiccator. Yield 28.41 g (94% based on the sesquihydrate).

A sample was recrystallized from aqueous propan-2-ol for analysis. m.p. 247.5-249°C (dec.). Found: C, 24.20; H, 5.90; N, 10.16; Br, 56.45. $\text{C}_{14}\text{H}_{41}\text{N}_5\text{Br}_5\text{O}_{1.5}$ requires C, 23.92; H, 5.88; N, 9.96; Br, 56.83%. I.r. (HCBd): 3519(sh), 3451 (i, br, $\nu_{\text{O-H}}$), 2950-2400 (i, br, several peaks, $\nu_{\text{N-H}}$) cm^{-1} . I.r. (nujol): 1615, 1519 (m, sp, δ_{NH_2}) cm^{-1} . (The absence of peaks at 1602, 1155 and 655 cm^{-1} indicates the absence of tosyl

contaminants). ^1H n.m.r. $\delta(\text{DCI})$ 1.75-2.25 (br m, 8H, $\text{C}-\underline{\text{CH}_2}-\text{C}$), 2.75-3.25 (br m, 20H, $\text{N}-\underline{\text{CH}_2}$), 4.90 (s, $-\underline{\text{NH}}$, $\underline{\text{HOD}}$). ^{13}C n.m.r. $\delta(\text{DCI})$ 24.86, 25.40 ($\text{C}-\underline{\text{CH}_2}-\text{C}$), 45.93, 46.64⁴ ($\text{N}-\underline{\text{CH}_2}$).

A similar detosylation in which the phenol was omitted resulted in considerably more darkening of the contents of the Carius tubes and afforded a yield of only 80%.

1,5,9,13,17-Pentaazacycloeicosane pentahydrobromide sesquihydrate
([20]aneN₅.(HBr)₅.1.5H₂O)

A sample of Ts₅-[20]aneN₅ (63 g, 60 mmol) divided among five Carius tubes each containing hydrogen bromide in glacial acetic acid (40% w/v, 64 cm³) was heated at 115°C over 3 hours. The contents of the five tubes were dissolved in water (800 cm³), extracted with toluene (5×200 cm³), resulting in substantial decolourization of the aqueous solution, and then with ether (3×200 cm³). The aqueous solution was then reduced to near dryness by rotary evaporation and propan-2-ol (1 dm³) was added. The mixture was digested at reflux temperature for 1 hour, filtered hot and washed with propan-2-ol, acetone and finally ether, then dried overnight in a vacuum desiccator. Yield 38.93 g (90% based on sesquihydrate).

An analytical sample was prepared by recrystallization from aqueous propan-2-ol. m.p. 251-254°C (dec.). Found: C, 24.95; H, 6.12; N, 9.74; Br, 55.71. C₁₅H₄₃N₅Br₅O_{1.5} requires C, 25.12; H, 6.04; N, 9.76; Br, 55.72%. I.r. (HCBd): 3410 (i, br, $\nu_{\text{O-H}}$), 2950-2380 (i, br, several peaks, ν_{NH_2} +) cm⁻¹. I.r. (nujol): 1600, 1570 (m, br, δ_{NH_2} +) cm⁻¹. (The absence of peaks at 1155 and 655 cm⁻¹ indicates the absence of tosyl contaminants).

^1H n.m.r. $\delta(\text{DCI})$ 2.20 (quintet, J 6.7 Hz, 10H, $\text{C}-\underline{\text{CH}_2}-\text{C}$), 3.08-3.40 (m, 20H, $\text{N}-\underline{\text{CH}_2}$), 6.01 (s, $-\underline{\text{NH}}$, $\underline{\text{HOD}}$). ^{13}C n.m.r. $\delta(\text{DCI})$ 24.30 ($\text{C}-\underline{\text{CH}_2}-\text{C}$), 46.57 ($\text{N}-\underline{\text{CH}_2}$).

Alternative Detosylation Methods

Sodium/Naphthalene Detosylation of Ts₅-[15]aneN₅

A 250 cm³ 3-neck round bottom flask fitted with a stirrer and solid addition funnel was flushed with nitrogen and charged with dried 1,2-dimethoxyethane (100 cm³), naphthalene (12.12 g, 68 mmol) and sodium (2.3 g, 100 mmol). After 1 hour the sodium had dissolved, producing an intensely green solution. Ts₅-[15]aneN₅ (5 g, 5 mmol) was added from the solid addition funnel, causing the solution to turn black-brown. Stirring was continued for 6 hours. A sample of the solution was subjected to t.l.c, and showed that only naphthalene and unreacted starting material were present. The reaction mixture was left for a further 19 hours (by which time most of the colour had discharged) and was then acidified with hydrochloric acid to pH 1.5. The solution was shaken with chloroform to extract organic materials, and the aqueous layer was reduced by rotary evaporation to near dryness. Propan-2-ol (250 cm³) was added but no amine hydrochloride was precipitated. (T.l.c. analysis of the chloroform extract showed the presence of unreacted starting material, and the absence of other spots in the t.l.c. indicated the absence of even partially detosylated products). An attempted detosylation of Ts₅-[18A]aneN₅ using the same procedure was also unsuccessful.

Concentrated Sulphuric Acid Detosylation of Ts₅-[16]aneN₅

A flask containing Ts₅-[16]aneN₅ (20 g, 20 mmol) and concentrated (95-98%) sulphuric acid (85 cm³, 1.5 mol) was heated on a steambath for 85 hours, producing a dark brown solution. Ethanol (300 cm³) was added on cooling, followed by ether (150 cm³). The precipitate was filtered with difficulty and heated with ethanol (250 cm³). Sodium hydroxide (25 g) in ethanol (250 cm³) was added. The solution was evaporated to near dryness

and extracted with chloroform ($5 \times 150 \text{ cm}^3$). The combined extracts were dried over sodium sulphate, the chloroform was removed by rotary evaporation, and the resulting oil was extracted into hot petroleum ether ($3 \times 50 \text{ cm}^3$). The solvent was stripped off by rotary evaporation to yield the desired product (1.2 g, 26%) which was distilled, b.p. $130-135^\circ\text{C}$ at 0.7 mm Hg, giving 700 mg of pure [16]aneN₅ (15% overall yield).

^1H n.m.r. $\delta(\text{CDCl}_3)$ 1.6-1.9 (br m, 7H, C-CH₂-C and -NH), 2.65-2.82 (m, 20H, N-CH₂); D₂O (shake) 1.7 (quintet, J 6 Hz, 2H, C-CH₂-C), 2.70 (s and t overlapping, J 6 Hz, 20H, N-CH₂). ^{13}C n.m.r. $\delta(\text{CDCl}_3)$ 29.38 (C-CH₂-C) 47.87, 48.60, 48.91, 49.88, 50.08 (N-CH₂).

2.2.8 Extraction of Free Amines from Amine Salts

It was considered advantageous to isolate the free amines for greater ease of preparation of the metal complexes. The large amounts of inorganic bromide salts that form on neutralisation of the amine may contaminate the desired product. Furthermore, some syntheses require the use of a non-aqueous solvent, and the amine salts are generally rather insoluble in solvents other than water.

1,4,7,10,13-Pentaazacyclopentadecane ([15]aneN₅)

Method A

[15]aneN₅.(HBr)₅.3H₂O (20.2 g, 30 mmol) was dissolved in aqueous sodium hydroxide (8 M, 30 cm³) and extracted with chloroform ($5 \times 200 \text{ cm}^3$). The chloroform extracts were dried over sodium sulphate, filtered, and the chloroform was removed by rotary evaporation. The resultant oil was heated to reflux temperature with petroleum ether (250 cm³) which was decanted from the waxy yellow residue. The petroleum ether was combined with that

obtained from further extractions of this residue, and evaporated to 25 cm³ on a steam bath, leaving a clear, colourless solution. Upon refrigeration long narrow brick-shaped crystals precipitated. These were filtered and vacuum desiccated. Yield 4.5 g (70%). m.p. 97-100°C (lit.⁷¹ 92°C) (phase transition bricks to needles 92°C). Found: C, 55.44; H, 11.55; N, 29.86. C₁₀H₂₅N₅ requires C, 55.77; H, 11.70; N, 32.53%. The nitrogen analysis was unsatisfactory. I.r. (HCBd): 3335, 3299, 3255, 3227 (m, sp, $\nu_{\text{N-H}}$) cm⁻¹. ¹H n.m.r. δ (CDCl₃) 1.79 (s, 5H, -NH, disappears in D₂O), 2.73 (s, 20H, N-CH₂). ¹³C n.m.r. δ (DCl), 45.06 (N-CH₂). m/e 217.5, 10%, (M+2H)⁺; 216.5, 100%, (M+H)⁺.

Alternatively, the chloroform extract could be distilled, b.p. 110-120°C at ~0.5 mm Hg leaving a small sample of higher boiling material that was identified as Ts-[15]aneN₅. Found: C, 54.84; H, 8.71. C₁₇H₃₁N₅SO₂ requires C, 55.25; H, 8.46%. I.r. (nujol): 3282(sp), 3230 (m, br, $\nu_{\text{N-H}}$) cm⁻¹. A doublet at 690 cm⁻¹ and 706 cm⁻¹ ($\delta_{\text{C-H,Ar}}$) together with the characteristic peaks at 1602 cm⁻¹ ($\nu_{\text{C-C,Ar}}$) and 1155 cm⁻¹ ($\nu_{\text{S=O}}$) could be used to establish the presence of the monotosylamide. ¹H n.m.r. δ (CDCl₃) 2.07 (s, 4H, -NH, disappears in D₂O), 2.42 (s, 3H, Ar-CH₃), 2.73 (s, ~12H, N-CH₂), 2.86 (t, J 6 Hz, ~4H, N(Ts)-C-CH₂), 3.19 (t, J 6 Hz, ~4H, N(Ts)-CH₂), 7.31 (d, J 8 Hz, ~2H, Ar), 7.71 (d, J 8 Hz, ~2H, Ar). ¹³C n.m.r. δ (CDCl₃) 20.21 (Ar-CH₃), 46.48, 46.76, 47.41, 47.68 (NH-CH₂), 50.43 (NTs-CH₂), 126.31, 128.46, 133.46, 142.28 (Ar). m/e 373.1, 3%, (M+3H)⁺; 372.1, 20%, (M+2H)⁺; 371.1, 100%, (M+H)⁺; 369.1, 3%, M⁺.

Method B

To [15]aneN₅.(HBr)₅.3H₂O (19.38 g, 29 mmol) in absolute ethanol (150 cm³) was added sodium hydroxide (6.25 g, 5 equivalents) in absolute ethanol (100 cm³). The mixture was heated at reflux temperature for 2 hours and the precipitated sodium bromide was removed by filtration. The ethanol

was removed by rotary evaporation and the residue was extracted with petroleum ether ($6 \times 500 \text{ cm}^3$). The extracts were combined and the solvent was removed by heating on a steam bath, leaving the desired product.

Yield 3.7 g (60%).

The residue from the extractions was subjected to vacuum sublimation (160°C at 0.5 mm Hg) and a further 1.4 g (22%) of product was obtained. Total yield 5.1 g (82%).

1,4,7,10,13-Pentaazacyclohexadecane monohydrate ([16]aneN₅.H₂O)

[16]aneN₅(HBr)₅.2H₂O (42.09 g, 63 mmol) was dissolved in aqueous sodium hydroxide (8 M, 50 cm³), the solution was filtered and extracted with chloroform ($5 \times 150 \text{ cm}^3$). The combined chloroform extracts were evaporated to dryness, leaving a pale yellow oil which was heated with petroleum ether (500 cm³) at reflux temperature for $\frac{1}{2}$ hour. The ethereal solution of the amine was decanted, and the oil was treated with further portions of petroleum ether until only a small amount of waxy material remained. The volume of the ethereal solution was reduced to 150 cm³ on a steam bath, and overnight refrigeration produced a crop of well-formed colourless needles which were removed by filtration and vacuum desiccated. Yield 10.81 g (69% monohydrate). m.p. $97-104^\circ\text{C}$ (lit.⁷¹ 94°C). Found: C, 53.47; H, 11.92; N, 27.71. C₁₁H₂₉N₅O requires C, 53.40; H, 11.82; N, 28.31%. I.r. (nujol): 3303, 3217 (i, $\nu_{\text{N-H}}$) cm⁻¹. ¹H n.m.r. $\delta(\text{CDCl}_3)$ 1.78 (m, 7H, -NH and C-CH₂-C), 2.72, 2.73 (20H, 2s and broad peak overlapping, NH-CH₂). When D₂O is added, the large peak at 1.78 p.p.m. is replaced by 1.71 (quintet, J 6 Hz, 2H, C-CH₂-C). ¹³C n.m.r. $\delta(\text{CDCl}_3)$ 29.01 (C-CH₂-C) 47.61; 48.40; 48.74, 49.63, 50.16 (N-CH₂). m/e, 232.2, 15%, (M+3H)⁺; 230.8, 100%, (M+2H)⁺; 229.3, 1%, M⁺.

1,4,7,10,14-Pentaazacycloheptadecane ([17A]aneN₅)

[17A]aneN₅.(HBr)₅.0.5H₂O (20.7 g, 31.5 mmol) was dissolved in aqueous sodium hydroxide (8 M, 50 cm³). The solution was shaken up with ether (5×100 cm³) to extract the free amine, and the combined ether extracts were dried over sodium sulphate. The ether was removed by rotary evaporation, leaving a colourless oil. Yield 5.68 g. Attempts to induce crystallization from petroleum ether were unsuccessful, so the product was vacuum distilled giving the desired product, b.p. 155-165°C at ~0.5 mm Hg. Yield 3.8 g (50%). On standing, the amine solidified. m.p. 18-22°C. Found: C, 58.73; H, 11.81; N, 27.85. C₁₂H₂₉N₅ requires C, 59.21; H, 12.01; N, 28.78%. However, the product is hygroscopic, and the analysis figures suggest the presence of a trace of water. I.r. (liquid film): 3287 (i, br, $\nu_{\text{N-H}}$) cm⁻¹. ¹H n.m.r. δ (CDCl₃) 1.67 (quintet, J 6 Hz, 4H, C-CH₂-C), 1.84 (5H, s, -NH, disappears in D₂O), 2.72 (s) and 2.73 (t, J 6 Hz), (20H together, NH-CH₂). ¹³C n.m.r. δ (CDCl₃) 30.04 (C-CH₂-C), 48.75, 49.25, 49.42², 49.91 (N-CH₂). m/e 246.7, 3%, (M+3H)⁺; 245.7, 55%, (M+2H)⁺; 243.4, 100%, M⁺.

The distillation residue (yield 1.9 g) appeared to contain an appreciable amount of the desired product, together with another compound that could not be identified. It did not contain any aromatic resonances in the ¹H n.m.r., so was not a partially detosylated product.

1,4,7,11,14-Pentaazacycloheptadecane ([17B]aneN₅)

[17B]aneN₅.(HBr)₅ (26 g, 40 mmol) was dissolved in aqueous sodium hydroxide (8 M, 40 cm³), the solution was filtered hot and extracted with hot chloroform (5×150 cm³). After drying over sodium sulphate, the chloroform was removed by rotary evaporation. The resulting oil was taken

up in hot petroleum ether (500 cm³), filtered, and the volume of the solution was reduced to 125 cm³. After overnight refrigeration the colourless rods that crystallized were filtered, but owing to the extremely hygroscopic nature of the product the free amine was stored under petroleum ether, and removed and stripped of solvent as required. Yield (of crude product only) 8.0 g (82%). Found: C, 58.89; H, 11.90; N, 28.42. C₁₂H₂₉N₅ requires C, 59.21; H, 12.01; N, 28.78%. The analysis figures are consistent with the uptake of a small amount (~0.1 mole equivalents) of water.

I.r. (nujol): 3300, 3220 (i,br,ν_{N-H}) cm⁻¹. ¹H n.m.r. δ(CDCl₃) 1.68 (quintet, J 5 Hz, C-CH₂-C), (combined 9H), 2.73 (s, N-CH₂), 2.74 (t, J 5.5 Hz, N-CH₂) (combined 20H). ¹³C n.m.r. δ(CDCl₃) 29.47 (C-CH₂-C), 49.58, 49.94, 50.11, 50.55 (N-CH₂).

1,4,7,11,15-Pentaaazacyclooctadecane ([18A]aneN₅)

[18A]aneN₅.(HBr)₅.1.5H₂O (26.85 g, 39 mmol) was dissolved in hot aqueous sodium hydroxide (8 M, 30 cm³), filtered hot and extracted with chloroform (10×75 cm³) which was dried over sodium sulphate, filtered and then stripped of solvent. After extraction with petroleum ether as before a pale yellow oil remained. Yield 5.28 g (53%). The aqueous layer was stripped of solvent by rotary evaporation and the residue was extracted by trituration with acetone (5×100 cm³). The crude product thus obtained was also treated with petroleum ether, and the ethereal solution was stripped of solvent, leaving a further 4.06 g (41%) of pale golden oil. (This was contaminated with diacetone alcohol formed in the base condensation of the acetone used to extract the amine). Total crude yield 9.34 g (93%). The oil was vacuum distilled giving the desired product as a colourless oil, b.p. 155-160°C at ~0.7 mm Hg, which could not be induced to crystallize. Yield 6.51 g (65%). I.r. (liquid film): 3273 (m, br, ν_{N-H}) cm⁻¹. ¹H n.m.r. δ(CDCl₃) 1.57 (s, NH, disappears in D₂O), 1.65 (quintet, J 6 Hz, C-CH₂-C), (combined 11H), 2.71 (s and overlapping t,

J 6 Hz, 20H, N-CH₂). ¹³C n.m.r. δ(CDCl₃) 29.05 (C-CH₂-C), 47.76, 48.06, 48.28, 49.10² (N-CH₂). m/e 259.8, 1%, (M+2H)⁺; 258.9, 5%, (M+H)⁺; 257.9, 1%, M⁺.

The distillation residue was shown by ¹H n.m.r. and ¹³C n.m.r. to contain partially tosylated material as well as more of the desired product.

1,4,8,11,15-Pentaazacyclooctadecane ([18B]aneN₅)

[18B]aneN₅.(HBr)₅.0.5H₂O (21.4 g, 32 mmol) was dissolved in hot aqueous sodium hydroxide (8 M, 30 cm³), filtered hot and extracted with chloroform (5×75 cm³) which was then dried over sodium sulphate. The chloroform was removed by rotary evaporation leaving a pale yellow oil. This was treated with boiling petroleum ether (3×200 cm³) as before, filtered hot, and the solution was stripped of solvent, leaving the desired product. Yield 5.9 g (72%). A small amount of material could be extracted from the solid residue of the aqueous phase by extraction with acetone as described for [18A]aneN₅, but the purity of this material was not checked. Additional yield 0.9 g (11%).

An alternative extraction procedure involved addition of excess sodium hydroxide solution to a sample of the amine hydrobromide, removing all the water by rotary evaporation and extracting the solid residue with boiling benzene and finally treating the product obtained with petroleum ether. A similar yield (72%) was obtained. The product could not be induced to crystallize. I.r. (liquid film): 3283 (i, ν_{N-H}) cm⁻¹. ¹H n.m.r. δ(CDCl₃), 1.74 (s, -NH, disappears in D₂O), 1.67 (overlapping quintet, J 6 Hz, C-CH₂-C), (combined 11H), 2.71 (s and overlapping t, J 6 Hz, 20H, N-CH₂). ¹³C n.m.r. δ(CDCl₃) 29.25², 29.44 (C-CH₂-C), 47.86, 47.97, 48.13, 48.71, 49.09 (N-CH₂).

1,4,8,12,16-Pentaazacyclononadecane ([19]aneN₅)

(i) [19]aneN₅.(HBr)₅.1.5H₂O (31.96 g, 45 mmol) was dissolved in hot aqueous sodium hydroxide (8 M, 40 cm³) and the solution was extracted with chloroform (5×100 cm³) (problems were experienced with emulsification). The combined chloroform extracts were dried over sodium sulphate and the solvent was removed by rotary evaporation. The resultant oil was treated with boiling petroleum ether (5×250 cm³) as before and the combined petroleum ether extracts were filtered hot and the solvent was removed by rotary evaporation, to leave a colourless oil which would crystallize on standing in the cold, but melts just above room temperature. Yield 5.72 g (46%). The aqueous solution remaining after extraction with chloroform was stripped of solvent by rotary evaporation and when extracted with acetone (as described in the preparation of [18A]aneN₅) and treated with boiling petroleum ether yielded a further 1.83 g (15%) of less pure product. (Again contaminated with diacetone alcohol).

The crude sample was distilled under vacuum yielding the desired product, b.p. 170–175°C at ~0.5 mm Hg. Satisfactory analysis figures were not obtained. I.r. (liquid film): 3279 (m, br, $\nu_{\text{N-H}}$) cm⁻¹. ¹H n.m.r. δ (CDCl₃) 1.65 (s, NH, disappears in D₂O), 1.65 (overlapping quintet, J 6 Hz, C-CH₂-C) (combined 13H), 2.69 (t, J 6 Hz, 20H, N-CH₂). ¹³C n.m.r. δ (CDCl₃) 29.66, 29.95 (C-CH₂-C), 48.32, 48.53, 48.66, 48.88, 49.15 (N-CH₂).

(ii) Ion Exchange Method

In an effort to improve the poor yield in which the free [19]aneN₅ was obtained, an ion exchange resin was employed. An aqueous solution of [19]aneN₅.(HBr)₅.1.5H₂O (2 g, 2.8 mmol) was put on a Dowex 1-X4 (20–50 mesh) anion exchange resin that had been converted to the hydroxide

form. The free amine was eluted with distilled water (600 cm^3) and the eluate was stripped of solvent by rotary evaporation. The product was taken up in petroleum ether, dried over sodium sulphate, filtered and the petroleum ether was removed to yield the required product as a colourless oil which solidified upon standing. Yield 0.69 g (89%). m.p. $45\text{--}53^\circ\text{C}$. Although the method was efficient in terms of percentage yield, it was cumbersome for larger quantities.

1,5,9,13,17-Pentaazacycloeicosane ([20]aneN₅)

[20]aneN₅.(HBr)₅.1.5H₂O (39.88 g, 55.6 mmol) was dissolved in hot aqueous sodium hydroxide (4 M, 100 cm^3) and heated on a steam bath for $\frac{1}{2}$ hour. The appreciable amount of insoluble material that remained was removed by filtration, and the solution was extracted with hot chloroform ($5\times 100\text{ cm}^3$). The chloroform extracts were dried over sodium sulphate, filtered and the solvent removed by rotary evaporation. The resultant oil was extracted by refluxing with petroleum ether ($3\times 250\text{ cm}^3$) and the ethereal extracts were evaporated leaving a white solid. Yield 5.5 g (35%). The aqueous layer was taken to dryness, refluxed with acetone ($3\times 100\text{ cm}^3$), the acetone extracts were taken to dryness, and the product was treated with petroleum ether ($2\times 250\text{ cm}^3$) as above yielding a further 2.55 g (16%) of less pure product. This second crop was subjected to vacuum distillation to give the same product as before, b.p. $135\text{--}140^\circ\text{C}$ at $\sim 0.3\text{ mm Hg}$. Yield 2.04 g. The product was recrystallized from petroleum ether. Total yield 7.54 g (48%). m.p. $79\text{--}81^\circ\text{C}$. Another preparation using 7.0 g of starting material and 25 cm^3 of 2.5 M aqueous sodium hydroxide yielded 1.8 g of solid product (67%). Found: C, 62.11; H, 12.30; N, 24.18. C₁₅H₃₅N₅ requires C, 63.11; H, 12.36; N, 24.54. The analytical service

reported that the product appeared to be hygroscopic, and the micro-analysis figures are consistent with the uptake of a small amount (~0.25 mol equivalents) of water. I.r. (HCBD): 3261, 3225 (i, sp, $\nu_{\text{N-H}}$) cm^{-1} . ^1H n.m.r. $\delta(\text{CDCl}_3)$ 1.65 (quintet, J 6 Hz, 10H, C-CH₂-C), 2.08 (s, 5H, -NH, disappears in D₂O), 2.69 (t, J 6 Hz, 20H, N-CH₂). ^{13}C n.m.r. $\delta(\text{CDCl}_3)$ 29.53 (C-CH₂-C), 48.93 (N-CH₂). m/e, 288.9, 1%, (M+3H)⁺; 287.9, 34%, (M+2H)⁺; 285.7, 100%, M⁺.

2.2.9 Attempted Non-Template Synthesis of Macrocyclic Amines with Glyoxal.

Attempted Synthesis of 1,4,8,11-tetraazacyclotetradec-2-ene⁵⁹ ([14]-2-ene-1,4,8,11-N₄)

To a stirred solution of 3,2,3-tet (10.46 g, 60 mmol) in water (40 cm³) and calcium hydroxide (10.38 g, 140 mmol) was added glyoxal disodium hydrogen sulphite monohydrate (18.18 g, 80 mmol) in small portions over 15 minutes. The reaction mixture was stirred at room temperature for 1½ hours and then heated at 100°C for 1 hour. The insoluble material was removed by filtration, the filter cake was triturated with boiling water (2×50 cm³), and the water was removed from the solution by rotary evaporation. The solid residue was dissolved in chloroform (100 cm³), dried over sodium sulphate and filtered. The chloroform was removed by rotary evaporation and the solid residue was recrystallized from diethyl ether. Yield 7.7 g (65%). Found: C, 55.58; H, 10.35; N, 25.96 (52.31, 10.43, 24.46; 51.91, 9.98, 23.97). These results are most consistent with the formula C₁₀H₂₀N₄·xH₂O.

(The analytical service reported that the product was hygroscopic).

I.r. (nujol): 3335, 3240 (m, sp, $\nu_{\text{N-H}}$) cm^{-1} . No $\nu_{(\text{C}=\text{C})}$ peak.

^{13}C n.m.r. $\delta(\text{CDCl}_3)$ 26.67, 45.03, 52.65, 54.79, 79.42.

m/e 198.2, 4%, $(M+2H)^{+}$; 197.2, 32%, $(M+H)^{+}$; 196.2, 7%, M^{+} .

(Based on $C_{10}H_{20}N_4$). Repeated efforts to reproduce the reported hydrogenation⁵⁹ of the product under a variety of different experimental conditions were uniformly unsuccessful.

Attempted Synthesis of 1,4,7,10-tetraazacyclododec-2-ene ([12]-2-ene N_4)

To a stirred solution of 2,2,2-tet (21.9 g, 0.15 mol) in distilled water (100 cm³) and calcium hydroxide (26 g, 0.35 mol) was added glyoxal disodium hydrogen sulphite monohydrate (42.65 g, 0.19 mol) over 15 minutes. After stirring at room temperature for 2 hours, the mixture was heated at 100°C for 1½ hours. A similar workup to that used in the previous synthesis resulted in the formation of a pale oil which was fractionally distilled to yield one product (20.5 g, ~80%).

b.p. 115-120°C at ~2 mm Hg. ¹³C n.m.r. δ (CDCl₃) 42.32, 50.62, 66.06, 77.19 (approximate ratio 2:4:1:1).

Attempts to repeat the reported hydrogenation⁵⁹ of the product were unsuccessful.

Attempted Synthesis of Macrocyclic Pentamines

The same method was followed using either 2,2,2,2-pent or 3,3,3,3-pent in place of the linear tetramines. In both cases an oil was obtained, and was shown to be unreacted starting material (recovery >90%) by mass spectroscopy, g.l.c. and n.m.r. (¹H and ¹³C).

2.2.10 G.l.c. Analysis of Free Amines

A 1 metre silanized glass column packed with Gas Chrom-Q 80-100 mesh (Applied Science Laboratories) coated with a 2% loading of Apiezon L and 9% KOH (column I) preconditioned overnight at 260°C was used in a Pye

Series 105 Chromatograph with an F.I.D. to investigate the purity of the free amines. The recording was continued for at least 60 minutes after the major amine peak appeared to confirm the absence of further products. A similar column with a 6% loading of Apiezon L and 2% KOH (column II) run at 169°C was used to investigate the purity of the linear amines. The R_f values are listed along with the experimental conditions in Table 2.2. The retention times of the impurities present in the crude samples are also listed. The purified samples (with the exception of 3,3,3,3-pent run on column I and the tricyclic tetramine derived from glyoxal) all showed single peak g.l.c. traces.

Table 2.2 Retention Times of Amines

Column I		
	R_f (min)	R_f of Impurities in Crude Product
[15]aneN ₅	3.9	1.5, 2.75, 23.0
[16]aneN ₅	5.0	1.2, 1.6, 2.3, 3.4
[17A]aneN ₅	6.9	10.8
[17B]aneN ₅	6.9	
[18A]aneN ₅	9.9	2.55, 4.7, 14.8
[18B]aneN ₅	9.9	
[19]aneN ₅	14.5	
[20]aneN ₅	21.5	
3,3,3,3-pent	5.95 (~10%)	7.9
3,3,3-tet	1.4	
Column II		
2,3-tri	0.8	
3,3-tri	1.2	
tren	1.9	
2,2,2-tet	2.25	
2,3,2-tet	3.5	
3,2,3-tet	5.6	0.8
3,3,3-tet	9.3	
2,2,2,2-pent	11.3	0.46, 0.87, 3.1, 3.85, 4.6
3,3,3,3-pent	78	
[18A]aneN ₅	102	
C ₁₀ H ₂₀ N ₄	11.8, 14.0 (<20%)	

Conditions:	Oven Temperature	200°C (Column I), 169°C (Column II)
	Injector Port	250°C (Column I), 200°C (Column II)
	Gas Flow	40 cm ³ min ⁻¹
	Sample Concentration	10-20 µg.µl ⁻¹
	Sample Volume	1 µl
	Solvent	Petroleum Ether [†]

[†] Samples dissolved in alcohols or water showed considerable tailing.

2.3 Synthesis of Metal Complexes

2.3.1 Copper Complexes

2.3.1.1 CuL(ClO₄)₂ Method A

A solution of sodium hydroxide (0.20 g, 5 mmol) in water (5 cm³) was added dropwise with stirring to a solution of copper perchlorate tetrahydrate (0.335 g, 1 mmol) and the ligand hydrobromide salt (1 mmol) in water (10 cm³). The complexation took place rapidly as shown by the immediate darkening of the mixture with the addition of each drop of the sodium hydroxide solution. An excess of solid sodium perchlorate (1 to 2 g) was dissolved in the reaction mixture and the solution was refrigerated until precipitation of the complex was complete. The product was filtered, washed with absolute alcohol, then propan-2-ol and vacuum desiccated. It could be readily recrystallized from aqueous sodium perchlorate.

CuL(ClO₄)₂ Method B

To a stirred solution of the free ligand (1 mmol) in absolute ethanol (10 cm³) was added copper perchlorate tetrahydrate (0.335 g, 1 mmol) in absolute ethanol (10 cm³) over 1 to 2 minutes. Reaction occurred rapidly and the product began to precipitate immediately. The solution was refrigerated until precipitation was complete, and the product was filtered, washed with propan-2-ol and vacuum desiccated. If the solution still contained appreciable amounts of the complex, propan-2-ol was added to the reaction mixture, and the ethanol was removed by rotary evaporation until the precipitation was complete. The products were once more recrystallized from aqueous sodium perchlorate. For yields obtained and analytical data see Table 2.3.

TABLE 2.3

Preparative and Analytical Data for CuL(ClO₄)₂ Complexes

Complex	Yield %	Found %			Calculated %		
		C	H	N	C	H	N
Cu([15]aneN ₅)(ClO ₄) ₂	80	25.10	5.27	14.63	25.14	5.27	14.66
Cu([16]aneN ₅)(ClO ₄) ₂	74	26.87	5.24	14.39	26.86	5.53	14.29
Cu([17A]aneN ₅)(ClO ₄) ₂	80	28.23	5.95	13.92	28.49	5.78	13.85
Cu([17B]aneN ₅)(ClO ₄) ₂	68	28.46	5.41	13.63	28.49	5.78	13.85
Cu([18A]aneN ₅)(ClO ₄) ₂	77	30.28	6.23	13.23	30.03	6.01	13.47
Cu([18B]aneN ₅)(ClO ₄) ₂	78	30.02	6.00	13.42	30.03	6.01	13.47
Cu([19]aneN ₅)(ClO ₄) ₂	71	31.29	6.00	12.91	31.49	6.23	13.12
Cu([20]aneN ₅)(ClO ₄) ₂	72	32.88	6.74	12.59	32.88	6.44	12.78
Cu(tetren)(ClO ₄) ₂	66	21.24	5.34	15.77	21.27	5.17	15.51
Cu(tetrpn)(ClO ₄) ₂	79	28.58	6.46	13.86	28.38	6.15	13.79

2.3.1.2 Cu L (NO₃)₂·xH₂O

To a stirred solution of the free ligand (1 mmol) in absolute ethanol (10 cm³) was added copper nitrate trihydrate (0.242 g, 1 mmol) in absolute ethanol (10 cm³). If precipitation did not occur, propan-2-ol (25 cm³) was added, ethanol was removed by rotary evaporation and the solution was refrigerated. The product was filtered, washed with propan-2-ol and vacuum desiccated. The solvent systems used for recrystallization are listed in Table 2.4 together with analytical figures and yields. (Refer to Tables 2.5 to 2.7 for the infrared spectral details of the perchlorate and nitrate salts of the copper complexes, and to Table 2.8 and Fig.2.1 for details of their electronic spectra).

2.3.2 Nickel Complexes

2.3.2.1 Ni L (ClO₄)₂

To a stirred solution of the free ligand (1 mmol) in absolute ethanol (10 cm³) was added nickel perchlorate hexahydrate (0.367 g, 1 mmol) in absolute ethanol (10 cm³) over several minutes. The reaction mixture was refrigerated overnight. If the product had not precipitated, propan-2-ol was added and the absolute ethanol removed by rotary evaporation. The precipitate that formed was collected by filtration, washed with propan-2-ol and vacuum desiccated. Yields, analytical data and the recrystallizing media are listed in Table 2.9.

2.3.2.2 Ni L (NO₃)₂·(solvent)

The same procedure was used as described for the synthesis of the perchlorate complexes, with nickel nitrate hexahydrate (0.291 g, 1 mmol) used in place of the nickel perchlorate hexahydrate. Yields, analytical

TABLE 2.4

Preparative and Analytical Data for $\text{CuL}(\text{NO}_3)_2 \cdot x\text{H}_2\text{O}$ Complexes

Complex	Yield %	Recrystallized from	Found %		Calculated %	
			C	H	C	H
$\text{Cu}([\text{15}] \text{aneN}_5)(\text{NO}_3)_2$	86	methanol/propan-2-ol	30.07	6.27	29.81	6.25
$\text{Cu}([\text{16}] \text{aneN}_5)(\text{NO}_3)_2$	92	methanol/acetone	31.97	6.74	31.69	6.53
$\text{Cu}([\text{17A}] \text{aneN}_5)(\text{NO}_3)_2$	86	ethanol/acetone	32.06	6.99	33.44	6.78
$\text{Cu}([\text{17B}] \text{aneN}_5)(\text{NO}_3)_2$	95	methanol/propan-2-ol	33.65	7.09	33.44	6.78
$\text{Cu}([\text{18A}] \text{aneN}_5)(\text{NO}_3)_2$	90	methanol/propan-2-ol	34.92	7.21	35.09	7.02
$\text{Cu}([\text{18B}] \text{aneN}_5)(\text{NO}_3)_2 \cdot \text{H}_2\text{O}$	84	ethanol/propan-2-ol	33.90	7.26	33.72	7.18
$\text{Cu}([\text{19}] \text{aneN}_5)(\text{NO}_3)_2$	75	methanol/propan-2-ol	36.46	7.41	36.63	7.25
$\text{Cu}([\text{19}] \text{aneN}_5)(\text{NO}_3)_2 \cdot \text{H}_2\text{O}$	83	not recrystallized	35.25	7.38	35.25	7.40
$\text{Cu}([\text{20}] \text{aneN}_5)(\text{NO}_3)_2 \cdot 1.5\text{H}_2\text{O}$	81	water/acetone	35.88	8.08	36.02	7.66
$\text{Cu}([\text{20}] \text{aneN}_5)(\text{NO}_3)_2 \cdot \text{H}_2\text{O} \cdot 0.5\text{CH}_3\text{OH}$		methanol/acetone	36.72	7.92	36.71	7.75
$\text{Cu}(\text{tetren})(\text{NO}_3)_2$	84	methanol	25.51	6.50	25.50	6.15
$\text{Cu}(\text{tetrpn})(\text{NO}_3)_2$	85	methanol/propan-2-ol	33.43	7.36	33.29	7.22

TABLE 2.5
Infrared Spectra of Cu L (ClO₄)₂ Complexes^a

Complex	ν (N-H)	ν (ClO ₄ ⁻)			Other Bands
		ν ₁ (A)	ν ₃ (T ₂)	ν ₄ (T ₂)	
Cu([15]aneN ₃)(ClO ₄) ₂	3281(i,sp), 3305(m,sp), 3344(i,sp)	942(s)	1095(vi,br)	619, 625(i,sp)	
Cu([16]aneN ₃)(ClO ₄) ₂	3257(m,sp), 3309(m,sp), 3328(sh)	939(sf)	1100(vi,br)	620(i,sp)	
Cu([17A]aneN ₃)(ClO ₄) ₂	3266(i), 3323(i)	930(sf)	1098(vi,br)	623(i,sp)	
Cu([17B]aneN ₃)(ClO ₄) ₂	3247(m,sp), 3295(m), 3355(m,sp)	927(sf)	1098(vi,br)	619(i,sp)	
Cu([18A]aneN ₃)(ClO ₄) ₂	3239(m), 3276(m), 3309(m)	936(sf)	1086(vi,br)	623(i,sp)	
Cu([18B]aneN ₃)(ClO ₄) ₂	3289(i), 3309(sh)	936(sf)	1098(vi,br)	625(i,sp)	
Cu([19]aneN ₃)(ClO ₄) ₂	3275(i,sp), 3303(sh)	933(sp)	1104(vi,br)	618(i,sp)	3583(w,br) ^b
Cu([20]aneN ₃)(ClO ₄) ₂	3277(i), 3295(i)	930(sp)	1093(vi,br)	620(i,sp)	3491(m,br), 3593(m,br)
Cu([20]aneN ₃)(ClO ₄) ₂ ^c	2443(i), 3289(i)	934(sp)	1075, 1085(vi,br)	620(i,sp)	3490(sh), 3544(w), 3589(m,sp)
Cu(tetren)(ClO ₄) ₂	3283(m,sp), 3357(m,sp), 3371(m,sp)	928(sf)	1095(vi,br)	620(i)	1587(m,sp) ^e
Cu(tetren)(ClO ₄) ₂ ^d	3170(sh), 3280(i), 3350(m)	925(vw)	1085(br)	622(vi)	1590(i) ^e
Cu(tetrim)(ClO ₄) ₂	3187(m), 3253(i,sp), 3277(i,sp), 3330(i,sp)	932(sr)	1092(vi,br)	620(i)	1602(i,sp) ^e

a frequencies in cm⁻¹

b ν_(C-H) in one sample that crystallized as a hydrate

c recrystallized from D₂O/NaClO₄; ν (N-D) 2443(i)

d ref. 284

e δ(NH₂)

TABLE 2.6
Infrared Spectra of Cu L (NO₃)₂ Complexes^a

Complex	ν (N-H)	ν (NO ₃) ^b		Other Bands
		ν_2 (A'')	ν_3 (E')	
Cu([15]aneN ₃)(NO ₃) ₂	3192(m), 3277(m)	825(sp)	1338(sh), 1353(m,br), 1376(sh)	
Cu([16]aneN ₃)(NO ₃) ₂	3207(m,br), 3275(sh)	826(sp)	1354(i,br)	
Cu([17A]aneN ₃)(NO ₃) ₂	3199(i), 3278(m)	828(m,sp)	1320-1350(i,br)	
Cu([17B]aneN ₃)(NO ₃) ₂	3167(sh), 3211(i), 3228(sh), 3337(m,sp)	828(m,sp)	1335(i,br)	
Cu([18A]aneN ₃)(NO ₃) ₂	3175(sh), 3220(i)	828(m,sp)	1337(i,br), 1370(i,br)	
Cu([18B]aneN ₃)(NO ₃) ₂ ·H ₂ O	3225(i)	827(m,sp)	1340(i,v,br)	
Cu([19]aneN ₃)(NO ₃) ₂	3214(i,br)	825(m,sp)	1338(i,br), 1383(i,br), 1400	
Cu([20]aneN ₃)(NO ₃) ₂ ·1.5H ₂ O	3240(i,br)	827(m,sp)	1315(i,br), 1372(i,br)	3437(m,br), 3503(m,br) ^d
Cu(tetren)(NO ₃) ₂	3201(i,sp), 3266(m,sp), 3355(m,sp), 3377(m,sp)	822(m,sp)	1312(i,br), 1374(i,br)	1590(m) ^e
Cu(tetren)(NO ₃) ₂ ^c	3205(sp), 3260(sh)	830(vi)	1355(br)	1595(i) ^e
Cu(tetpin)(NO ₃) ₂	3181(m,sp), 3223(m,sp), 3269(m,sp)	827(m,sp)	1353(i,br), 1397(i)	1613(i,sp), 1620(sh) ^e

^a frequencies in cm⁻¹

^b ν_1, ν_4 obscured by ligand vibrations

^c ref. 284

^d ν (O-H)

^e ν (NH₂)

TABLE 2.7

Infrared Spectra of Cu L (NO₃)₂ Complexes
(overtone and combination bands of the nitrate ion, cm⁻¹)

Complex	$\nu_1 + \nu_3$	$\nu_1 + \nu_4$	$2\nu_1$
Cu([15]aneN ₅)(NO ₃) ₂	2360, 2390, 2416	1753, 1760	2038
Cu([16]aneN ₅)(NO ₃) ₂	2367	1755	2075, 2150
Cu([17A]aneN ₅)(NO ₃) ₂	2368	1747	
Cu([17B]aneN ₅)(NO ₃) ₂	2357	1751	
Cu([18A]aneN ₅)(NO ₃) ₂	2368	1748	2050
Cu([18B]aneN ₅)(NO ₃) ₂ ·H ₂ O	2365	1748	2080
Cu([19]aneN ₅)(NO ₃) ₂	2375	1748	
Cu([20]aneN ₅)(NO ₃) ₂ ·1.5H ₂ O ^a	2350, 2390, 2410	1750	2080
Cu(tetren)(NO ₃) ₂	2348, 2390, 2405	1753, 1761	2080, 2150
Cu(tetren)(NO ₃) ₂ ^b	2380	1750	
Cu(tetrpn)(NO ₃) ₂	2328, 2355, 2390, 2423	1743, 1754	2110

a $\mu_{\text{eff}} = 1.84$ B.M. (25°C)

b ref. 284.

TABLE 2.8

Electronic Spectra of Copper(II) Complexes^a

Complex ^b	$\lambda_{\max}$		Comments	Reference
[Cu([15]aneN ₅)] ²⁺	585(193)	820(65)		this work
	585(200)			167
	585		no ϵ reported	90
	588(220)	825(75)	chloride anion solvent water (?)	6
[Cu([16]aneN ₅)] ²⁺	565(140)	810(38)		this work
	562		no ϵ reported	90
	568(160)	805(70)	chloride anion solvent water (?)	6
[Cu([17A]aneN ₅)] ²⁺	573(205)	810(40)		this work
[Cu([17B]aneN ₅)] ²⁺	586(186)	815(62)		this work
	585		no ϵ reported	90
[Cu([18A]aneN ₅)] ²⁺	616(211)	850(97)		this work
[Cu([18B]aneN ₅)] ²⁺	585(198)	820(85)		"
[Cu([19]aneN ₅)] ²⁺	625(235)	835(109)		"
[Cu([20]aneN ₅)] ²⁺	600(245)	850(55)		"
[Cu(tetren)] ²⁺	630(182)	800(sh)		"
	625(145)	800(sh)	solvent methanol	284
	632(190)	820(sh)		124
[Cu(tetrpn)] ²⁺	740(253)			this work
[Cu(Me ₇ tetren)] ²⁺	720(350)		solvent 1:1 methanol/acetone	95
[Cu(pyaneN ₅)] ²⁺	600(175)	870(72)		49
[Cu(L)] ²⁺ ^c	638		solid state	286
	684(205)			
[Cu(tpen)] ⁺ ^d	599(248)	840(31)	square pyramidal(?)	98

a $\lambda_{\max}$ in nm; values in parentheses are extinction coefficients (ϵ), units $M^{-1}cm^{-1}$.

b complexes are nitrate or perchlorchlorate salts, and the solvent is water unless otherwise specified.

c L = {1-(2-aminoethyl)-4,8,11-Me₃-1,4,8,11-[14]aneN₄}.

d tpen = N,N,N'-tris[2-(2'-pyridyl)ethyl]ethylenediamine.

Electronic Spectra of Copper(II) Complexes

fig 2.1

TABLE 2.9
Preparative and Analytical Data for $\text{NiL}(\text{ClO}_4)_2$ Complexes

Complex	Yield %	Recrystallized from	Found %			Calculated %		
			C	H	N	C	H	N
$\text{Ni}([\text{15}] \text{aneN}_5)(\text{ClO}_4)_2$	85	(i) ethanol/2-propanol (ii) aqueous sodium perchlorate	25.65	5.10	14.62	25.39	5.33	14.81
$\text{Ni}([\text{16}] \text{aneN}_5)(\text{ClO}_4)_2$	71	aqueous sodium perchlorate	27.21	5.34	14.36	27.13	5.59	14.38
$\text{Ni}([\text{17A}] \text{aneN}_5)(\text{ClO}_4)_2$	80	methanol/2-propanol	28.89	6.14	13.83	28.77	5.83	13.98
$\text{Ni}([\text{17B}] \text{aneN}_5)(\text{ClO}_4)_2$	74	aqueous lithium perchlorate	28.64	6.18	13.80	28.77	5.83	13.98
$\text{Ni}([\text{18A}] \text{aneN}_5)(\text{ClO}_4)_2$	89	aqueous sodium perchlorate	30.06	6.27	13.25	30.32	6.07	13.60
$\text{Ni}([\text{18B}] \text{aneN}_5)(\text{ClO}_4)_2$	89	aqueous sodium perchlorate	30.59	6.31	13.61	30.32	6.07	13.60
$\text{Ni}([\text{19}] \text{aneN}_5)(\text{ClO}_4)_2$	86	aqueous sodium perchlorate	32.18	6.33	13.13	31.78	6.29	13.24
$\text{Ni}([\text{20}] \text{aneN}_5)(\text{ClO}_4)_2$	76	aqueous sodium perchlorate	33.39	6.87	12.74	33.17	6.50	12.90
$\text{Ni}(\text{tetrapn})(\text{ClO}_4)_2$	74	aqueous sodium perchlorate	28.68	6.38	13.56	28.65	6.21	13.93

TABLE 2.10

Preparative and Analytical Data for $\text{NiL}(\text{NO}_3)_2$ Complexes

Complex	Yield %	Recrystallized from	Found %		Calculated %		
			C	H	C	H	N
$\text{Ni}([15]\text{aneN}_5)(\text{NO}_3)_2$	50	water/acetone	30.28	6.36	30.17	6.33	24.64
$\text{Ni}([16]\text{aneN}_5)(\text{NO}_3)_2$	74	methanol/propan-2-ol	32.15	6.47	32.06	6.60	23.80
$\text{Ni}([17\text{A}]\text{aneN}_5)(\text{NO}_3)_2 \cdot 0.5\text{H}_2\text{O}$	75	methanol/propan-2-ol	33.24	6.71	33.12	6.95	22.54
$\text{Ni}([17\text{B}]\text{aneN}_5)(\text{NO}_3)_2$	87	methanol/ethanol	34.05	6.53	33.82	6.86	23.01
$\text{Ni}([18\text{A}]\text{aneN}_5)(\text{NO}_3)_2$	78	water/propan-2-ol	35.73	7.23	35.47	7.10	22.28
$\text{Ni}([18\text{B}]\text{aneN}_5)(\text{NO}_3)_2 \cdot 0.5\text{CH}_3\text{OH}$	85	methanol/ethanol	35.48	7.25	35.54	7.29	21.50
$\text{Ni}([19]\text{aneN}_5)(\text{NO}_3)_2 \cdot 0.5\text{CH}_3\text{OH}$	79	methanol/propan-2-ol	36.89	7.23	37.04	7.50	20.86
$\text{Ni}([20]\text{aneN}_5)(\text{NO}_3)_2 \cdot 0.5\text{H}_2\text{O}$	88	methanol/acetone	38.07	7.74	37.75	7.60	20.55
$\text{Ni}([20]\text{aneN}_5)(\text{NO}_3)_2 \cdot 1.5\text{H}_2\text{O}$		methanol/propan-2-ol	36.45	7.77	36.37	7.73	19.80
$\text{Ni}(\text{tetrpn})(\text{NO}_3)_2$	87	methanol/propan-2-ol	33.84	7.34	33.66	7.30	22.90

TABLE 2.11
Infrared Spectra of Ni L (ClO₄)₂ Complexes^a

Complex	ν (N-H)	ν (ClO ₄) ^b		Other Bands	ν_{eff} ^c
		ν_1 (T ₂)	ν_2 (T ₂)		
Ni([15]aneN ₃)(ClO ₄) ₂	3288, 3310(m,sp)	1050(vi,br), 1085(sh)	613, 625(i,sp)		3.12 ^{d,e} (1.13)
Ni([16]aneN ₃)(ClO ₄) ₂	3275, 3313, 3338(m,sp)	1044, 1102(vi,br)	624(i,sp)		3.11 ^d (3.01)
Ni([17A]aneN ₃)(ClO ₄) ₂	3269, 3315(m,sp)	1065-1085(vi, v,br)	613(i,sp)		3.12
Ni([17B]aneN ₃)(ClO ₄) ₂	3271, 3281, 3314(m)	1060-1085(vi, v,br)	615(i,sp)		3.11 ^d (3.39)
Ni([18A]aneN ₃)(ClO ₄) ₂	3280(i), 3315(i)	1084, 1094(vi,br)	619(i,sp)		3.14
Ni([18B]aneN ₃)(ClO ₄) ₂	3273(sh), 3293(i,sp)	1072, 1097(vi,br)	613(i,sp)		3.10
Ni([19]aneN ₃)(ClO ₄) ₂	3273(i)	1091(vi,br)	620(i,sp)		3.23
Ni([20]aneN ₃)(ClO ₄) ₂	3275(i), 3295(sh)	1091(vi,br)	620(i,sp)	3489, 3577(m) ^f	3.14
Ni(tetren)(ClO ₄) ₂	3297(sh), 3317(i,sp), 3363(i,sp)	1090(vi,br)	619(i,sp)	1597(m), 1635(sh) ^g , 3541(m,br)	-
Ni(tetren)(ClO ₄) ₂	3179(w), 3283, 3323(m,sp)	1095(vi,br)	620 i,sp	1595(i,sp) ^g , 3503(w,br)	3.18

^a frequencies in cm⁻¹

^b ν_1 (A) obscured by ligand vibrations

^c ν_{eff} , B.M.: 25°C

^d ref. 134

^e presumed to be a misprint

^f δ (NH₂)

^g c.f. Cu([20]aneN₃)(ClO₄)₂

TABLE 2.12

Infrared Spectra of Ni L (NO₃)₂ Complexes^a

Complex	ν (N-H)	ν (NO ₃)		Other Bands
		ν_2 (A'')	ν_3 (E')	
Ni([15]aneN ₃)(NO ₃) ₂	3229(i), 3261(i), 3377(sh)	821(m,sp)	1322, 1347, 1369, 1390, 1402(i)	
Ni([16]aneN ₃)(NO ₃) ₂	3247(i,sp), 3288(m,sp), 3315(m,sp)	821(m,sp), 827(m,sp)	1283, 1313, 1358, 1408(i)	
Ni([17A]aneN ₃)(NO ₃) ₂ · 0.5H ₂ O	3239(i,sp), 3291(m,sp)	821(sh), 824(m,sp)	1310, 1362(i)	1684(w,br) ^c , 3390(sh) ^d
Ni([17B]aneN ₃)(NO ₃) ₂	3228(i,sp), 3248(i,sp), 3277(i,sp), 3288(i)	827(m,sp)	1265, 1310, 1330, 1345, 1367(i,sp)	
Ni([18A]aneN ₃)(NO ₃) ₂	3232(i), 3270(m)	826(m,sp)	1326, 1357, 1370(i)	
Ni([18B]aneN ₃)(NO ₃) ₂ · 0.5CH ₃ OH	3259(m,sp), 3277(sh)	820, 826(m,sp)	1298, 1310, 1323, 1373, 1410(i)	1625(w), 3457(m,br) ^d
Ni([19]aneN ₃)(NO ₃) ₂ · 0.5CH ₃ OH	3223(i,sp)	825(m,sp)	1342(i, v.br)	1650(w), 3458(m,br) ^d
Ni([20]aneN ₃)(NO ₃) ₂ · 0.5H ₂ O	3216(i,sp), 3253(i,sp)	825(m,sp)	1332, 1377, 1397(i,br)	1624(w) ^c , 3424, 3510(m) ^d
Ni([20]aneN ₃)(NO ₃) ₂ · 1.5H ₂ O				1592, 1641(w,br) ^c , 3423(m), 3500(sh) ^d
Ni(tetren)(NO ₃) ₂ · H ₂ O	3241(m,sp), 3287(sh), 3292(m,sp), 3310(m,sp), 3335(m,sp), 3365(m,sp)	817(sh), 822(m,sp), 828(sh)	1327(i), 1368(i), 1372(i), 1390(i,sp)	1543(m), 1574(m), 1605(m,sp), 1610(sh) ^{c,e}
Ni(tetrapn)(NO ₃) ₂	3185(m), 3242(i,sp), 3269(i,sp), 3319(sh)	826(m,sp)	1318, 1330, 1365, 1380, 1395(i,br)	3623(m,sp) ^d 1593(m,sp), 1609(sh) ^e

^a frequencies in cm⁻¹^b ν_1, ν_2 , obscured by ligand vibrations^c δ (H₂O)^d ν (O-H)^e δ (NH)₂

TABLE 2.13

Infrared Spectra of $\text{Ni L}(\text{NO}_3)_2$ Complexes
(Overtone and combination bands of the nitrate ion, cm^{-1})

Complex	$\nu_1 + \nu_3$	$\nu_1 + \nu_4$	$2\nu_1^a$
$\text{Ni}([15]\text{aneN}_5)(\text{NO}_3)_2$	2360, 2391	1765(sh), 1767	2049
$\text{Ni}([16]\text{aneN}_5)(\text{NO}_3)_2$	2330, 2383, 2435	1743, 1749, 1756	2015, 2055
$\text{Ni}([17\text{A}]\text{aneN}_5)(\text{NO}_3)_2 \cdot 0.5\text{H}_2\text{O}$	2330, 2360, 2390	1753	2025, 2060
$\text{Ni}([17\text{B}]\text{aneN}_5)(\text{NO}_3)_2$	2342, 2380, 2435	1750, 1759, 1772	2040, 2060
$\text{Ni}([18\text{A}]\text{aneN}_5)(\text{NO}_3)_2$	2355, 2393	1752	2065
$\text{Ni}([18\text{B}]\text{aneN}_5)(\text{NO}_3)_2 \cdot 0.5\text{CH}_3\text{OH}$	2350, 2406, 2446	1743, 1767	2025, 2055, 2080
$\text{Ni}([19]\text{aneN}_5)(\text{NO}_3)_2 \cdot 0.5\text{CH}_3\text{OH}$	2360	1738, 1748	~ 2050
$\text{Ni}([20]\text{aneN}_5)(\text{NO}_3)_2 \cdot 0.5\text{H}_2\text{O}$	2326, 2346	1753, 1757	~ 2050
$\text{Ni}(\text{tetrpn})(\text{NO}_3)_2$	2352, 2403	1747, 1750, 1759	2080

a v. weak

TABLE 2.14

Electronic Spectra of Nickel(II) Complexes^a

Complex	$\nu(^3E_g \rightarrow ^3B_{1g})$	$\nu(^1E_g \rightarrow ^3E_g)$	$\nu(^3A_{2g} \rightarrow ^3B_{2g})$	$\nu(^1A_{1g} \rightarrow ^3B_{1g})$	$\nu(^1B_{2g} \rightarrow ^3B_{1g})$	$\nu(^3E_g \rightarrow ^3B_{1g})$	$\frac{\nu(^3E_g \rightarrow ^3B_{1g})}{\nu(^1E_g \rightarrow ^3B_{1g})}$	Comments ^b
Ni([15]aneN ₃)(ClO ₄) ₂	356	549	~770			1136	2.07	ss
	350(24)	526(12)	791(20)		837(21)	~1000(sh)	1.90	c
	350(16)	526(8)	783(20)		828(21)	951(sh)	1.81	d
	352(14)	520(8)	775(18)		830(23)			
Ni([16]aneN ₃)(ClO ₄) ₂	347	524	775(sh)			1066	2.03	ss
	339.8(13)	522(7)	785(5.5)		821(6)	964(7)	1.85	
	328(20)	520(6.7)	775(5.4)		816(5.9)	960(7)	1.85	c
Ni([17A]aneN ₃)(ClO ₄) ₂	358	552			833(sh)	1124	2.04	ss
	351(11.5)	555(7.2)	590(sh)	795(sh, 8.3)		960(8.3)	1.73	
Ni([17B]aneN ₃)(ClO ₄) ₂	356	543	818			1148	2.11	ss
	352(10)	548.5(7.0)	795(sh, 8.3)		825(sh)	936(12.4)	1.71	e
	351(12)	547(7.1)	790(sh, 7.8)		825(sh)	932(12)	1.70	
	347(19)	542(7.7)	783(sh, 8.2)		828(sh)	915(12)	1.69	c
Ni([18A]aneN ₃)(ClO ₄) ₂	363	559	714			1279	2.29	ss
	361.2(35.6)	559(17.3)	~800(sh, 4.5)		~300(sh, 6.5)	1175(sh, 6)	2.10	
Ni([18B]aneN ₃)(ClO ₄) ₂	362	557	774			1277	2.29	ss
	355(25)	555(10.9)	788(6.2)	861(7.6)	887(7.7)	~1175(3)	2.12	
Ni([19]aneN ₃)(ClO ₄) ₂	379	583	769			1351	2.32	ss
	372(10.3)	577(4.3)	~710(8)		~880(5)	1290(13)	2.24	
Ni([20]aneN ₃)(ClO ₄) ₂	372	571	~769			1347	2.31, 2.36	ss
	369(108)	573(50)	725(5)		~850(sh)	1320(13)	2.30	
	370(108)	573(50)	725(6)		~850(sh)	1307(12)	2.28	e
Ni(tetrapn)(ClO ₄) ₂	374	590						
	371(29)	589(16)			~850(sh)	1010(4.6)	1.71	ss
Ni(tetren)(ClO ₄) ₂								
Ni(Me ₃ tetren)(ClO ₄) ₂	412	694						
	412(135)	694(40)						
Ni(tren)(ClO ₄) ₂ ⁱ								

^a λ_{max} in nm; values in parentheses are extinction coefficient, (ε) units M⁻¹ cm⁻¹. Assignments for spectral transitions based on ref. 134.^b Solution spectra are in water unless otherwise specified; ss=solid state reflectance spectra.^c ref. 134^d ref. 167^e NO₃⁻ added^f ref. 124^g ref. 95^h ref. 98ⁱ tpen=N,N'-tris[2-(2'-pyridyl)ethylenediamine]^j solvent 1:1 methanol

TABLE 2.15
Molar Conductivities of Metal Complexes^a

Complex	Ni L (NO ₃) ₂		Ni L (ClO ₄) ₂		Cu L (NO ₃) ₂		Cu L (ClO ₄) ₂	
Solvent	Nitromethane ^b	Methanol ^b	Nitromethane	Acetone	Nitromethane	Nitromethane	Nitromethane	Acetone
Ligand								
[15]aneN ₅	72 (80)	125 (144)	140 [73] ^c	-	94	165 [125] ^c	-	-
[16]aneN ₅	74 (83)	115 (130)	130	-	90	161	-	-
[17A]aneN ₅	76 (86)	116 (131)	153	-	88	173	141	141
[17B]aneN ₅	76 (85)	98 (110)	137	130	87	159	-	-
[18A]aneN ₅	77 (86)	117 (134)	154	-	93	-	143	143
[18B]aneN ₅	70 (78)	94 (105)	145	-	76	-	140	140
[19]aneN ₅	-	158 (178)	-	148	78	166	-	-
[20]aneN ₅	-	163 (181)	-	162	82	163	-	-
tetrpn	-	108 (122)	-	142	-	-	144	144
Average Λ_M	74(+3) (83(+3))	110(+11) ^d (125(+14))	143(+9)	146(12)	86(+7)	165(+5)	142(+2)	142(+2)

^a Λ_M -units S cm² mol⁻¹ for solutions ~1 mM concentration at 25.0(±0.1) °C

^b values in parentheses represent molar conductivity of solutions diluted 50%

^c ref. 167

^d excluding complexes of [19]aneN₅ and [20]aneN₅

data and the recrystallizing media are listed in Table 2.10. (Refer to Tables 2.11-2.13 for infrared spectral data and magnetic susceptibilities of perchlorate and nitrate salts of nickel(II), Table 2.14 for details of their electronic spectra, and Table 2.15 for all conductivity data.)

2.3.3 Cobalt Complexes

Standard literature preparations were followed for the synthesis of $[\text{Co}(\text{NH}_3)_5 \text{H}_2\text{O}](\text{ClO}_4)_3$,²⁸⁷ $\text{Co}(\text{NH}_3)_5\text{Br}_3$,²⁸⁸ $\text{Co}(\text{NH}_3)_5\text{Cl}_3$ ²⁸⁹ and $\text{Na}_3\text{Co}(\text{CO}_3)_3 \cdot 3\text{H}_2\text{O}$ ²⁴⁶ (the latter was stored in a vacuum desiccator over phosphorus pentoxide).

2.3.3.1 Cobalt(III) complexes of [15]aneN₅

$[\text{Co}([15]\text{aneN}_5)\text{Br}]\text{Br}_2 \cdot \text{H}_2\text{O} / [\text{Co}([15]\text{aneN}_5)\text{Br}]\text{ZnBr}_4$ Method A

A solution of [15]aneN₅ (0.215 g, 1 mmol) in distilled water (10 cm³) and $\text{Co}(\text{NH}_3)_5\text{Br}_3$ (0.384 g, 1 mmol) was heated on a hot water bath for 8 hours. Gradual dissolution of the $\text{Co}(\text{NH}_3)_5\text{Br}_3$ was accompanied by the evolution of ammonia, giving an orange solution. Lithium bromide (1 g, 11 mmol) was added, and heating was continued until the solution became plum coloured. Hydrobromic acid (47%, 2 cm³) was added, followed by propan-2-ol (15 cm³). After a week, the crystalline product was collected by filtration, washed with methanol and vacuum desiccated. Yield of $[\text{Co}([15]\text{aneN}_5)\text{Br}]\text{Br}_2 \cdot \text{H}_2\text{O}$ 0.15 g (30%). The i.r. and ¹³C n.m.r. spectra were identical to those obtained for the analytically pure sample prepared by Method C.

A repeat of this synthesis in which the reaction mixture was taken almost to dryness before addition of the propan-2-ol yielded 0.50 g of crude product. This was dissolved in hydrobromic acid (2 M, 5 cm³), a solution of zinc bromide (0.5 g) in hydrobromic acid (47%, 5 cm³) was

added, and the resulting white crystalline material was removed by filtration. (This product was shown to be the hydrobromide salt of uncomplexed [15]aneN₅ by i.r.). The solution was heated on the steambath to reduce the volume to 3 cm³. The product which crystallized on overnight refrigeration was filtered, washed with absolute ethanol and vacuum desiccated. A second recrystallization from hydrobromic acid/zinc bromide was carried out.

Yield of [Co([15]aneN₅)Br]ZnBr₄ (after two recrystallizations) 0.36 g (50%). (The i.r. spectrum of the product was identical to that of the analytically pure sample prepared by Method C).

Method A (ii)

(In order to investigate the possibility that different isomers of the complex might be obtained by using different solvent systems, the reaction was repeated in DMSO). A solution of [15]aneN₅ (0.215 g, 1 mmol) in dry DMSO (20 cm³) and Co(NH₃)₅Br₃ (0.384 g, 1 mmol) was heated at 90°C for 10 hours. The solution turned brown as slow dissolution of the bromopentammine salt occurred. After overnight refrigeration, precipitated Co(NH₃)₅Br₃ (0.13 g, ~35%) was removed from the solution. Addition of propan-2-ol resulted in the precipitation of a brown gummy solid which could not be induced to crystallize and gave an i.r. spectrum with broad, ill-defined peaks. The resonances in the ¹³C n.m.r. spectrum were broader than is normally observed, and were superimposed on a very broad band (~20 p.p.m. wide). The resonances present in an authentic sample of [Co([15]aneN₅)Br]²⁺ were all observed, and it appeared that the desired product was one of the major products, but a large number of peaks were also present between 40 and 50 p.p.m. that could not be assigned. (There were no peaks in the ¹³C n.m.r. spectrum that corresponded to the CH₃- of DMSO).

[Co([15]aneN₅)Br]ZnBr₄ Method B

To a stirred slurry of Na₃Co(CO₃)₃·3H₂O (0.362 g, 1 mmol) in distilled water (25 cm³) was added solid [15]aneN₅(HBr)₅ (0.620 g, 1 mmol) over several minutes. After the evolution of carbon dioxide had ceased, and the reaction mixture had changed from green to red-orange, hydrobromic acid (2 M, 0.5 cm³) was added to bring the pH to 7. Heating on the steam-bath for 1 hour produced a purple-brown solution, to which was added a solution of zinc bromide (1 g) in hydrobromic acid (9 M, 10 cm³). The volume of the mixture was reduced to 10 cm³ by rotary evaporation, and methanol (30 cm³) and acetone (10 cm³) were added. After several days' refrigeration, the crystals that had formed were removed by filtration, washed with absolute ethanol and dried. The product was dissolved in hydrobromic acid (2 M, 3 cm³) and zinc bromide (0.75 g) in concentrated hydrobromic acid (47%, 10 cm³) was added. The well-formed crystals that separated on overnight refrigeration were collected by filtration, washed with absolute ethanol and vacuum desiccated. Yield 0.26 g (35%). (The i.r. and ¹³C n.m.r. spectra were identical to those obtained for the analytically pure sample prepared by Method C).

[Co([15]aneN₅)Br]Br₂·H₂O/[Co([15]aneN₅)Br]ZnBr₄ Method C

(In the following preparation all solutions were deoxygenated by bubbling nitrogen through them for at least 10 minutes and the reactions were performed under a blanket of nitrogen).

To a stirred solution of [15]aneN₅ (0.454 g, 2.1 mmol) in absolute ethanol (10 cm³) was added dropwise over 30 minutes cobalt bromide hexahydrate (0.689 g, 2.1 mmol) in absolute ethanol (15 cm³). Bromine (0.185 g, 1.16 mmol) in absolute ethanol (11 cm³) was then added dropwise over 10 minutes, resulting in the formation of a blue-black precipitate. Stirring was continued for 15 minutes and the product was

filtered, washed with absolute ethanol, and dried. (Crude yield >90%). It was recrystallized from hydrobromic acid (2 M, 5 cm³)/ethanol (15 cm³). Yield of [Co([15]aneN₅)Br]Br₂·H₂O 0.76 g (74%). Found: C, 22.54; H, 5.28; N, 12.94; Br, 45.05. CoC₁₀H₂₇N₅Br₃O requires C, 22.58; H, 5.12; N, 13.17; Br, 45.06%. I.r. (nujol): 3467, 3379 (m, sp, $\nu_{\text{O-H}}$), 3276, 3160, 3129, 3063 (m, sp, $\nu_{\text{N-H}}$), 1617 (m, sp, $\delta_{\text{H}_2\text{O}}$) cm⁻¹. ¹³C n.m.r. δ (HNO₃/D₂O) 59.63, 58.53, 57.59, 57.08, 56.79, 55.52, 55.08², 52.02, 51.27 (γ -isomer).

Co([15]aneN₅)Br₃·H₂O (0.050 g) was dissolved in hydrobromic acid (2 M, 3 cm³), zinc bromide (0.20 g) in concentrated hydrobromic acid (9 M, 9 cm³) was added and the product that precipitated after overnight refrigeration was collected by filtration, washed with absolute ethanol and vacuum desiccated. Yield of [Co([15]aneN₅)Br]ZnBr₄ 0.046 g (64%) Found: C, 16.46; H, 3.70; N, 9.59; Br, 54.22. CoC₁₀H₂₅N₅Br₅Zn requires Co, 16.25, H, 3.41; N, 9.48; Br, 54.05%. I.r. (nujol): 3223, 3170, 3126 (i, sp, $\nu_{\text{N-H}}$) cm⁻¹. (See fig. 2.2 for i.r. spectrum of compound).

[Co([15]aneN₅)Cl]ZnCl₄·0.5H₂O Method A (i)

A solution of [15]aneN₅ (0.220 g, 1 mmol) in distilled water (10 cm³) and Co(NH₃)₅Cl₃ (0.255 g, 1 mmol) was heated for 6 hours on a steambath. The Co(NH₃)₅Cl₃ dissolved rapidly and ammonia was evolved, giving a ruby red solution which was rotary evaporated to near dryness. Propan-2-ol (30 cm³) was added and the resultant oily product was separated and washed with further propan-2-ol. It was then dissolved in hydrochloric acid (10 M, 5 cm³) and zinc chloride (1 g) was added. After overnight heating at 80°C, methanol (40 cm³) was added, the solution was filtered and refrigerated. The product that precipitated after several days was collected by filtration, washed with methanol, then

Infrared Spectra of $[\text{Co}([\text{15}] \text{aneN}_5)\text{Cl}]\text{ZnCl}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$ and $[\text{Co}([\text{15}] \text{aneN}_5)\text{Br}]\text{ZnBr}_4$

fig 2.2

ethanol and vacuum desiccated. Yield 0.20 g (39%). (The i.r. and ^{13}C n.m.r. spectra are identical to those obtained for the analytically pure sample prepared by Method D). There appeared to be a considerable amount of cobalt(II) present in the filtrate, as shown by the rapid and reversible change from blue to red as water and organic solvents respectively were added.

$[\text{Co}([15]\text{aneN}_5)\text{Cl}]\text{Cl}_2$ Method A (ii)

To a reaction mixture with the same composition as that described above was added activated charcoal (0.10 g). The evolution of ammonia occurred more rapidly, and after one hour had ceased, leaving a brown solution, which was filtered, then rotary evaporated to near dryness. The material remaining was taken up in ethanol (10 cm^3) and propan-2-ol (20 cm^3) was added. The brown material that precipitated on cooling was collected by filtration, washed with propan-2-ol and dried at 120°C . Yield 0.30 g (79% crude). The product was dissolved in hydrochloric acid (0.1 M, 5 cm^3), concentrated hydrochloric acid (10 M, 5 cm^3) was added and the solution was heated on a steambath for 1 hour, but efforts to isolate the chloro- complex failed. The properties exhibited by the solution indicated the presence of large amounts of cobalt(II).

$[\text{Co}([15]\text{aneN}_5)\text{Cl}]\text{Cl}_2$ Method C

(The following reaction was carried out under a blanket of nitrogen with nitrogen-saturated solutions). To a stirred solution of $[15]\text{aneN}_5$ (0.202 g, 0.94 mmol) in absolute ethanol (10 cm^3) was added cobalt chloride hexahydrate (0.224 g, 0.94 mmol) in absolute ethanol (15 cm^3). A purple precipitate was produced. Chlorine gas was bubbled through the solution for several minutes, with considerable evolution

of heat, and the precipitation of a blue product. The reaction mixture was taken to dryness by rotary evaporation, and the solid remaining was dissolved in methanol (10 cm³), filtered to remove a small amount of black material, and reprecipitated with propan-2-ol (50 cm³). Yield 0.20 g (56% crude). This synthesis produced the same isomers as Method D (q.v.), as shown by the ¹³C n.m.r. spectrum, but they are present in different proportions. (The relative intensities of the two sets of ¹³C n.m.r. peaks in this synthesis is 3:4 compared with a ratio of 1:3 for the product obtained by Method D). The i.r. spectrum is identical to that obtained for the analytically pure sample prepared by Method D, despite the difference in the relative intensities of the two different sets of ¹³C n.m.r. peaks.

[Co([15]aneN₅)Cl]ZnCl₄·0.5H₂O Method D

To a stirred solution of [15]aneN₅ (0.215 g, 1 mmol) in methanol (10 cm³) was added over 2 minutes cobalt chloride hexahydrate (0.238 g, 1 mmol) in methanol (10 cm³). The solution immediately turned brown, indicating the rapid formation of the peroxo-complex. Hydrogen peroxide † (30 vol, 1 cm³, excess) was added, and the solution was heated at 60°C for 10 minutes. Concentrated hydrochloric acid (10 M, 5 cm³) was carefully added (caution: effervescence!) followed by zinc chloride (0.5 g). The solution immediately turned claret, and well-formed burgundy coloured crystals precipitated. The product was filtered from the hot solution, washed with a small amount of methanol (slightly soluble) and vacuum desiccated. Yield 0.39 g (75%).

To a small sample (0.200 g) dissolved in hydrochloric acid (0.1 M, 2 cm³) at 80°C was added zinc chloride (1.0 g) in hydrochloric acid (10 M, 10 cm³). Heating was continued until the volume of the

solution was reduced to $\sim 5 \text{ cm}^3$. The product was filtered after overnight refrigeration, washed with ethanol and vacuum desiccated. Yield 0.16 g (80%). Found: C, 23.11, H, 5.13; N, 13.39. $\text{CoC}_{10}\text{H}_{26}\text{N}_5\text{O}_{0.5}\text{Cl}_5\text{Zn}$ requires C, 22.84; H, 4.98; N, 13.32%. I.r. (nujol): 3541, 3463 (m,br, $\nu_{\text{O-H}}$), 3235, 3175, 3138 (i,sp, $\nu_{\text{N-H}}$), 1617 (w,sp, $\delta_{\text{O-H}}$) cm^{-1} . Apart from the presence of peaks in the i.r. spectrum corresponding to water and the shift of the three $\nu_{(\text{N-H})}$ peaks to higher energy, the spectrum is virtually indistinguishable from that of $[\text{Co}([\text{15}] \text{aneN}_5)\text{Br}]\text{ZnBr}_4$ (see fig.2.2). ^{13}C n.m.r. $\delta(\text{HCl} / \text{D}_2\text{O})$ 59.61, 57.80, 57.47, 57.27, 56.15², 55.08, 54.68, 52.04, 49.90; 56.54, 55.64, 55.44, 53.34, 51.33. (The relative intensities of the two sets of resonances listed is γ -isomer: α -isomer $\sim 3:1$).

$[\text{Co}([\text{15}] \text{aneN}_5)\text{Cl}](\text{ClO}_4)_2 \cdot \text{H}_2\text{O}$ Method B

To a stirred slurry of $\text{Na}_3\text{Co}(\text{CO}_3)_3 \cdot 3\text{H}_2\text{O}$ (0.43 g, 1.19 mmol) in water (15 cm^3) was added a solution of $[\text{15}] \text{aneN}_5$ (0.234 g, 1.09 mmol) in hydrochloric acid (1.09 M, 5 cm^3). After the evolution of carbon dioxide had ceased and the solution had changed from green to red, it was heated on the steambath for 1 hour. A small amount of insoluble material was removed by filtration and sodium perchlorate (0.22 g, 9.45 mmol) was added. After several days' refrigeration a crop of reddish-brown crystals had formed. They were filtered, washed with propan-2-ol and vacuum desiccated. Yield 0.19 g (35%). Found: C, 22.86; H, 4.95; N, 13.38; Cl, 20.59. $\text{CoC}_{10}\text{H}_{27}\text{N}_5\text{Cl}_3\text{O}_9$ requires C, 22.81; H, 5.17; N, 13.30; Cl, 20.20%. I.r. (nujol): 3500 (w,br, $\nu_{\text{O-H}}$), 3269, 3253, 3212 (m,sp, $\nu_{\text{N-H}}$), 1620 (w, $\delta_{\text{O-H}}$); 1110, 1067(sh) (i,br, $\nu_3(\text{ClO}_4^-)$), 622 (m,sp, $\nu_4(\text{ClO}_4^-)$) cm^{-1} .

This synthesis was shown by ^{13}C n.m.r. to produce the same isomers as the previous ones but in this instance the two sets of peaks in the spectrum were of approximately equal intensity.

$[\text{Co}_2([\text{15}] \text{aneN}_5)_2\text{O}_2](\text{ClO}_4)_4 \cdot \text{H}_2\text{O}$ Method D

To a stirred solution of $[\text{15}] \text{aneN}_5$ (0.204 g, 0.95 mmol) in distilled water (5 cm³) was added cobalt perchlorate hexahydrate (0.347 g, 0.95 mmol) in water (10 cm³) over 5 minutes. A solution of sodium perchlorate (3 g) in water (20 cm³) was added, and the solution was aerated for 1 hour. The pale brown product that separated was filtered, washed with ethanol and vacuum desiccated. Yield 0.35 g (73%). The product was dissolved in distilled water (40 cm³) at room temperature, filtered to remove any undissolved material and sodium perchlorate (3 g) in water (10 cm³) was added. After overnight refrigeration, the product was filtered, washed with ethanol and vacuum desiccated.

Found: C, 24.33; H, 5.45; N, 13.53. $\text{Co}_2\text{C}_{20}\text{H}_{52}\text{N}_{10}\text{O}_{19}\text{Cl}_4$ requires C, 24.11; H, 5.26; N, 14.06%. I.r. (nujol): 3518 (m,br, $\nu_{\text{O-H}}$), 3245 (m,br, $\nu_{\text{N-H}}$), 1625 (m,br, $\delta_{\text{O-H}}$), 1102 (vi,br, $\nu_3(\text{ClO}_4^-)$), 624 (m,sp, $\nu_4(\text{ClO}_4^-)$) cm⁻¹. The peaks in the ¹³C n.m.r. spectrum (fig. 2.3) appear broadened, and are not of uniform size, making interpretation difficult. Furthermore, the ¹³C n.m.r. spectrum is indistinguishable from that obtained for $[\text{Co}([\text{15}] \text{aneN}_5)\text{OH}]^{2+}$ (q.v.) prepared by a variety of methods.

$[\text{Co}([\text{15}] \text{aneN}_5)\text{H}_2\text{O}](\text{ClO}_4)_3$ Method A

A solution of $[\text{15}] \text{aneN}_5$ (0.215 g, 1 mmol) in water (25 cm³) and $[\text{Co}(\text{NH}_3)_5\text{H}_2\text{O}](\text{ClO}_4)_3$ (0.461 g, 1 mmol) was heated on a steambath for 2 hours. Ammonia was evolved and the solution turned red-brown. A small amount of insoluble material was removed by filtration and perchloric acid (2 M, 2 cm³) was added. Ethanol (20 cm³) and propan-2-ol (20 cm³) were added and after overnight refrigeration, the product was removed by filtration, washed with ethanol and vacuum desiccated.

^{13}C n.m.r. Spectra of Peroxo[†] and Hydroxo^{*} Cobalt(III) Complexes of [15]aneN₅

fig 2.3

Yield 0.29 g (49%). The product was recrystallized from perchloric acid/propan-2-ol. In a repeat of this synthesis the reaction mixture was taken to near dryness by rotary evaporation and the remaining solution was examined by ^{13}C n.m.r. spectroscopy, which revealed that an appreciable amount of the macrocyclic amine had not reacted.

2.3.3.2 Cobalt(III) Complexes of [16]aneN₅

[Co([16]aneN₅)Br]ZnBr₄ Method A

A solution of [16]aneN₅·H₂O (0.247 g, 1 mmol) in water (15 cm³) and Co(NH₃)₅Br₃ (0.384 g, 1 mmol) was heated on the steambath for 2 hours with rapid evolution of ammonia. The red solution was filtered hot, hydrobromic acid (9 M, 5 cm³) was added, and the solution rapidly turned dark violet. Heating was continued for 1 hour and the volume of the solution was reduced to 5 cm³ by rotary evaporation. Propan-2-ol (25 cm³) was added, the product which precipitated on cooling was collected by filtration, washed with ethanol and dried at 120°C. Yield (of the tribromide) 0.52 g (92%). The crude product was dissolved in hydrobromic acid (0.5 M, 4 cm³) and zinc bromide (1 g) in hydrobromic acid (9 M, 10 cm³) was added. After overnight refrigeration the precipitated product was collected by filtration, washed with ethanol, and vacuum desiccated. Yield 0.58 g (77%). The i.r. and ^{13}C n.m.r. spectra are identical to those obtained for the analytically pure sample prepared by Method C.

[Co([16]aneN₅)Br]Br₂·2H₂O·0.25(C₂H₅OH)/[Co([16]aneN₅)Br]ZnBr₄ Method C

(All solutions were thoroughly outgassed with nitrogen, and the reaction was carried out under nitrogen.)

To a stirred solution of [16]aneN₅·H₂O (0.495 g, 2 mmol) in absolute ethanol (15 cm³) was added dropwise a solution of cobalt bromide

hexahydrate (0.654 g, 2 mmol) in absolute ethanol (10 cm³) over 10 minutes. A magenta precipitate was formed. Stirring was continued as bromine (0.16 g, 1 mmol) in absolute ethanol (10 cm³) was added over 5 minutes leading to the formation of a dark purple precipitate. The ethanol was removed by rotary evaporation and the product was dissolved in hydrobromic acid (9 M, 10 cm³) and acetone (50 cm³) was added to reprecipitate the product, which was collected by filtration, washed with copious acetone and vacuum desiccated. Yield 1.09 g (95% of crude product). The product was recrystallized from hydrobromic acid (9 M)/ethanol. Yield 0.84 g (75%). Found: C, 23.99; H, 5.77; N, 12.17; Br, 41.63. $\text{CoC}_{11.5}\text{H}_{32.5}\text{N}_5\text{Br}_3\text{O}_{2.25}$ requires C, 24.00; H, 5.69; N, 12.17; Br, 41.65%. (The N/Br ratio is exactly as expected, and from this, the required surplus C, H and O was calculated, giving the formulation $[\text{Co}([16]\text{aneN}_5)\text{Br}]\text{Br}_2 \cdot 2\text{H}_2\text{O} \cdot 0.25(\text{C}_2\text{H}_5\text{OH})$.) I.r. (nujol): 3153, 3461 (m, sp, $\nu_{\text{O-H}}$), 3195, 3128, 3107 (m, $\nu_{\text{N-H}}$), 1619, 1612 (m, $\delta_{\text{O-H}}$) cm⁻¹.

Because of the unsatisfactory analysis figures obtained the compound was converted to the tetrabromozincate salt as described in the previous synthesis. Found: C, 17.85; H, 3.75; N, 9.26; Br, 53.07. $\text{CoC}_{11}\text{H}_{27}\text{N}_5\text{Br}_5\text{Zn}$ requires C, 17.54; H, 3.61; N, 9.30; Br, 53.04%. I.r. (nujol): 3201, 3167 (m, sp, $\nu_{\text{N-H}}$) cm⁻¹. ¹³C n.m.r. $\delta(\text{HNO}_3/\text{D}_2\text{O})$ 58.90, 56.84, 56.57, 54.93, 50.94, 28.15. (The latter peak is approximately half the height of the previous five).

$\text{Co}([16]\text{aneN}_5)\text{Cl}]\text{ZnCl}_4 \cdot \text{H}_2\text{O} / [\text{Co}([16]\text{aneN}_5)\text{Cl}]\text{ZnCl}_4$ Method A

A solution of $[16]\text{aneN}_5 \cdot \text{H}_2\text{O}$ (0.247 g, 1 mmol) in water (20 cm³) and $\text{Co}(\text{NH}_3)_5\text{Cl}_3$ (0.251 g, 1 mmol) was heated on the steambath for 90 minutes. The evolution of ammonia was rapid and the solution turned red. The volume of the solution was reduced to 5 cm³ by rotary evaporation

and zinc chloride (0.6 g) in hydrochloric acid (12 M, 5 cm³) was added. After 10 minutes heating at 80°C, the solution was allowed to cool to room temperature, and addition of methanol (10 cm³) resulted in precipitation of the product. After overnight refrigeration the product was collected by filtration, washed with methanol, and vacuum desiccated. Yield (of [Co([16]aneN₅)Cl]ZnCl₄.H₂O) 0.46 g (83%).

A sample (0.31 g) was dissolved in hydrochloric acid (0.1 M, 10 cm³) and zinc chloride (1 g) in hydrochloric acid (4 M, 10 cm³) was added, followed by propan-2-ol (15 cm³). The precipitate was collected by filtration, washed with ethanol and vacuum desiccated. Yield 0.23 g (75%). Found: C, 24.21; H, 5.55; N, 12.59. CoC₁₁H₂₉N₅Cl₅OZn requires C, 24.07; H, 5.32; N, 12.76%. I.r. (nujol): 3501, 3398 (m,sp,ν_{O-H}), 3203, 3179 (i,sp,ν_{N-H}), 1607 (w,δ_{O-H}). ¹³C n.m.r. δ(HNO₃/D₂O) 59.31, 56.30, 55.82, 54.97, 50.63, 28.22. (The latter peak is approximately half the height of the previous five).

A sample dried at 120°C overnight was shown by i.r. and microanalysis to be [Co([16]aneN₅)Cl]ZnCl₄. Found: C, 25.11; H, 5.36; N, 13.20. CoC₁₁H₂₇N₅Cl₅Zn requires C, 24.88; H, 5.13; N, 13.19%. I.r. (nujol): 3210, 3173 (m,sp,ν_{N-H}) cm⁻¹. The fingerprint region of the i.r. was virtually indistinguishable from that of [Co([16]aneN₅)Br]ZnBr₄ (see fig. 2.4).

[Co([16]aneN₅)Cl]ZnCl₄.H₂O Method D

To a stirred solution of [16]aneN₅.H₂O (0.495 g, 2 mmol) in methanol (10 cm³) was added dropwise cobalt chloride hexahydrate (0.476 g, 2 mmol) in methanol (10 cm³). The brown solution was heated (60°C) for 5 minutes, and hydrogen peroxide (10%, 1.5 cm³) was added. The solution was filtered to remove insoluble material, and zinc chloride (1 g)

Infrared Spectra of $[\text{Co}([\text{16}] \text{aneN}_5)\text{X}]\text{ZnX}_4$

fig 2.4

in hydrochloric acid (4 M, 10 cm³) was carefully added. Heating was continued for 1 hour and the solution was then refrigerated overnight. The product that precipitated was filtered, washed with methanol and vacuum desiccated. Yield 0.88 g (80%). A sample of 0.70 g of the product was dissolved in hydrochloric acid (0.1 M, 10 cm³) at 70°C, and zinc chloride (1 g) in hydrochloric acid (12 M, 10 cm³) was added. The product crystallized as well-formed platelets on standing overnight, which were collected by filtration, washed with methanol, then propan-2-ol and vacuum desiccated. Yield 0.43 g (61%). Further product could be recovered from the mother liquor on addition of ethanol (20%). The i.r. and ¹³C n.m.r. spectra are identical to those obtained for the monohydrate prepared by Method A.

[Co₂([16]aneN₅)₂O₂](ClO₄)₄·2H₂O Method D

To a stirred solution of [16]aneN₅·H₂O (0.124 g, 0.5 mmol) in methanol (20 cm³) was added over 15 minutes cobalt perchlorate hexahydrate (0.183 g, 0.5 mmol) in methanol (10 cm³). The mixture was heated (50°C) and stirred for 15 minutes and the brown product was filtered, washed with methanol then absolute ethanol and vacuum desiccated. Yield 0.24 g (88%). It was recrystallized by dissolving in water (40 cm³) at room temperature, filtering and adding sodium perchlorate (1 g). The precipitate was treated as above. Yield 0.20 g (73%). Found: C, 25.48; H, 5.63; N, 13.07; Cl, 13.64. Co₂C₂₂H₅₈N₁₀O₂₀Cl₄ requires C, 25.35; H, 5.61; N, 13.44; Cl, 13.60%. I.r. (nujol): 3604 (m,br,ν_{O-H}), 3269 (i,br,ν_{N-H}), 1627 (m,δ_{O-H}), 1104 (vi,ν₃(ClO₄⁻), 625 (i,sp,ν₄(ClO₄⁻) cm⁻¹. ¹³C n.m.r. δ(D₂O) 57.51, 54.63, 54.39, 54.18, 49.95, 27.52. (The latter peak is approximately half the height of the previous five). (Note: spectrum reference T.M.S.). Treatment of the

product with perchloric acid produced a product with the same ^{13}C n.m.r. spectrum as $[\text{Co}([16]\text{aneN}_5)\text{H}_2\text{O}]^{3+}$ produced by other methods.

$[\text{Co}_2([16]\text{aneN}_5)_2\text{O}_2]\text{Cl}_4$ Method D

To a stirred solution of $[16]\text{aneN}_5\cdot\text{H}_2\text{O}$ (0.115 g, 0.46 mmol) in acetone (20 cm^3) at 50°C was added dropwise over 20 minutes cobalt chloride hexahydrate (0.119 g, 1 mmol) in acetone (10 cm^3). A brown precipitate formed on the addition of each drop. The product was filtered from the hot solution, washed with copious acetone and vacuum desiccated. The waxy solid was digested with methanol (15 cm^3) at 50°C for $\frac{1}{2}$ hour, propan-2-ol (15 cm^3) was added, the solution was cooled and the pale brown solid was filtered, washed with propan-2-ol and vacuum desiccated. Yield 0.16 g (70-80% depending on the degree of hydration). It was not possible to prepare a sample suitable for microanalysis, but the sample had the same ^{13}C n.m.r. spectrum as that prepared in the previous synthesis.

$[\text{Co}([16]\text{aneN}_5)\text{H}_2\text{O}](\text{ClO}_4)_3$ Method A

A solution of $[16]\text{aneN}_5\cdot\text{H}_2\text{O}$ (0.247 g, 1 mmol) in water (10 cm^3) with $[\text{Co}(\text{NH}_3)_5\text{H}_2\text{O}](\text{ClO}_4)_3$ (0.461 g, 1 mmol) and activated charcoal (200 mg) was heated on the steambath for 1 hour. The hot solution was filtered, acidified with perchloric acid (2 M, 1 cm^3), and the volume was reduced to $\sim 2 \text{ cm}^3$. Ethanol (5 cm^3) and propan-2-ol (15 cm^3) were added and the mixture was heated under reflux for 1 hour. The product was filtered, washed with propan-2-ol and dried at 120°C . Yield 0.56 g (92%).

A sample was recrystallized by dissolving in perchloric acid (2 M) and adding excess sodium perchlorate, producing well-formed red needles.

I.r. (nujol): 3611, 3536 (w, ν_{O-H}), 3237 (i, ν_{N-H}), 1610 (w, br, δ_{O-H}), 1120, 1076 ($vi, \nu_3(ClO_4^-)$), 622 ($i, sp, \nu_4(ClO_4^-)$) cm^{-1} .

^{13}C n.m.r. ($HClO_4/D_2O$) 59.82, 55.45², 55.02, 50.44, 28.16. (The peaks at 55.45 and 28.16 p.p.m. were approximately twice and half the height respectively of the other three peaks).

However, recrystallization of another sample from ethanol/propan-2-ol containing a few drops of perchloric acid appeared to produce a different crystalline form. I.r. (nujol): 3533 (m, ν_{O-H}), 3293, 3261, 3232 (i, ν_{N-H}), 1620 (w, δ_{O-H}), 1089 ($vi, \nu_3(ClO_4^-)$), 622 ($i, sp, \nu_4(ClO_4^-)$) cm^{-1} . The sample was not suitable for analysis, but the ^{13}C n.m.r. spectrum was identical to that obtained for the form prepared previously.

2.3.3.3 Cobalt(III) Complexes of [17A]aneN₅

[Co([17A]aneN₅)Br]Br₂·H₂O Method A

A solution of [17A]aneN₅·(HBr)₅·0.5H₂O (0.648 g, 0.99 mmol) in water (10 cm³) and Co(NH₃)₅Br₃ (0.348 g, 1 mmol) was heated on the steam-bath for 2 hours. Lithium hydroxide (0.44 M, 4 cm³) was added to neutralize the solution (pH ~6) and heating was continued for 1 hour. The resulting alkaline solution (pH ~9) was filtered to remove cobalt oxide. Hydrobromic acid (9 M, 10 cm³) was added and the volume of the solution was reduced to ~5 cm³ on the steambath. Addition of propan-2-ol produced a small amount of a flesh-pink precipitate which was filtered, and the solution was refrigerated for several days. The well-formed dark purple crystals that precipitated were removed by filtration, washed with ethanol and vacuum desiccated. Yield 0.16 g (29%).

Found: C, 25.63; H, 5.61; N, 12.43; Br, 42.51. $\text{CoC}_{12}\text{H}_{31}\text{N}_5\text{Br}_3\text{O}$ requires C, 25.73; H, 5.58; N, 12.51; Br, 42.80%. I.r. (nujol): 3526, 3462 (m, $\nu_{\text{O-H}}$), 3097 (i, sp, $\nu_{\text{N-H}}$), 1611 (m, sp, $\delta_{\text{O-H}}$) cm^{-1} . ^{13}C n.m.r. $\delta(\text{HNO}_3/\text{D}_2\text{O})$ 59.46, 58.39, 57.08, 56.76, 54.26², 51.83, 51.52, 50.27, 47.11, 23.19, 22.40.

$[\text{Co}([17\text{A}] \text{aneN}_5)\text{Br}]\text{Br}_2 \cdot 0.5(\text{CH}_3\text{OH}) / [\text{Co}([17\text{A}] \text{aneN}_5)\text{Br}]\text{ZnBr}_4$ Method C

(The following reaction was carried out in an inert atmosphere - see synthesis of $[\text{Co}([15] \text{aneN}_5)\text{Br}]\text{ZnBr}_4$ Method C for details).

To a stirred solution of $[17\text{A}] \text{aneN}_5$ (0.276 g, 1.13 mmol) in absolute ethanol (10 cm^3) was added over 10 minutes a solution of cobalt bromide hexahydrate (0.371 g, 1 equiv.) in absolute ethanol. A pink precipitate was formed. Dropwise addition over 10 minutes of a solution of bromine (0.100 g, 0.625 mmol) in absolute ethanol yielded a dark blue-purple precipitate on dissolution of the product already present. The precipitate was removed by filtration, washed with absolute alcohol, acetone, then vacuum desiccated. The filtrate rapidly turned brown on exposure to the air, suggesting incomplete reaction with the bromine. Hydrobromic acid (9 M, 5 cm^3) was added to the filtrate and the purple product that precipitated was filtered, washed with absolute ethanol, acetone and vacuum desiccated. The infrared spectra of both products were identical so they were combined. Yield 0.57 g (90%). The product was recrystallized from 47% hydrobromic acid/methanol (76% overall yield). Found: C, 26.95; H, 5.95; N, 12.11; Br, 42.76. $\text{CoC}_{12.5}\text{H}_{31}\text{N}_5\text{Br}_3\text{O}_{0.5}$ requires C, 26.90; H, 5.60; N, 12.55; Br, 42.95%. (The formula weight and required additional C and O were calculated from the N and Br analysis figures which were consistent with each other). I.r. (nujol): 3556 (w), 3422 (m, $\nu_{\text{O-H}}$), 3083 (i, br, $\nu_{\text{N-H}}$), 1607 (m, sp, $\delta_{\text{O-H}}$) cm^{-1} .

The fingerprint region of the i.r. spectrum of this compound was indistinguishable from that of the product obtained in the previous synthesis.

Because of the unsatisfactory analysis figures that were obtained the product was converted to the tetrabromozincate salt as described in the synthesis of $[\text{Co}([\text{16}] \text{aneN}_5)\text{Br}]\text{ZnBr}_4$. Found: C, 18.83; H, 3.82; N, 9.01; Br, 52.18. $\text{CoC}_{12}\text{H}_{29}\text{N}_5\text{Br}_5\text{Zn}$ requires C, 18.79; H, 3.81; N, 9.13; Br, 52.07%. I.r. (nujol): 3238, 3209, 3176, 3147 ($\text{m, sp, } \nu_{\text{N-H}}$) cm^{-1} . The ^{13}C n.m.r. spectrum is identical to that of the sample prepared using Method A.

$[\text{Co}([\text{17A}] \text{aneN}_5)\text{Cl}]\text{ZnCl}_4 \cdot 2\text{H}_2\text{O}$ Method A

A solution of $[\text{17A}] \text{aneN}_5$ (0.243 g, 1 mmol) in water (20 cm^3), and $\text{Co}(\text{NH}_3)_5\text{Cl}_3$ (0.251 g, 1 mmol) was heated on the steambath for 5½ hours. Zinc chloride (2 g, excess) in hydrochloric acid (12 M, 20 cm^3) was added, and heating was continued overnight. (The total volume of the reaction mixture decreased to 20 cm^3). Methanol (10 cm^3) and ether (25 cm^3) were added to precipitate the product which was collected by filtration and washed with acetone. (The washings were initially blue, suggesting the presence of cobalt(II)). Yield (of $[\text{Co}([\text{17A}] \text{aneN}_5)\text{Cl}_3]$) 0.45 g (77%).

The product was dissolved in hydrochloric acid (0.1 M, 10 cm^3), zinc chloride (1 g) and hydrochloric acid (12 M, 10 cm^3) were added and the solution was heated on the steambath for several hours to reduce the volume to 10 cm^3 . After overnight refrigeration the well-formed dark burgundy crystals were filtered, washed with ethanol and vacuum desiccated. Yield 0.47 g (80%). Found: C, 24.89; H, 5.63; N, 11.99. $\text{CoC}_{12}\text{H}_{33}\text{N}_5\text{Br}_5\text{O}_2\text{Zn}$ requires C, 24.81; H, 5.72; N, 12.06%.

I.r. (nujol): 3576, 3450 (m, $\nu_{\text{O-H}}$), 3230(sh), 3210(sh), 3182 (i, $\nu_{\text{N-H}}$), 1615 (m, sp, $\delta_{\text{O-H}}$) cm^{-1} . ^{13}C n.m.r. $\delta(\text{HNO}_3/\text{D}_2\text{O})$ 59.50, 58.84, 56.34, 55.86, 54.28, 53.69, 51.14, 50.72, 49.71, 46.78, 23.23, 22.49.

The sample that was used in the structural determination (q.v.) had an identical ^{13}C n.m.r. spectrum to the sample prepared in this synthesis.

[Co([17A]aneN₅)Cl]ZnCl₄.2H₂O Method D

To a stirred solution of [17A]aneN₅ (0.487 g, 2 mmol) in methanol (10 cm^3) at 50°C was added over 5 minutes a solution of cobalt chloride hexahydrate (0.476 g, 2 mmol). Hydrogen peroxide (30 vol, 2 cm^3) was carefully added, and heating was continued for a further 5 minutes. Zinc chloride (1 g) in hydrochloric acid (4 M, 10 cm^3) was added, followed by a further portion of methanol (20 cm^3). After overnight refrigeration, the product that had precipitated was collected by filtration, washed with ethanol and vacuum desiccated. Yield 0.25 g (22%). The product was recrystallized from zinc chloride/hydrochloric acid as described in the previous synthesis (80% recovery). The i.r. and ^{13}C n.m.r. spectra are identical to those obtained for the analytically pure sample prepared and characterized in the previous synthesis (Method A).

[Co₂([17A]aneN₅)₂O₂](ClO₄)₄·x(H₂O) Method D

To a stirred solution of [17A]aneN₅ (0.46 g, 1.89 mmol) in methanol (10 cm^3), was added cobalt perchlorate hexahydrate (0.69, 1.89 mmol) in methanol (10 cm^3) over 5 minutes. The brown precipitate that rapidly formed was filtered, washed with ethanol, then methanol and vacuum desiccated. Yield 1.05 g (essentially quantitative). The

product was dissolved in water (40 cm³) at room temperature, sodium perchlorate (4 g) was added and after overnight refrigeration the precipitate that had formed was collected by filtration, washed with ethanol and vacuum desiccated. It was not possible to prepare a sample that was satisfactory for analysis. I.r. (nujol): 3559 (m,br, $\nu_{\text{O-H}}$), 3250 (m,br, $\nu_{\text{N-H}}$), 1620 (m,br, $\delta_{\text{O-H}}$), 1072 (vi,br, $\nu_3(\text{ClO}_4^-)$), 622 (i,sp, $\nu_4(\text{ClO}_4^-)$) cm⁻¹.

[Co([17A]aneN₅)H₂O](ClO₄)₃ Method A

A solution of [17A]aneN₅ (0.243 g, 1 mmol) in water (20 cm³) with [Co(NH₃)₅H₂O](ClO₄)₃ (0.461 g, 1 mmol) and activated charcoal (0.48 g) was heated on the steambath for 2½ hours. The red solution was filtered hot to remove the charcoal and any insoluble by-products, and reduced in volume to 5 cm³ by rotary evaporation. Perchloric acid (1.9 M) was used to acidify the mixture (pH <1) and propan-2-ol (20 cm³) was added to precipitate a red product which was filtered, washed with absolute ethanol and vacuum desiccated. Yield 0.52 g (84%).

The product was dissolved in acetone (10 cm³) containing a few drops of dilute perchloric acid and propan-2-ol (25 cm³) was added. The acetone was removed by rotary evaporation and the precipitate was filtered, washed with propan-2-ol and vacuum desiccated.

I.r. (nujol): 3517 (m,br, $\nu_{\text{O-H}}$), 3237 (m,br, $\nu_{\text{N-H}}$), 1625 (m,br, $\delta_{\text{O-H}}$), 1050-1090 (i,vbr, $\nu_3(\text{ClO}_4^-)$), 622 (i,sp, $\nu_4(\text{ClO}_4^-)$) cm⁻¹.

¹³C n.m.r. $\delta(\text{HClO}_4/\text{D}_2\text{O})$ 62.87, 58.75, 57.83, 56.00, 55.13, 54.79, 54.45, 50.92, 50.68, 43.44, 29.88, 27.70 as well as those resonances corresponding to [Co([17A]aneN₅)H₂O]³⁺ (see Section 2.4.1.3), in the approximate ratio 1:2.

2.3.3.4 Cobalt(III) Complexes of [17B]aneN₅

Co([17B]aneN₅)Br]ZnBr₄ Method A

A solution of [17B]aneN₅ (0.23 g, 0.94 mmol) in water (10 cm³) and Co(NH₃)₅Br₃ (0.36 g, 0.94 mmol) was heated on the steambath for 1½ hours. The burgundy solution was filtered hot and zinc bromide (1 g) in hydrobromic acid (9 M, 10 cm³) was added. Heating was continued for 45 minutes until the solution turned dark purple, and precipitation commenced. After overnight refrigeration, the purple precipitate (contaminated with a small amount of white material) was filtered, washed with ethanol and dried at 120°C. The product was heated with hydrobromic acid (1.5 M, 15 cm³) and the material that did not dissolve on heating was removed by filtration, washed with methanol and dried at 120°C. Yield (γ-isomer) 0.18 g (24%). The i.r. and ¹³C n.m.r. spectra were identical to those obtained for the analytically pure sample prepared by Method C.

To the solution containing the remaining product was added further zinc bromide (0.25 g), and heating was continued for several hours until the volume of the solution had decreased to ~10 cm³. The precipitate that formed was filtered hot, washed with methanol and dried at 120°C. Yield (α-isomer) 0.31 g (39%). I.r. (nujol): 3169, 3107 (i,sp,v_{N-H}) cm⁻¹ (see fig.2.5 for details of the fingerprint region of the i.r. spectrum). ¹³C n.m.r. δ(d₆-DMSO) 57.71, 54.84, 54.09, 50.75², 24.90. ¹³C n.m.r. δ(HBr/D₂O) 57.67, 54.85, 54.25, 51.11, 50.70, 24.68. (The ¹³C n.m.r. spectrum in HBr/D₂O also contained appreciable amounts of the hydrolysis products (q.v.)).

Infrared Spectra of α - and δ -[Co([17B]aneN₅)Br]ZnBr₄

fig 2.5

[Co([17B]aneN₅)Br]Br₂/[Co([17B]aneN₅)Br]ZnBr₄ Method B

To a stirred slurry of Na₃Co(CO₃)₃·3H₂O (1 g, 2.8 mmol) in water (20 cm³) was added solid [17B]aneN₅(HBr)₅ (1.3 g, 2 mmol) over 2 minutes. After the initial rapid evolution of carbon dioxide had ceased (10 minutes) the mixture was heated on the steambath for 45 minutes. The rose-red solution was filtered hot to remove the cobalt oxide, and hydrobromic acid (9 M, 50 cm³) was added. Heating was continued for 2 hours, and the volume of the solution was then reduced to ~5 cm³ by rotary evaporation. The solution was heated and ethanol (25 cm³) was added. The crystalline precipitate that formed on cooling was filtered, washed with propan-2-ol and vacuum desiccated. Yield 0.92 g (85%). I.r. (nujol): 3437 (w,br,ν_{O-H}), 3178, 3137, 3085, 3056 (i,ν_{N-H}) cm⁻¹. The ¹³C n.m.r. spectrum contained seventeen peaks corresponding to a mixture of both the isomers prepared in the previous synthesis (method A). The α-isomer with the six peak ¹³C n.m.r. spectrum (the more soluble tetrabromozincate salt) accounted for approximately one-third of the yield. (Each of the peaks in its ¹³C n.m.r. spectrum corresponds to two equivalent carbon atoms).

A sample (0.30 g) was dissolved in hydrobromic acid (2 M, 3 cm³) with heating and zinc bromide (0.30 g) in hydrobromic acid (2 M, 3 cm³) was added. After overnight refrigeration the product was filtered, washed with ethanol and vacuum desiccated. Yield (0.27 g, 90% recovery). Found: C, 18.81; H, 3.90; N, 8.63; Br, 52.07. CoC₁₂H₂₉N₅Br₅Zn requires C, 18.79; H, 3.81; N, 9.13; Br, 52.07%. I.r. (nujol): 3225(sh), 3175, 3131 (i,ν_{N-H}) cm⁻¹.

[Co([17B]aneN₅)Br]Br₂·CH₃OH/[Co([17B]aneN₅)Br]ZnBr₄ Method C

(The following preparation was carried out in the absence of oxygen - see synthesis of [Co([15]aneN₅)Br]ZnBr₄-Method C for details).

To a stirred solution of [17B]aneN₅ (0.212 g, 0.87 mmol) in dry methanol (15 cm³) was added over 10 minutes, a solution of cobalt bromide hexahydrate (0.285 g, 0.87 mmol), resulting in the formation of a pale pinkish flocculent precipitate. A solution of bromine (0.080 g, 0.5 mmol) in dry methanol (15 cm³) was added over 10 minutes. The pink precipitate redissolved, and a dark purple product precipitated in its place as the bromine was added. The precipitate was collected by filtration, washed with propan-2-ol and vacuum desiccated. The filtrate still appeared to contain appreciable amounts of the product, so the solvent was removed by rotary evaporation and the residue, after dissolution in a small volume (~2 cm³) of methanol was precipitated with propan-2-ol and dried. Both products had identical infrared spectra, so they were combined. Yield (γ-isomer) 0.47 g (94%). The product was dissolved in methanol (150 cm³) and the solution was heated until the total volume had decreased to ~25 cm³. After overnight refrigeration, the precipitate was filtered, washed with propan-2-ol and vacuum desiccated. Yield 0.40 g (85% recovery). Found: C, 26.79; H, 5.82; N, 12.23; Br, 41.84. CoC₁₃H₃₃N₅Br₃O requires C, 27.20; H, 5.79; N, 12.20; Br, 41.76%. I.r. (nujol): 3527, 3419 (m,sp, ν_{O-H}), 3106, 3063 (i, ν_{N-H}), 1615 (vw,sp,δ_{O-H}) cm⁻¹. ¹³C n.m.r. δ(HClO₄/D₂O) 59.09, 57.04, 54.16, 53.83², 53.17, 51.44, 50.08, 47.38, 45.67, 23.86, 19.71 (γ-isomer).

A sample was converted to the tetrabromozincate salt as described in the synthesis of [Co([16]aneN₅)Br]ZnBr₄. Found: C, 18.97; H, 4.21; N, 8.98. CoC₁₂H₂₉N₅Br₅Zn requires C, 18.79; H, 3.81; N, 9.13%. I.r. (nujol): 3225(m), 3176, 3133 (i,sp,ν_{N-H}) cm⁻¹. (See fig. 2.5 for details of the fingerprint region of the i.r. spectrum).

In a repeat of this synthesis, the complexation reaction was carried out at 50°C to prevent the precipitation of the cobalt(II) complex initially formed, and heating was continued after addition of the bromine, with no apparent effect on the yield of product or on the nature of the product that was formed.

[Co([17B]aneN₅)Cl]ZnCl₄ Method A(i)

A solution of [17B]aneN₅ (0.258 g, 1.06 mmol) in water (10 cm³) and Co(NH₃)₅Cl₃ (0.265 g, 1.06 mmol) was heated on the steambath for 8½ hours. The solution was filtered and zinc chloride (1 g, excess) in hydrochloric acid (12 M, 10 cm³) was added. The well-crystallized product which formed was filtered, washed with methanol and vacuum desiccated. Yield (γ-isomer) 0.21 g (36%). It was recrystallized from zinc chloride/hydrochloric acid as described in the synthesis of [Co([17A]aneN₅)Cl]ZnCl₄·2H₂O. Found: C, 26.48; H, 5.57; N, 12.71; Cl, 32.69. CoC₁₂H₂₉N₅Cl₅Zn requires C, 26.45; H, 5.36; N, 12.85; Cl, 32.53%. I.r. (nujol): 3196, 3129 (m,sp, ν_{N-H}) cm⁻¹. (See fig. 2.6 for details of the fingerprint region of the i.r. spectrum). ¹³C n.m.r. δ(HNO₃/D₂O) 59.11, 57.42, 53.82, 53.39², 52.70, 50.65, 49.60, 46.45, 45.36, 23.84, 19.65 (γ-isomer).

As there appeared to be a considerable amount of product still in solution the filtrate was taken to near dryness by rotary evaporation, further zinc chloride (1 g) and hydrochloric acid (12 M, 10 cm³) were added, followed by propan-2-ol (50 cm³). The product that precipitated was removed by filtration, washed with propan-2-ol and vacuum desiccated. Yield (α-isomer) 0.26 g (45%). I.r. (nujol): 3517, 3429 (m,br,ν_{O-H}), 3162 (m,ν_{N-H}), 1608 (w,δ_{O-H}) cm⁻¹. (see fig. 2.6 for details of the fingerprint region of the i.r. spectrum). ¹³C n.m.r. δ(HNO₃/D₂O) 57.02, 54.02, 53.51, 49.93, 49.62, 24.29. A small amount (~5%) of an unidentified

Infrared Spectra of α - and δ -[Co([17B]aneN₅)Cl]ZnCl₄

fig 2.6

product was also present with ^{13}C n.m.r. resonances at 61.58, 57.94, 54.65, 44.47 and 29.59 p.p.m. Other resonances of this compound may be present, but only those clearly separated from the resonances of the major product are listed. Resonances corresponding to the less soluble isomer previously isolated were also present in the spectrum, but they account for <5% of the product. Combined yield 0.47 g (81%).

Method A (ii)

The synthesis described above was repeated with the addition of activated charcoal (0.37 g). The yields of the two isomers were 30% and 26% respectively, although it is possible that this simply reflects the presence of a greater proportion of the more soluble isomer, which could not be completely isolated in either synthesis.

[Co(17B)aneN₅)H₂O](ClO₄)₃ Method A (i)

A solution of [17B]aneN₅ (0.258 g, 1.06 mmol) in water (10 cm³) and [Co(NH₃)₅H₂O](ClO₄)₃ (0.487 g, 1.06 mmol) was heated on the steambath for 9 hours. The solution was filtered, acidified with perchloric acid (2 M, 1 cm³), and taken to near dryness by rotary evaporation. Propan-2-ol (20 cm³) was added and the precipitate collected by filtration, washed with propan-2-ol and vacuum desiccated. Yield 0.52 g (80%). The product was taken up in a small volume of methanol (~3 cm³) containing a few drops of dilute perchloric acid, propan-2-ol (50 cm³) was added and the methanol removed by heating. The precipitate was filtered and washed as before. Yield 0.47 g (90% recovery).

Method A (ii)

The synthesis described above was repeated with the addition of activated charcoal (0.28 g), and the product was obtained in 73% yield. However, a subsequent attempt involving activated charcoal produced the product in 94% yield, so no conclusion can be drawn regarding the relative efficiency of the two reactions. I.r. (nujol): 3530 (m,br, $\nu_{\text{O-H}}$), 3230 (m,br, $\nu_{\text{N-H}}$), 1615 (m,br, $\delta_{\text{O-H}}$), 1090 (vi,br, $\nu_3(\text{ClO}_4^-)$), 619 ($\nu_4(\text{ClO}_4^-)$) cm^{-1} . The ^{13}C n.m.r. spectrum of a sample dissolved in nitric acid (2 M) was complex, with both aquo and both nitrate isomers identified in the aquation reactions (q.v.) being present, as well as another product, labelled the δ -aquo isomer (refer section 2.4.1.4).

2.3.3.5 Cobalt(III) Complexes of [18A]aneN₅Attempted Synthesis of [Co([18A]aneN₅)Br]Br₂ Method A (i)

A solution of [18A]aneN₅ (0.260 g, 1 mmol) in water (25 cm^3) and $\text{Co}(\text{NH}_3)_5\text{Br}_3$ (0.384 g, 1 mmol) was heated on the steambath for 18 hours with slow dissolution of the $\text{Co}(\text{NH}_3)_5\text{Br}_3$ and gradual evolution of ammonia. The red solution was filtered, lithium bromide (2 g, excess) was added, and heating was continued until the volume of solution was reduced to $\sim 5 \text{ cm}^3$. Methanol (15 cm^3) was added, and the solution was heated under reflux. A small amount of a pale pink material precipitated and the solution turned brown. All attempts to isolate a solid material from the solution were unsuccessful.

Method A (ii)

An identical reaction mixture to which was added activated charcoal (0.14 g) was heated on the steambath for 4 hours with more rapid dissolution

of the $\text{Co}(\text{NH}_3)_5\text{Br}_3$. Attempts to isolate a product from the reaction mixture by precipitation of the tetrabromozincate salt were unsuccessful.

Attempted Synthesis of $[\text{Co}([\text{18A}] \text{aneN}_5)\text{Br}]\text{Br}_2$ Method B

To a stirred slurry of $\text{Na}_3\text{Co}(\text{CO}_3)_3 \cdot 3\text{H}_2\text{O}$ (0.362 g, 1 mmol) in water (25 cm^3) was added solid $[\text{18A}] \text{aneN}_5(\text{HBr})_5 \cdot 1.5\text{H}_2\text{O}$ (0.70 g, 1 mmol) over 10 minutes. Stirring was continued for a further 10 minutes until the initially rapid effervescence had ceased. A small amount of insoluble material was filtered from the red solution, which was acidified with hydrobromic acid (9 M, 1 cm^3). The solution gradually turned brown. Overnight heating at $\sim 70^\circ\text{C}$ produced a green solution which was taken to dryness by rotary evaporation. Refluxing with methanol (20 cm^3) resulted in a pinkish solution and a salmon precipitate which was shown to be impure amine hydrobromide (by i.r.).

$[\text{Co}([\text{18A}] \text{aneN}_5)\text{Br}]\text{Br}_2$ Method C (i)

(The reaction was carried out in the absence of oxygen. See synthesis of $[\text{Co}([\text{15}] \text{aneN}_5)\text{Br}]\text{ZnBr}_4$ -Method C for details).

To a stirred solution of $[\text{18A}] \text{aneN}_5$ (0.400 g, 1.55 mmol) in absolute ethanol (15 cm^3) at 50°C was added a solution of cobalt bromide hexahydrate (0.508 g, 1.55 mmol) in absolute ethanol (10 cm^3), over 5 minutes, resulting in the formation of a magenta precipitate. The mixture was refluxed and stirred for 1 hour. Bromine (0.125 g, 0.78 mmol) in absolute ethanol (10 cm^3) was added dropwise, the magenta product dissolved, and was replaced by a green precipitate. Heating was continued for a further hour to ensure completeness of reaction. The precipitate was filtered, washed with propan-2-ol, and vacuum desiccated. Yield 0.80 g (92%).

A sample (0.26 g) was dissolved in methanol (200 cm³), giving a green solution. Lithium bromide (1 g) was added, the solution rapidly turned purple, and a green precipitate formed. This was removed by filtration, and the volume of methanol was reduced by rotary evaporation to ~50 cm³. However, only further green material precipitated, even though the solution remained purple throughout. It was not possible to isolate the purple product from any of the solutions prepared. All attempts to do so resulted in the reprecipitation of the original green product. (For further investigation of the green to purple spectral change, refer to section 2.4.2).

Method C (ii)

The same reaction was carried out on a 1 millimolar scale in methanol and without heating. The product was appreciably soluble in methanol, so ether was added to complete the precipitation. The same product appeared to be formed (from the i.r. spectrum) but a lower yield was obtained (0.38 g, 68%). The complex (0.16 g) was dissolved in hydrobromic acid (1 M, 20 cm³) and zinc bromide (2 g) was added. After several days' refrigeration the well-formed green crystals were filtered, washed with ethanol and vacuum desiccated. The product obtained was not the expected tetrabromozincate salt but a pure sample of $[\text{Co}([18\text{A})\text{aneN}_5)\text{Br}]\text{Br}_2$. Found: C, 28.33; H, 5.77; N, 12.54; Br, 43.69. $\text{CoC}_{13}\text{H}_{31}\text{N}_5\text{Br}_3$ requires C, 28.08; H, 5.62; N, 12.60; Br, 43.11%. I.r. (nujol): 3150, 3108, 3067, 3018 (i,sp, $\nu_{\text{N-H}}$) cm⁻¹ (see fig. 2.7. for i.r. spectral details).

Attempts to obtain the ¹³C n.m.r. spectrum of a sample of the green product in solution were unsuccessful. Solutions of the green material turned purple within the time required to acquire a meaningful spectrum. (The green material was not very soluble in either aqueous solution or in DMSO).

Infrared Spectrum of $[\text{Co}([\text{18A}] \text{aneN}_5)\text{Br}]\text{Br}_2$

fig. 2.7

^{13}C n.m.r. of purple solution: $\delta(\text{HNO}_3/\text{D}_2\text{O})$ 58.33, 55.37, 54.50, 52.60, 51.13, 22.35 p.p.m. (there were also peaks corresponding to uncomplexed, protonated amine present in the spectrum). (See fig. 2.8).

The solid state ^{13}C n.m.r. spectrum was obtained using a Varian XL-200 spectrometer. A 0.20 g portion of the product was pressed in a Kel-F rotor, and spectra were obtained at two different rotation speeds (2.4 KHz and 2.6 KHz). Each 0.5 ms contact time was followed by 30 ms of data acquisition and 0.2 s delay. The spectra were acquired over 0.8 hour and 1.5 hours respectively. They showed two unresolved bands at 25.5 and 55.8 (55.5) p.p.m. (fig. 2.8) corresponding to the two different types of carbon atom present in the sample; those adjacent to a nitrogen atom in either a five- or six-membered chelate ring ($\text{N}-\underline{\text{C}}-\text{C}$) and the β -carbon atom in the middle of each six-membered chelate ring ($\text{C}-\underline{\text{C}}-\text{C}$).

2.3.3.6 Cobalt(III) Complexes of [18B]aneN₅

Attempted Synthesis of $[\text{Co}([18\text{B}] \text{aneN}_5)\text{Br}]\text{Br}_2$ Method A

A solution of [18B]aneN₅ (0.263 g, 1.02 mmol) in water (30 cm³) with $\text{Co}(\text{NH}_3)_5\text{Br}_3$ (0.392 g, 1.02 mmol) and activated charcoal (0.17 g) was heated on the steambath for 4 hours. The charcoal was removed by filtration leaving a red-purple solution which was acidified to pH 3 with a small amount of hydrobromic acid (2 M). Lithium bromide (0.17 g, 20 mmol) was added and the solution was heated on the steambath for a further hour and then taken almost to dryness by rotary evaporation. Propan-2-ol (25 cm³) was added and a brown oil was produced. Attempts to isolate a pure product from this oil were unsuccessful.

Solid State and Solution ^{13}C n.m.r. Spectra of $[\text{Co}([18\text{A}] \text{aneN}_5)\text{Br}]\text{Br}_2$

fig 2.8

Attempted Synthesis of $[\text{Co}([\text{18B}] \text{aneN}_5)\text{Br}]\text{Br}_2$ Method B (i)

To a stirred slurry of $\text{Na}_3\text{Co}(\text{CO}_3)_3 \cdot 3\text{H}_2\text{O}$ (0.18 g, 0.5 mmol) in water (5 cm^3) was added $[\text{18B}] \text{aneN}_5(\text{HBr})_5 \cdot 0.5\text{H}_2\text{O}$ (0.33 g, 0.49 mmol) over 5 minutes. After the initially rapid effervescence had ceased, the solution was heated at 70°C for 15 minutes, hydrobromic acid (2 M, 0.25 cm^3) was added and heating was continued for a further $\frac{1}{2}$ hour. The solution was taken almost to dryness by rotary evaporation and propan-2-ol (30 cm^3) was added. A small amount of purple material precipitated, and this was filtered from the blue solution. Attempts to recrystallize the crude product from methanol/propan-2-ol simply led to the formation of further blue solution which displayed the characteristics expected of a solution containing cobalt(II). (It rapidly turned red on addition of a few drops of water, and this colour change could be reversed on addition of more propan-2-ol).

Method B (ii)

A repeat synthesis on a 1 millimolar scale was also unsuccessful. A pale greenish oily product was obtained, from which crude ligand hydrobromide was separated (identified by i.r.). Again the reaction mixture exhibited the properties of a solution of cobalt in the 2+ oxidation state.

 $[\text{Co}([\text{18B}] \text{aneN}_5)\text{Br}]\text{Br}_2 \cdot \text{H}_2\text{O} \cdot 0.5\text{CH}_3\text{OH}$ Method C

(This reaction was carried out in the absence of oxygen as described in the synthesis of $[\text{Co}([\text{15}] \text{aneN}_5)\text{Br}]\text{ZnBr}_4$ by Method C).

To a stirred solution of $[\text{18B}] \text{aneN}_5$ (0.506 g, 1.97 mmol) in absolute ethanol (15 cm^3) at 50°C was added a solution of cobalt bromide hexahydrate (0.650 g, 1.99 mmol) in methanol (15 cm^3) over 10 minutes. Heating was continued for $\frac{1}{2}$ hour and then bromine (0.175 g, 1.09 mmol) in methanol (10 cm^3)

was added dropwise. The reaction mixture was heated for a further $\frac{1}{2}$ hour and then 20 cm³ of the solvent was removed by distillation. The black-purple product was collected by filtration, washed with ethanol and vacuum desiccated. Yield 0.98 g (84%). A small sample was recrystallized from methanol/aqueous lithium bromide for analysis purposes. Found: C, 27.56; H, 5.80; N, 11.91; Br, 40.51. $\text{CoC}_{13.5}\text{H}_{35}\text{N}_5\text{O}_{1.5}\text{Br}_3$ requires C, 27.48; H, 5.97; N, 11.88; Br, 40.63%. I.r. (nujol): 3416 (m, $\nu_{\text{O-H}}$), 3083 (m, $\nu_{\text{N-H}}$), 1610 (w, $\delta_{\text{O-H}}$) cm⁻¹. It was not possible to obtain a ¹³C n.m.r. spectrum, as hydrolysis was too rapid. The ¹³C n.m.r. spectrum of $[\text{Co}([\text{18B}] \text{aneN}_5)\text{Br}]\text{Br}_2$ dissolved in perchloric acid was the same as that obtained for a sample that had been treated with excess silver perchlorate (refer to section 2.4.1.6).

In an attempt to prepare the tetrabromozincate salt, a further sample was dissolved in 1:1 hydrobromic acid (1 M)/methanol (5 cm³), filtered, and zinc bromide (1 g) in absolute ethanol was added. Upon overnight refrigeration a purple product that was contaminated with substantial amounts of a white crystalline material had precipitated. The white product was identified as crude ligand hydrobromide, indicating that an appreciable amount of decomposition had occurred.

Attempted Synthesis of $[\text{Co}([\text{18B}] \text{aneN}_5)\text{Cl}]\text{Cl}_2$ Method D

$[\text{Co}_2([\text{18B}] \text{aneN}_5)_2\text{O}_2](\text{ClO}_4)_4 \cdot x\text{H}_2\text{O}$

To a stirred solution of $[\text{18B}] \text{aneN}_5$ (0.267 g, 1.03 mmol) in absolute ethanol (15 cm³) was added dropwise cobalt perchlorate hexahydrate (0.380 g, 1.04 mmol) in absolute ethanol (30 cm³). A brown precipitate formed with the addition of each drop. The product was filtered, washed with propan-2-ol and dried at 120°C. Yield 0.46 g (75-80%).

I.r. (nujol): 3565 (m,br, $\nu_{\text{O-H}}$), 3249 (i, $\nu_{\text{N-H}}$), 1612 (m, $\delta_{\text{O-H}}$), 1090 (vi, $\nu_3(\text{ClO}_4^-)$), 620 (i,sp, $\nu_4(\text{ClO}_4^-)$) cm^{-1} . The ^{13}C n.m.r. spectrum (run in D_2O) was complex, with peaks corresponding to the uncomplexed amine predominating. In the regions where the resonances of the complex would be expected, a number of peaks were present, and they were superimposed on broad bands (~ 10 p.p.m. band width) which are indicative of paramagnetic impurities. As there was no evidence for uncomplexed ligand in the original product (the free ligand is soluble in ethanol, and the presence of protonated ligand would be apparent from the i.r. spectrum). the product presumably decomposes in water on the time-scale of the acquisition of the ^{13}C n.m.r. spectrum.

The $[\text{Co}_2([\text{18B}] \text{aneN}_5)_2\text{O}_2](\text{ClO}_4)_4 \cdot x(\text{H}_2\text{O})$ (0.36 g) was dissolved in hydrochloric acid (3 M, 3 cm^3) and zinc chloride (0.6 g) was added. The solution was heated on the steambath for 1 hour, and methanol (10 cm^3) was added. The gummy brown product that formed was separated by decantation. Attempts to induce crystallization were unsuccessful. Solutions of the product behaved in a manner which suggested that predominantly cobalt(II) salts were present.

Because of the possibility of decomposition of the peroxo-complex by acid, a sample was dissolved in water and treated with ammonium chloride rather than hydrochloric acid, but this method also proved unsuccessful.²⁹⁰

Attempted Synthesis of $[\text{Co}([\text{18B}] \text{aneN}_5)\text{H}_2\text{O}](\text{ClO}_4)_3$ Method A.

A solution of $[\text{18B}] \text{aneN}_5$ (0.263 g, 1.02 mmol) in water (10 cm^3) with $[\text{Co}(\text{NH}_3)_5\text{H}_2\text{O}](\text{ClO}_4)_3$ (0.470 g, 1.02 mmol) and charcoal (0.15 g) was heated on the steambath for 3 hours. The charcoal was removed by filtration and the red-purple solution was acidified with perchloric acid ($\text{pH} \leq 1$). The volume of solution was reduced to 5 cm^3 by rotary evaporation and

ethanol (15 cm³) was added. A white crystalline material was removed by filtration and propan-2-ol (20 cm³) was added. A brown oil separated but all attempts to induce crystallization failed.

2.3.3.7 Cobalt(II) and Cobalt(III) Complexes of [19]aneN₅

Attempted Synthesis of [Co([19]aneN₅)Br](ClO₄)₂ Method B

To a stirred slurry of Na₃Co(CO₃)₃·3H₂O (0.73 g, 2 mmol) in water (10 cm³) was added a solution of [19]aneN₅·(HBr)₅·1.5H₂O (1 g, 1.4 mmol) in water (10 cm³). Although carbon dioxide was evolved, the solution remained green. Refluxing the reaction mixture for 1 hour resulted in the formation of a dark red solution, which was filtered hot to remove cobalt oxide. Perchloric acid (9 M, 5 cm³) was carefully added, causing the solution to rapidly turn yellow. Workup (rotary evaporation and addition of propan-2-ol) led to the isolation of a white product (which was identified as the protonated amine by i.r.).

Attempted Synthesis of [Co([19]aneN₅)Br](ClO₄)₂ Method D

To a stirred solution of [19]aneN₅·(HBr)₅·1.5H₂O (0.7 g, 1 mmol) and cobalt perchlorate hexahydrate (0.365 g, 1 mmol) in water (10 cm³) was added an aqueous solution of sodium hydroxide (1.21 M, 4.1 cm³, 5 equivalents) dropwise with heating. A flesh coloured precipitate began to form before all the base had been added. The solution was heated at 60°C and aerated for 2 hours. The cobalt oxide that formed was removed by filtration and the solution was taken to near dryness by rotary evaporation. The residue was digested with acetone (50 cm³) and the resulting gummy brown powder was removed from the green solution by filtration, washed with acetone and vacuum desiccated. Yield 0.75 g.

The solid was taken up in perchloric acid (1.5 M, 6 cm³) and hydrobromic acid (9 M, 6 drops). The solution remained brown on heating for 1 hour at 70°C. Addition of propan-2-ol (25 cm³) and refrigeration produced a brown oil which was separated by decantation. Attempts to separate any complex or induce crystallization were unsuccessful.

[Co([19]aneN₅)](ClO₄)₂ (I)/[Co₂([19]aneN₅)₂O₂](ClO₄)₄ (II) Method D

(The following reaction was carried out in a nitrogen atmosphere as described in the synthesis of [Co([15]aneN₅)Br]ZnBr₄ by Method C).

To a stirred solution of [19]aneN₅ (0.27 g, 1 mmol) in methanol (20 cm³) was added a solution of cobalt perchlorate hexahydrate (0.37 g, 1 mmol) in methanol (10 cm³) over 1 hour, producing a dull purple solid. The solid was rapidly filtered, washed with propan-2-ol and vacuum desiccated. Yield (I): 0.24 g (44%). Found: C, 31.91; H, 6.36; N, 13.23; Cl, 13.64. CoC₁₄H₃₃N₅Cl₂O₈ requires C, 31.77; H, 6.28; N, 13.23; Cl, 13.40.

I.r. (nujol): 3259 (i,sp,v_{N-H}), 1092 (vi,v₃(ClO₄⁻), 620 (i,sp,v₄(ClO₄⁻) cm⁻¹. $\mu_{\text{eff}} = 4.6$ B.M. $\Lambda = 152$ (acetone) S cm² mole⁻¹.

The filtrate (which rapidly turned brown on exposure to air) was left standing overnight and the light brown product that formed was filtered, washed with propan-2-ol and vacuum desiccated. Yield (II): 0.21 g (39%) (accounting for 83% of starting material. I.r. (nujol): 3569 (m,br,v_{O-H}), 3256 (m,v_{N-H}), 1640 (m, $\delta_{\text{O-H}}$), 1102 (vi,sp,v₃(ClO₄⁻), 624 (i,sp,v₄(ClO₄⁻) cm⁻¹. The ¹³C n.m.r. spectrum (run in dilute perchloric acid) contained predominantly those peaks that correspond to the uncomplexed ligand, although a complex pattern of peaks with low intensity appeared in the region where the peaks for the metal complex would be expected to occur.

Attempted Synthesis of [Co([19]aneN₅)Br]Br₂ Method C[†]

To a stirred solution of [19]aneN₅ (0.272 g, 1 mmol) in methanol (10 cm³) was added over 5 minutes a solution of cobalt bromide hexahydrate (0.327 g, 1 mmol) in methanol (15 cm³), giving a purple solution. Bromine (0.080 g, 0.5 mmol) in methanol (10 cm³) was added dropwise, and the solution turned yellow brown. No product precipitated, so the volume of the solution was reduced to ~10 cm³ and propan-2-ol (20 cm³) was added. The hygroscopic green precipitate (which turned brown as it absorbed moisture) was collected, washed with propan-2-ol, acetone and placed (still moistened with acetone) in a vacuum desiccator. Once dry, it appeared to be stable in air. Yield 0.29 g.

I.r. (nujol): 3380 (m,br, $\nu_{\text{O-H}}$), 3200 (m,br, $\nu_{\text{N-H}}$) cm⁻¹. The i.r. spectrum was of poor quality, with broad peaks. The ¹³C n.m.r. was also inconclusive, with peaks corresponding to the uncomplexed ligand and broad bands suggesting substantial paramagnetic impurities, and this was confirmed by magnetic susceptibility measurements. The filtrate was reduced in volume by rotary evaporation, more propan-2-ol was added, and a brown product (with an i.r. spectrum similar to that of the green product) was obtained. Yield 0.15 g.

When either product was dissolved in nitric acid (2 M) or hydrochloric acid (0.1 M) immediate decomposition occurred, and addition of acetone resulted in the precipitation of the ligand salts (identified by i.r.).

[†]This reaction was carried out in the absence of oxygen as described in the synthesis of [Co([15]aneN₅)Br]ZnBr₄ by Method C.

2.3.3.8 Cobalt Complexes of [20]aneN₅

Attempted Synthesis of Cobalt(III) Complexes of [20]aneN₅

The synthetic methods used with the other pentaaza-macrocycles were all tried with [20]aneN₅ but no evidence for the formation of cobalt(III) complexes of [20]aneN₅ was found. Invariably the uncomplexed ligand was recovered, or intractable brown gums were obtained. Synthetic routes involving reaction of Na₃Co(CO₃)₃·3H₂O with the ligand hydrobromide, and Co(NH₃)₅Br₃, [Co(NH₃)₅H₂O](ClO₄)₃, Co(ClO₄)₂·6H₂O, CoCl₂·6H₂O with the free ligand as well as attempted oxidation of the cobalt(II) complex with bromine were all uniformly unsuccessful. The stability of the cobalt(II) state in complexes with [20]aneN₅ (q.v.) gives some indication that this is perhaps to be expected.

[Co([20]aneN₅)](ClO₄)₂

To a stirred solution of [20]aneN₅ (0.31 g, 1.08 mmol) in absolute ethanol (10 cm³) at 40°C was added a solution of cobalt perchlorate hexahydrate (0.40 g, 1.09 mmol) in absolute ethanol (5 cm³) over 2 minutes. Stirring and heating were continued for 10 minutes, the mixture was cooled, and the claret precipitate was collected by filtration, washed with propan-2-ol and dried at 120°C for 1 hour. Yield 0.58 g (98%). The product can be recrystallized by dissolving it in acetone and adding propan-2-ol until the solution becomes turbid. The well-formed crystals that precipitate over several days collapse to a microcrystalline state on air drying (presumably acetone of crystallization is lost). Found: C, 33.18; H, 6.63; N, 12.89. CoC₁₅H₃₅N₅Cl₂O₈ requires C, 33.16; H, 6.49; N, 12.89%. I.r. (nujol): 3586, 3483 (m; these are not ν_{O-H} bands), 3476(sh), 3466 (i,sp, ν_{N-H}), 1094 (vi,sp, ν₃(ClO₄⁻), 626 (i,sp, ν₄(ClO₄⁻) cm⁻¹. μ_{eff} = 5.06 B.M. (high-spin d⁷). λ = 179 (methanol), 163 (acetone), 129 (nitromethane) s cm² mole⁻¹.

Attempts to recrystallize the product from water simply resulted in decomposition of the complex to cobalt hydroxide.

2.3.3.9 Co(III) Complexes of tetren(2,2,2,2-pent)

α -[Co(tetren)Br]Br₂ Method C (i)[†]

(The reaction was carried out in an oxygen-free atmosphere - see synthesis of [Co([15]aneN₅)Br]ZnBr₄-Method C for details).

To a stirred solution of pure tetren (0.379 g, 2 mmol) in absolute ethanol (15 cm³) was added over 5 minutes a solution of cobalt bromide hexahydrate (0.654 g, 2 mmol) in absolute ethanol (15 cm³). Bromine (0.160 g, 1 mmol) in absolute ethanol (10 cm³) was added dropwise, and stirring was continued for a further $\frac{1}{2}$ hour. The purple product was filtered, washed with propan-2-ol and vacuum desiccated. Yield 0.74 g (76%). This was identified as the α -isomer by comparison with samples prepared using the literature method.^{62,268}

¹³C n.m.r. δ (HBr/D₂O) 57.65, 56.90, 55.70, 52.89, 52.05, 51.90, 48.84, 43.71. (The filtrate rapidly turned brown on exposure to air, indicating that not all of the cobalt(II) complex had been oxidised, despite the addition of a stoichiometric amount of bromine).

[†] For α , β and $\alpha\alpha$ nomenclature, see ref.269.

α -[Co(tetren)Br]Br₂ Method C (ii)

The above procedure was repeated using dry DMF in place of absolute ethanol as the solvent. The yield was slightly lower than above, but the same isomer was obtained (identified by i.r. and ¹³C n.m.r.).

 β -[Co(tetren)Br]ZnBr₄

This was prepared from β -[Co(tetren)NO₂]ZnBr₄ as described in the literature^{62,268} and the i.r. and visible spectral parameters were consistent with those reported. ¹³C n.m.r. δ (HBr/D₂O) 59.85, 58.29, 58.15, 55.70, 52.69, 52.21, 47.65, 43.98. The ¹³C n.m.r. spectrum showed that the solution also contained a considerable amount of the α -isomer.

 α -[Co(tetren)]ZnCl₄

This was prepared in good yields from purified ligand using literature methods (Methods A and E, ref. 62). The i.r. and spectral data agreed with the values reported in the literature.^{62,268} ¹³C n.m.r. δ (HCl/D₂O) 58.21, 55.96, 55.60, 53.38, 51.17, 50.58, 48.93, 42.63.

 β -[Co(tetren)Cl]ZnCl₄

This was prepared by the literature method from the α -complex via β -[Co(tetren)NO₂]ZnCl₄.^{62,268} The i.r. and visible spectral data were the same as those reported.^{62,268} ¹³C n.m.r. δ (HCl/D₂O) β -[Co(tetren)Cl]²⁺ 59.62, 58.06, 57.63, 56.07, 52.55, 52.19, 47.41, 42.69. The product was contaminated with an appreciable amount of the α -isomer. Likewise, the intermediate nitrito complex, which was reported as being pure β -[Co(tetren)NO₂]ZnCl₄ had a ¹³C n.m.r. spectrum that was consistent with

the presence of two products. Their respective resonances could readily be differentiated on the basis of the difference in their concentrations (and hence peak heights). ^{13}C n.m.r. $\delta(\text{D}_2\text{O})$ $[\text{Co}(\text{tetren})\text{NO}_2]^{2+}$

Product A: 59.38, 57.19, 57.02, 55.26, 52.81, 52.68, 47.62, 41.49;

Product B: 57.45, 55.58, 54.29, 53.84, 50.99, 50.85, 48.87, 42.55.

$\alpha\alpha$ - $[\text{Co}(\text{tetren})\text{Cl}]\text{ZnCl}_4$

In one synthesis using $\text{Co}(\text{NH}_3)_3(\text{NO}_2)_3$ (Method D, ref. 62) the ^{13}C n.m.r. spectrum of the isolated product contained twelve peaks, eight of which could be identified as belonging to α - $[\text{Co}(\text{tetren})\text{Cl}]^{2+}$, and the remaining four peaks were assigned to the symmetrical isomer, $\alpha\alpha$ - $[\text{Co}(\text{tetren})\text{Cl}]^{2+}$. On the basis of the relative heights of the two sets of peaks, it appeared that the two isomers were present in approximately equal concentrations. ^{13}C n.m.r. $\delta(\text{HNO}_3/\text{D}_2\text{O})$ $\alpha\alpha$ - $[\text{Co}(\text{tetren})\text{Cl}]^{2+}$ 58.66, 57.45, 56.11, 43.97.

2.3.3.10 Attempted Synthesis of Cobalt(III) Complexes of tetrpn(3,3,3,3-pent)

$[\text{Co}(\text{tetrpn})\text{Br}]\text{Br}_2$ Method A

A solution of tetrpn (0.553 g, 2.5 mmol) in water (10 cm³) with $\text{Co}(\text{NH}_3)_5\text{Br}_3$ (0.864 g, 2.25 mmol) and activated charcoal (0.2 g) was warmed to 60°C. Rapid evolution of ammonia occurred. After 4 hours, the plum coloured solution (pH ~8.5) was filtered and divided into five portions. They were treated as follows: (i) Hydrobromic acid (9 M, 5 cm³) was added, and the brown solution turned green on heating. (This green/brown equilibrium appears to be temperature dependent). No pure product could be isolated. To the other solutions zinc bromide (ii), ammonium hexafluorophosphate (iii), sodium perchlorate (iv) and dilute

perchloric acid (v) were added. Each solution turned brown but no crystalline product was obtained from any solution. Precipitation with propan-2-ol after removal of the aqueous solvent produced only intractable brown material in each case.

[Co(tetrpn)Br]Br₂ Method C

(The following reaction was carried out in the absence of oxygen as described in the synthesis of [Co([15]aneN₅)Br]ZnBr₄-Method C).

To a stirred solution of tetrpn (0.491 g, 2 mmol) in methanol (25 cm³) was added a solution of cobalt bromide hexahydrate (0.651 g, 2 mmol) in methanol (15 cm³) over 10 minutes. Bromine (0.16 g, 1 mmol) in absolute ethanol (10 cm³) was added dropwise to the plum coloured solution. The solution turned blue, but no precipitate formed. The volume of the solution was reduced by rotary evaporation. The green-grey precipitate that formed on exposure to air was collected by filtration. When this hygroscopic material was dissolved in dilute hydrobromic acid, immediate decomposition occurred and only uncomplexed amine hydrobromide could be recovered from the solution.

[Co(tetrpn)Cl]X

The attempted synthesis of [Co(tetrpn)Cl]ZnCl₄ using tetrpn and Na₃Co(CO₃)₃·3H₂O produced only the hydrochloride salt of the uncomplexed amine. A similar result was achieved in the attempted synthesis of [Co(tetrpn)Cl]CoCl₄ by hydrogen peroxide oxidation of a mixture of cobalt chloride hexahydrate and the free ligand in aqueous solution (Method D).

[Co₂(tetrpn)₂O₂](ClO₄)₄ Method D

To a stirred solution of tetrpn (0.245 g, 1 mmol) in ethanol (15 cm³) was added dropwise a solution of cobalt perchlorate hexahydrate (0.366 g, 1 mmol) in ethanol (10 cm³). The brown flocculent precipitate which rapidly formed was collected by filtration, washed with propan-2-ol and dried at 120°C. Yield 0.45 g. Attempts to convert this into the chloro complex by reaction with dilute hydrochloric acid resulted in decomposition to the hydrochloride salt of the free ligand (identified by i.r.).

2.3.4 Synthesis of Rhodium(III) Complexes

In order to investigate the effect of increased cationic radius on the stability and product composition of metal complexes, the reactions of [16]aneN₅ and [20]aneN₅ with rhodium(III) were investigated.

2.3.4.1 [Rh([16]aneN₅)Cl]Cl₂

To rhodium chloride (0.152 g, 0.58 mmol) in methanol (3 cm³) was added a solution of [16]aneN₅ (0.19 g, 0.77 mmol) in methanol (2 cm³), resulting in an immediate lightening of the solution. The mixture was heated under reflux for 20 minutes, filtered hot and then taken to near dryness by rotary evaporation. Acetone (5 cm³) and chloroform (5 cm³) were added to precipitate the product and to take up the excess free amine. The precipitate was filtered, washed with acetone and dried at 120°C. Yield 0.24 g (96%). The ¹³C n.m.r. spectrum of the product in hydrochloric acid (0.1 M) showed the presence of more than one isomer, although it was not possible to separate the resonances into groups on the basis of their relative intensities. ¹³C n.m.r. δ (HCl/D₂O) 60.27,

59.46, 58.33, 56.12, 55.64, 55.19, 54.42, 53.58, 53.12, 52.80, 52.40, 52.14, 51.54, 50.41, 48.37, 47.90, 46.46, 45.90, 29.47, 26.48 (fig. 2.9).

2.3.4.2 [Rh([20]aneN₅)Cl](ClO₄)₂

A solution of rhodium chloride (0.141 g, 0.53 mmol) and [20]aneN₅ (0.143 g, 0.5 mmol) in methanol (40 cm³) was heated under reflux for 1 hour. The mixture was filtered hot, concentrated perchloric acid (0.9 g) was added and the product which precipitated on addition of propan-2-ol (20 cm³) was filtered, washed with propan-2-ol and vacuum desiccated. Yield 0.14 g (45%). The ¹³C n.m.r. spectrum of the product in dilute perchloric acid was complex (fig. 2.9) indicating that more than one isomer was present. ¹³C n.m.r. δ (HClO₄/D₂O) 54.32, 53.64, 52.79, 52.19, 51.64, 51.10, 50.51, 50.05, 49.54, 49.01, 47.66, 47.12, 46.24, 45.68, 44.92, 44.52, 43.44, 41.91, 41.70, 26.87, 25.74, 25.14, 24.56, 23.94, 23.08, 22.98, 22.82, 22.39, 22.09, 21.31, 19.72.

^{13}C n.m.r. Spectra of Complexes of $[\text{16}] \text{aneN}_5$ and $[\text{20}] \text{aneN}_5$
with Rhodium (III)

fig. 2.9

2.4 Chemical, Spectral and Structural Properties of Cobalt Complexes

2.4.1 Ligand Substitution Reactions of Cobalt(III) Complexes

The stereochemistry and product composition of the silver(I) and mercury(II) ion induced aquation reactions, base hydrolysis, spontaneous aquation and various anation reactions were investigated by ^{13}C n.m.r. spectroscopy. Except where specified, products of the reaction were not isolated or purified because unless quantitative recovery could be achieved, the product composition would be determined by the differences in relative solubility of the various isomers rather than being a true reflection of the steric course of the reaction. Product composition was determined on the basis of the relative intensities of the resonances of the respective products, and is therefore clearly only approximate.

2.4.1.1 Substitution Reactions of Cobalt(III) Complexes of [15]aneN₅

Silver(I) Induced Aquation

A sample of γ -[Co([15]aneN₅)Br]Br₂ dissolved in nitric acid (2 M) was heated with three equivalents of silver nitrate. The precipitated silver bromide was removed by filtration, the solution was taken to near dryness, and the ^{13}C n.m.r. spectrum of the reaction mixture was obtained. The products were a symmetrical isomer (α) and a non-symmetrical isomer (γ) of [Co([15]aneN₅)NO₃]²⁺ in the ratio 3:2. ^{13}C n.m.r. δ (HNO₃/D₂O) α -isomer 56.28, 56.13, 54.47, 51.83, 50.13; γ -isomer 60.21, 57.72, 57.27², 56.89, 55.35, 55.09, 54.21, 52.11, 48.35. Small amounts of the symmetrical α -[Co([15]aneN₅)H₂O]³⁺ (~2%) and another product, tentatively identified as another symmetrical isomer β -[Co([15]aneN₅)H₂O]³⁺ (~2%) were also present.

A sample of γ -[Co([15]aneN₅)Br]Br₂ in methanol was heated with three equivalents of silver nitrate, and after the silver bromide was removed by filtration, the solution was taken to near dryness by rotary evaporation and the product was quantitatively precipitated by propan-2-ol. The ¹³C n.m.r. spectrum again showed the presence of both α -[Co([15]aneN₅)NO₃]²⁺ (~40%), γ -[Co([15]aneN₅)NO₃]²⁺ (~40%) as well as α -[Co([15]aneN₅)H₂O]³⁺ (~20%). ¹³C n.m.r. δ (HNO₃/D₂O) α -aquo isomer 57.18, 56.55, 54.69, 52.42, 50.44; and a trace of the β -aquo isomer (<2%).

The product was twice recrystallized from nitric acid.

Found: C, 25.98; H, 5.51; N, 24.33. CoC₁₀H₂₅N₈O₉ requires C, 26.09; H, 5.47; N, 24.35 (i.e. pure [Co([15]aneN₅)NO₃](NO₃)₂).

Treatment of a further sample of γ -[Co([15]aneN₅)Br]Br₂ dissolved in perchloric acid (2 M) with three equivalents of silver perchlorate gave a mixture of α -[Co([15]aneN₅)H₂O]³⁺ (40%), γ -[Co([15]aneN₅)H₂O]³⁺ (40%) and the product tentatively identified as β -[Co([15]aneN₅)H₂O]³⁺ (20%). The product was put on a column of SP-Sephadex (ϕ 1.2×20 cm) and eluted with aqueous sodium perchlorate (0.4 M). The separation was not clean, but the broad band was collected in separate fractions, and one fraction contained an approximately equal amount of α -[Co([15]aneN₅)H₂O]³⁺ and the isomer identified as β -[Co([15]aneN₅)H₂O]³⁺. ¹³C n.m.r. δ (HClO₄/D₂O) β -isomer: 58.36, 57.35, 56.82, 55.10, 49.12; γ -isomer 60.09, 58.12, 57.18, 56.34², 55.47, 55.12, 54.70, 52.38, 48.90.

Mercury(II) Induced Aquation

A sample of γ -[Co([15]aneN₅)Br]Br₂ dissolved in nitric acid (2 M) was heated with three equivalents of mercury(II) nitrate. The solution was filtered, and taken to near dryness by rotary evaporation. The ¹³C n.m.r. spectrum of the mixture was quite complex. The α - and γ -isomers

of $[\text{Co}([\text{15}] \text{aneN}_5)\text{NO}_3]^{2+}$ were the predominant products, accounting for 45% and 35% of the product composition respectively. However the α -, β - and γ -isomers of $[\text{Co}([\text{15}] \text{aneN}_5)\text{H}_2\text{O}]^{3+}$ were also present.

Similar treatment of $[\text{Co}([\text{15}] \text{aneN}_5)\text{Cl}]\text{ZnCl}_4$ (a mixture of both the α -isomer (15%) and the γ -isomer (85%)) with five equivalents of mercury(II) nitrate resulted in a ^{13}C n.m.r. spectrum that showed the presence of the α -nitrate (25%), γ -nitrate (30%), α -aquo (25%), γ -aquo (15%) and β -aquo (~5%) cobalt(III) complexes of $[\text{15}] \text{aneN}_5$.

Base Hydrolysis Reactions

Samples of γ - $[\text{Co}([\text{15}] \text{aneN}_5)\text{Br}]\text{Br}_2$ dissolved in either sodium hydroxide (0.01 M) or ammonia (2 M) gave similar ^{13}C n.m.r. spectra with nine broadened peaks of different intensities (refer fig. 2.3).

^{13}C n.m.r. $\delta(\text{OH}^-/\text{D}_2\text{O})$ (relative intensities in parentheses) 59.05(28), 56.64(66), 55.60(68), 54.76(100), 54.26(73), 53.07(23), 52.88(25), 51.57(78), 49.63(48), 48.12(25). In more concentrated base, the resonances are even further broadened (including the dioxane resonance) and the spectrum is considerably simplified. ^{13}C n.m.r. $\delta(\text{OH}^-/\text{D}_2\text{O})$ relative intensities in parentheses) 56.6(36), 55.2(100), 53.0(44), 49.9(31) (refer fig. 2.3).

Upon acidification of the base hydrolysis products obtained from γ - $[\text{Co}([\text{15}] \text{aneN}_5)\text{Br}]\text{Br}_2$ with nitric acid, a complex ^{13}C n.m.r. spectrum was obtained, in which α - and γ - $[\text{Co}([\text{15}] \text{aneN}_5)\text{H}_2\text{O}]^{3+}$ and γ - $[\text{Co}([\text{15}] \text{aneN}_5)\text{NO}_3]^{2+}$ account for ~90% of the product. A small amount of γ - $[\text{Co}([\text{15}] \text{aneN}_5)\text{Br}]^{2+}$ was also present. When a sample hydrolysed with ammonia was acidified with hydrobromic acid and heated, the principal product was

* γ - $[\text{Co}([\text{15}] \text{aneN}_5)\text{Br}]^{2+}$ (~80%) although a small amount of γ - $[\text{Co}([\text{15}] \text{aneN}_5)\text{H}_2\text{O}]^{3+}$ (~10%) was also present, as well as a number of

other small resonances which could not be identified due to the considerable overlapping with the larger peaks (these were estimated to account for ~10% of the total).

Other Substitution Reactions

A sample of γ -[Co([15]aneN₅)Br]Br₂ was heated in ammonia (2 M) on the steambath for 1 hour, and then acidified with a small amount of dilute hydrochloric acid. Sodium nitrite was added, and on heating the solution changed from red to yellow as anation proceeded. The ¹³C n.m.r. spectrum of the reaction mixture showed that only one product was present. ¹³C n.m.r. (HCl/D₂O) 59.73, 58.01, 57.15, 56.33², 55.29, 54.37, 53.47, 52.17, 50.54. Heating the reaction mixture with concentrated trifluoromethane sulphonic acid for one hour resulted in the formation of α -[Co([15]aneN₅)Cl]²⁺ (25%) and γ -[Co([15]aneN₅)Cl]²⁺ (75%).

A sample of γ -[Co([15]aneN₅)Br]Br₂ twice heated to dryness with concentrated hydrochloric acid on the steambath gave a mixture of α -[Co([15]aneN₅)Cl]²⁺ (20%) and γ -[Co([15]aneN₅)Cl]²⁺ (80%), as well as a small amount of protonated ligand (~1%). Similar treatment of [Co([15]aneN₅)Cl]ZnCl₄ (α -isomer 25%, γ -isomer 75%) with concentrated hydrobromic acid resulted in a mixture of γ -[Co([15]aneN₅)Br]²⁺ (55%), γ -[Co([15]aneN₅)Cl]²⁺ (35%), a small amount of α -[Co([15]aneN₅)Cl]²⁺ (<3%) and protonated ligand ($\leq$ 10%) indicating that some decomposition had also taken place.

Chlorine gas was bubbled through a solution of γ -[Co([15]aneN₅)Br]Br₂ in methanol for 5 minutes. The solution was then heated for 10 minutes, and the procedure was repeated. The solvent was removed by rotary evaporation, and the residue was dissolved in dilute nitric acid. The ¹³C n.m.r. spectrum showed that the only species present were α -[Co([15]aneN₅)Cl]²⁺ (15%) and γ -[Co([15]aneN₅)Cl]²⁺ (85%).

2.4.1.2 Substitution Reactions of Cobalt(III) Complexes of [16]aneN₅

Induced Aquation Reactions

Treatment of $[\text{Co}([16]\text{aneN}_5)\text{Br}]\text{ZnBr}_4$ or $[\text{Co}([16]\text{aneN}_5)\text{Cl}]\text{ZnCl}_4$ with five equivalents of silver perchlorate (as described in section 2.4.1.1) resulted in the formation of the single isomer of $[\text{Co}([16]\text{aneN}_5)\text{H}_2\text{O}]^{3+}$ that has been previously prepared.

A sample of $[\text{Co}([16]\text{aneN}_5)\text{Br}]\text{Br}_2$ in nitric acid (2 M) was heated with three equivalents of mercury(II) nitrate. The ^{13}C n.m.r. spectrum showed the presence of a mixture of the $[\text{Co}([16]\text{aneN}_5)\text{H}_2\text{O}]^{3+}$ (35%), $[\text{Co}([16]\text{aneN}_5)\text{NO}_3]^{2+}$ (55%) and $[\text{Co}([16]\text{aneN}_5)\text{Br}]^{2+}$ (10%) cations. ^{13}C n.m.r. $\delta(\text{HNO}_3/\text{D}_2\text{O})$ $[\text{Co}([16]\text{aneN}_5)\text{NO}_3]^{2+}$ 59.47, 55.67, 55.17, 54.72, 50.03, 28.20. (The resonance at 28.20 p.p.m. is approximately half the intensity of the other four).

Base Hydrolysis Reactions

Samples of $[\text{Co}([16]\text{aneN}_5)\text{X}]\text{ZnX}_4$ ($\text{X}=\text{Cl}^-$, Br^-) or $[\text{Co}([16]\text{aneN}_5)\text{H}_2\text{O}](\text{ClO}_4)_3$ in either ammonia (2 M) or sodium hydroxide (0.1 M) rapidly turned orange and in each case produced the same isomer of $[\text{Co}([16]\text{aneN}_5)\text{OH}]^{2+}$. ^{13}C n.m.r. $\delta(\text{OH}^-/\text{D}_2\text{O})$ 58.25, 55.20, 54.49, 50.24, 28.31 (the resonances at 54.49 and 28.31 p.p.m. are respectively double and half the intensity of the other three resonances).

Acidification of a solution of $[\text{Co}([16]\text{aneN}_5)\text{OH}]^{2+}$ derived from the chloro complex resulted in the formation of a mixture of the chloro (30%), nitrate (40%) and aquo (30%) complexes. When a solution of $[\text{Co}([16]\text{aneN}_5)\text{OH}]^{2+}$ derived from the bromo complex was acidified with perchloric acid (2 M) the bromo complex was quantitatively reformed, but if hydrochloric acid (2 M) was used, a mixture of the chloro and bromo complexes was obtained.

Other Substitution Reactions

Treatment of a solution of $[\text{Co}([\text{16}] \text{aneN}_5)\text{H}_2\text{O}]^{3+}$ in perchloric acid (0.1 M) with sodium nitrite resulted in the formation of a single nitrito isomer. ^{13}C n.m.r. $\delta(\text{HClO}_4/\text{D}_2\text{O})$ 59.08, 56.03, 55.30, 54.60, 50.67, 28.02. (The high field resonance was half the intensity of the other five resonances).

A sample of $[\text{Co}([\text{16}] \text{aneN}_5)\text{Br}]\text{Br}_2$ dissolved in dilute hydrochloric acid gave a ^{13}C n.m.r. spectrum after $2\frac{1}{2}$ hours which indicated that substantial aquation had occurred (the resonances corresponding to the chloro complex were $\sim\frac{1}{2}$ the intensity of those corresponding to the bromo complex). Similarly, dissolution of $[\text{Co}([\text{16}] \text{aneN}_5)\text{H}_2\text{O}](\text{ClO}_4)_3$ in nitric acid (~ 1.5 M) gave a ^{13}C n.m.r. spectrum after $2\frac{1}{2}$ hours with resonances corresponding to the nitrate complex $\sim 1\frac{1}{2}$ times the intensity of those corresponding to the aquo complex.

2.4.1.3 Substitution Reactions of Cobalt(III) Complexes of [17A]aneN₅ Silver(I) Induced Aquation

Treatment of $[\text{Co}([\text{17A}] \text{aneN}_5)\text{Br}]\text{Br}_2$ dissolved in perchloric acid (2 M) with three equivalents of silver perchlorate (refer section 2.4.1.1) resulted in the formation of a single isomer of $[\text{Co}([\text{17A}] \text{aneN}_5)\text{H}_2\text{O}]^{3+}$. ^{13}C n.m.r. $\delta(\text{HClO}_4/\text{D}_2\text{O})$ 59.17, 59.07, 55.47, 54.76, 54.14, 52.10, 51.12, 50.00, 49.86, 46.29, 22.66, 22.42.

Base Hydrolysis Reactions

Samples of $[\text{Co}([\text{17A}] \text{aneN}_5)\text{Br}]\text{Br}_2$ or $[\text{Co}([\text{17A}] \text{aneN}_5)\text{H}_2\text{O}](\text{ClO}_4)_3$ dissolved in either ammonia (1.5 M) or sodium hydroxide (0.1 M) all resulted in the formation of the same single isomer of $[\text{Co}([\text{17A}] \text{aneN}_5)\text{OH}]^{2+}$. ^{13}C n.m.r. $\delta(\text{OH}^-/\text{D}_2\text{O})$ 57.66, 56.81, 54.40², 53.66,

52.12, 49.80, 48.93², 46.28, 22.93². Heating with concentrated hydrochloric acid led to the formation of the single chloro isomer previously prepared.

Other Substitution Reactions

The ¹³C n.m.r. spectrum of a sample of [Co([17A]aneN₅)Br]Br₂ dissolved in nitric acid (2 M) run overnight showed that considerable hydrolysis had occurred. The intensity of the aquo resonances was $\sim \frac{1}{2}$ that of the resonances corresponding to the bromo complex, and resonances that have been assigned to the nitrate complex (see below) were $\sim \frac{1}{4}$ the intensity of those of the bromo complex. After heating the contents of the n.m.r. tube at 90°C for several hours the ¹³C n.m.r. showed that little further hydrolysis had occurred, indicating that equilibrium had been established quite rapidly.

A sample of [Co([17A]aneN₅) H₂O] (ClO₄)₃ dissolved in nitric acid (1.5 M) gave a ¹³C n.m.r. spectrum in which resonances corresponding to [Co([17A]aneN₅)H₂O]³⁺ (25%) and a set of resonances assigned to [Co([17A]aneN₅)NO₃]²⁺ (70%) accounted for the majority of the product composition. ¹³C n.m.r. δ (HNO₃/D₂O) [Co([17A]aneN₅)NO₃]²⁺ 58.97, 58.79, 55.86, 54.60, 53.76, 52.63, 51.42, 50.89, 49.08, 46.17, 22.85, 22.55.

2.4.1.4 Substitution Reactions of Cobalt(III) Complexes of [17B]aneN₅ Silver(I) Induced Aquation

Treatment of either γ -[Co([17B]aneN₅)Cl]ZnCl₄ or γ -[Co([17B]aneN₅)Br]Br₂ in perchloric acid with five and three equivalents of silver perchlorate respectively (see section 2.4.1.1) gives rise to the same ¹³C n.m.r. spectrum containing seventeen resonances which may readily be divided into two sets on the basis of relative peak heights.

^{13}C n.m.r. $\delta(\text{HClO}_4/\text{D}_2\text{O})$: α - $[\text{Co}([\text{17B}] \text{aneN}_5)\text{H}_2\text{O}]^{3+}$ 55.21, 54.20, 50.44, 49.22, 48.55, 22.80; γ - $[\text{Co}([\text{17B}] \text{aneN}_5)\text{H}_2\text{O}]^{3+}$ 59.61, 58.07, 53.92, 53.59, 52.53, 51.68, 50.11, 46.39, 45.12, 23.39, 19.28. (There is one less resonance listed in the spectrum of the γ -isomer than expected for this product, and this is presumably masked by one of the resonances of the α -isomer). The α -isomer accounts for 75% of the product in both hydrolysis reactions.

A sample of α - $[\text{Co}([\text{17B}] \text{aneN}_5)\text{Cl}]\text{ZnCl}_4$ dissolved in nitric acid (2 M) was similarly treated with five equivalents of silver nitrate. The ^{13}C n.m.r. spectrum of the resulting spectrum contained six peaks corresponding to one symmetrical isomer. ^{13}C n.m.r. $\delta(\text{HNO}_3/\text{D}_2\text{O})$ 55.12, 53.60, 50.87, 49.69, 48.53, 22.88. These resonances have been assigned to α - $[\text{Co}([\text{17B}] \text{aneN}_5)\text{NO}_3]^{2+}$. A small amount (<15% of the total) of α - $[\text{Co}([\text{17B}] \text{aneN}_5)\text{H}_2\text{O}]^{3+}$ was also present. After two months the α -aquo isomer accounted for ~35% of the product.

A sample of $[\text{Co}([\text{17B}] \text{aneN}_5)\text{Br}]\text{Br}_2$ prepared by Method B (q.v.) (comprising ~35% of the α -bromo isomer and ~65% of the γ -bromo isomer) in nitric acid (2 M) was treated with three equivalents of silver nitrate. The ^{13}C n.m.r. spectrum contained peaks corresponding to the α -aquo (<10%), α -nitrato (~45%), γ -aquo (<10%) species as well as a set of resonances that has been assigned to γ - $[\text{Co}([\text{17B}] \text{aneN}_5)\text{NO}_3]^{2+}$ (~40%). ^{13}C n.m.r. $\delta(\text{HNO}_3/\text{D}_2\text{O})$ 59.24, 57.62, 53.90, 52.54, 52.25, 51.97, 51.82, 49.72, 46.58, 44.84, 23.45, 19.18. The resonance at 49.72 p.p.m. is coincident with one of the α - $[\text{Co}([\text{17B}] \text{aneN}_5)\text{NO}_3]^{2+}$ resonances, but it has been identified from the mercury(II) induced aquation reaction (q.v.) in which the α -nitrato complex does not occur.

Mercury(II) Induced Aquation

A sample of α -[Co([17B]aneN₅)Cl]ZnCl₄ dissolved in nitric acid (2 M) was treated with five equivalents of mercury(II) nitrate. The ¹³C n.m.r. spectrum of the reactant solution showed that the α -nitrato complex had been formed almost exclusively. A small amount (<5%) of γ -[Co([17B]aneN₅)NO₃]²⁺ that was identified in the product is most likely to have resulted from the contamination of the starting material with a similar amount of γ -[Co([17B]aneN₅)Cl]²⁺.

A sample of γ -[Co([17B]aneN₅)Br]Br₂ dissolved in nitric acid (2 M) was treated with three equivalents of mercury(II) nitrate. The ¹³C n.m.r. spectrum showed the presence of the γ -nitrato (~60%) and γ -aquo (~40%) species, with some evidence for a very small amount (<2%) of the α -nitrato species.

Base Hydrolysis Reactions

Both α -[Co([17B]aneN₅)Br]Br₂ and γ -[Co([17B]aneN₅)Cl]ZnCl₄ produced the same seventeen peak ¹³C n.m.r. spectrum when dissolved in concentrated ammonia. These resonances may readily be divided into two sets on the basis of their different relative intensities. (The symmetrical isomer accounts for 65% of the product). ¹³C n.m.r. δ (OH⁻/D₂O)

α -[Co([17B]aneN₅)OH]²⁺ 53.35, 53.03, 50.34, 47.54, 47.46, 23.17;

γ -[Co([17B]aneN₅)OH]²⁺ 57.55, 56.33, 52.55, 52.22, 51.67, 49.49, 48.81, 45.14, 44.88, 23.79, 19.67. (A further resonance expected for the γ -isomer is presumably masked by one of the α -isomer resonances).

Acidification (with nitric acid) of the base hydrolysis products obtained from the chloro complex resulted in a mixture of the α -chloro (35%), α -aquo (20%), α -nitrato (20%), γ -aquo (10%) and γ -nitrato (10%) species, but little if any of the γ -chloro complex (<5%).

A sample of γ -[Co([17B]aneN₅)Br]Br₂ which had been treated with silver nitrate and subsequently with ammonia was acidified with hydrobromic acid and heated for one hour on the steambath. The ¹³C n.m.r. spectrum showed the presence of the α -bromo (15%), α -nitrate (45%), α -aquo (20%) and γ -bromo (20%) species, but no evidence for either the γ -aquo or γ -nitrate complexes.

Addition of concentrated ammonia to a solution of γ -[Co([17B]aneN₅)H₂O]³⁺ (obtained by mercury(II) induced aquation of the γ -bromo complex) gave the same two hydroxo isomers in the same relative proportions as before. However, a solution of α -[Co([17B]aneN₅)NO₃]²⁺ (obtained by mercury(II) induced aquation of the α -chloro complex) when made basic with concentrated ammonia gave a ¹³C n.m.r. spectrum which showed the presence of the α -hydroxo (50%) and γ -hydroxo (40%) species as well as a small amount ($\leq 10\%$) of a further product which was not present in any of the other basic solutions and which could not be identified. ¹³C n.m.r. δ (NH₃/D₂O) 57.95, 57.16, 56.99, 55.46, 51.60, 45.05, 23.80, 23.50. An incomplete set of resonances is listed, and there is evidence that the others corresponding to this compound are masked by resonances of the α - and γ -hydroxo isomers).

One sample of [Co([17B]aneN₅)H₂O](ClO₄)₃ which was prepared by Method A (ii) (q.v.), was shown to contain only α -[Co([17B]aneN₅)H₂O]³⁺ (~45%) and δ -[Co([17B]aneN₅)H₂O]³⁺ (~55%) when dissolved in perchloric acid (1.5 M). Upon treatment with sodium hydroxide (0.2 M) this sample gave not only the previously identified α -hydroxo (30%) and γ -hydroxo (10%) isomers, but also another product which presumably arises from the base hydrolysis of the δ -aquo isomer. ¹³C n.m.r. δ (OH⁻/D₂O) 61.76, 55.52, 55.07, 53.26, 52.66, 52.41, 50.72, 48.87, 48.57, 42.35, 29.60, 23.93.

Other Substitution Reactions

A sample of α -[Co([17B]aneN₅)Br]Br₂ dissolved in hydrochloric acid (2 M) gave a mixture of the α -aquo (25%), α -bromo (25%) and α -chloro (50%) species, with no evidence for the formation of any γ -isomers. A similar sample dissolved in nitric acid (2 M) produced a mixture of the α -aquo (35%), α -bromo (30%) and α -nitrate (35%) species.

A mixture of α -[Co([17B]aneN₅)H₂O]³⁺ (75%) and γ -[Co([17B]aneN₅)H₂O]³⁺ (25%) (produced by the silver(I) induced aquation of γ -[Co([17B]aneN₅)Br]Br₂) was dissolved in concentrated hydrochloric acid and heated to dryness on the steambath. The procedure was repeated, and the resultant product was shown to be a mixture of the α -chloro (60%) and γ -chloro (40%) isomers.

A sample of [Co([17B]aneN₅)H₂O](ClO₄)₃ prepared by Method A (ii) (q.v.), was dissolved in nitric acid (2 M). The ¹³C n.m.r. spectrum contained resonances corresponding to the α -aquo (20%), α -nitrate (20%), γ -aquo (30%) and γ -nitrate (~5%) species as well as the δ -aquo isomer previously referred to. Another sample prepared by the same method (but obtained in lower yield on precipitation from the reaction mixture) was dissolved in nitric acid (2 M) giving a ¹³C n.m.r. spectrum in which there were no resonances corresponding to the γ -isomers. Only the α -aquo (25%), α -nitrate (30%) and δ -aquo (45%) species were present.

¹³C n.m.r. δ (HNO₃/D₂O) δ -[Co(17B)aneN₅)H₂O]³⁺ 62.31, 56.99, 56.31, 52.81, 50.93, 50.41, 49.69, 43.42, 29.79, 23.61. Only ten of the twelve resonances expected for a complex with no plane of symmetry could be resolved from the spectrum owing to its complexity.

A mixture of α - and γ -[Co([17B]aneN₅)H₂O]³⁺ was converted to [Co([17B]aneN₅)SO₃]²⁺,²⁹¹ and the ¹³C n.m.r. spectrum of the reaction mixture showed that only one isomer had been formed.

¹³C n.m.r. δ (d₆-DMSO) 56.08, 54.96, 54.06, 53.61, 52.77, 52.21, 49.25, 45.71, 45.51, 44.71, 23.80, 20.17.

2.4.1.5 Substitution Reactions of Cobalt(III) Complexes of [18A]aneN₅

The treatment of $[\text{Co}([18\text{A}] \text{aneN}_5)\text{Br}]\text{Br}_2$ in dilute perchloric acid with silver perchlorate led to an appreciable amount of decomposition. A satisfactory ^{13}C n.m.r. spectrum of the aquo complex could not be obtained, as precipitation of further decomposition product appeared to take place continually, and only a spectrum with a very poor signal/noise ratio resulted. Likewise, attempts to investigate the base hydrolysis products were unsuccessful due to decomposition.

2.4.1.6 Substitution Reactions of Cobalt(III) Complexes of [18B]aneN₅ Silver(I) Induced Aquation

A sample of $[\text{Co}([18\text{B}] \text{aneN}_5)\text{Br}]\text{Br}_2$ was dissolved in perchloric acid (0.2 M) and treated with three equivalents of silver perchlorate. Precipitated silver bromide was removed by filtration, the solution was taken to near dryness by rotary evaporation, propan-2-ol was added and the product was quantitatively precipitated by addition of ether.

^{13}C n.m.r. $\delta(\text{HClO}_4/\text{D}_2\text{O})$ 59.89, 54.64, 54.46, 54.39, 51.20, 50.87, 49.55, 49.24, 48.36, 48.23, 24.40, 23.99, 22.11.

Base Hydrolysis Reactions

Samples of $[\text{Co}([18\text{B}] \text{aneN}_5)\text{Br}]\text{Br}_2$ and the silver(I) induced hydrolysis product both produced the same ^{13}C n.m.r. spectrum when dissolved in ammonia (1.5 M). ^{13}C n.m.r. $\delta(\text{NH}_3/\text{D}_2\text{O})$ 57.94, 54.88, 53.86, 53.28, 51.52, 49.93, 47.87², 47.16², 24.72², 22.20.

Other Substitution Reactions

A sample of $[\text{Co}([18\text{B}] \text{aneN}_5)\text{Br}]\text{Br}_2$ dissolved in perchloric acid (0.4 M) produced the same ^{13}C n.m.r. spectrum as the silver(I) induced aquation reaction. When a sample was dissolved in nitric acid (2 M), the

spectrum was more complex. The resonances corresponding to the aquo complex were present, as well as a set of resonances of lower intensity which have been assigned to $[\text{Co}([\text{18B}] \text{aneN}_5) \text{NO}_3]^{2+}$. ^{13}C n.m.r. δ ($\text{HNO}_3/\text{D}_2\text{O}$) 55.43, 55.28, 54.37, 53.70, 52.57, 50.39, 50.20, 46.40, 24.38, 24.15, 22.76. (Two further resonances are presumably masked by those of the aquo complex).

Chlorine gas was bubbled through a suspension of $[\text{Co}([\text{18B}] \text{aneN}_5)\text{Br}]\text{Br}_2$ (0.26 g, 0.47 mmol) in methanol (20 cm^3) for five minutes, and the solution was then heated for ten minutes. The procedure was repeated twice, propan-2-ol (25 cm^3) was added, and the product was collected by filtration, washed with propan-2-ol and vacuum desiccated. Yield 0.17 g (91%). I.r. (nujol): 3377(m), 3137, 3131 (i), 3061(m) ($\nu_{\text{N-H}}$). The fingerprint region of the i.r. spectrum is quite different from that of the bromo complex (see fig. 2.10).

2.4.1.7 Substitution Reactions of Cobalt(III) Complexes of tetren Mercury(II) Induced Aquation

A sample of α - $[\text{Co}(\text{tetren})\text{Cl}]\text{ZnCl}_4$ dissolved in nitric acid (2 M) was treated with five equivalents of mercury(II) nitrate, resulting in the formation of predominantly one product, α - $[\text{Co}(\text{tetren})\text{H}_2\text{O}]^{3+}$.

^{13}C n.m.r. δ ($\text{HNO}_3/\text{D}_2\text{O}$) 59.00, 56.00, 55.09, 54.43, 50.86, 49.67, 49.09, 41.86. Five smaller resonances corresponding to another product were also identified (58.35, 56.71, 50.38, 49.27, 43.90 p.p.m.) and presumably the other resonances expected are masked by those of the major product.

Other Substitution Reactions

A sample of α - $[\text{Co}(\text{tetren})\text{Br}]\text{Br}_2$ dissolved in dilute perchloric acid showed the presence of a small amount (~20%) of α - $[\text{Co}(\text{tetren})\text{H}_2\text{O}]^{3+}$ indicating that acid hydrolysis was taking place.

Infrared Spectra of $[\text{Co}([\text{18B}] \text{aneN}_5)\text{X}]\text{X}_2$

Pure α -[Co(tetren)Br]Br₂ (0.20 g, 0.4 mmol) was dissolved in hydrochloric acid (12 M, 5 cm³) and digested for 48 hours at 90°C. Ethanol (10 cm³) and propan-2-ol (20 cm³) were added, the product that precipitated was collected by filtration, washed with propan-2-ol and vacuum desiccated. Yield 0.13 g (89%). This was identified as the α -chloro complex by ¹³C n.m.r. A small amount of the α -aquo complex (~5%) was also shown to be present in the n.m.r. sample.

Conversion of the α -chloro and α -bromo complexes to the nitrito complex and subsequent conversion to the β -bromo and β -chloro complexes has been described (section 2.3.3.9).

2.4.2 Electronic Spectra of Cobalt(II) and Cobalt(III) Complexes

2.4.2.1 Cobalt(III) Complexes

Spectral parameters of the bromo and chloro complexes are listed in Tables 2.16 (a and b), together with data for related [CoN₅X]²⁺ systems. To minimize the effects of hydrolysis, the complexes were dissolved in dilute acid and the spectra were run immediately. For the complexes of [18B]aneN₅ however, hydrolysis was rapid even in acidic solution and DMSO was used as the solvent.

Dissolution of the chloro or bromo complexes in either dilute sodium hydroxide or ammonia led to the rapid formation of the hydroxo complexes. Their spectral parameters are listed in Table 2.17. Solutions of the aquo complexes were prepared by two different methods. Silver induced aquation of an acidic solution of the halo complex or acidification of the base hydrolysis product both gave identical spectra (Table 2.18).

TABLE 2.16(a)

Electronic Spectra of $[\text{Co L Br}]^{2+}$

Complex	Visible Absorption Maxima ^a		
$[\text{Co}(\text{NH}_3)_5\text{Br}]^{2+}$ ^b	552(57.6)	470(sh,11.5)	310(sh,831)
α - $[\text{Co}(\text{tetren})\text{Br}]^{2+}$ ^c	548(132)	480(sh,100)	
β - $[\text{Co}(\text{tetren})\text{Br}]^{2+}$ ^c	550(121)	480(98)	
$[\text{Co}(\text{pyaneN}_5)\text{Br}]^{2+}$ ^d	525(sh)	462(209)	364(sh)
$[\text{Co}([15]\text{aneN}_5)\text{Br}]^{2+}$	574(142)	477(162)	~ 325(sh,900)
$[\text{Co}([16]\text{aneN}_5)\text{Br}]^{2+}$	565(118)	~ 470(sh,37) ^g	~ 330(sh,1000)
$[\text{Co}([17\text{A}]\text{aneN}_5)\text{Br}]^{2+}$	571(123)	505(sh,80) ^h	
$[\text{Co}([17\text{B}]\text{aneN}_5)\text{Br}]^{2+}$ ^e	572(100)	500(sh,64) ⁱ	
$[\text{Co}([18\text{A}]\text{aneN}_5)\text{Br}]^{2+}$	590(105)		
$[\text{Co}([18\text{B}]\text{aneN}_5)\text{Br}]^{2+}$ ^f	603(95)	525(91)	

a λ_{max} in nm, numbers inside parentheses are extinction coefficients (ϵ) units $\text{M}^{-1} \text{cm}^{-1}$.

b ref. 292

c ref. 268

d ref. 49

e difference between spectral parameters of γ -isomer and mixture of α - and γ -isomers is within the experimental uncertainty.

f spectrum in DMSO.

g peak resolved at 466 nm

h peak resolved at 495 nm

i peak resolved at 486 nm

TABLE 2.16 (b)

Electronic Spectra of $[\text{Co L Cl}]^{2+}$

Complex	Visible Absorption Maxima ^a		
$[\text{Co}(\text{NH}_3)_5\text{Cl}]^{2+}$ ^b	534(50)	467(sh)	364(47)
$\alpha\text{-}[\text{Co}(\text{tetren})\text{Cl}]^{2+}$ ^c	522(109)	480(sh, 105)	362(103)
$\beta\text{-}[\text{Co}(\text{tetren})\text{Cl}]^{2+}$ ^c	525(99)	480(101)	360(107)
$\text{u-}[\text{Co}(\text{datn})\text{Cl}]^{2+}$ ^d	521(165)	480(sh, 120)	366(152)
$[\text{Co}(\text{pyaneN}_5)\text{Cl}]^{2+}$ ^e	540(sh)	460(245)	340(sh)
$[\text{Co}([\text{15}] \text{aneN}_5)\text{Cl}]^{2+}$ ^f	505(253)		345(342)
$[\text{Co}([\text{15}] \text{aneN}_5)\text{Cl}]^{2+}$	540(sh, 125) ^h	474(170)	365(130)
$[\text{Co}([\text{16}] \text{aneN}_5)\text{Cl}]^{2+}$	544(88)	470(sh, ~40) ⁱ	363(87)
$[\text{Co}([\text{17A}] \text{aneN}_5)\text{Cl}]^{2+}$	545(95)	~490(sh) ^j	381(123)
$\gamma\text{-}[\text{Co}([\text{17B}] \text{aneN}_5)\text{Cl}]^{2+}$	551(86)	495(sh, 65) ^k	376(107)
$[\text{Co}([\text{18B}] \text{aneN}_5)\text{Cl}]^{2+}$ ^g	565(77)	528(80)	390(sh, 145)

a λ_{max} in nm, numbers inside parentheses are extinction coefficients
(ϵ) units $\text{M}^{-1} \text{cm}^{-1}$

b ref. 292

c ref. 62, 268

d ref. 93

e ref. 49

f ref. 167

g spectrum in DMSO

h peak resolved at 563 nm

i peak resolved at 458 nm

j peak resolved at 479 nm

k peak resolved at 475 nm

TABLE 2.17

Electronic Spectra of $[\text{Co L OH}]^{2+}$

Complex	Visible Absorption Maxima ^a		
$[\text{Co}(\text{NH}_3)_5\text{OH}]^{2+}$ ^b	503(62.5)		370(70.8)
$[\text{Co}(\text{tetren})\text{OH}]^{2+}$ ^c	490(149)		348(147)
" $[\text{Co}([\text{15}] \text{aneN}_5)\text{Cl}]^{2+}$ " ^d	505(253)		345(342)
$[\text{Co}([\text{15}] \text{aneN}_5)\text{OH}]^{2+}$	488(200)		350(220)
$[\text{Co}([\text{16}] \text{aneN}_5)\text{OH}]^{2+}$	498(100)		362(110)
$[\text{Co}([\text{17A}] \text{aneN}_5)\text{OH}]^{2+}$	512(118)	385(105)	~370(sh, ~100)
$[\text{Co}([\text{17B}] \text{aneN}_5)\text{OH}]^{2+}$	517(122)	389(110)	360(sh, 95)
$[\text{Co}([\text{18A}] \text{aneN}_5)\text{OH}]^{2+}$	522(120)		
$[\text{Co}([\text{18B}] \text{aneN}_5)\text{OH}]^{2+}$	525(116)	390(sh)	375(120)

a λ_{max} in nm, numbers inside parentheses are extinction coefficients (ϵ) units $\text{M}^{-1} \text{cm}^{-1}$.

b ref. 293

c ref. 268

d ref. 167

TABLE 2.18

Electronic Spectra of $[\text{Co L H}_2\text{O}]^{3+}$

Complex	Visible Absorption Maxima ^a	
$[\text{Co}(\text{NH}_3)_5\text{H}_2\text{O}]^{3+}$ ^b	485 (48)	340
$[\text{Co}(\text{tetren})\text{H}_2\text{O}]^{3+}$ ^c	472 (122)	350 (85.3)
u- $[\text{Co}(\text{datn})\text{H}_2\text{O}]^{3+}$ ^d	513 (157)	470 (sh, 115) 365 (142)
$[\text{Co}([15]\text{aneN}_5)\text{H}_2\text{O}]^{3+}$ ^e	450 (305)	
$[\text{Co}([15]\text{aneN}_5)\text{H}_2\text{O}]^{3+}$	465 (190)	347 (120)
$[\text{Co}([16]\text{aneN}_5)\text{H}_2\text{O}]^{3+}$	500 (64)	470 (sh) 346 (73)
$[\text{Co}([17\text{A}]\text{aneN}_5)\text{H}_2\text{O}]^{3+}$	499 (99)	365 (103)
$[\text{Co}([17\text{B}]\text{aneN}_5)\text{H}_2\text{O}]^{3+}$	500 (110)	360 (120)
$[\text{Co}([18\text{A}]\text{aneN}_5)\text{H}_2\text{O}]^{3+}$	536 (110)	352 (sh, 140)
$[\text{Co}([18\text{B}]\text{aneN}_5)\text{H}_2\text{O}]^{3+}$	504 (100)	367 (120)

a λ_{max} in nm, numbers inside parentheses are extinction coefficients
(ϵ) units $\text{M}^{-1} \text{cm}^{-1}$.

b ref. 294

c ref. 268

d ref. 93

e ref. 167

When dissolved in dilute mineral acid, $[\text{Co}([\text{18A}] \text{aneN}_5)\text{Br}]\text{Br}_2$ gave a green solution which turned pink over a number of hours at room temperature (or several minutes at 80°C , although subsequent decomposition occurred at the higher temperature). The spectral change is shown in figure 2.11 (nitric acid) and figure 2.12 (perchloric acid). The isosbestic points suggest that in each case a single reaction is taking place. The product in the latter reaction has the same λ_{max} and ϵ_{max} as a sample of $[\text{Co}([\text{18A}] \text{aneN}_5) \text{H}_2\text{O}]^{3+}$ prepared by silver induced aquation of the bromo complex, whereas dissolution of the bromo complex in nitric acid resulted in a solution with $\lambda_{\text{max}} \sim 544$ and $\epsilon_{\text{max}} \sim 125$.

Dissolution of $[\text{Co}([\text{18B}] \text{aneN}_5)\text{Br}]\text{Br}_2$ in dilute mineral acid led to rapid aquation. The visible spectrum obtained was identical to that of the aquo complex. The spectrum of the bromo complex was thus run in DMSO.

2.4.2.2 Cobalt(II) Complexes

The solution spectra of $[\text{Co}([\text{19}] \text{aneN}_5)](\text{ClO}_4)_2$ and $[\text{Co}([\text{20}] \text{aneN}_5)](\text{ClO}_4)_2$ in non-coordinating solvents, and the solid state spectra of these complexes are all very similar (fig. 2.13). Their conductivities, magnetic moments and spectral parameters are listed in Table 2.19 together with those of a number of five- and six-coordinate cobalt(II) amine complexes for comparison.

Hydrolysis of $[\text{Co}(\text{[18A]aneN}_5)\text{Br}]^{2+}$ in Nitric Acid

fig 2.11

fig 2.12

fig 2.13

2.4.3 Structural Study of $[\text{Co}(\text{[17A]aneN}_5)\text{Cl}]\text{Br}_{0.33}\text{Cl}_{1.67}\text{H}_2\text{O}$

2.4.3.1 Synthesis

To a stirred solution of $[\text{17A]aneN}_5 \cdot (\text{HBr})_5 \cdot 0.5\text{H}_2\text{O}$ (1.3 g, 2 mmol) and sodium hydroxide (0.4 g, 10 mmol) in water (2 cm³) was added a solution of cobalt chloride hexahydrate (0.5 g, 2.1 mmol) and hydrogen peroxide (30 volume, 0.5 cm³) in water (5 cm³) over 20 minutes. Hydrochloric acid (12 M, 4 cm³) and zinc chloride (0.4 g) were added and the reaction mixture was heated for 2 hours. The product that crystallized on standing was recrystallized twice by dissolving in hydrochloric acid (0.1 M, ~10 cm³) and adding a few drops of concentrated hydrochloric acid containing zinc chloride (10% w/v). A small amount of material suitable for X-ray structural analysis crystallized slowly on the second recrystallization.

2.4.3.2 Crystal Data

$[\text{Co}(\text{C}_{12}\text{H}_{29}\text{N}_5)\text{Cl}]\text{Br}_{0.33}\text{Cl}_{1.67}\text{H}_2\text{O}$, $m_r = 441.54$, orthorhombic, $a = 1208.5(1)$, $b = 2205.5(3)$, $c = 1318.9(2)$ pm, $U = 3674 \times 10^9$ pm³, $\rho_{\text{obs}} = 1.600(5)$ g cm⁻³ (by flotation), $z = 8$, $\rho_{\text{calc}} = 1.60$ g cm⁻³. Space group Pbca was determined by systematic absences $0k\ell$, $k=2n+1$; $h0\ell$, $\ell=2n+1$ and $hk0$, $h=2n$ from Weissenberg and Precession photographs. Nickel filtered Cu-K α radiation, $\lambda = 154.18$ pm, $\mu(\text{Cu-K}\alpha) = 121.1$ cm⁻¹.

The crystal habit was tabular and a cut fragment (dimensions 0.26×0.36×0.25 mm) with six faces $(-1,-1,-2)$, $(-1,-1,1)$, $(0,0,-1)$, $(-2,10,0)$, $(-1,-1,1)$ and $(1,1,1)$ was used. The cell dimensions were determined by least-squares refinement of 12 high-angle reflections with the Hilger & Watts Y290 four circle diffractometer used for data collection.

X-ray data were obtained using the θ , 2θ scan technique with a scan step in θ of 0.1° and a counting time of 1s. Each reflection was scanned through a range of 0.56° centred on the Cu-K α peak. Background counts were accumulated for 14s at each extremity of the scan using stationary crystal and counter. The intensities of three strong reflections well separated in reciprocal space were periodically monitored during data collection. These showed a decrease of about 3% in their mean values over the period and the data was scaled accordingly.

All independent reflections with $\theta < 62^\circ$ were measured. The 2132 reflections with intensity $I > 3\sigma(I)$ were corrected for Lorentz and polarization effects and for absorption by the analytical method and were used in the final refinement.

The structure was solved by direct methods using Multan 77.²⁹⁶ All calculations were made using SHELX,²⁹⁷ with scattering factors therein, or from crystallographic tables.²⁹⁸ Initial refinement with isotropic temperature factors and with a chloride ion at position Cl(2) gave an R value of 0.199 and R_w of $0.162^\dagger$. Although the structure of the cation was apparent at this stage, the electron density at Cl(2) was too high. A model that assumed random replacement of some of the chloride at this site by bromide optimized with the replacement of a third of the chloride at Cl(2) by bromide. This model supported by the density measurements, was used for further refinement, with Co and Cl given anisotropic thermal factors. ($R=0.070$, $R_w=0.094$). Final refinement with analytical absorption corrections (0.301-0.484), with hydrogen atoms in calculated positions (116 parameters) and with anisotropic thermal factors for O(1), converged with $R=0.056$ and $R_w=0.071$.

$$^\dagger R = \sum (|F_o - F_c|) / \sum |F_o|; \quad R_w = [\sum w(|F_o| - |F_c|)^2 / \sum w|F|^2]^{1/2}$$

A view of the complex cation, together with the crystallographic numbering scheme and selected bond lengths is shown in fig. 2.14.

(Hydrogen atoms have been omitted for the sake of clarity). The structure of the cation is represented by the tables of bond lengths (Table 2.20), bond angles (2.21), dihedral angles (2.22) and deviations of atoms from selected planes (2.23). (The equations of the planes listed in Table 2.23 are defined by the parameters listed in Table 2.24). The coordinates of the non-hydrogen atoms are listed in Table 2.25 and their thermal parameters in Table 2.26, while the coordinates of the hydrogen atoms (together with their thermal parameters and crystallographic numbering scheme) are listed in Table 2.27. The hydrogen bonding network that links the coordinated amine nitrogen atoms to the non-coordinated chlorine atoms and Cl(3) to the water molecule is represented by the hydrogen bond contact distances and angles given in Table 2.28.

Structure of the $[\text{Co}([\text{17A}] \text{aneN}_5)\text{Cl}]^{2+}$ Complex Cation

fig 2.14

TABLE 2.20

Interatomic distances (pm) with standard deviations

Atoms	Dist.	Atoms	Dist.
Co-Cl(1)	225.8(2)	Co-N(1)	198.9(6)
Co-N(2)	200.9(5)	Co-N(3)	200.1(6)
Co-N(4)	196.1(5)	Co-N(5)	197.0(5)
N(1)-C(1)	147.8(9)	N(1)-C(12)	148.5(8)
N(2)-C(3)	147.4(8)	N(2)-C(4)	149.5(8)
N(3)-C(6)	149.3(8)	N(3)-C(7)	147.3(8)
N(4)-C(8)	149.9(8)	N(4)-C(9)	149.8(8)
N(5)-C(10)	148.5(8)	N(5)-C(11)	148.1(8)
C(1)-C(2)	150.5(10)	C(2)-C(3)	152.0(10)
C(4)-C(5)	151.6(10)	C(5)-C(6)	149.9(9)
C(7)-C(8)	150.2(10)	C(9)-C(10)	152.2(10)
C(11)-C(12)	147.7(9)		

TABLE 2.21

Bond angles (degrees) with standard deviations

Atoms	Angle	Atoms	Angle
Cl(1)-Co-N(1)	88.5(2)	Cl(1)-Co-N(2)	90.7(2)
Cl(1)-Co-N(3)	91.5(2)	Cl(1)-Co-N(4)	175.4(2)
Cl(1)-Co-N(5)	89.6(2)	N(1)-Co-N(2)	91.7(2)
N(1)-Co-N(3)	174.5(2)	N(1)-Co-N(4)	94.4(2)
N(1)-Co-N(5)	84.4(2)	N(2)-Co-N(3)	93.7(2)
N(2)-Co-N(4)	92.8(2)	N(2)-Co-N(5)	176.1(2)
N(3)-Co-N(4)	85.3(2)	N(3)-Co-N(5)	90.2(2)
N(4)-Co-N(5)	87.1(2)	Co-N(1)-C(1)	119.7(4)
Co-N(1)-C(12)	110.7(4)	C(1)-N(1)-C(12)	110.9(5)
Co-N(2)-C(3)	113.1(4)	Co-N(2)-C(4)	116.6(4)
C(3)-N(2)-C(4)	107.4(5)	Co-N(3)-C(6)	117.7(4)
Co-N(3)-C(7)	110.7(4)	C(6)-N(3)-C(7)	112.4(5)
Co-N(4)-C(8)	107.7(4)	Co-N(4)-C(9)	110.4(4)
C(8)-N(4)-C(9)	113.1(5)	Co-N(5)-C(10)	110.1(4)
Co-N(5)-C(11)	109.2(4)	C(10)-N(5)-C(11)	114.9(5)
N(1)-C(1)-C(2)	113.8(6)	C(1)-C(2)-C(3)	115.5(7)
N(2)-C(3)-C(2)	111.7(6)	N(2)-C(4)-C(5)	113.7(6)
C(4)-C(5)-C(6)	113.4(6)	N(3)-C(6)-C(5)	112.9(6)
N(3)-C(7)-C(8)	109.9(6)	N(4)-C(8)-C(7)	108.3(6)
N(4)-C(9)-C(10)	110.2(5)	N(5)-C(10)-C(9)	109.8(6)
N(5)-C(11)-C(12)	108.2(6)	N(1)-C(12)-C(11)	108.4(6)

TABLE 2.22

Some dihedral angles (degrees)

Atoms	Angle	Atoms	Angle
Co-N(1)-C(1)-C(2)	-52.0	C(12)-N(1)-C(1)-C(2)	177.3
Co-N(1)-C(12)-C(11)	31.0	C(1)-N(1)-C(12)-C(11)	166.3
Co-N(2)-C(4)-C(5)	56.5	Co-N(3)-C(6)-C(5)	-57.1
C(7)-N(3)-C(6)-C(5)	73.4	Co-N(3)-C(7)-C(8)	23.2
C(6)-N(3)-C(7)-C(8)	-110.7	Co-N(4)-C(8)-C(7)	43.7
C(9)-N(4)-C(8)-C(7)	-78.6	Co-N(4)-C(9)-C(10)	-28.1
C(8)-N(4)-C(9)-C(10)	92.7	Co-N(5)-C(10)-C(9)	-31.4
C(11)-N(5)-C(10)-C(9)	92.4	Co-N(5)-C(11)-C(12)	41.6
C(10)-N(5)-C(11)-C(12)	-82.7	N(1)-C(1)-C(2)-C(3)	-2.9
C(1)-C(2)-C(3)-N(2)	66.7	N(2)-C(4)-C(5)-C(6)	-67.6
C(4)-C(5)-C(6)-N(3)	67.1	N(3)-C(7)-C(8)-N(4)	-43.8
N(4)-C(9)-C(10)-N(5)	38.9	N(5)-C(11)-C(12)-N(1)	-47.1
Co-N(2)-C(3)-C(2)	-67.5		

TABLE 2.23

Deviations from selected planes

Deviations in pm from weighted mean planes defined by underlined atoms. Estimated standard deviations 0.6-1 pm.

Plane

1	<u>N(1)</u> -0.3, <u>N(2)</u> 0.3, <u>N(3)</u> -0.3, <u>N(5)</u> 0.3, Co -0.2.
2	<u>N(2)</u> 7.4, <u>N(5)</u> 8.1, <u>Cl(1)</u> -0.7, <u>N(4)</u> -8.3, Co 0.8
3	<u>Cl(1)</u> 0.2, <u>N(3)</u> 1.9, <u>N(1)</u> 1.8, <u>N(4)</u> -2.0, Co -7.6
4	<u>Co</u> , <u>N(1)</u> , <u>N(5)</u> , C(11) -46.4, C(12) 15.6
5	<u>Co</u> , <u>N(2)</u> , <u>N(3)</u> , C(4) -84.4, C(5) -50.7, C(6) -84.5
6	<u>Co</u> , <u>N(4)</u> , <u>N(5)</u> , C(9) 21.0, C(10) -31.3
7	<u>Co</u> , <u>N(3)</u> , <u>N(4)</u> , C(7) 25.9, C(8) -60.1
8	<u>N(2)</u> 0.0, C(4) 0.0, <u>N(3)</u> 0.0, <u>C(6)</u> 0.0, Co -78.2, C(5) 70.8
9	<u>C(1)</u> 1.3, <u>C(2)</u> -1.9, <u>Co</u> -0.1, <u>N(2)</u> 0.7, N(1) -59.0, C(3) -72.2

TABLE 2.24

Equations of the planes in Table 2.23

The equations of the planes are of the form $Ax+By+Cz-D = 0$

Plane	A	B	C	D
1	0.4101	-0.6973	-0.5879	-11.1549
2	0.8667	0.4971	-0.0410	-1.2180
3	-0.3431	0.5015	-0.7942	-7.7231
4	0.4095	-0.6959	-0.5899	-11.1771
5	0.4090	-0.6962	-0.5899	-11.1764
6	0.8955	0.4434	-0.0394	-1.4467
7	-0.3123	0.5427	-0.7797	-7.5534
8	0.1204	-0.9812	-0.1507	-4.8155
9	0.1431	-0.8253	-0.5462	-10.3184

TABLE 2.25

Atomic coordinates with standard deviations for
non-hydrogen atoms

The value in parentheses following any parameter is the estimated standard deviation in the least significant quoted digit, as derived from the appropriate least-squares inversion matrix.

Atom	$10^4 x$	$10^4 y$	$10^4 z$
Co	-2235.7(8)	1457.5(4)	9939.4(7)
Cl(1)	-2966(1)	2158.1(7)	10931(1)
Cl/Br(2) ^A	4229(1)	9694.9(5)	3539(1)
Cl(3)	360(1)	8084.0(7)	3846(1)
N(1)	-866(5)	1932(2)	9831(4)
N(2)	-1654(5)	1041(2)	11167(4)
N(3)	-3666(5)	1020(2)	9932(4)
N(4)	-1710(5)	853(2)	9011(4)
N(5)	-2706(5)	1893(2)	8728(4)
C(1)	225(6)	1657(3)	9983(5)
C(2)	314(7)	1315(3)	10952(6)
C(3)	-698(6)	1334(3)	11635(5)
C(4)	-2468(6)	916(3)	11992(5)
C(5)	-3463(6)	570(3)	11641(5)
C(6)	-4201(6)	898(3)	10930(5)
C(7)	-3581(6)	499(3)	9292(6)
C(8)	-2390(6)	320(3)	9196(6)
C(9)	-1764(6)	1061(3)	7937(5)
C(10)	-2678(6)	1511(3)	7822(5)
C(11)	-2037(5)	2429(3)	8642(5)
C(12)	-877(6)	2284(3)	8888(5)
O(1)	2981(7)	4046(3)	4883(5)

^A Chloride/bromide site. See text.

TABLE 2.26

Thermal parameters for non-hydrogen atoms

Atom	$10^2 U$ (or U_{eq}) ^A	Atom	$10^2 U$ (or U_{eq})
Br/Cl(2) ^B	3.9	C(2)	4.9(2)
Cl(3)	3.6	C(3)	3.8(2)
Co(1)	2.2	C(4)	3.7(2)
Cl(1)	3.3	C(5)	3.8(2)
O(1)	9.2	C(6)	3.6(2)
N(1)	2.9(1)	C(7)	3.9(2)
N(2)	2.8(1)	C(8)	4.0(2)
N(3)	3.3(1)	C(9)	3.6(2)
N(4)	2.7(1)	C(10)	3.4(2)
N(5)	2.7(1)	C(11)	3.3(2)
C(1)	3.7(2)	C(12)	3.6(2)

Thermal parameters for atoms refined anisotropically^C

Atom	$10^2 U_{11}$	$10^2 U_{22}$	$10^2 U_{33}$	$10^2 U_{23}$	$10^2 U_{13}$	$10^2 U_{12}$
Br/Cl(2) ^B	3.84(7)	3.51(7)	4.50(7)	-0.68(6)	-1.17(6)	1.10(6)
Cl(3)	2.88(9)	4.21(10)	3.84(9)	0.89(7)	0.77(7)	0.56(8)
Co(1)	2.19(5)	2.50(5)	1.97(5)	0.03(4)	-0.04(4)	-0.08(5)
Cl(1)	3.19(9)	3.42(9)	3.22(9)	-0.52(7)	-0.02(7)	0.43(7)
O(1)	8.5(6)	9.5(6)	9.6(6)	-3.3(4)	-1.1(4)	2.1(5)

$$U_{eq} = \frac{1}{3} \sum_i \sum_j U_{ij} a_i a_j (a_i \cdot a_j).$$

^BOccupancy factor: Cl 1.67, Br 0.33. See Text.

^CThe form of the thermal ellipsoid is:

$$\exp -2\pi^2 [U_{11}a^2h^2 + \dots + 2U_{23}k\ell b^*c^* + \dots]$$

TABLE 2.27

Hydrogen atom coordinates^A and thermal parameters^B

Atom	Bonded to atom	10^4 x	10^4 y	10^4 z
H(1)	N(1)	-920	2166	10423
H(2)	C(1)	359	1402	9430
H(3)	C(1)	773	1952	9992
H(4)	C(2)	449	922	10779
H(5)	C(2)	925	1463	11325
H(6)	C(3)	-885	1728	11761
H(7)	C(3)	-528	1147	12258
H(8)	N(2)	-1449	679	10878
H(9)	C(4)	-2102	703	12508
H(10)	C(4)	-2721	1275	12260
H(11)	C(5)	-3883	461	12219
H(12)	C(5)	-3207	231	11304
H(13)	C(6)	-4394	1257	11238
H(14)	C(6)	-4851	676	10815
H(15)	N(3)	-4174	1287	9640
H(16)	C(7)	-3991	192	9593
H(17)	C(7)	-3871	580	8638
H(18)	C(8)	-2155	137	9804
H(19)	C(8)	-2309	58	8644
H(20)	N(4)	-955	761	9131
H(21)	C(9)	-1075	1231	7757
H(22)	C(9)	-1911	742	7502
H(23)	C(10)	-3370	1319	7754
H(24)	C(10)	-2534	1739	7235
H(25)	N(5)	-3455	2015	8785
H(26)	C(11)	-2306	2712	9103
H(27)	C(11)	-2081	2575	7970
H(28)	C(12)	-559	2067	8349
H(29)	C(12)	-466	2630	8988

^A Refined using riding model on heavy atom (see SHELX ref.297) with N-H, C-H of 0.95 Å.

^B Two group thermal parameters (i) For hydrogens on nitrogen atoms (1, 8, 15, 20, 25), U 0.044(8) Å² (ii) All others, U 0.047(5) Å².

TABLE 2.28

Hydrogen bond contact distances (pm) and angles (degrees)

Atoms	Distances		Angles A-H...B	Symm. Op. ^A
	A-H	H...B		
N(1)-H(1)...Cl(3)	242	324	143.4	(i)
N(2)-H(8)...Cl(2)	243	330	138.5	(ii)
N(3)-H(15)...Cl(3)	229	324	176.7	(iii)
N(4)-H(20)...Cl(2)	246	331	148.9	(iv)
N(5)-H(25)...Cl(3)	232	321	157.0	(iii)
O(1)-H...Cl(3)		329	-	(v)

^ASymmetry operations (to bring atom B into contact with H)

(i) $-x, y-0.5, 1.5-z$ (ii) $x-0.5, y-1.0, 1.5-z$

(iii) $-0.5-x, 1.0-y, 0.5+z$ (iv) $0.5-x, 1.0-y, 0.5+z$

(v) $0.5-x, y-0.5, z$

2.5 Acid-Dissociation Kinetics of Copper Complexes

2.5.1 Data Acquisition and Analysis

The rates of acid dissociation of the copper(II) complexes of the pentaazamacrocycles with nitric acid were determined using a Canterbury SF-3A stopped-flow for the rapid reactions and a Pye Unicam SP700 or SP3300 for reactions with half-lives greater than a few seconds.

The concentration of the copper complex was typically 1.0-4.0 millimolar after mixing, and the acid concentration was varied over the range 0.1 M - 0.75 M [HNO₃]. The nitric acid solutions were prepared by dilution of a standardised nitric acid solution, and both the acid and complex solutions were adjusted to a constant ionic strength ($I = 1.00$ M) with sodium nitrate. Rates were also determined using higher acid concentrations, but here the ionic strength was naturally greater than unity. The kinetics were studied at 25.0(±0.1)°C except where otherwise stated.

The reactions were carried out under pseudo first-order conditions by ensuring that the acid concentration was at all times considerably in excess of the metal complex concentration, and could therefore be taken as remaining constant throughout the course of the acid dissociation. The use of a variable drive unit to dispense different volumes of reactant solution from each syringe in the stopped-flow allowed a range of different complex concentrations to be examined, and together with the variety of standard acid solutions used, enabled a comprehensive acid-dependence profile to be obtained for each complex.

Reactions were studied at or near the absorption maximum of each complex. The Canterbury SF-3A has a 2 mm path length and the stopped-flow was calibrated to give a 3 volt deflection on the oscilloscope for the

0-100% transmittance range. A bias voltage was applied to offset the photomultiplier output and the storage oscilloscope could thus be used to monitor small voltage (and therefore absorbance) changes corresponding to a total absorbance drop of typically 0.05 absorbance units. The change in the output voltage of the photomultiplier as a function of time during the reaction was recorded on the storage oscilloscope. The traces were photographed on 35 mm film, enlarged and traced onto graph paper. For each acid concentration at least three photographs of different reactions were taken, and each trace consisted of at least two overlapping curves to ensure that a good "push" had occurred.

The voltage-time data was analysed using the STPFLO program (see Appendix II) which converts the data to absorbance vs time coordinates and performs a linear regression giving the slope (corresponding to the rate) and intercept (corresponding to A_0 - the initial absorbance of the solution) as well as a correlation coefficient for the $\ln(A-A_\infty)$ vs time plot. These graphs were linear for at least three half-lives, indicating that the reactions are indeed first order under the conditions of the experiment. In any case where the correlation coefficient was less than 99.9%, graphs of $\ln(A-A_\infty)$ vs time were constructed to determine whether any small but systematic curvature was being overlooked by the regression program. In general it was found that if the correlation coefficient was between 99% and 99.9% then a systematic curvature was indeed present. In these cases the latter part of the curved plot was rejected and the slope was recalculated on the basis of the initial linear part of the graph. Curves with a correlation coefficient <99% were rejected.

The slower reactions (the acid dissociation of $[\text{Cu}([\text{15}] \text{aneN}_5)]^{2+}$ in nitrate and perchlorate medium) were studied in conventional spectrophotometers using 1.000 cm path length silica cells thermostatted at 25.0°C.

The reactant solutions were also thermostatted before use, and then mixed using precision syringes or micropipettes with volumes that were reproducible to better than 1%. Alternatively, a solid sample of the copper complex was rapidly dissolved (<10 s) in a thermostatted acid solution of the required concentration and ionic strength. Using this method, the acid dissociation kinetics could be studied in solutions up to 1.00 M in acid concentration. In either case, the decrease in absorbance with time (at the absorbance maximum of the copper complex in the visible region of the spectrum) was obtained using the time-drive mode, and from these traces, plots of $\ln(A-A_\infty)$ vs time were constructed to determine the kinetic parameters.

In the case of the acid dissociation kinetics of $[\text{Cu}([\text{15}] \text{aneN}_5)]^{2+}$ in the most dilute acid solutions studied (0.05 M and 0.1 M), the reactant solutions did not become colourless, and the visible spectrum resembled that of the original complex considerably diluted together with the $\text{Cu}^{2+}(\text{aq})$ species. Addition of copper(II) nitrate to these equilibrated solutions led to a rapid increase in the intensity of the peak at 585 nm (λ_{max} of $[\text{Cu}([\text{15}] \text{aneN}_5)]^{2+}$).

For $[\text{Cu}([\text{17A}] \text{aneN}_5)]^{2+}$, the temperature dependence of the rate constant was used to derive activation parameters from the Arrhenius plot. The slope of the plot of $\ln k$ against T^{-1} corresponds to $-E_a/R$ and the intercept to $\ln A$. Hence, using the relationships²⁹⁹

$$\Delta H_T^\ddagger = E_a - nRT \quad 2.1$$

(where $n=1$ for liquid phase reactions).

$$\Delta S_{298}^{\ddagger} = R(\ln A - 30.46) \text{ J K}^{-1} \text{ mol}^{-1} * \quad 2.2$$

$\Delta H_{298}^{\ddagger}$ and $\Delta S_{298}^{\ddagger}$ have been determined.

The results of the acid dissociation kinetics studies are listed in Tables 2.29(a) to 2.37(b) and figures 2.15 to 2.23.

$$* \text{ from } A = \frac{RT}{Nh} \exp\left(n + \frac{\Delta S^{\ddagger}}{R}\right)$$

TABLE 2.29(a)

Acid Dissociation Kinetics of $[\text{Cu}(\text{[15]aneN}_5)]^{2+}$

$[\text{H}^+]$ mol dm^{-3}	$[\text{H}^+]^2$ $\text{mol}^2 \text{dm}^{-6}$	$k_{\text{obs}}^{\text{a}}$ s^{-1}	$k_{\text{calc}}^{\text{b}}$ s^{-1}
0.050	0.0025	0.00126(5) ^c	0.00039
0.100	0.0100	0.0023(2) ^c	0.0016
0.20	0.040	{ 0.006(1) 0.0062(2) ^c	0.0063
0.25	0.063	0.0106(4)	0.0098
0.30	0.090	0.0139(1) ^c	0.0140
0.35	0.123	0.019(1)	0.019
0.40	0.160	{ 0.024(1) 0.0250(5) ^c	0.0251
0.45	0.203	0.031(1)	0.0318
0.50	0.250	{ 0.039(1) 0.0395(7) ^c	0.0392
0.60	0.360	0.056(1) ^c	0.057
0.70	0.490	0.076(2) ^c	0.077
0.80	0.640	0.105(5) ^c	0.100
0.90	0.810	0.125(5) ^c	0.127
1.33 ^d		0.51(2)	0.28
2.00 ^e		1.2 (1)	0.63
2.66 ^f		1.8 (1)	1.11
3.00 ^g		2.0 (2)	1.41

^a k_{obs} obtained by mixing solutions of metal complex and acid unless otherwise labelled (see c); the values in parentheses represent the uncertainty in the final figure of k_{obs} .

^b Based on $k_{\text{calc}} = 0.157(\pm 0.005) [\text{H}^+]^2 + 0.0000(\pm 0.0015)$ (uncertainties $\pm 3\sigma$ by linear regression on values $[\text{H}^+] \leq 0.9 \text{ M}$; $r = 0.9992$).

^c k_{obs} obtained by dissolving solid metal complex in acid solution.

^d $I = 2.00$ ^e $I = 2.50$ ^f $I = 3.00$ ^g $I = 3.25$.

TABLE 2.29(b)

Acid Dissociation Kinetics of
 $[\text{Cu}([15]\text{aneN}_5)]^{2+}$ in the Presence of Weak Acid

$[\text{H}^+]$ mol dm ⁻³	$[\text{HOAc}]$ mol dm ⁻³	$k_{\text{obs}}^{a,b}$ s ⁻¹
0.40	0.00	0.0250(5)
0.40	0.08	0.0251(5)
0.40	0.20	0.0245(5)
0.40	0.32	0.0247(5)
0.40	0.40	0.0246(5)

^a The values in parentheses represent the uncertainty in the final figure of k_{obs} .

^b Obtained by dissolving the solid complex in solutions with the acid concentrations listed.

Acid Dissociation Kinetics of $[\text{Cu}([\text{15}] \text{aneN}_5)]^{2+}$

fig 2.15 a

Acid Dissociation Kinetics of $[\text{Cu}([15]\text{aneN}_5)]^{2+}$ including values with $I > 1.0 \text{ M}$

fig 2.15 b

TABLE 2.30(a)

Acid Dissociation Kinetics of $[\text{Cu}([16]\text{aneN}_5)]^{2+}$

$[\text{H}^+]$ mol dm^{-3}	$k_{\text{obs}}^{\text{a}}$ s^{-1}	$k_{\text{calc}}^{\text{b}}$ s^{-1}
0.10	0.132(8)	0.133
0.15	0.29(3)	0.28
0.20	0.46(3)	0.47
0.23	0.60(2)	0.59
0.25	0.64(4)	0.67
0.27	0.74(3)	0.75
0.30	0.87(2)	0.87
0.33	0.99(2)	0.99
0.38	1.13(5)	1.16
0.40	1.25(7)	1.25
0.45	1.37(5)	1.42
0.50	1.50(4)	1.56
0.53	1.63(2)	1.65
0.60	1.82(6)	1.81
0.67	2.00(10)	1.95
0.68	1.98(8)	1.97
0.75	2.15(10)	2.08

^aThe values in parentheses represent the uncertainty in the final figure of k_{obs} .

^bBased on $k_{\text{calc}} = \frac{13.9(\pm 0.1) [\text{H}^+]^2}{1+4.9(\pm 0.5) [\text{H}^+]^2}$.

(uncertainties $\pm 3\sigma$ by linear regression; $r=0.9997$).

TABLE 2.30(b)

Acid Dissociation Kinetics of
 $[\text{Cu}(\text{[16]aneN}_5)]^{2+}$ in the Presence of Weak Acid

$[\text{H}^+]$ mol dm ⁻³	$[\text{HOAc}]$ mol dm ⁻³	$k_{\text{obs}}^{\text{a}}$ s ⁻¹
0.50	0.00	1.50(4)
0.50	0.025	1.56(10)
0.50	0.20	1.59(10)
0.50	0.30	1.53(5)
0.50	0.40	1.51(2)
0.50	0.50	1.50(4)

^aThe values in parentheses represent the uncertainty in the final figure of k_{obs} .

Acid Dissociation Kinetics of $[\text{Cu}([16]\text{aneN}_5)]^{2+}$

fig 2.16 a

Acid Dissociation Kinetics of $[\text{Cu}([\text{16}] \text{aneN}_5)]^{2+}$

fig 2.16 b

TABLE 2.31(a)

Acid Dissociation Kinetics of $[\text{Cu}([\text{17A}] \text{aneN}_5)]^{2+}$

$[\text{H}^+]$ mol dm^{-3}	k_{obs}^a s^{-1}			
	6.8°C	15.0°C	25.0°C	35.0°C
0.050	-	-	1.75(9)	-
0.067	-	-	2.40(5)	-
0.100	-	-	3.37(9)	-
0.15	1.39(5)	2.54(7)	5.7 (4)	10.1(2)
0.20	1.84(4)	3.36(10)	6.5 (3)	13.2(1)
0.23	-	-	-	15.9(3)
0.25	2.30(6)	4.18(10)	8.7 (7)	16.3(2)
0.27	2.49(8)	4.62(20)	-	17.8(6)
0.30	2.60(8)	5.07(15)	10.3 (6)	19.6(5)
0.33	3.03(5)	-	-	21.7(4)
0.35	3.07(7)	5.90(10)	11.9 (3)	22.9(3)
0.40	3.50(16)	6.30(10)	14.4 (4)	26.3(3)
0.45	4.07(6)	7.16(10)	16.5 (5)	29.0(4)
0.47	4.10(8)	-	-	31.1(9)
0.50	4.41(7)	8.41(20)	16.8 (6)	32.7(4)
0.53	4.87(16)	8.90(10)	17.3(10)	34.7(6)
0.60	5.50(20)	10.0 (3)	20.0(10)	39.9(9)
0.67	5.96(10)	10.8 (6)	23.5(9)	43.5(13)
0.68	6.36(35)	11.0 (3)	-	-
0.75	6.60(43)	-	26(1)	48(1)
1.00 ^b	11.6(5)	21.0 (6)	38(2)	82(2)
1.33 ^c	15.5(10)	30.5(10)	59(4)	112(5)
1.50 ^d	17(1)	-	-	135(5)
2.00 ^e	32(1)	-	102(5)	227(20)
2.66 ^f	42(4)	-	-	256(50)
3.00 ^g	62(5)	-	-	-

^a The values in parentheses represent the uncertainty in the final figure of k_{obs} .

^b_I = 1.50

^c_I = 1.66

^d_I = 1.75

^e_I = 2.50

^f_I = 3.00

^g_I = 3.25

TABLE 2.31(b)

Acid Dissociation Kinetics of
 $[\text{Cu}([\text{17A}] \text{aneN}_5)]^{2+}$ in Weak Acid

Acid	[HA]	$[\text{H}^+]$ ^a	k_{obs} ^b	k_{calc} ^c
	mol dm ⁻³	mol dm ⁻³	s ⁻¹	s ⁻¹
Acetic	0.50	3.5×10^{-3}	0.52(3)	0.52
	0.67	4.0×10^{-3}	0.67(3)	0.67
Chloroacetic	0.50	3.2×10^{-2}	5.6(5)	5.6
	0.67	3.7×10^{-2}	7.3(5)	7.3

^a see ref. 285 for pK_a values at $I=1.00$.

^b The value in parentheses represents the uncertainty in the final figure of k_{obs} .

^c Based on $k_{\text{calc}} = 34[\text{H}^+] + 0.8[\text{HOAc}]$ for acetic acid
 $k_{\text{calc}} = 34[\text{H}^+] + 9[\text{HClOAc}]$ for monochloroacetic acid.

Acid Dissociation Kinetics of $[\text{Cu}([\text{17A}] \text{aneN}_5)]^{2+}$

fig 2.17 a

Acid Dissociation Kinetics of $[\text{Cu}([\text{17A}] \text{aneN}_5)]^{2+}$
including values with $I > 1.0 \text{ M}$

fig 2.17 b

TABLE 2.32

Rate Constants and Activation Parameters
for the Acid Dissociation of $[\text{Cu}([\text{17A}] \text{aneN}_5)]^{2+}$

Temp. ^a °C	k ^b s ⁻¹	k ₀ ^{b,c} s ⁻¹	r ^d
6.8	9.0(±0.5)	0.00(±0.24)	0.998
15.0	16.0(±0.8)	0.16(±0.36)	0.998
25.0	34(±2)	0.09(±0.39)	0.997
35.0	64(±2)	0.6 (±0.9)	0.999

$$E_a = 51.3(\pm 0.6) \text{ kJ mol}^{-1} \text{ }^b$$

$$\Delta H_{298}^\ddagger = 48.8(\pm 0.6) \text{ kJ mol}^{-1} \text{ }^b$$

$$\Delta S_{298}^\ddagger = -52.0(\pm 3) \text{ J K}^{-1} \text{ mol}^{-1} \text{ }^b$$

^a temperatures ±0.1 °C

^b uncertainties ±3σ by linear regression using values listed in Table 2.31(a): 0.05 M ≤ [H⁺] ≤ 0.75 M

^c values experimentally indistinguishable from zero.

^d correlation coefficient for $k_{\text{obs}} = k[\text{H}^+] + k_0$

fig 2.18

TABLE 2.33

Acid Dissociation Kinetics of $[\text{Cu}(\text{[17B]aneN}_5)]^{2+}$

$[\text{H}^+]$ mol dm^{-3}	$k_{\text{obs}}^{\text{a}}$ s^{-1}	$k_{\text{calc}}^{\text{b}}$ s^{-1}
0.15	31.3(3)	31.3
0.20	35.0(5)	34.5
0.28	39.7(8)	39.7
0.30	40.9(6)	40.9
0.37	44.8(8)	45.3
0.40	47.5(10)	47.2
0.41	48.0(10)	47.8
0.45	50.4(10)	50.3
0.50	53.4(10)	53.5
0.60	63(3)	59.7
0.67	60(3)	64.0
0.75	63(3)	69.0

^a the values in parentheses represent the uncertainty in the final figure of k_{obs}

^b based on $k_{\text{calc}} = \frac{23(\pm 1) [\text{H}^+] + 62(\pm 2) [\text{H}^+]^2}{0.005(\pm 0.001) + [\text{H}^+]}$

(uncertainties $\pm 3\sigma$ by regression; $r = 0.999$ using values for $[\text{H}^+] \leq 0.5 \text{ M}$).

Acid Dissociation Kinetics of $[\text{Cu}([\text{17B}] \text{aneN}_5)]^{2+}$

fig 2.19

TABLE 2.34

Acid Dissociation Kinetics of $[\text{Cu}([\text{18A}] \text{aneN}_5)]^{2+}$

$[\text{H}^+]$ mol dm^{-3}	$k_{\text{obs}}^{\text{a}}$ s^{-1}	$k_{\text{calc}}^{\text{b}}$ s^{-1}
0.15	13.3(10)	13.2
0.20	14.7(7)	15.3
0.23	16.2(4)	16.6
0.25	17.2(4)	17.4
0.27	18.7(4)	18.3
0.30	19.2(4)	19.5
0.33	20.9(4)	20.7
0.35	21.7(5)	21.6
0.40	23.7(5)	23.6
0.45	25.9(5)	25.7
0.47	26.3(7)	26.5
0.50	27.8(7)	27.7
0.53	29.0(7)	28.9
0.60	31.2(10)	31.8
0.67	34.7(10)	34.6
0.68	34.4(10)	35.0
0.75	37.2(10)	37.9

^a The values in parentheses represent the uncertainty in the final figure of k_{obs} .

^b Based on $k_{\text{obs}} = \frac{8.0(\pm 0.4) [\text{H}^+] + 40.5(\pm 0.6) [\text{H}^+]^2}{0.010(\pm 0.003) + [\text{H}^+]}$

(uncertainties $\pm 3\sigma$ by regression; $r = 0.999$).

Acid Dissociation Kinetics of $[\text{Cu}([18\text{A}] \text{aneN}_5)]^{2+}$

fig 2.20

TABLE 2.35(a)

Acid Dissociation Kinetics of $[\text{Cu}(\text{[18B]aneN}_5)]^{2+}$

$[\text{H}^+]$ mol dm^{-3}	$k_{\text{obs}}^{\text{a}}$ s^{-1}	$k_{\text{calc}}^{\text{b}}$ s^{-1}
0.10	2.02(10)	2.11
0.15	2.85(15)	2.81
0.20	3.60(10)	3.50
0.25	4.35(15)	4.18
0.27	4.72(8)	4.46
0.30	4.97(8)	4.87
0.33	5.32(8)	5.28
0.35	5.50(10)	5.55
0.38	6.00(10)	5.96
0.40	6.3 (2)	6.2
0.45	7.0 (2)	6.9
0.47	7.1 (2)	7.2
0.50	7.5 (2)	7.6
0.60	8.8 (2)	9.0
0.67	9.6 (6)	9.9
0.75	11.0 (5)	11.0
1.00 ^c	14.3 (6)	14.4
1.33 ^d	18.1 (8)	18.9
1.50 ^e	20.6 (9)	21.2

^a The figures in parentheses represent the uncertainty in the final figure of k_{obs} .

^b Based on $k_{\text{calc}} = \frac{0.9(\pm 0.2) [\text{H}^+] + 13.6(\pm 0.5) [\text{H}^+]^2}{0.007(\pm 0.002) + [\text{H}^+]}$

(uncertainties $\pm 3\sigma$ by regression; $r = 0.9987$, using values with $[\text{H}^+] \leq 0.75 \text{ M}$).

^c $I = 1.50$

^d $I = 1.67$

^e $I = 1.75$

TABLE 2.35(b)

Acid Dissociation Kinetics of
 $[\text{Cu}([\text{18B}] \text{aneN}_5)]^{2+}$ in the Presence of Weak Acid

$[\text{H}^+]$ mol dm ⁻³	$[\text{HOAc}]$ mol dm ⁻³	k_{obs} ^a s ⁻¹	k_{calc} ^b s ⁻¹
0.50	0.00	7.5(2)	7.6
0.50	0.05	7.7(2)	7.7
0.50	0.30	8.4(2)	8.5
0.50	0.50	9.0(3)	9.1

^a The values in parentheses represent the uncertainty in the final figure of k_{obs} .

^b Based on $k_{\text{calc}} = \frac{0.9 [\text{H}^+] + 13.6 [\text{H}^+]^2}{0.007 + [\text{H}^+]} + 3.0 [\text{HOAc}]$

Acid Dissociation Kinetics of $[\text{Cu}([18\text{B}]aneN_5)]^{2+}$

fig 2.21 a

Acid Dissociation Kinetics of $[\text{Cu}([\text{18B}] \text{aneN}_5)]^{2+}$ including values with $I > 1.0 \text{ M}$

fig 2.21 b

TABLE 2.36

Acid Dissociation Kinetics of $[\text{Cu}([\text{19}] \text{aneN}_5)]^{2+}$

$[\text{H}^+]$ mol dm^{-3}	$k_{\text{obs}}^{\text{a}}$ s^{-1}	$k_{\text{calc}}^{\text{b}}$ s^{-1}
0.05	91(7)	100
0.10	123(7)	119
0.15	130(4)	129
0.20	132(6)	136
0.25	143(4)	142
0.30	149(10)	147
0.35	151(4)	152
0.40	156(6)	156
0.45	164(4)	160
0.50	161(6)	164
0.525	173(4)	166
0.533	167(6)	167
0.60	172(5)	172
0.003 ^c	41(2)	18

^a The values in parentheses represent the uncertainty in the final figure of k_{obs} .

^b Based on $k_{\text{calc}} = \frac{136(\pm 8) [\text{H}^+] + 70(\pm 10) [\text{H}^+]^2}{0.020(\pm 0.008) + [\text{H}^+]}$

obtained by nonlinear regression.

^c Value for 0.5 mol dm^{-3} acetic acid.

Acid Dissociation Kinetics of $[\text{Cu}([\text{19}] \text{aneN}_5)]^{2+}$

fig 2.22

TABLE 2.37(a)

Acid Dissociation Kinetics of $[\text{Cu}([\text{20}] \text{aneN}_5)]^{2+}$

$[\text{H}^+]$ mol dm^{-3}	$k_{\text{obs}}^{\text{a}}$ s^{-1}	$k_{\text{calc}}^{\text{b}}$ s^{-1}
0.050	45(5)	44
0.10	55(5)	55
0.15	60(5)	61
0.20	62(5)	64
0.25	69(5)	67
0.30	71(5)	69
0.33	70(5)	70
0.50	74(5)	75
1.00	100(10)	86
2.00	135(25)	106

^a The values in parentheses represent the uncertainty in the final figures of k_{obs} .

^b Based on $k_{\text{calc}} = \frac{70(\pm 7) [\text{H}^+] + 19(\pm 2) [\text{H}^+]^2}{0.030(\pm 0.005) + [\text{H}^+]}$

TABLE 2.37(b)

Dissociation Kinetics of $[\text{Cu}([20]\text{aneN}_5)]^{2+}$
in Acetic Acid

$[\text{HOAc}]$ mol dm^{-3}	$[\text{H}^+] \times 10^3$ ^c mol dm^{-3}	k_{obs} ^a s^{-1}	k_{calc} ^b s^{-1}
0.10	1.55	13.5(5)	3.4
0.30	2.70	25.0(1)	5.8
0.40	3.12	26.0(1)	6.6
0.50	3.49	30.0(1)	7.3

^a The values in parentheses represent the uncertainty in the final figure of k_{obs} .

^b Based on $k_{\text{calc}} = \frac{70 [\text{H}^+] + 19 [\text{H}^+]^2}{0.030 + [\text{H}^+]}$

^c Calculated using pK_a value for I=100 (ref. 285).

Acid Dissociation Kinetics of $[\text{Cu}([\text{20}] \text{aneN}_5)]^{2+}$

fig 2.23

Chapter 3

DISCUSSION OF RESULTS

3.1 Synthesis of Macrocyclic Amines3.1.1 Cyclization Reaction

The Richman and Atkins procedure⁶⁵ for the synthesis of macrocyclic amines is well established as an efficient route requiring neither metal template nor high dilution methods. The use of segments of relatively similar length in the cyclization step has been proposed as one requirement for high yields, and this is supported by the different yields obtained in the synthesis of Ts₆-[18]aneN₆ from two different pairs of starting segments (scheme 13).

SCHEME 13

However, in the absence of a template effect⁶⁵ it is less likely that both 'ends' of the target molecule would couple simultaneously, and the species LXXI has been proposed as the immediate precursor to the final product.

LXXI

If this is the case, the different segments would both give the same intermediate, and no difference would be expected in the yields of the different cyclization reactions. It seems likely therefore, that other factors (such as the relative stabilities of the different tosylates or of the sodium salts of the tosylamides in the conditions present during the reaction) are significant. This is borne out by the similarity of the yields of Ts₅-[15]aneN₅ obtained by two different routes (Scheme 14)

SCHEME 14

with different relative segment sizes, and by the absence of any pattern in the yields of the other cyclization reactions.

The most critical factor in maximising the yield of the cyclization reaction appears to be the exclusion of water from the reaction mixture. When the solvent (DMF) was thoroughly dried and distilled prior to use, and protected from atmospheric moisture during the reaction, the yields were significantly improved. When low yields were obtained, the predominant contaminant was the linear tosylamide precursor of the sodium salt, so the failure of the cyclization reaction had occurred even before the first coupling reaction. (The tosylamides themselves are not powerful enough nucleophiles to attack the tosylates). When sodium salts of the tosylamides were dissolved in DMF and exposed to the atmosphere for several hours at 110°C and then recovered from the solution, an appreciable amount of hydrolysis occurred, resulting in the reformation of the parent tosylamide.

The other important factor appears to be the instability of the tosylates at $\geq 100^\circ\text{C}$ in the cyclization mixture. If the formation of the macrocycle is slow, the decomposition of the tosylate can compete with the cyclization reaction, and this has indeed been shown to take place.⁸⁰ In order to increase the rate of cyclization, the concentration of the cyclization reagents in the DMF was increased by a factor of >3 over those originally used by Richman and Atkins. This also lessens the relative concentration of water in the system, and therefore hydrolysis of the sodium salt of the tosylamide is reduced. Again, considerable improvement was observed in the yield of the cyclization product.

In some cyclization reactions using this method, (notably those involving synthesis of triazamacrocycles), partially cyclized linear products or larger macrocycles resulting from the condensation of four

segments instead of two, have been reported.^{65,75,76,267} In the present study, little evidence was found for the formation of an appreciable amount of partially cyclized material, or the 2+2 cyclic adducts, although attempts to purify the detosylated amines (derived from crude tosylamides) by distillation did result in the isolation of small amounts of unidentified higher boiling residues in some cases.

The absence of an N-H stretching vibration in the infrared spectrum of the cyclization product, together with a single S=O stretching vibration at $\sim 1150\text{ cm}^{-1}$ could readily be used to establish the absence of unreacted starting material. The ^{13}C n.m.r. spectra were also used to confirm the purity of the products. Each of the macrocycles prepared has at least nominally C_2 symmetry (if conformational differences are ignored) and the number of resonances in the ^{13}C n.m.r. spectra indicate that even the tosylated macrocycles are conformationally labile on the n.m.r. timescale. Assignment of particular resonances to specific carbon atoms in the macrocyclic ring was not attempted (except where symmetry arguments could be applied, or to distinguish between carbon atoms adjacent to a nitrogen atom and those bonded to two other carbon atoms), as the chemical shift of any atom appeared to be sensitive to changes in the species up to six atoms away in the macrocyclic chain. In principle, however, it should be possible to assign the resonances on the basis of an extension of the parameters of Lindman and Adams.³⁰⁰

3.1.2 Detosylation Reactions

Detosylation of the macrocycles has previously been achieved by two distinct methods. Either the macrocyclic tosylamide was heated at $\sim 100^\circ\text{C}$ for several days in concentrated sulphuric acid^{69,71}

(1-2 moles of $\sim \text{N-Ts}/\text{dm}^3$ of acid) to effect hydrolytic detosylation, or heated at reflux temperature with $\sim 30\%$ hydrobromic acid in glacial acetic acid for periods of a day or longer^{70,82,244} (0.05-0.1 moles of $\sim \text{N-Ts}/\text{dm}^3$ of acid), resulting in reductive detosylation. The first method was rejected on the grounds of the difficulty of workup reported and the protracted heating required, and the latter on the grounds that excessive quantities of the hydrobromic acid/acetic acid mixture were consumed.

The use of a considerably smaller amount of hydrobromic acid in glacial acetic acid was made possible by performing the detosylation in sealed reaction tubes containing the tosylated macrocycle in approximately ten times the concentration reported by other workers. The greater concentration of tosylamide resulted in a considerably increased reaction rate, and the detosylation was generally complete after several hours. However, in some cases problems were encountered with the limited solubility of the partially detosylated hydrobromide salts due to the high concentrations of macrocycle being used, and longer periods of heating, or a second detosylation of the residues was found to be necessary to overcome the problem and maximise the yield.

The use of phenol as a bromine scavenger⁸² led to an increased yield of product in the detosylation of $\text{Ts}_5\text{-[19]aneN}_5$, but with the other macrocycles, the yield did not appear to improve significantly with the addition of phenol.

3.1.3 Free Macrocyclic Amines

The macrocyclic amines synthesised in this study comprise all possible combinations of dimethylene and trimethylene bridges between five secondary amine groups arranged in a monocyclic configuration (LXXII-LXXIX).

It is evident that in terms of their symmetry, they can be grouped into complementary pairs as shown. Their conformational lability in solution is shown by the n.m.r. spectra which in each case show degenerate resonances reflecting the highest symmetry possible for each macrocycle.

The synthesis of the previously unknown ligand tetrpn (LXXX) was undertaken to provide a linear pentamine analogue of the pentaazamacrocycles

which is capable of forming only six-membered chelate rings, as a contrast to tetren (LXXXI) which forms only five-membered chelate rings.

Attempts to repeat the reported non-template cyclization of linear amines with glyoxal in the presence of calcium hydroxide produced the tricyclic species LXXXII and LXXXIII from 2,2,2-tet and 3,2,3-tet,

formed by bridging addition of the glyoxal across all four amine groups. These are the same products that are obtained in the absence of calcium hydroxide, but the yields are considerably improved. (This may be due to the use of the glyoxal bisulphite adduct rather than aqueous glyoxal⁶⁰ which is known to polymerize on standing³⁰¹). Neither of the linear pentamines gave a stable condensation product with glyoxal, and only starting material could be isolated from the crude reaction mixture on distillation.

Although elemental analysis of the free amines was generally unsatisfactory (most are moisture sensitive), other standard techniques all produced satisfactory results. The ^1H and ^{13}C n.m.r. spectra provide a ready means of characterization for the free amines, but as the chemical shifts of the ^{13}C n.m.r. resonances appear to be pH and concentration dependent in aqueous solution, it is preferable to run the spectra in deuterated chloroform, where concentration dependence is not observed. The ^{13}C resonances of the free amines in CDCl_3 and their tosylamide counterparts have quite similar chemical shifts, whereas the resonances are all shifted to higher field in aqueous solution (both acidic and alkaline). Analysis by g.l.c. confirmed not only the purity of the amines, but also provided good linear plots of molecular weight against the logarithm of retention time (fig. 3.1) as has previously been reported for both macrocyclic and linear amines.³⁰² This suggests that the amine functions do not interact significantly with the stationary phase as the linear relationship remains unaffected by variations in the number of primary or secondary amine groups present in the molecule.

fig 3.1

3.2 Copper(II) and Nickel(II) Complexes

3.2.1 Preparation of Complexes

Preparation of the copper(II) and nickel(II) complexes of both the linear and the macrocyclic pentamines was readily achieved in high yield by mixing solutions of the appropriate metal salt and the free amine in alcohol. This method was preferred to that of reacting the ligand hydrobromide with a metal carbonate,¹⁶⁷ or neutralization of a mixture of the amine hydrobromide and the metal salt with base. Both of the latter methods produce considerable amounts of inorganic salts in solution, as well as requiring the reaction to be carried out in water. In contrast to the previously reported synthesis of $\text{Ni}([\text{17B}] \text{aneN}_5)(\text{ClO}_4)_2$,¹³⁴ no yellow intermediate was observed, and the complexation reaction occurred rapidly with the addition of each drop of the metal salt (as for all the other complexation reactions).

3.2.2 Structure of the Copper(II) and Nickel(II) Complexes

The copper(II) and nickel(II) complex cations comprise a metal atom surrounded by the cyclic or linear pentamine which is capable of coordinating through the five nitrogen donors (although there is a possibility that not all of the amine groups are coordinated). The coordination sphere may also include one or more coordinated anions. Five, six and even seven-coordination^{1,31,154,303,304} are all known for copper(II) and nickel(II) complexes. Infrared and visible spectroscopy as well as conductivity measurements were used to elucidate the coordination number and geometry of the complexes.

3.2.2.1 Infrared Spectra of the Perchlorate Complexes

When a perchlorate anion forms a single covalent bond via one of the oxygen atoms, its symmetry is lowered from T_d to C_{3v} and the infrared spectrum is significantly affected.³⁰⁵⁻³⁰⁷ The intense ν_3 band at $\sim 1100\text{ cm}^{-1}$ (antisymmetric stretch) is replaced by two bands at $\sim 1050\text{ cm}^{-1}$ and $\sim 1120\text{ cm}^{-1}$ while the ν_4 band at $\sim 625\text{ cm}^{-1}$ (antisymmetric bend) is split into bands at $\sim 615\text{ cm}^{-1}$ and $\sim 630\text{ cm}^{-1}$. However, assignment of the structure on this basis alone must be made with caution, as differing degrees of coordination can markedly affect the spectrum. Hydrogen bonding interactions involving the perchlorate anion can also lead to a reduction in symmetry, obscuring the difference between ionic and monodentate bonding. In the case of the complexes involved in the present study, the possibility of one ionic and one monodentate perchlorate being present complicates the matter further, as there would then be three peaks around 1100 cm^{-1} and three around 620 cm^{-1} , and they would quite possibly remain unresolved, particularly if the perchlorate anion were only weakly coordinated.

Among the copper(II) complexes, only $\text{Cu}([\text{15}] \text{aneN}_5)(\text{ClO}_4)_2$ shows any splitting of the ν_4 band ($619, 625\text{ cm}^{-1}$; Table 2.5). This splitting is less than that normally observed for monodentate perchlorate,^{306,307} and the splitting expected in the ν_3 band for coordinated perchlorate is completely absent. Although some broadening of the ν_3 band is present in a number of the other copper(II) complexes, there is no well-defined splitting of the magnitude expected upon coordination, and the broadening is more likely to be the result of the slightly different environments of two ionic perchlorates.

Similarly, only $\text{Ni}([\text{15}] \text{aneN}_5)(\text{ClO}_4)_2$ exhibits splitting of the ν_4 band ($619, 625\text{ cm}^{-1}$; $\Delta\nu_4\ 6\text{ cm}^{-1}$ Table 2.11). In this case the ν_3 band is

also split ($1050, 1085\text{ cm}^{-1}$; $\Delta\nu_3\ 35\text{ cm}^{-1}$ Table 2.11), but these values are substantially less than those expected for monodentate perchlorate ($\Delta\nu_4\sim 15\text{ cm}^{-1}$; $\Delta\nu_3\geq 80\text{ cm}^{-1}$),^{306,307} and it is possible that "semi-coordination"^{308,309,324,325} or interactions of the perchlorate ions in the crystal lattice may be responsible. In the case of $\text{Ni}([16]\text{aneN}_5)(\text{ClO}_4)_2$, although the ν_3 band is split ($1044, 1102\text{ cm}^{-1}$), no corresponding splitting of the ν_4 band is observed. The complexes of both the seventeen and the eighteen-membered macrocycles also show appreciable broadening of the ν_3 band, but again there is no evidence of splitting in the ν_4 band. So although weak interactions between the perchlorate ions and the complex cation may be present, there is no unambiguous infrared spectral evidence for coordinated perchlorate in any of the complexes investigated.

3.2.2.2 Infrared Spectra of the Nitrate Complexes

The nitrate anion can function as either an ionic, monodentate, bidentate or bridging ligand. By analogy with the perchlorate ion, the symmetry is lowered from D_{3h} in ionic nitrate to C_{2v} or C_s upon coordination.³¹⁰ Curtis and Curtis³¹¹ have reported fundamental absorption bands of the nitrate ion acting as ionic, monodentate or bidentate ligands in a series of nickel(II) polyamine complexes. The ν_1 band ($\sim 1000\text{ cm}^{-1}$) of the ionic nitrate becomes infrared active upon coordination, but its presence or absence could not be confirmed in the present study because of the presence of ligand bands in the same region. The ν_3 band ($\sim 1370\text{ cm}^{-1}$) and the ν_4 band ($\sim 700\text{ cm}^{-1}$) are split upon coordination of the nitrate, and the distinction between monodentate and bidentate coordination is reflected in the different degree of splitting ($\Delta\nu_3$: monodentate $\sim 110\text{ cm}^{-1}$, bidentate $\sim 190\text{ cm}^{-1}$; $\Delta\nu_4$: monodentate $\sim 15\text{ cm}^{-1}$, bidentate $\sim 45\text{ cm}^{-1}$).

The ν_4 band was however obscured by ligand bands, so only the ν_3 band could be used to investigate the possibility of coordination.

In both the copper(II) and nickel(II) complexes the ν_3 band showed considerable complexity (Tables 2.6 and 2.12), although in most complexes the maximum splitting was less than the 110 cm^{-1} reported for monodentate coordination. (In no case was the splitting as large as that expected for bidentate coordination which was also considered unlikely for other reasons). If the complexes contain both ionic and monodentate nitrate, there should be three ν_3 bands, and their overlap with the ligand bands observed in the region could well be expected to lead to complex envelopes such as those observed, particularly if a hydrogen bonding network involving the nitrates and the amine-hydrogens were also present. Unequivocal assignments could thus not be made on the basis of the fundamental bands in the infrared spectra.

Examination of the overtone and combination bands of the nitrate spectrum has the advantage that no interfering ligand vibrations are present, but they are generally very weak. The weak peaks observed at $\sim 2300\text{ cm}^{-1}$ and $\sim 1750\text{ cm}^{-1}$ have been assigned to the $(\nu_1 + \nu_3)$ and $(\nu_1 + \nu_4)$ combination bands, and that at $\sim 2000\text{ cm}^{-1}$ to the $(2\nu_1)$ overtone.³¹¹ The splitting of the ν_3 and ν_4 fundamentals are accompanied by a corresponding splitting of their combination bands.

The infrared spectra of thick mulls of the nitrate salts were run, and the overtone and combination bands are listed in Tables 2.7 and 2.13. Unfortunately, the results are not as clear as those obtained by Curtis and Curtis for the complexes investigated in their study.³¹¹ Compared with reference compounds known to contain ionic and monodentate nitrate (e.g. $[\text{Ni}(\text{teta})](\text{NO}_3)_2$ and $[\text{Ni}(\text{tetb})\text{NO}_3]\text{NO}_3$), the combination bands of the compounds in this study were generally very broad. This is presumably

a reflection of the breadth of the fundamental absorptions giving rise to the combination bands. Consequently the splitting was largely masked by the broad spread of the peaks. So once again, although the spectra are consistent with the presence of coordinated nitrate, the results are not conclusive.

3.2.2.3 Other Infrared Bands

The N-H stretching bands show no discernible pattern, and cover a 200 cm^{-1} range. Most complexes contain more than one $\nu_{(\text{N-H})}$ band, resulting from the different environments of the various amine groups. In each case however, the $\nu_{(\text{N-H})}$ bands in the perchlorate salts occur at lower energy than those in the corresponding nitrates, suggesting that some hydrogen bonding network involving the anions and the N-H is present. This could also account for the broadening of the anion bands in the infrared spectrum.

The infrared spectra of $\text{Cu}([20]\text{aneN}_5)(\text{ClO}_4)_2$ and $\text{Ni}([20]\text{aneN}_5)(\text{ClO}_4)_2$ contain pairs of bands at 3491 , 3593 cm^{-1} and 3489 , 3577 cm^{-1} respectively. As both complexes are anhydrous salts, these are not $\nu_{(\text{O-H})}$ bands. Recrystallization of $\text{Cu}([20]\text{aneN}_5)(\text{ClO}_4)_2$ from deuterium oxide does not shift the peaks, but does lead to increased intensity and sharpness of the peak at 3593 cm^{-1} , and another sharp peak appears at 3544 cm^{-1} , so the band is somehow related to the amine functionality. Although the sample was heated for some time in deuterium oxide, the N-H peak at $\sim 3280\text{ cm}^{-1}$ did not disappear entirely, so the amine protons appear to have appreciably different exchange rates.

3.2.2.4 Conductivity Studies³¹²

The use of conductivity measurements in organic solvents to characterize coordination compounds is well established, although consistent experimental conditions based on a sound theoretical basis have not always been rigidly adhered to. The use of a single concentration to obtain the molar conductivity has serious limitations, particularly as the expected conductivity ranges of the different electrolyte types in different solvents appears to vary with the nature of the cation and the anion.

Nitromethane has been proposed as the preferred solvent,³¹² and it has been used in the present study whenever possible. When the complexes were not soluble in nitromethane, either methanol or acetone was used. Methanol has been reported to be an acceptable solvent, but acetone has apparently proven rather unreliable. However, in this study, the results of conductivity measurements using acetone as the solvent were quite consistent with those obtained using other solvents. In common with many other workers, solutions of approximately millimolar concentration have been used, and the values obtained largely agree with those tabulated for the different electrolyte types in the particular solvent used. However, as Geary points out,³¹² the most valid conclusions can be drawn from comparisons of the different values obtained for series in which closely related complex cations (or anions) are balanced by the same anion (or cation), thus minimising the effect of varying ionic mobilities and other complicating factors.

The molar conductivities of the complexes studied are listed in Table 2.15. In nitromethane, all the nitrate salts that were soluble have molar conductivities indicative of 1:1 electrolytes whereas the perchlorates in the same solvent have molar conductivities characteristic of 1:2 electrolytes (Table 3.1).

TABLE 3.1

Molar Conductivities in Nitromethane^a

Complex ^b	Electrolyte Type	1:1	1:2
Cu L (NO ₃) ₂		86	-
Ni L (NO ₃) ₂		74	-
Cu L (ClO ₄) ₂		-	165
Ni L (ClO ₄) ₂		-	143
Typical values ^c		75-95	150-180

a Λ_M , S cm² mol⁻¹; t=25°C

b Average of all complexes studied

c ref. 312

Although the Ni L (ClO₄)₂ complexes apparently have molar conductivities slightly lower than the typical values quoted for 1:2 electrolytes, it is notable that for both the copper(II) and the nickel(II) complexes the ratio of the molar conductivities of the 1:1 and 1:2 electrolytes is almost identical.

As the nitrate salts of the nickel(II) complexes of [19]aneN₅, [20]aneN₅ and tetrpn were not soluble in nitromethane, their conductivities were determined in methanol. It can be seen from Table 3.2 that the average molar conductivity of the other nickel(II) nitrate salts is typical of a 1:1 electrolyte, as is that of the tetrpn complex, whereas the complexes of the two largest macrocycles are 1:2 electrolytes.

TABLE 3.2

Molar Conductivities in Methanol^a

Complex	Electrolyte Type	1:1	1:2
Ni L (NO ₃) ₂ ^b		111	-
Ni(tetrpn)(NO ₃) ₂		108	-
Ni([19]aneN ₅)(NO ₃) ₂		-	158
Ni([20]aneN ₅)(NO ₃) ₂		-	163
Typical values ^c		80-115	160-220

a Λ_M , S cm² mol⁻¹; t=25°C

b average for all ligands of macrocyclic ring size 15-18

c ref. 312

The conductivities of Ni([19]aneN₅)(ClO₄)₂, Ni([20]aneN₅)(ClO₄)₂ and Ni(tetrpn)(ClO₄)₂ were determined in acetone together with that of Ni([17B]aneN₅)(ClO₄)₂ (which is a 1:2 electrolyte in nitromethane) as a reference. They all had similar molar conductivities, so it is concluded that they are all 1:2 electrolytes. (The alternative is that Ni([17B]aneN₅)(ClO₄)₂ contains a coordinated perchlorate in acetone, but no coordinated perchlorate in nitromethane, and this is considered to be highly improbable. Furthermore if the nitrate anion is unable to coordinate to the complex cation containing the nineteen or twenty-membered macrocycle, the perchlorate anion is even less likely to do so).

The conductivities of the perchlorate salts of the copper(II) complexes that are insoluble in nitromethane were determined in acetone together with that of Cu([17A]aneN₅)(ClO₄)₂ (which is a 1:2 electrolyte in nitromethane). Their molar conductivities were very closely grouped, and close to the values obtained for the nickel(II) complexes of the perchlorates in acetone. Hence it is concluded that these are also

1:2 electrolytes. Reliable values for the molar conductivity of 1:2 electrolytes in acetone are scarce³¹² but the close agreement between the values obtained for the nickel(II) and copper(II) complexes and with the two complexes that are 1:2 electrolytes in nitromethane gives considerable credibility to these results.

The values obtained by Hay¹⁶⁷ for the molar conductivities of $\text{Cu}([\text{15}] \text{aneN}_5)(\text{ClO}_4)_2$ and $\text{Ni}([\text{15}] \text{aneN}_5)(\text{ClO}_4)_2 \cdot \text{H}_2\text{O}$ in nitromethane contrast sharply with the values obtained in this study (Table 2.15) and suggest that both the perchlorate salts are 1:1 electrolytes. Considering the tendency of copper(II) towards five coordination,³⁰³ the known five-coordinate structures of the closely related $\text{Cu}(\text{pyaneN}_5)(\text{PF}_6)_2$ ¹⁵⁴ and $\text{Cu}(\text{dibenzo}[\text{b},\text{o}][1,5,9,13,17]\text{pentaazacycloeicosa}[4,13]\text{diene})(\text{ClO}_4)_2$,¹⁵⁵ as well as the relatively poor donor ability of the perchlorate anion, six-coordination seems unlikely under the circumstances, and the preferential coordination of a perchlorate over one of the amine groups (to preserve five-coordination) even less likely. Furthermore, no indication is given of the concentration at which the values were obtained (although Λ_M is concentration dependent). The discrepancy in the value for $\text{Ni}([\text{15}] \text{aneN}_5)(\text{ClO}_4)_2$ is larger, and nickel(II) readily adopts octahedral coordination. Hay's nickel(II) complex was prepared by a different method from that used in this work, and is reported to be a hydrate (although the reported analytical figures are consistent with the formulation $\text{Ni}(\text{C}_{10}\text{H}_{25}\text{N}_5)(\text{ClO}_4)_2$ rather than with that of the hydrated salt). However, it is possible that Hay has prepared a different isomer, that is hydrated in the solid state and contains a coordinated perchlorate in nitromethane. The visible reflectance spectrum of the sample prepared in this study is also consistent with five-coordination (at least in the solid state) (see section 3.2.2.6) and there is no evidence for hydration, either in the infrared spectrum or in the analytical results.

In conclusion, the conductivity data suggests that with the exception of the nineteen and twenty-membered macrocyclic nickel(II) nitrate complexes, all the $\text{Ni L (NO}_3)_2$ and $\text{Cu L (NO}_3)_2$ complexes contain one ionic and one coordinated nitrate, but that none of the perchlorates are coordinated (although the slightly lowered conductivity values may reflect some small measure of ion association). Perhaps the most surprising feature of these results is the observation that although $\text{Cu([19]aneN}_5\text{)(NO}_3)_2$ and $\text{Cu([20]aneN}_5\text{)(NO}_3)_2$ both have one coordinated and one ionic nitrate the corresponding nickel(II) complexes appear not to contain a coordinated nitrate.

3.2.2.5 Stereochemistry and Spectral Properties of the Copper(II) Complexes

As a consequence of the Jahn-Teller theorem, the d^9 copper(II) system is required to undergo a distortion to remove the degeneracy of the ground state that exists when it is surrounded by an environment of cubic symmetry.³¹⁵ Even for a non-symmetric environment, the theorem is still applicable¹⁴⁹ and hence the ability of copper(III) to adopt a wide range of stereochemistries, including distorted octahedral, square pyramidal and trigonal bipyramidal geometry which are all possible for the pentaaza-macrocyclic complexes and their linear analogues.

In considering the stereochemistry of the copper(II) complexes, the possibility that only four of the five amine groups may be coordinated cannot be overlooked. The concept of cumulative ring strain in multidentate ligands is well established,^{121, 316} and in linear amines such strain can be relieved by non-coordination of a terminal donor group. The ligands 2,3-tri and 2,2,2-tet have been shown to act as monoprotonated bidentate and tridentate ligands in copper(II) complexes under acid conditions,^{126, 317} whereas the hexamine ligands 2,2,2,2,2-hex, penten and ptetraen[†] all

[†]See Appendix

coordinate to copper(II) using only five of the six amine groups.^{126,319} Similarly, one isomer of $\text{Cu}(3, 22, 3\text{-tet})\text{Cl}_2$ is postulated to be five-coordinate with two coordinated chlorides, and only three of the four amine groups of the tetradentate ligand coordinated to copper(II).³²⁰ The electronic absorption spectrum of $\text{Cu}(\text{Me}_7\text{tetren})(\text{ClO}_4)_2$ changes markedly on addition of one equivalent of tetramethylammonium thiocyanate, and it is thought that thiocyanate replaces one of the terminal tertiary amine groups in the coordination sphere of the complex.⁹⁵ Even among the stable tetraaza-macrocyclic copper(II) complexes, the ready protonation of a complexed ligand is inferred from the shift in the half-wave potential of $[\text{Cu}([15]\text{aneN}_4)]^{2+}$ with pH.¹⁸⁷

The only evidence of monoprotection of coordinated pentaazamacrocyclic ligands comes from similar determinations of the shift in $E_{1/2}$ with pH.⁹⁰ The values of $\text{pK}_a(\text{CuHL})$ for $L = [15]\text{aneN}_5$, $[16]\text{aneN}_5$ and $[17\text{B}]\text{aneN}_5$ are given as 4.3, <5 and 4.7 respectively,⁹⁰ and there was no evidence for further protonation in the range $3.8 < \text{pH} < 5.4$ whereas tetren has two observed protonation steps in this range ($\text{pK}_a(\text{CuHL}) = 5.2$, $\text{pK}_a(\text{CuH}_2\text{L}) = 3.8^{124}$).

It may safely be concluded therefore that in neutral solution or in poorly coordinating solvents all five nitrogen donors of the ligands are coordinated. There is little difference in the absorption spectra of the complexes in nitromethane and water, and even addition of excess sodium thiocyanide to an aqueous solution of $[\text{Cu}([20]\text{aneN}_5)]^{2+}$ (arguably one of the more strained complexes), appears to have little if any effect on the absorption spectrum of the complex.

The structures of two pentaazamacrocyclic copper(II) complexes have been determined, involving fifteen and twenty-membered macrocyclic rings respectively.^{154,155} However both macrocycles contain sites of unsaturation which impose steric restraints on the ligand geometry, so direct comparisons

with the structures of fully saturated macrocyclic pentamine complexes must be made with caution. Furthermore, the counter anions in the two complexes (hexafluorophosphate and perchlorate) are uncoordinated (as are the perchlorates in this study) whereas the ligand geometry may be altered by the coordination of an anion (as in the case of those copper(II) complexes for which the presence of coordinated nitrate was established.

The fifteen membered macrocyclic complex $\text{Cu}(\text{pyaneN}_5)(\text{PF}_6)_2$, is described as having distorted trigonal bipyramidal geometry,¹⁵⁴ but in fact could better be described as having distorted square pyramidal geometry. The pyridine ring is shifted below the basal plane, the copper-pyridyl amine bond is shortened ($1.90 \text{ \AA}$) and the copper-nitrogen bond trans to this correspondingly elongated ($2.10 \text{ \AA}$), but all the other bond lengths and angles are consistent with relatively distortion free square pyramidal geometry involving five-membered chelate rings.³²¹ The spectral parameters are also characteristic of square pyramidal rather than trigonal bipyramidal geometry.^{49,149,150}

The twenty membered macrocyclic complex $\text{Cu}(\text{Bzo}_2[20]\text{dienatoN}_5)(\text{ClO}_4)_2^\dagger$ is described as having a distorted square pyramidal geometry and the copper-apical nitrogen bond length ($2.22 \text{ \AA}$) is appreciably greater than that of the copper-basal amine bonds ($2.06 \text{ \AA}$), and this is indicative of the weaker bonding of the apical nitrogen atom which is commonly observed for such geometry.³²² No spectral parameters are given. The complex is reported to be rather strained, and the ligand can be displaced from the copper(II) by treatment with DMF.

It is clear that the less sterically hindered saturated pentaaza-macrocycles should readily be able to adopt similar square pyramidal geometry or elongated tetragonal octahedral geometry in the cases where there is a coordinated nitrate.

[†]See Appendix

The electronic spectra of the copper(II) complexes are listed in Table 2.8 and the spectra are displayed in fig. 2.1. All the macrocyclic complexes have a main band between 585 nm and 625 nm and a well resolved lower energy band between 805 nm and 850 nm. The spectral parameters reported are those derived from aqueous solutions of the perchlorate salts. The position of the main band remains unchanged for aqueous solutions of the nitrate salts and for samples of either anion type in nitromethane. The position and intensity of the low energy band appears to be only slightly sensitive to the nature of the anion or the solvent used. The close similarity of the spectra indicates that there is some uniformity in the stereochemistry of the complexes, and the two bands are reported to be characteristic of five coordinate square pyramidal geometry.^{119,149,150,323} The copper(II) complexes of [15]aneN₅ and [16]aneN₅ have also been investigated using e.s.r. and cyclic voltammetry.⁶ Comparison with fifteen membered macrocycles containing N₄O and N₄S donor sets as well as with a variety of macrocycles with an N₄ donor set has enabled the square pyramidal geometry of these pentaazamacrocycles and its relationship to electrochemical and spectroscopic properties to be fully explored.

The position of the main d-d band ($d_{xy} \rightarrow d_{x^2-y^2}$, $d_{xz,yz} \rightarrow d_{x^2-y^2}$) is principally determined by the nature of the equatorial field, as demonstrated by the invariance of $\lambda_{\max}$ among the N₄S, N₄O and N₅ donor set fifteen membered macrocycles, which all have the same N₄ donor set and chelate ring sizes in the basal plane of the square pyramid.⁶ The lower energy band ($d_{z^2} \rightarrow d_{x^2-y^2}$) is indicative of axial coordination, and its energy is sensitive to the nature of the axial ligand (as long as this ligand has no π -bonding potential¹⁴⁹). Although the position of this band varies from complex to complex as expected (Table 2.8), the presence or absence of a sixth coordinating group appears to have no effect. Thus

the perchlorate salts, which do not contain a coordinated anion in nitromethane, and the nitrate salts, which are 1:1 electrolytes in nitromethane and must therefore contain one coordinated nitrate group, have very similar absorption spectra. The concept of "semi-coordination"^{149,308,324,325} has been introduced to describe the bonding of species in the axial sites of the copper(II) coordination shell at a distance greater than that normally associated with bond formation. It is possible that the bonding of the nitrate ion takes this form, and it therefore has less effect on the energy levels of the copper(II) ion than the equatorial N₄ donor set and the axial donor nitrogen atom, which is constrained by the ligand geometry to be more closely bonded to the metal cation than a monodentate ligand in the same site would be. Clearly the measurement of single crystal esr spectra and polarized single crystal electronic spectra (or structural determinations) are needed to fully elucidate the stereochemistry and electronic properties of the complexes.

The electronic spectrum of $[\text{Cu}(\text{tetrpn})]^{2+}$ is significantly different from those of the macrocyclic pentamines. Only one (d-d) transition (λ_{max} 740 nm) is resolved, although shoulders at ~650 nm and ~870 nm are clearly evident. This spectrum bears a marked resemblance to that of $[\text{Cu}(\text{Me}_7\text{tetren})]^{2+}$ ⁹⁵ which is reported to have trigonal bipyramidal geometry (on the basis of the similarity of its X-ray powder pattern to that of the related five coordinate nickel(II) and cobalt(II) complexes).

A variety of cobalt(II) and copper(II) complexes of the tripodal tetramines tren, Me₆-tren and trpn[†] have been prepared and shown to have trigonal bipyramidal geometry.^{119b,326-329} The complex $[\text{Cu}(\text{NH}_3)_2][\text{Ag}(\text{SCN})_3]$ ³³⁰ has also been shown to contain a trigonal bipyramidal Co-N₅ chromophore. The copper(II) complexes display a single main visible absorption peak (at significantly higher wavelengths ($\lambda > 760$ nm)^{119b,150,323,331} than their square pyramidal counterparts) as well as a high energy shoulder. The

[†]See Appendix

$[\text{Cu}(\text{trpn})]^{2+}$ complex³³² is an exception in that the two peaks are resolved and the high energy band has the larger extinction coefficient. (However, this spectrum is resolved from that of a mixture of three pH dependent species, so has some degree of uncertainty).

It is concluded that the copper complex of tetrpn has distorted trigonal bipyramidal geometry on the basis of the similarity of its absorption spectra to that of complexes with known trigonal bipyramidal geometry, and the significant difference from the spectra of the copper(II) complexes of the pentaazamacrocycles.

3.2.2.6 Stereochemistry and Spectral Properties of the Nickel(II) Complexes

The nickel(II) complexes can also exhibit various coordination numbers. Square planar geometry can be ruled out on spectral grounds (as well as being unlikely on structural grounds) and seven-coordination is only known for cases where ligand geometry dictates (e.g. pentagonal bipyramidal geometry when a quinquedentate ligand is constrained to planar coordination³⁰⁴) or in the case of heptadentate ligands.³³³ However, both five and six-coordination are possible for the nickel(II) pentamine complexes. For six-coordinate nickel(II) complexes, octahedral geometry predominates, but for five-coordinate complexes both square pyramidal and trigonal bipyramidal geometry are well known.

Once again, the possibility that only four of the five amine donors are coordinated must be considered. Pendant amine groups attached to macrocyclic tetramines can readily become non-coordinating in acid solutions or in the presence of strongly coordinating ligands.^{50,286} Likewise $[\text{Ni}(\text{Me}_7\text{-tetren})(\text{SCN})_2]$ is a non-electrolyte in nitromethane, indicating that both thiocyanate groups are coordinated; spectral evidence suggests that one of the terminal amine groups is not coordinated.⁹⁵ On the other

hand there is no previous evidence for non-coordination of amine groups in nickel(II) complexes of the monocyclic pentamines^{49,134} or in the linear tetren analogue¹²⁴ and even the branched hexamines (which act as pentadentates with copper(II)) remain fully coordinated to nickel(II) in neutral solution.³¹⁹

Six-Coordinate Complexes

Regular octahedral geometry (O_h symmetry) leads to an electronic spectrum consisting of only three bands for the d^8 case, but as tetragonal distortions from octahedral geometry increase, the number of spin-allowed transitions increases, theoretically up to a maximum of six for a complex with D_{4h} symmetry. There are seldom more than five peaks observed, as the splitting of the peaks is often small compared with their bandwidths and they remain unresolved.^{334,335} Another complication that may arise is that spin-forbidden transitions may steal intensity from nearby spin-allowed bands and appear to have similar intensity to spin-allowed transitions.³³⁶ The symmetry of the six-coordinate macrocyclic pentamine complexes is considerably less than D_{4h} . Ignoring the methylene backbone, there is an equatorial N_4 donor set and two different axial donors so the complexes can be considered to have pseudo C_{4v} symmetry. Although reductions in symmetry beyond D_{4h} should result in further splitting of the bands, this additional splitting is generally small and merely results in peak broadening.^{131,132,336} Distortion from octahedral geometry reveals itself primarily in splitting of the lowest lying spin-allowed excited state and is less evident in higher excited states.^{136,336} Spectral analysis for the nickel(II) macrocyclic pentamine complexes is hampered by the complexity of their spectra in the low energy region (Table 2.14), and clearly structural information and single crystal polarized spectra are necessary to fully resolve their electronic properties.

On the basis of the conductivity measurements (Table 2.15), the nitrate salts of the nickel(II) complexes formed with tetrpn and the fifteen to eighteen membered macrocycles are shown to be 1:1 electrolytes in poorly coordinating solvents, and are therefore presumed to be six-coordinate in the solid state (with a coordinated nitrate). It is likely that complexes of these amines will also be six-coordinate in solution, with a water molecule occupying the sixth coordination site.

The spectral parameters of the complexes are listed in Table 2.14. The values for the complexes of [15]aneN₅, [16]aneN₅ and [17B]aneN₅ are in good agreement with those previously reported,^{134,167} with the exception of the position of the high energy band ($\nu_4 = {}^3E_g^c + {}^3B_{1g}$) of [Ni([16]aneN₅)]²⁺ and the corresponding extinction coefficient.¹³⁴ The ν_4 band measured in this study is appreciably less intense and has a narrower bandwidth than that in the published spectrum, where it appears to tail off on the high energy side, unlike the other complexes. It is conceivable that an impurity with a high intensity band in the UV is responsible for altering the position, intensity and bandwidth of the ν_4 band in the reported spectrum.

Band assignments for tetragonally distorted octahedral complexes have a well-established theoretical basis,³³⁴⁻⁶ and have been carried out for complexes of [15]aneN₅, [16]aneN₅ and [17B]aneN₅.¹³⁴ They may be extended to the other six-coordinated macrocyclic complexes in this study which all have similar spectral features.

The ν_1/ν_3 ratio ($\nu_1 = {}^3E_g^a + {}^3B_{1g}$; $\nu_3 = {}^3E_g^b + {}^3B_{1g}$) of the complexes with tetrpn and the fifteen to eighteen membered macrocycles in solution falls in the range 1.7-1.9, which is consistent with octahedral geometry.³³⁷⁻³⁴⁰ Low energy shoulders are present on the ν_1 bands of the eighteen membered macrocyclic complexes in aqueous solution. It would be tempting to assign

these to a five-coordinate/six-coordinate equilibrium, but the conductivity values of the nitrate salts in poorly coordinating solvents show no evidence of five-coordination, and the molar extinction coefficients are lower than those generally observed for five-coordinate geometry.^{338,340} This complexity of the ν_1 band, and the complete resolution of this band in the nickel(II) complex of [15]aneN₅ are indicative of severe distortion of the octahedral environment in these complexes.¹³⁶

The molar extinction coefficients of octahedral nickel(II) complexes are generally low ($\epsilon \sim 1-30$)^{339,340} and the fifteen to eighteen membered macrocyclic nickel(II) complexes have ϵ values at the upper end of this range. Increased asymmetry of the ligand field has been shown to lead to enhanced intensity of the d-d transitions,^{161,341} and the geometric constraints imposed by the macrocyclic ligands could reasonably be expected to cause such distortions of the octahedral field. The eighteen membered macrocyclic complexes which presumably experience the greatest amount of steric crowding (and hence the greatest distortion from octahedral geometry) have considerably higher molar extinction coefficients than their analogues with smaller macrocyclic ring size. The spectra of these complexes are markedly different from those of the tetragonal nickel(II) tetraazamacrocyclic complexes¹³¹ and more closely resemble those of compounds in which the equatorial donor fields do not completely encircle the metal.^{336,342} In particular, the strong dependence of D_q^{xy} on macrocyclic ring size is absent, as the equatorial donor set is not constrained by being part of a closed ring.¹²⁷ (This difference can also be seen in the contrasting electrochemical behaviour of the nickel(II)/nickel(III) tetraaza and pentaazamacrocyclic complexes.⁷¹)

The $[\text{Ni}(\text{pyaneN}_5) \text{H}_2\text{O}]^{2+}$ complex has similar spectral parameters⁴⁹ to that of the fully saturated pentaazamacrocyclic complexes, indicating

that even replacement of an equatorial secondary amine donor group by a pyridyl amine donor has little effect on the tetragonal field.

The $[\text{Ni}(\text{tetrpn}) \text{H}_2\text{O}]^{2+}$ chromophore has a similar spectrum to that of the six-coordinate macrocyclic complexes although the ν_3 and ν_4 bands ($\nu_4 = {}^3E_g^c + {}^3B_{1g}$) appear at lower energies (closer to the values observed for the five coordinate complexes - Table 2.14), and the molar extinction coefficients are also indicative of a severely distorted octahedral field. The spectrum of the analogous $[\text{Ni}(\text{tetren}) \text{H}_2\text{O}]^{2+}$ has similar spectral features to the complexes of smaller ring size (although it does not exhibit the splitting of the ν_1 band present in $[\text{Ni}([15]\text{aneN}_5) \text{H}_2\text{O}]^{2+}$).

Five-Coordinate Complexes

On the basis of conductivity measurements (Table 2.15) the perchlorate salts of all the nickel(II) pentamine complexes and the nitrate salts of $[19]\text{aneN}_5$ and $[20]\text{aneN}_5$ are shown to be 1:2 electrolytes (and thus five-coordinate) in poorly coordinating solvents, and it can be concluded that they are probably five coordinate in the solid state. It should be noted that although Hay reports that $[\text{Ni}([15]\text{aneN}_5)](\text{ClO}_4)_2$ is a 1:1 electrolyte in nitromethane,¹⁶⁷ both the results of Fabbrizzi⁷¹ and of the present study show it to be a 1:2 electrolyte.

The solid state spectra of all the perchlorate salts of the nickel(II) complexes are listed in Table 2.14. There are significant differences in the peaks positions of the solid state and corresponding solution spectra, particularly in the lowest energy band ($\nu_1 = {}^3E_g^a + {}^3B_{1g}$). For the solid state spectra, the ratio ν_1/ν_3 falls in the range 2.03-2.36 which is typical of five-coordinate species.^{337,338}

The nickel(II) complexes of $[19]\text{aneN}_5$ and $[20]\text{aneN}_5$ have a ν_1/ν_3 ratio of 2.24 and 2.30 respectively in aqueous solution, and the values remain unchanged on addition of excess nitrate, indicating that they remain

five-coordinate in water. This is not altogether surprising in light of the five-coordinate nature of their nitrate salts in non-aqueous solution, in contrast to the coordinated nitrate that is present in the other complexes. Furthermore, the five-coordinate nature of $[\text{Ni}([\text{19}] \text{aneN}_5)]^{2+}$ and $[\text{Ni}([\text{20}] \text{aneN}_5)]^{2+}$ in solution is supported by their high molar extinction coefficients.^{338,340}

The principal geometries for five-coordinate complexes are square pyramidal (C_{4v}) and trigonal bipyramidal (D_{3h}).³⁴³ The particular stereochemistry adopted by a complex depends on a number of factors, but the size and shape of the ligand itself probably has the most profound effect, especially for multidentate ligands.^{340,343-345} Although crystal field and ligand field analyses have been performed for both geometries,³⁴³⁻³⁴⁶ and it is possible to assign the spectral bands in compounds of known geometry, the stereochemistry of a compound cannot always be unequivocally assigned on the basis of its electronic spectrum, particularly as compounds will seldom have ideal C_{4v} or D_{3h} geometry, but may well have a stereochemistry that is intermediate between the two.^{340,344,345}

A variety of nickel(II) complexes have been prepared for each geometry. The tripodal tetramines comprise the majority of nickel(II) complexes for which trigonal bipyramidal geometry has been established by x-ray crystallography, and their electronic spectra all have very similar features.^{216,295,343,344,352} Nickel(II) complexes of the N-methylated linear amines Me_7 -tetren,⁹⁵ Me_5 -dien[†],³⁴⁷ and Me_4 -daes[†]³⁴⁸ have been assigned the same geometry on the basis of the similarity of their spectra. (On the other hand, the nickel(II) complexes of Me_6 -trien[†] appear to be octahedral or square planar in both solid state and solution³⁴⁹). A number of triazamacrocyclic nickel(II) complexes have tentatively been

[†] See Appendix

assigned trigonal bipyramidal geometry on spectral grounds³³⁷ although their spectra are strongly reminiscent of square pyramidal complexes (vide infra).

Square pyramidal geometry has been unequivocally established for $\text{Ni}(\text{Me}_3\text{-[12]-eneN}_4)(\text{SCN})_2^{\dagger,31}$; on the basis of the similarity of the solid state and solution spectra³³⁸ it is concluded that this geometry is retained in solution. The branched pentamine tpen ($\text{NNN}'\text{-tri[2-(2'-pyridyl)-ethyl]ethylenediamine}^{\dagger}$) also forms a square pyramidal nickel(II) complex.^{98,350} The complex apparently retains square pyramidal geometry in solution.⁹⁸ Nickel(II) complexes of the tetramine 3, 22,3-tet[†] can also display square pyramidal geometry.³¹⁸ The same geometry has been proposed for a number of other complexes on the basis of their electronic spectra, although x-ray structural determinations have not been performed to confirm these assignments.^{45,159,170,286,351} One characteristic difference between the two limiting geometries of the five-coordinate complexes is the position of the ν_4 band. In trigonal bipyramidal complexes it is found above 400 nm,^{95,216,295,343-348,352} whereas in square pyramidal complexes it appears below 400 nm.^{159,170,286,320,338,346,351}

The solid state spectra of the perchlorate salts and the solution spectra of $[\text{Ni}([\text{19}] \text{aneN}_5)]^{2+}$ and $[\text{Ni}([\text{20}] \text{aneN}_5)]^{2+}$ (Table 2.14) closely resemble those of the latter group of compounds indicating that these complexes (like their copper(II) analogues) are most likely to have square pyramidal geometry. There appears to be a progressive increase in the steric crowding and ring strain in these complexes as five-membered chelate rings are replaced by six-membered chelate rings. The increased distortion from regular geometry is shown in the spectral parameters of the eighteen membered macrocyclic complexes, and in the inability of the nineteen and

[†] See Appendix

twenty membered complexes to adopt the generally favoured octahedral coordination in solution.

An indication of the strain present in the $[\text{Ni}([20]\text{aneN}_5)]^{2+}$ cation is that on addition of excess thiocyanate, a colour change occurs, and the resulting compound can be extracted into benzene, suggesting that a neutral complex has been formed. The infrared spectrum of this complex is consistent with the presence of two coordinated thiocyanate groups ($\nu_{\text{C}\equiv\text{N}}$ 2070, 2095 cm^{-1}).³⁰⁵ There are also four sharp amine peaks ($\nu_{\text{N-H}}$ 3197, 3252, 3306, 3333 cm^{-1}) in place of the more closely spaced peaks in the nitrate and perchlorate salts, and these are taken as indicating that one of the amine groups is no longer coordinated to the metal, and that it has been replaced by one of the thiocyanate groups, giving rise to an octahedral complex.

In conclusion, the perchlorate salts of all the complexes, and the nitrate salts of the two largest macrocycles are five-coordinate in the solid state, with postulated square pyramidal geometry. The remainder of the nitrate salts of the complexes are six-coordinate in the solid state with a coordinated nitrate. In solution, the complexes (again with the exception of those formed with the two largest macrocycles) have tetragonally distorted octahedral geometry with a coordinated water molecule, while those of the nineteen and twenty membered macrocycles remain five-coordinate with square pyramidal geometry.

3.3 Cobalt(II), Cobalt(III) and Rhodium(III) Complexes

3.3.1 Structure and Isomerism of Cobalt(III) Complexes

Linear pentamine ligands can be bound to five of the six sites of a cobalt(III) ion in four distinct topologies (ignoring the different diastereoisomeric configurations possible for the secondary amines that join coplanar chelate rings marked with asterisks in species LXXXV and LXXXVI and also the different conformations that each chelate ring can adopt). (Species LXXXIV-LXXXVII).

However, monocyclic pentamines can adopt only one topology (the presence of a chelate ring joining the terminal amine groups in structures LXXXIV-LXXXVI results in the same topology for each, and it is not possible to form such a bridge in structure LXXXVII for which the terminal amine groups are trans to each other).

With the exception of [15]aneN₅ and [20]aneN₅ (in which all five chelate rings are equivalent) all the other macrocyclic pentamines in this study can be arranged around the metal with three different dispositions of the chelate rings (LXXXVIII-XC).

meso
LXXXVIII

rac
LXXXIX

rac
XC

One chelate ring is marked in the above figures, and is shown in the three positions that it can occupy. Each of the uncomplexed macrocyclic ligands has a plane of symmetry perpendicular to the macrocyclic plane bisecting the chelate ring marked and passing through the furthest amine nitrogen. As structures LXXXIX and XC above do not contain a plane of symmetry, they can both exist as their respective non-superimposable mirror images.

The other source of isomerism (present for all the different complexes, including those formed with [15]aneN₅ and [20]aneN₅) is due to the different configurations that can be adopted by the N-H at the centre of a meridional N₃ donor set. The three possible configurations are shown in structures XCI-XCIII.

syn-meso (⇓)

XCI

anti-meso (⋈)

XCII

rac (⋈)

XCIII

('syn' and 'anti' are used to refer to the relationship between the orientation of the N-H bonds shown and the Co-X bond). When the geometric and configurational isomerism are considered in conjunction, the degeneracy of the two types of isomerism is lifted, and there are in fact a total of eleven possible diastereoisomeric forms. They are shown as structures XCIV-CIV in figure 3.2. The ones marked with an asterisk are mesomeric, while the remainder are enantiomeric, giving rise to a total of twenty isomers for each complex (ignoring conformational isomers). There would be more isomers but for the fact that each ligand has at least C_{2v} symmetry. The two ligands with D_{5h} symmetry exist only as the isomers XCIV-XCVI owing to the equivalence of the three topological arrangements of the macrocycle around the cation.

For each of the stereoisomers, there is also the possibility that the chelate rings may adopt a number of different conformations. The preferred conformation of each chelate ring will depend on the overall nature of the complex cation but there is considerable evidence that in solution the energy barrier between the various conformations that can be adopted by five and six-membered chelate rings is small.³⁵³ It has been shown that the rate of interconversion between conformers is generally rapid on the nmr timescale.^{71,263,267,354}

3.3.2 ^{13}C n.m.r. spectra of the Complexes

As the cobalt(III) cation is diamagnetic in its low-spin state, it has been possible to obtain invaluable information regarding the isomeric purity of the complexes formed, identifying specific isomers in favourable cases, and in establishing the steric course of various ligand exchange reactions from the ^{13}C n.m.r. spectra. Unlike the proton n.m.r. spectra in which the resonances are split due to coupling and often overlap to

Isomerism of Cobalt(III)-Macrocyclic Pentamine Complexes

fig 3.2

give complex envelopes that are difficult to resolve, the decoupled singlet ^{13}C resonances are characterized by very narrow bandwidths, so that even closely spaced resonances can be identified. Hence the presence of individual components in a mixture of isomers can often be identified by comparison with isomerically pure products or by comparison of relative peak heights. In contrast to proton spectra, the area under individual resonances in a ^{13}C n.m.r. spectrum cannot be directly correlated to the number of carbon atoms responsible for a particular resonance because variations in spin lattice relaxation times (T_1) together with the Nuclear Overhauser Effect cause different carbon atoms to respond differently to the signal.³⁵⁵ However, in the cobalt(III) complexes of the pentaaza-macrocycles, all the carbon atoms are expected to have similar T_1 values³⁵⁶ (they are all secondary carbon atoms, and are linked to similar species) and it is found that the peak intensities may be interpreted (at least semiquantitatively) as corresponding to the concentration of different species. If a ^{13}C resonance of a complex is half or double the intensity of the others in the same complex it can be safely assumed that this reflects the relative number of carbon atoms responsible for the resonance.^{160,234,357,358}

The ^{13}C n.m.r. spectra were acquired in acidic solution (with the exception of those involving base hydrolysis reactions), in order to ensure that possible scrambling of the isomers through configurational inversion of the two 'planar' nitrogens did not take place. Such inversion of configuration requires preliminary deprotonation of the amine, and this is suppressed in acid leading to a substantial decrease in its rate.^{166,358-360}

The positions of individual ^{13}C resonances are not only affected by the position of the atom in the macrocyclic ring but also by the micro-

environment of the carbon atom in the complex cation.^{273,361} Hence it has not been possible to assign individual carbon atoms to specific resonances, although the $\text{C}-\underline{\text{CH}_2}-\text{C}$ and $\text{C}-\underline{\text{CH}_2}-\text{NH}-\text{C}$ carbon atoms are readily differentiated as the latter appear significantly downfield of the former.

The meso isomers have a plane of symmetry and so they are expected to have $\frac{1}{2}n$ resonances[†] unless the plane of symmetry bisects a six-membered chelate ring, in which case there will be $\frac{1}{2}(n+1)$ resonances (barring accidental degeneracy). On this basis they can readily be distinguished from the less symmetrical isomers.

3.3.3 Properties of Cobalt(III) Complexes

3.3.3.1 General Synthetic Methods for Cobalt(III) Complexes

Under different conditions it is sometimes possible to selectively prepare either the kinetically or the thermodynamically favoured products. The cobalt(III) complexes were prepared by a range of methods in an effort to synthesise a variety of stereoisomers. Aquo or halo pentammine complexes heated with the free ligand in aqueous solution (Method A), and the reaction of $\text{Na}_3\text{CO}(\text{CO}_3)_3 \cdot 3\text{H}_2\text{O}$ with an aqueous solution of the ligand salt (Method B) provided methods where the precursor was a cobalt(III) species, while oxidation of the cobalt(II) ligand complex with bromine (Method C) or oxygen (Method D) involved a labile cobalt(II) precursor.

Rather surprisingly, all the macrocycles (with the exception of [15]aneN₅ and [17B]aneN₅) gave single isomeric forms of each complex. However, the different methods of synthesis did produce the isomeric forms of complexes with these two macrocycles in different proportions. The bromine oxidation (Method C) in particular resulted in the clean formation

[†] Where n is the number of carbon atoms in the macrocycle.

of a single isomer of each complex; however the single chlorine oxidation that was performed produced two diastereoisomers (see section 3.3.3.3), so it is not possible to draw general conclusions about the different syntheses.

The tetrahalozincates of cobalt(III) halo pentamines generally form well-crystallized complexes, and provide ideal salts for analytical purposes.²⁵⁹ However, they are considerably less soluble in water than the corresponding halides, and in some cases this led to difficulties in preparation of ^{13}C n.m.r. samples. The dihalide salts of the halopentamines are considerably more soluble in water or alcohols, but often contained water or alcohol of crystallization in their lattices on recrystallization, and generally did not give well-formed crystals. The aquopentamines were generally isolated as the perchlorate salts (clearly it is not practicable to use halides in view of their sometimes rapid anation), but did not generally form well-crystallized products, as they were quite soluble in water and the lower alcohols.

3.3.3.2 Complexes of tetren

The cobalt(III) complexes of tetren were prepared by standard literature methods^{62,268} as well as by the bromine oxidation method, initially to gain some insight into the differences that could be expected in the ^{13}C n.m.r. spectra of very similar isomers of the same complex. ^{13}C n.m.r. is clearly a far more sensitive indicator of isomeric composition than either infrared^{249,362-364} or visible^{249,362-365} spectroscopy, particularly where mixtures of isomers are concerned. Even small amounts of isomeric contaminants could be detected, and in some cases (e.g. the formation of $\beta\text{-}[\text{Co}(\text{tetren})(\text{NO}_2)]^{2+}$ and the subsequent ligand exchange processes) it was clear that the original synthetic methods did not give exclusively the products reported.^{62,268}

The original syntheses were reported to give yields of ~15% using crude ligand. This is purely a function of the amount of tetren in the starting material, as the yields were vastly improved (~80%) when pure tetren was used.

3.3.3.3 Complexes of [15]aneN₅

Only three distinct diastereoisomers exist for these complexes XCIV-XCVI two of which have a plane of symmetry. Although in other studies, the fingerprint region of the infrared spectra has been used to identify different diastereoisomeric forms of the same complex^{62,249,362,363,364} this has not been possible for complexes of $[\text{Co}([15]\text{aneN}_5)\text{X}]\text{ZnX}_4$ ($\text{X}=\text{Br}, \text{Cl}$). The infrared spectra of the two halo tetrahalozincates are virtually indistinguishable, despite the fact that the bromo complex has been shown to be exclusively the rac isomer, whereas the chloro complex is a mixture of the rac isomer and one of the two possible meso isomers. Furthermore, the infrared spectra of different samples of the chloro tetrachlorozincate complex (which contain different proportions of these two isomers) have identical spectra.

If the chelate rings are conformationally labile as expected, the two symmetrical meso isomers will have at most five distinct peaks in the ¹³C n.m.r. spectra and the rac isomer no more than ten. The bromo complex prepared by Methods A, B and C all gave a product (γ-isomer) with a nine peak ¹³C n.m.r. (However, one peak was double the height of the others, and is taken to correspond to two carbon atoms in equivalent environments). Such a spectrum can either correspond to an equal mixture of the two meso isomers, or to the pure rac isomer. The former possibility has been dismissed as it is unlikely that three different synthetic methods would all give exactly the same isomeric composition, and on the basis of

the isomer composition of the chloro complex formed from it in several different ligand substitution reactions (q.v.).

Although the reaction of $[\text{Co}(\text{NH}_3)_5\text{Br}]\text{Br}_2$ with [15]aneN₅ in DMSO resulted in the formation of the rac bromo isomer as the major product, unreacted amine was still present in the reaction mixture, as well as some paramagnetic impurity (the peaks were all broadened), and a number of resonances in the ^{13}C n.m.r. slightly upfield from those of the complex indicated the presence of a further product (possibly partially complexed macrocycle). So although the product was not clean, it did appear to produce principally the same isomer as the other methods.

Synthesis of the chloro complex by Methods A, B and D gave products which have fourteen peak ^{13}C n.m.r. spectra. In most cases the resonances could readily be divided into groups of five and nine on the basis of their substantially different intensities. The group of nine resonances once again includes one which has twice the intensity of the others and corresponds to two non-equivalent carbon atoms in similar microenvironments. There is unequivocally a mixture of the rac (γ) and one meso (α) isomer. No evidence could be found for the presence of the other meso isomer (β). The question remains whether the α isomer is the syn (XCIV) or anti (XCV) meso isomer. This is discussed in the context of the ligand exchange reactions, and the balance of evidence points to the latter. If so, this is in contrast to the known structures of the complexes of the meso- $[\text{Co}([16]\text{aneN}_5)\text{Cl}]^{2+}$ and meso- $[\text{Co}([18\text{A}]\text{aneN}_5)\text{Br}]^{2+}$ complex cations, but these complexes both contain six-membered chelate rings in the equatorial plane, and this could readily account for their contrasting behaviour. The chloro complex has also been prepared by oxidation of the cobalt(II) complex with chlorine (by analogy with the bromine oxidation), and a mixture of the same two isomers ($\alpha+\gamma$) was obtained. (A small amount of

uncomplexed ligand was also present in the reaction mixture). The relative proportions of the two isomers varied from synthesis to synthesis, and may be approximately determined from the different intensities of the two sets of resonances (bearing in mind that each resonance in the ^{13}C spectrum of the meso isomer corresponds to two equivalent carbon atoms). However, the isomer ratio does not accurately represent the reaction product composition, except in those cases where the reaction mixture was examined, rather than the product which separated from the reaction mixture. This could be particularly relevant in the case of the product formed in the reaction with $\text{Na}_3\text{Co}(\text{CO}_3)_3 \cdot 3\text{H}_2\text{O}$ as the perchlorate salt was isolated (not in good yield) rather than the tetrachlorozincate, and also in the chlorine oxidation reaction (where the chloride salt was isolated). In every case, however, the rac isomer was the principal product and the meso (α) isomer accounted for 20% (Method A - tetrachlorozincate salt), 35% (Method B - perchlorate salt), 40% (Method 'C' - chloride salt) and 15% (Method D - tetrachlorozincate salt).

Hay has also prepared the chloro complex by Method B ¹⁶⁷ and he postulates on the basis of the ^{13}C n.m.r. spectrum that all three isomers are present. However, his spectrum (acquired in water) shows considerable complexity and a very poor S/N ratio despite a substantial number of transients ($\sim 190,000$). It is quite different (fig. 3.3) from the spectrum run on a sample (dissolved in 1.5 M acid) that was prepared by a repetition of his synthesis. It is postulated that Hay's spectrum is the result of base hydrolysis (occurring over the prolonged acquisition time of the ^{13}C n.m.r.), as it resembles the ^{13}C n.m.r. spectrum of $[\text{Co}([\text{15}] \text{aneN}_5) \text{OH}]^{2+}$ (fig. 3.3).

It is perhaps significant that the corresponding synthetic methods which give both meso and rac isomers for the chloro complex form

^{13}C n.m.r. Spectra of Cobalt(III) Complexes of [15]aneN₅

fig 3.3

only the rac isomer of the bromo complex. Thus the product composition appears to be determined by the nature of the product rather than that of the reactants (this is also shown in the aquation reactions - q.v.).

The ^{13}C n.m.r. spectrum of an aqueous reaction mixture originally containing equimolar amounts of $[\text{Co}(\text{NH}_3)_5 \text{H}_2\text{O}](\text{ClO}_4)_3$ and $[\text{15}] \text{aneN}_5$ (but acidified before the spectrum was acquired) showed that not all the ligand had reacted (~15% remained uncomplexed) and that at least two (and probably all three) of the possible isomers were formed.

Ligand Substitution Reactions

A variety of ligand substitution reactions was carried out in order to gain some insight into the relationship between the various isomeric forms. They are summarized in Scheme 15. In general it can be seen that the isomeric composition of the product appears to be determined by the nature of the entering group rather than that of the leaving group. However, this in no way precludes the presence of an intermediate of reduced coordination, as different incoming groups may preferentially attack the intermediate on different faces depending on steric considerations and on whether the incoming species can more easily be loosely associated (e.g. hydrogen bonded) with one face of the complex cation than the others. There is also clear evidence for the presence of nitrate species in the induced aquation reaction products, but it is not possible to determine whether this is the result of anion competition during the aquation,³⁶⁶ or subsequent replacement of the aquo complex by the nitrate anion.

Treatment of $\text{rac-}[\text{Co}([\text{15}] \text{aneN}_5) \text{NO}_2] \text{Cl}_2$ with acid, and $\text{rac-}[\text{Co}([\text{15}] \text{aneN}_5) \text{Br}] \text{Br}_2$ with concentrated hydrochloric acid or chlorine all produce a mixture of the same two isomers (rac and one meso) of the chloro complex, although not in the same relative proportions. It is

Ligand Substitution Reactions of Cobalt (III) Complexes of [15]aneN₅

SCHEME 15

possible to rationalize such isomerizations in acidic solution by invoking the formation of a five-coordinate intermediate and allowing for the possibility of attack from either side of the intermediate as shown (Scheme 16). Attack on the third face of the postulated five-coordinate intermediate is not possible because of steric obstruction by a chelate ring.

SCHEME 16

If this mechanism is correct, it is clear that the symmetrical product formed must be the anti-meso isomer XCV. The syn-meso isomer cannot be formed by such an inversion, nor can it isomerize by this

mechanism unless fairly drastic bond ruptures take place. For the less symmetrical macrocycles such an inversion would not only result in the formation of a different diastereoisomer, but a different geometrical isomer would be formed in the process, and the ^{13}C n.m.r. could be used to confirm the mechanism. However, there is no way of differentiating between the three "geometrical isomers" for [15]aneN₅. (It would be possible to label the ligand by selective methylation of the apical nitrogen but this would quite probably affect the nature of the transition state; using a ligand with a selectively enriched ^{13}C or ^{15}N atom would not be feasible as the complex which formed would probably be an equilibrium mixture with the enriched atom equally distributed between all five possible positions).

Another possibility is that the ligand replacement and isomerization reactions happen independently. In this case, the isomerization would require the deprotonation of one "flat" amine group (i.e. one which is coplanar with the amine donors on each side), followed by a conformational change of the two chelate rings attached to the nitrogen, and subsequent reprotonation. Although this mechanism is known to occur in basic solution where proton exchange is appreciable^{258,359,360,367-370} the rate of nitrogen inversion is slow compared with the rate of proton exchange,^{359,360} and it would therefore be expected that in strongly acidic solutions (such as those in the anation studies) this pathway would not contribute significantly to isomerization. There is evidence however for a pH independent proton exchange in some cases,³⁶⁸ and for relatively rapid configurational inversions of secondary amine groups even in acidic solution,^{73,166,250} although it should be pointed out that the latter is for an N-H group at the junction of two six-membered chelate rings, whereas the corresponding N-H at the junction of two five-membered chelate rings

(as is the case in [15]aneN₅), is considerably slower.^{250,272,358}

However, other factors related to the geometry of the macrocyclic complex may be contributing to an enhanced proton exchange rate.

Another possible mode of isomerization that does not involve bond rupture (and may simply succeed ligand replacement that has occurred with retention of configuration) involves the Bailar (trigonal) twist or Ray-Dutt (rhomboid) twist about a pseudo C₃ axis.^{358,371} However, investigation of models shows that the nature of macrocyclic pentamines precludes such twist mechanisms for either of the meso isomers. The configurations of the diastereoisomeric amines in the rac isomers are both reversed, and the ligand undergoes a geometrical isomerization, which in the case of a ligand with C_{5v} symmetry such as [15]aneN₅ has the net effect of converting the complex to its enantiomer. This mechanism on its own would not be sufficient to explain the observed behaviour, but it could be a contributing pathway. Any pH-independent loss of optical activity of a sample of enantiomerically pure γ -[Co[15]aneN₅)Br]²⁺ would be most likely to result from such a twist mechanism.

Treatment of a mixture of the γ -(rac) and α -(meso) isomers of [Co([15]aneN₅)Cl]²⁺ with hydrobromic acid gives principally the γ -(rac) bromo complex, as well as a small amount of both parent chloro complexes. The presence of an appreciable concentration of the uncomplexed ligand indicates that significant decomposition of the complex has occurred. There is no evidence for the formation of any other bromo isomer in the reaction.

If the mechanism for this reaction proceeds via an intermediate of reduced coordination (similar to that shown in Scheme 16) both the rac and the anti-meso [Co([15]aneN₅)Cl]²⁺ complexes can form rac-[Co([15]aneN₅)Br]²⁺, whereas the syn-meso chloro complex cannot rearrange to form the rac bromo complex. Nor could the twist mechanisms be invoked to account for the rearrangement of the two meso isomers. Hence the

symmetrical chloro complex must be the anti-meso isomer, unless one of the 'planar' nitrogen atoms is undergoing inversion of configuration (which would require deprotonation of the amine in strongly acidic solution).

Although the known preference of five-membered chelate rings to adopt a skewed conformation³⁵³ readily accounts for the predominance of the rac complexes, there is little information available to indicate any preference for the syn or anti arrangement of hydrogens if the five-membered chelate ring is in an envelope conformation. In $[\text{Co}(\text{pyaneN}_5)\text{Cl}]^{2+}$, one of the 'planar' nitrogen donors is part of the pyridine ring, and although the other is on the same side of the equatorial plane as the chlorine¹⁵⁴ its configuration may well be determined by the presence of the methyl group on the adjacent carbon atom. Of the two principal isomers of $[\text{Co}(\text{tetren})\text{X}]^{n+}$ ($\alpha\beta\text{-R}$ (CV) and $\alpha\beta\text{-S}$ (CVI)) the latter is more stable than

+ the former by $\sim 8 \text{ kJ mol}^{-1}$,²⁶⁹ and although this is reassuring in terms of the structure proposed for $\alpha\text{-}[\text{Co}([\text{15}] \text{aneN}_5)\text{Cl}]^{2+}$, comparisons with such open-chain pentamines must be made with considerable caution.

The ^{13}C n.m.r. spectra of solutions formed on addition of ammonia to either the pure rac (γ) bromo complex or to a mixture of the rac (γ) and meso (α) chloro complexes were identical, and clearly showed the presence of more than one isomer (fig. 2.3). There is considerable overlapping of the resonances corresponding to different isomers and they are considerably broader than those in the spectra of the parent halo

complexes. As the pH is increased, they become broader and the spectrum collapses to four peaks, one of which is more than double the height of the other three (fig. 2.3). This behaviour is consistent with the previously discussed mechanism for inversion of configuration involving deprotonation of the amine followed by conformational changes in the two adjacent chelate rings. The change in the spectrum with increasing pH results from the increased rate of deprotonation. In moderately basic solution, the effective rate of configurational change (the result of the pH-dependent deprotonation and the pH-independent inversion of a deprotonated nitrogen) is slow on the n.m.r. timescale, and each carbon atom is seen in its different possible environments (although the observed broadening indicates that the rate of configurational change is not insignificant on the n.m.r. timescale). With increasing pH, the rate of deprotonation increases and correspondingly, the rate of configurational change of the nitrogen atoms increases. As this rate approaches the n.m.r. timescale, the peaks begin to coalesce and the ^{13}C spectrum comprising four broad peaks represents the averaging of the environment of each carbon atom. (At higher temperatures these peaks should sharpen, as the inversion of the deprotonated nitrogen becomes faster, and each carbon atom is 'seen' in its time-averaged environment). The behaviour observed for $[\text{Co}([\text{15}] \text{aneN}_5) \text{OH}]^{2+}$ contrasts markedly with that of $[\text{Co}([\text{17B}] \text{aneN}_5) \text{OH}]^{2+}$, which shows no evidence of coalescence of the resonances corresponding to the two isomers, indicating that in the latter complex, the conversion of one isomeric form to the other is slow on the n.m.r. timescale.

When the products of base hydrolysis are acidified with hydrobromic acid, the principal products are the rac-bromo (80%) and rac-aquo (~10%) complexes; similar acidification with nitric acid results in the formation

of predominantly (meso + rac)-aquo product (with some rac-nitrato isomer). Treatment of a sample of the reacidified base hydrolysis product with chlorine gas gives the (meso + rac) chloro complex; another sample treated with sodium nitrite (after acidification) gave exclusively the rac-nitro complex. As the protonation of the hydroxo complex is expected to be rapid, the anation reactions should all involve the same initial isomeric composition of aquo complexes. The varying isomeric composition of the products must therefore be determined by the nature of the incoming group.

A variety of silver(I) and mercury(II) induced aquation reactions have been carried out, both in perchloric acid and nitric acid. They have a number of common features. The proportion of meso products is higher than that of the rac products, and the concentration of nitrato complex exceeds that of the aquo products. The difference between the induced aquation products and those obtained from base hydrolysis followed by acidification presumably arises because the induced hydrolysis involves competition between water and the nitrate anion for an intermediate of reduced coordination. The nitrate anion has been shown to be a good competitor for the postulated $[\text{Co}(\text{NH}_3)_5]^{3+}$ intermediate.³⁶⁶ It has been suggested that this is due to the poor solvation of the nitrate anion, and the greater electrostatic attraction of the $[\text{Co}(\text{NH}_3)_5]^{3+}$ intermediate for the uninegative nitrate anion than for the neutral water molecule.³⁶⁶ However, the level of competition observed here is unprecedented, and it is possible that there is a loose association of the nitrate ion with the parent complex cation (such as a hydrogen bonding interaction²⁶¹) causing the effective concentration of the nitrate anion near the complex cation to be greater than in the bulk solution.

The other notable feature of the induced aquation reactions is the substantial inversion of configuration that takes place (e.g. the

exclusively rac-bromo complex gives rise to predominantly meso products). This is in marked contrast to the observation that the aquation reactions of the tetraazamacrocyclic complexes proceed largely with retention of configuration.^{162,165,166} However, the ability to rotate a 'planar' coordinated amine to the site formerly occupied by the departing group as a means of configurational inversion has no parallel among the tetraazamacrocyclic complexes with the N_4 donor group in the equatorial plane. Clearly the nature of the inversion mechanism and the extent of anion competition/ligand exchange warrants further investigation.

3.3.3.4 Complexes of [16]aneN₅

Although complexes of cobalt(III) with [16]aneN₅ can in theory exist in eleven different isomeric forms (XCIV-CIV, fig. 3.2) every synthesis and ligand exchange reaction resulted in the formation of a single isomeric product. Furthermore, this isomer can be readily identified as one of the two meso isomers on the basis of the ¹³C n.m.r. spectra, which contain only six peaks (in some cases an accidental degeneracy reduces this number to five), indicating that there is a plane of symmetry through the complex cation.

Bombieri and coworkers have prepared $[Co([16]aneN_5)Cl](ClO_4)_2$ by aerial oxidation of the cobalt(II) complex and subsequent treatment with concentrated hydrochloric acid (Method D). A crystal structure determination¹³⁵ has shown that the syn-meso isomer (XCIV) is formed. The same isomer was shown (by ¹³C n.m.r.) to be the sole product in the reaction of $Co(NH_3)_5Cl_3$ with [16]aneN₅, and the other meso complexes are also likely to be the syn isomer for a variety of reasons. Treatment of the sole bromo complex formed (by Method A or C) with concentrated hydrochloric acid gives the syn-meso chloro complex, and if the original bromo complex were the other meso

isomer, the ligand exchange would require the configurational inversion of both diastereoisomeric nitrogens in strongly acidic solution. This is quite unlikely, particularly as there is no evidence for the existence of the rac diastereoisomer or for more than one meso diastereoisomer even in basic solution where such configurational changes would most readily occur. (The halo and aquo complexes all give the same ^{13}C n.m.r. spectrum on treatment with base). Even the possibility of a twist mechanism or of a cobalt-nitrogen bond rotation (through a five-coordinate intermediate) can be excluded as the product of either mechanism would no longer be a meso geometrical isomer, and consequently the ^{13}C n.m.r. spectrum would comprise eleven peaks.

Induced aquation of either halo complex in acid gives a single isomer, and this is the same isomer that is formed in the reaction of $[\text{Co}(\text{NH}_3)_5 \text{H}_2\text{O}](\text{ClO}_4)_3$ with $[\text{l6}] \text{aneN}_5$. The peroxo species (which also has a clean six peak ^{13}C n.m.r. spectrum and is the precursor of the syn-meso chloro complex) gives the same aquo complex on treatment with perchloric acid.

There is considerable evidence that ligand substitution is reasonably rapid in cobalt(III) complexes of $[\text{l6}] \text{aneN}_5$. When $[\text{Co}([\text{l6}] \text{aneN}_5) \text{H}_2\text{O}](\text{ClO}_4)_3$ is dissolved in nitric acid (~1.5 M) an equilibrium mixture of the aquo complex (~40%) and another complex postulated to be the nitrate complex (~60%) is formed. (The same complex dissolved in perchloric acid of the same concentration gives only the five peak ^{13}C n.m.r. spectrum of the aquo complex). A sample of $[\text{Co}([\text{l6}] \text{aneN}_5)\text{Cl}]\text{ZnCl}_4$ dissolved in ammonia and subsequently reacidified with nitric acid was shown to contain the aquo, chloro and nitrate complexes. The bromo complex when dissolved in dilute hydrochloric acid underwent substantial ligand exchange over the acquisition time of the

^{13}C n.m.r. spectrum (~2 hours). The presence of the nitrate complex in the induced aquation product mixture cannot therefore be attributed to anion competition for the five-coordinate intermediate formed on abstraction of the halide, as it may simply be the result of subsequent ligand exchange.

The particular disposition of the macrocyclic ring around the cobalt(III) is understandable in light of the known stability of a 5,6,5 arrangement of three successive chelate rings in a plane.^{121,152} The most stable conformation for a six-membered chelate ring is a symmetrical chair,³⁵³ and this is consistent with the formation of a meso isomer. However, the observation that only one of the meso diastereoisomers exists under any of the conditions studied is rather surprising. Models of the complex show that neither the anti-meso or the rac isomers appear to be particularly strained or subject to excessive non-bonding interactions. Yet synthetic methods that would be expected to produce the kinetically favoured products and those expected to produce the thermodynamically favoured products all result in the same isomer. Admittedly, once the syn-meso isomer has been formed, only mechanisms that involve deprotonation and subsequent inversion of the diastereoisomeric nitrogen atoms can produce a configurational change while retaining the 5,6,5 arrangement of chelate rings in the equatorial plane. Presumably a strain energy minimisation calculation would provide insight into the cause of the significantly greater stability of the syn-meso isomer.

3.3.3.5 Complexes of [17A]aneN₅

Synthesis of the bromo complex of [17A]aneN₅ by two different methods (from Co(NH₃)₅Br₃ (Method A) and by bromine oxidation of the cobalt(II) complex (Method C)) resulted in the formation of the same single isomer. The ¹³C n.m.r. had nine resonances (one twice the intensity of the others) corresponding to carbon atoms adjacent to a nitrogen, and two separate resonances corresponding to the central carbon atom of the six-membered chelate rings. Both ¹³C n.m.r. spectra also contained resonances corresponding to [Co([17A]aneN₅)NO₃]²⁺ and [Co([17A]aneN₅)H₂O]³⁺, but as the initial tetrabromozincate salts contained no water or nitrate (by microanalysis), this was clearly the result of spontaneous aquation of the sample in nitric acid. (The complexes were only sparingly soluble in dilute nitric acid so the spectra were acquired overnight). The bromo complexes were even less soluble in perchloric acid, and the addition of hydrobromic acid to suppress hydrolysis simply resulted in precipitation of further bromo complex, so it was not possible to obtain a spectrum without some hydrolysis taking place.

The chloro complex prepared from Co(NH₃)₅Cl₃ (Method A), or by aerial oxidation of the cobalt(II) complex followed by treatment with hydrochloric acid (Method D) had a ¹³C n.m.r. spectrum consisting of twelve resonances of equal intensity. The pattern of resonances in the bromo and chloro complexes is very similar. Treatment of the bromo complex with concentrated hydrochloric acid gives the same chloro complex as that previously observed.

The same single isomer of $[\text{Co}([\text{17A}] \text{aneN}_5) \text{H}_2\text{O}]^{3+}$ was obtained on spontaneous or silver(I) induced aquation of either the bromo or chloro complex, as well as from the reaction of $[\text{Co}(\text{NH}_3)_5 \text{H}_2\text{O}](\text{ClO}_4)_3$ with $[\text{17A}] \text{aneN}_5$. Addition of base to either halo complex gave only one isomer of $[\text{Co}([\text{17A}] \text{aneN}_5) \text{OH}]^{2+}$, and there was no evidence for the presence of either of the other two possible diastereoisomers even at high pH.

When the aquo complex was dissolved in nitric acid, the ^{13}C n.m.r. spectrum showed that there was only a small amount of the aquo complex in solution, and the twelve major resonances in the spectrum have been assigned to the nitrate complex. These resonances were absent from the spectrum of the aquo complex dissolved in perchloric acid. The existence of the nitrate complex has been established for other macrocycles (e.g. $[\text{Co}([\text{15}] \text{aneN}_5) \text{NO}_3](\text{NO}_3)_2$) by microanalysis, but it has not been possible to isolate a pure sample of the complex in this case owing to its high solubility.

On the basis of these observations it seems likely that each of the products has the same stereoisomeric form. However, as it is not possible to determine even which geometrical isomer is present from the ^{13}C n.m.r. spectra, let alone which diastereoisomeric form, the crystal structure of the chloro complex was determined. The ^{13}C n.m.r. of the sample used for the structural determination was the same as that obtained in the other syntheses.

The ^{13}C n.m.r. spectrum of the crude reaction mixture in one synthesis of the aquo complex (from $[\text{Co}(\text{NH}_3)_5 \text{H}_2\text{O}](\text{ClO}_4)_3$ and $[\text{17A}] \text{aneN}_5$) contained twelve resonances in addition to those identified as γ - $[\text{Co}([\text{17A}] \text{aneN}_5) \text{H}_2\text{O}]^{3+}$. The resonances corresponding to the central carbon atoms in the six-membered chelate rings are further downfield than

those observed in other complexes of [17A]aneN₅ (their chemical shifts are closer to that of the corresponding carbon atom in complexes of [16]aneN₅). The resonances corresponding to carbon atoms adjacent to a nitrogen atom also cover a far wider range (42.4–62.9 ppm) than that observed in other complexes of [17A]aneN₅. Indeed the peak at 42.4 ppm is in the region where the uncomplexed protonated amine resonances are observed, and the possibility of a partially coordinated macrocycle cannot be excluded. Alternatively, a small amount of another isomeric form of the aquo complex has been formed in this reaction. It has not proven possible to isolate this minor component, but clearly the system warrants further investigation.

3.3.3.6 Structure of [Co([17A]aneN₅)Cl]Br_{0.33}Cl_{1.67}·H₂O

The structure of the complex cation is shown in fig. 2.14. The cobalt(III) cation has near-regular octahedral coordination – the average Co–N bond length (198.6 pm) is similar to that observed in related complexes^{135,250,269,270,372,373}; the Co–Cl bond length (225.8 pm) is also quite regular.^{135,269,270,373}

The geometrical isomer formed is the one in which the three nitrogen atoms attached to six-membered chelate rings coordinate in the same plane. (i.e. the N₃ donor set of the "dipropylenetriamine fragment" of the macrocyclic pentamine is meridionally coordinated). This is not surprising as the two other geometrical isomers both involve facial coordination of the two six-membered chelate rings, which is a more strained arrangement. House and coworkers found that acidopentamine cobalt(III) complexes incorporating 3,3-tri (dpt) invariably had this ligand in a meridional configuration.^{363,373,374} Other complexes have also been shown to contain meridionally coordinated 3,3-tri,^{250,272} although recently a

tri- μ -hydroxo cobalt(III) complex of 3,3-tri has been shown to contain the ligand coordinated facially²⁷² and evidence has been presented for facial coordination of both ligands in $[\text{Co}(2,2\text{-tri})(3,3\text{-tri})]^{3+}$.²⁵⁰ From examination of molecular models, it is evident that the other two geometrical isomers of cobalt(III) complexes with [17A]aneN₅ involve considerable steric crowding of the chelate rings.

The hydrogen atom on the nitrogen common to the six-membered chelate rings is on the opposite side of the equatorial N₄ donor plane from the chlorine atom (anti), while that on the other diastereoisomeric nitrogen (N(1) in the numbering scheme) is on the same side (syn). Consequently, the six-membered chelate ring containing N(2) and N(3) adopts a regular chair conformation (Table 2.22 and Planes 5 and 8 of Table 2.23) while that incorporating N(1) and N(2) adopts a symmetric skew boat conformation with N(1) and C(3) as the bow and stern. Although both six-membered chelate rings in $\text{Co}(3,3\text{-tri})\text{Cl}_3$ have the stable chair conformation,³⁷⁵ the more closely related α - and β - $[\text{Co}(\text{en})(3,3\text{-tri})\text{Cl}]^{2+}$ cations both have the same chair/skew-boat arrangement of the six-membered chelate rings^{373,374} as does the mer- $[\text{Co}(2,2\text{-tri})(3,3\text{-tri})]^{3+}$ cation.²⁵⁰

The five-membered chelate rings (λ , δ , λ gauche conformations) all have N-Co-N bite angles (Table 2.21) and dihedral angles (Table 2.22) within the range normally observed for five-membered chelate rings in multidentate ligands.^{135,250,265,269,376} Although there is some evidence for strain within the macrocycle (reflected in angular distortions) the values are not significantly greater than those observed for other chelated multidentate ligands.

The fact that all the ligand replacement reactions proceed without isomerization is understandable in light of this structure. The only possible twist mechanism produces an isomeric

form in which both six-membered chelate rings are attached to the axial nitrogen, and they are therefore facially coordinated (resulting in severe steric crowding. Rotation of a Co-N bond from the equatorial plane to the vacated sixth coordination site results in the formation of an isomer in which one of the six-membered chelate rings is linked to the axial nitrogen, and again, the two six-membered chelate rings are facially coordinated. Thus the sole stable product is the one formed with retention of configuration, although it does not account for the complete absence of the other two diastereoisomers of this geometrical isomer in base (molecular models give no indication of excessive strain upon inversion of one or both 'planar' nitrogens).

3.3.3.7 Complexes of [17B]aneN₅

Unlike the complexes of [16]aneN₅, [17A]aneN₅, [18A]aneN₅ and [18B]aneN₅ which exist in single isomeric forms, the halo, aquo, nitrate and hydroxo complexes of [17B]aneN₅ all have two isomeric forms. (An additional aquo complex has also been tentatively identified (c.f. [Co([17A]aneN₅) H₂O]³⁺) and is discussed separately). In each case the two isomers are readily distinguishable on the basis of their ¹³C n.m.r. spectra. One isomer (denoted α) has a six resonance spectrum, and is clearly one of the symmetrical meso diastereoisomers (XCIV or XCV (fig. 3.2), while the other (denoted γ) has a twelve resonance spectrum (in some cases reduced to eleven by an accidental degeneracy of two resonances). In theory the γ-isomer could be any one of the isomers that does not possess a plane of symmetry (structures XCVI-CIV, fig. 3.2); the number can readily be reduced to a choice between no more than two (vide infra). The relationship between the two isomeric forms was investigated using a number of substitution reactions, and the results are summarised in Scheme 17.

The preparation of $[\text{Co}([17\text{B}] \text{aneN}_5)\text{Br}]\text{ZnBr}_4$ from either $\text{Co}(\text{NH}_3)_5\text{Br}_3$ (Method A) or $\text{Na}_3\text{Co}(\text{CO}_3)_3 \cdot 3\text{H}_2\text{O}$ (Method B) gives a mixture of both isomers, whereas bromine oxidation of the cobalt(II) macrocyclic complex (Method C) gives exclusively the γ -isomer. The chloro complex (prepared by Method A) is also a mixture of the two isomers.

The ^{13}C n.m.r. spectra of the γ -bromo and γ -chloro complexes are very similar, and the i.r. spectra of the corresponding tetrabromo- and tetrachlorozincate salts (the less soluble product in each case) bear a striking resemblance to each other (figs. 2.5-6). Furthermore, the γ -bromo and γ -chloro complexes both give the same product composition on treatment with base and also on silver(I) induced aquation. It seems likely therefore that they both have the same isomeric form.

The α -bromo complex undergoes ligand exchange over several hours to give the α -chloro and α -aquo complexes in hydrochloric acid (1.5 M) or the α -nitrate and α -aquo complexes in nitric acid (1.5 M). This behaviour is in marked contrast to the exceedingly slow rate of ligand exchange observed for the α -chloro, γ -chloro and γ -bromo complexes in acid solution. The only mechanism by which the syn-meso and anti-meso isomers can be interconverted involves configurational inversion of both diastereoisomeric nitrogens, and this is highly unlikely to occur in strongly acidic solution. Hence all the α -complexes must have the same isomeric form.

Both possible meso isomers have a stable 6,5,6 arrangement of chelate rings in the equatorial plane. In the anti-meso isomer, both six-membered chelate rings can adopt the favoured chair conformation, whereas in the syn-meso isomer, they would be in the somewhat less stable symmetric skew boat conformation. (The $[\text{Co}([18\text{A}] \text{aneN}_5)\text{Br}]^{2+}$ cation with a 6,6,6 arrangement of chelate rings in the equatorial plane adopts

the anti-meso configuration (section 3.3.3.8), whereas the $[\text{Co}([\text{16}] \text{aneN}_5)\text{Cl}]^{2+}$ cation, with a 5,6,5 chelate ring arrangement has the syn-meso configuration,¹³⁵ so there is little guidance from the structures of similar complexes). However, the ready interconversion of the α and γ isomers in acidic solution (as observed in the silver(I) induced aquation of the halo complexes, and the reanation of the aquo complexes) is only possible if the α -isomers have the anti-meso configuration. The alternative involves configurational inversion of a diastereoisomeric nitrogen and is considered less likely for the reasons previously presented (section 3.3.3.3). No twist mechanisms can be invoked to account for the conversion of a symmetrical isomer to a non-symmetrical isomer without inversion of the configuration of at least one nitrogen. The proposed mechanism is shown in Scheme 18.

SCHEME 18

The γ -isomer formed by this pathway has a 5,6,5 arrangement of chelate rings in the equatorial plane, but unlike $[\text{Co}(\text{[16]aneN}_5)\text{Cl}]^{2+}$ (which has the syn-meso configuration and the six-membered chelate ring in a chair conformation), the diastereoisomeric nitrogens have the rac configuration, and the six-membered chelate ring is therefore constrained to adopt a symmetric skew boat conformation. The other six-membered chelate ring is joined to the axial nitrogen but it is not clear from models which conformation it will adopt. This arrangement of the macrocycle around the metal is exactly the one that Paoletti and coworkers have proposed for the nickel(II) complex on thermodynamic and spectral grounds.¹³⁴

The alternative structure for the γ -complexes is the rac isomer with the 6,5,6 chelate ring arrangement in the equatorial plane. In this case, the change from the α to the γ isomers involves inversion of the configuration of a nitrogen, and also precludes the rotation of a bound Co-N from the equatorial plane to the vacated axial site, as this would produce a different geometrical isomer. With this mechanism, the possibility that the α isomers have the syn-meso configuration cannot be excluded. In fact the observation that it is not possible to rearrange the syn-meso isomer (either by twist mechanisms or by rotation of an equatorial Co-N bond to the vacated axial site in the intermediate) makes it the more likely structure for the α -isomer, if this mechanism is operative.

The former structural assignment (with a 5,6,5 arrangement of chelate rings in the equatorial plane) is also supported by the observed chemical shifts of the central carbon atoms in the six-membered chelate rings. In each of the γ -complexes there are two resonances separated by ~ 4.2 ppm (the lower at ~ 19.5 ppm, and the higher at > 23.4 ppm). For

six-membered chelate rings linking nitrogen atoms in the equatorial plane these shifts should be similar, and in no case have they been observed below 22 ppm in the pentaazamacrocyclic complexes (c.f. complexes of [16]aneN₅, [17A]aneN₅, [18A]aneN₅, [18B]aneN₅ and the symmetrical complexes of [17B]aneN₅), or in linear tetramines.²⁷⁴ The peak at ~19.5 ppm clearly corresponds to a carbon atom in a different microenvironment. Furthermore, in a study on the cobalt(III) complexes of the ligand 3,2,3-tet,³⁷⁷ the ¹³C n.m.r. spectra of the cis-β complexes (which have the same arrangement of chelate rings as the fragment of the macrocycle containing the two six-membered chelate rings in different planes) had two distinct resonances separated by 4.0-4.8 ppm corresponding to the central carbon atoms in the "axial" and "equatorial" six-membered chelate rings. The balance of evidence therefore favours the anti-meso configuration for the α-complexes, and the 5,6,5 arrangement of chelate rings in the equatorial plane with the rac configuration for the diastereoisomeric nitrogens for the γ-isomer (Scheme 18 species a and b).

Both α and γ isomers of various complexes give the same proportions of the α-hydroxo (~60%) and γ-hydroxo (~40%) complexes on treatment with base. Silver(I) induced aquation of the γ-halo complexes in acidic solution gives substantial inversion, whereas the α-isomers generally undergo ligand replacement with retention of configuration. It would appear therefore that the α-isomer is the more stable. The formation of exclusively γ-[Co([17B]aneN₅)Br]²⁺ upon bromine oxidation of the cobalt(II) complex must be kinetically controlled, whereas the mixture of isomers obtained in the other syntheses is the result of thermodynamic control. The observation that only the single isomer γ-[Co([17B]aneN₅)SO₃]⁺ is formed from a mixture of the α and γ-aquo complexes suggests that the nature of the incoming group is also important in determining the product stereochemistry.

Although the induced aquation reactions that were carried out in nitric acid produced mixtures of the aquo and nitrate complexes, it is not possible to attribute the presence of the nitrate complexes to competition for a five-coordinate intermediate, as the aquo complexes appear to undergo ready conversion to the nitrate complex. The substantial difference between the product composition of mercury(II) and silver(I) induced aquation of the γ -bromo complexes indicates that the two reactions do not proceed via a common intermediate.³⁷⁸

The preparation of the aquo complex by method A (from $[\text{Co}(\text{NH}_3)_5 \text{H}_2\text{O}](\text{ClO}_4)_3$) gives a mixture of the α - and γ -aquo complexes, identified from spontaneous and induced aquation studies. However, another product (denoted the δ -aquo isomer) is also formed in the reaction. The ^{13}C n.m.r. spectrum has a number of similarities to that of the unidentified $[\text{Co}([\text{17A}] \text{aneN}_5) \text{H}_2\text{O}]^{3+}$ isomer. One of the resonances corresponding to the central carbon atom of a six-membered chelate ring is significantly downfield of those in the α - and γ -aquo complexes. The syn-meso complexes of $[\text{16}] \text{aneN}_5$ have a resonance with a similar chemical shift, and this suggests that this isomer is possibly the diastereoisomeric form of the γ -complexes in which both N-H groups are on the same side of the equatorial plane as the monodentate ligand. The resonances corresponding to carbon atoms adjacent to a nitrogen cover the same broad range as those in the unidentified $[\text{Co}([\text{17A}] \text{aneN}_5) \text{H}_2\text{O}]^{3+}$ complex (43.4-62.3 ppm). The peak at 43.4 ppm is in the region where resonances of the uncomplexed protonated amine occur, and the possibility that the macrocycle is only partially coordinated cannot be dismissed. The base hydrolysis product of the δ -aquo isomer has the same distinguishing features as the aquo complex, indicating that it does not readily rearrange to the α - or γ -hydroxo species.

3.3.3.8 Complexes of [18A]aneN₅

The attempted synthesis of the halo or aquo complexes of [18A]aneN₅ using Methods A, B or D were all unsuccessful, and unreacted amine salts were recovered from many of the reaction mixtures. This is similar to the behaviour observed for [16]aneN₄,¹⁶⁰ which arguably is similarly strained. However, the bromine oxidation of the cobalt(II) complex of [18A]aneN₅ gave [Co([18A]aneN₅)Br]Br₂ in excellent yield.

The most striking feature of the complex is that unlike the remainder of the bromo complexes (which all had the expected colour of a bromopentamine) it is green, seemingly due to the absence of the band at ~500 nm in the electronic spectrum (Table 2.16). The possibility that the green colour resulted from the formation of a trans-dibromo complex (with only four of the five amine groups coordinating) was rejected as the spectral parameters were quite different from those of other green trans dibromo-tetramines, and because the i.r. spectrum of the complex recrystallized from acidic solution did not contain the $\nu_{(\text{NH}_2^+)}$ bands that would result from protonation of an uncoordinated amine. The formation of the dibromide salt in preference to the tetrabromozincate on recrystallization of the complex from hydrobromic acid/zinc bromide is uncharacteristic for these (and other) bromopentamine complexes.

The complex was rather insoluble in most solvents, and the solutions invariably changed colour during attempts to acquire a meaningful ¹³C n.m.r. spectrum. The resulting spectrum (of the hydrolysis product) comprises only six resonances, five corresponding to carbon atoms adjacent to nitrogen and a single resonance corresponding to the central carbon atoms in the three six-membered chelate rings. The complex must therefore have a plane of symmetry, and hence it can be identified as one of the meso isomers with the three six-membered chelate rings forming the equatorial

donor plane. This arrangement is not surprising in light of the known preference of even 3,3-tri (which contains only two six-membered chelate rings) for meridional coordination.^{250,272,363,373-375}

As it was not possible to acquire a ^{13}C n.m.r. spectrum of the bromo complex in solution, the solid state ^{13}C spectrum was run. Unfortunately the spectrum consisted of only two broad bands corresponding to the two different types of carbon atom ($\text{CH}_2\text{-N}$ and $\text{C-CH}_2\text{-C}$) with no resolved fine structure, so it was not possible to draw any conclusions regarding the structure of the complex cation. (It did, however, confirm that there were no uncoordinated nitrogen atoms.³⁵⁶)

A structural determination of $[\text{Co}([\text{18A}] \text{aneN}_5)\text{Br}]\text{Br}_2$ is underway and the preliminary results ($R=5.2\%$) indicate that the complex cation does indeed have the 6,6,6 arrangement of chelate rings in the equatorial plane. The complex is in the anti-meso configuration, and all three six-membered chelate rings adopt the chair conformation (fig. 3.4).

Induced aquation and base hydrolysis led to substantial decomposition so it was not possible to investigate these reactions by ^{13}C n.m.r. Similar ready decomposition of $\text{trans-}[\text{Co}([\text{16}] \text{aneN}_4)\text{Cl}_2]^{2+}$ in water has been noted, and is attributed to the ease of reduction of cobalt(III) to cobalt(II) in this complex.¹⁶⁰ The observation that the cobalt(II) state becomes more stable for the larger macrocycles could account for the relative ease of decomposition observed for the complexes of $[\text{18A}] \text{aneN}_5$ and the difficulties encountered in their synthesis.

Treatment of a suspension of $[\text{Co}([\text{18A}] \text{aneN}_5)\text{Br}]\text{Br}_2$ in methanol with lithium chloride leads to a rapid ($\sim$ minutes) colour change from green to blue-purple, and it is probable that the chloro complex has been formed in a metathetical reaction. Although the chloro complex appears to hydrolyse considerably more slowly than the bromo complex, solubility

Structure of the $[\text{Co}([\text{18A}] \text{aneN}_5)\text{Br}]^{2+}$ Complex Cation

fig 3.4

problems have precluded investigation of the complex by ^{13}C n.m.r. (the system is being further investigated).

3.3.3.9 Complexes of [18B]aneN₅

Once again, the only method that was successful in producing a pure product was bromine oxidation of the cobalt(II) complex (Method C). The other three methods led to the formation of intractable oils; even the brown peroxo complex obtained by aerial oxidation of the cobalt(II) complex appeared to undergo substantial decomposition in water (on the basis of the ^{13}C n.m.r. spectrum).

The nature of the ligand is such that at least one of the six-membered chelate rings must be linked to the axial nitrogen, and models indicate that the steric crowding has become rather severe.

The ^{13}C n.m.r. spectrum of the bromo complex dissolved in perchloric acid (1.5 M) is identical to that of the silver(I) catalysed aquation product, indicating that the spontaneous aquation reaction is rapid. In nitric acid there are additional resonances which have been assigned to the nitrate complex. The spectrum (of the aquo complex) has eight resonances corresponding to $\text{CH}_2\text{-N}$ (two of which have double the intensity of the other six) and three separate resonances for the central carbon atoms of the three six-membered chelate rings. The hydroxo complex also has eight resonances corresponding to $\text{CH}_2\text{-N}$ (although the pattern is quite different from that of the aquo complex) and two of the high field resonances ($\text{C-CH}_2\text{-C}$) are degenerate.

It is not possible to establish which of the isomeric forms the complexes have adopted on the basis of the ^{13}C n.m.r. spectra, although the two symmetric isomers can be excluded as their spectra should contain at most seven resonances. The rac diastereoisomer of the symmetrical

geometrical isomer is considered to be unlikely as it contains two out-of-plane six-membered chelate rings (attached to the axial nitrogen) which involves considerable steric crowding. Furthermore in this isomer, the adjacent six-membered chelate rings would be in their less favoured facial mode of coordination (see section 3.3.3.6). The geometrical isomer in which the equatorial plane contains the 6,5,6 arrangement of chelate rings also requires the two adjacent six-membered chelate rings to adopt the less favoured facial coordination. The third geometrical isomer with the 5,6,6 arrangement of chelate rings in the equatorial plane and the axial nitrogen linked to the equatorial plane by five- and six-membered chelate rings appears to be the least strained. The ^{13}C n.m.r. spectra are not inconsistent with this arrangement (c.f. complexes of [17A]aneN₅ which also has a 5,6,6 arrangement of chelate rings in the equatorial plane) but a crystal structure determination or strain energy minimisation calculation are needed to characterize the system.

3.3.3.10 Spontaneous Aquation Reactions

The kinetics of spontaneous aquation of halopentamines (especially the chloropentamines) has been extensively investigated.^{371,379} The retarding effect of increased chelation and the accelerating effects of increased crowding or expansion of chelate ring size are all well established.^{371,379-382} It would be expected that the aquation rate of $[\text{Co}([\text{15}] \text{aneN}_5)\text{Br}]^{2+}$ should be less than that of $[\text{Co}(\text{tetren})\text{Br}]^{2+}$ (estimated $\leq 2 \times 10^{-8} \text{ s}^{-1}$) and successively increasing the number of six-membered chelate rings²⁵⁹ (and strain) will lead to increased aquation rates. There is no evidence of spontaneous aquation in acidic solutions of $[\text{Co}([\text{15}] \text{aneN}_5)\text{Br}]^{2+}$, $[\text{Co}([\text{16}] \text{aneN}_5)\text{Br}]^{2+}$ or $\gamma\text{-}[\text{Co}([\text{17B}] \text{aneN}_5)\text{Br}]^{2+}$ left overnight, whereas $[\text{Co}([\text{17A}] \text{aneN}_5)\text{Br}]^{2+}$ and $\alpha\text{-}[\text{Co}([\text{17B}] \text{aneN}_5)\text{Br}]^{2+}$ show appreciable aquation over a similar period.

The spontaneous aquation rate of $[\text{Co}([\text{18A}] \text{aneN}_5)\text{Br}]^{2+}$ has been determined in both nitric and perchloric acid ($k \sim 5 \times 10^{-5} \text{ s}^{-1}$ at 25°C). This value is not unreasonable, if both the degree of chelation and the number of six-membered chelate rings are taken into consideration.³⁷⁹ However, the spontaneous aquation rate of $[\text{Co}([\text{18B}] \text{aneN}_5)\text{Br}]^{2+}$ is significantly greater. The reaction is almost complete in the time taken to dissolve the sample, suggesting that the rate constant is several orders of magnitude greater than for the isomeric $[\text{18A}] \text{aneN}_5$. The relief of steric strain on formation of an intermediate of reduced coordination has been implicated in the enhanced aquation rates of a number of cobalt(III) complexes.^{166,381,382} Clearly there is appreciable strain associated with the disposition of the five and six-membered chelate rings around the metal cation, and the rate enhancement is not merely dependent on the number of five and six-membered chelate rings, otherwise the complexes of both isomeric eighteen-membered macrocycles would have similar spontaneous aquation rates. The different spontaneous aquation rates observed for α - and γ - $[\text{Co}([\text{17B}] \text{aneN}_5)\text{Br}]^{2+}$ likewise reflect the difference in the strain associated with the two dispositions of the macrocycle about the metal cation.

The spontaneous aquation rate of $[\text{Co}([\text{18B}] \text{aneN}_5)\text{Br}]^{2+}$ is unparalleled among the bromopentamines, but may be compared with that of $[\text{Co}([\text{16}] \text{aneN}_4)\text{Cl}_2]^+$ ($k_1 = 2.57 \text{ s}^{-1}$ at 25°C ,¹⁶⁶). The loss of a chloride ion from a divalent monochloro species is about 100 times slower than from a monovalent dichloro species,³⁸⁰ but the loss of a bromide is about five times faster than the loss of a chloride,³⁷⁹ so the expected aquation rate of a species such as $\text{trans-}[\text{Co}([\text{16}] \text{aneN}_4)(\text{NH}_3)\text{Br}]^{2+}$ would be of the same order of magnitude as that observed for $[\text{Co}([\text{18B}] \text{aneN}_5)\text{Br}]^{2+}$. The cobalt(III) complexes of $[\text{16}] \text{aneN}_4$ and $[\text{18B}] \text{aneN}_5$ are significantly

more strained than those formed with the corresponding smaller ring macrocycles (as evident from the difficulties experienced in their preparation) and the unusually large aquation rates can largely be attributed to this strain.

3.3.3.11 Complexes of [19]aneN₅, [20]aneN₅ and tetrpn

All attempts to prepare the cobalt(III) complexes of these ligands were unsuccessful. Even the bromine oxidation method, which was successful for the eighteen-membered macrocycles (where all other methods failed), did not yield the desired products. The ¹³C n.m.r. spectra of the brown aerial oxidation products of cobalt(II) with [19]aneN₅ and tetrpn (which appeared to be the desired peroxo complexes) showed the presence of only uncomplexed ligand, indicating that any complex which may have been present was unstable in water. Solutions containing cobalt(II) and [20]aneN₅ appeared not to react with oxygen at all. (For a discussion of the relative stability of the cobalt(II) and cobalt(III) complexes, see section 3.3.5).

3.3.4 Electronic Spectra of Cobalt(III) Complexes

3.3.4.1 Analysis of Spectra

The spin-paired d⁶ system of a cobalt(III) ion in an octahedral field¹⁵⁸ will give rise to a spectrum consisting of two spin-allowed transitions from the ground state (fig. 3.5) (¹T_{1g} ← ¹A_{1g} and ¹T_{2g} ← ¹A_{1g}). On reduction to C_{4v} symmetry (to which these systems can be approximated, as previously discussed, section 3.2.2.6) the excited states are both split (¹T_{1g} → ¹E_g^a + ¹A_{2g}; ¹T_{2g} → ¹B_{2g} + ¹E_g^b). However, the lower energy spin allowed transition is more susceptible to lowered symmetry and the higher energy spin allowed transitions (resulting from splitting of the

fig 3.5 Energy Levels for the Singlet States of a Tetragonal d^6 Ion

$^1T_{2g}$ state) often remain unresolved.^{136,334,336} Furthermore, the higher energy transitions are often not observed as they are obscured by the tail of the charge transfer bands in the ultraviolet region of the spectrum.

A crystal field model has been developed¹⁵⁸ for the interpretation of the spectra of such complexes in terms of the crystal field potential Dq . Although the crystal field theory is now considered to have serious drawbacks, the values obtained from this treatment still have considerable value as empirical ligand field parameters that can be useful in comparing the complexes of a group of related ligands.¹⁵⁸ For compounds with C_{4v} symmetry, the relevant equations are

$$10Dq^{xy} = E(^1A_{2g} + ^1A_{1g}) + C \quad 3.1$$

$$Dt = \frac{4}{35} [E(^1A_{2g} + ^1E_g^a)] \quad 3.2$$

$$Dq^z = Dq^{xy} - \frac{7}{2}Dt \quad 3.3$$

Dq^{xy} and Dq^z represent the equatorial and axial ligand field

A number of approximations or assumptions are inherent in the treatment. The energy of the ${}^1A_{2g}$ component of the low energy band is predicted to have the same energy as the ${}^1T_{1g}$ band in the parent octahedral complex. Although this may be generally valid for the amines and their derivatives, it has been shown to be invalid for the tetraazamacrocyclic complexes in which the macrocycle is coordinated in the equatorial plane (for which there is an inverse relationship between Dq^{xy} and Dq^z 127,131,160,161). Even where the ${}^1A_{2g}$ and ${}^1E_g^a$ bands are clearly resolved, some workers choose to evaluate Dt using the $({}^1T_{1g} + {}^1A_{1g})$ transition of the parent octahedral complex, or even simply the average values of a related series of Co-N₆ donor systems rather than the $({}^1A_{2g} + {}^1A_{1g})$ transition, although this involves the implicitly contradictory assumptions that the equatorial donor ligands provide a constant ligand field strength from the octahedral complex to the derivative substituted C_{4v} complex and that at the same time the $({}^1A_{2g} + {}^1A_{1g})$ transition does not represent the true equatorial ligand field strength (i.e. the equatorial donor field strength has not remained constant on substitution). An alternative treatment has been developed³⁸⁴ in which Dt is evaluated as expressed in equation 3.2, the Racah B parameter as

$$B = \frac{1}{16}[E({}^1E_g^b, {}^1B_{2g} + {}^1A_{2g})] \quad 3.4$$

and the ratio C/B is taken to be unchanged from that of the parent octahedral complex. (C should preferably be evaluated from equation 3.5, but this is usually not possible as the transition to the ${}^3T_{1g}$ level is generally obscured).

$$E({}^3T_{1g} + {}^1A_{1g}) = 10Dq - 3C \quad 3.5$$

This method does not rely on the assumption that the in-plane ligand field strength remains unchanged when the axial field is altered, but the results obtained are not altogether satisfactory.³⁸⁴

If the (${}^1E_g^a + {}^1A_{1g}$) and (${}^1A_{2g} + {}^1A_{1g}$) bands are not resolved, there are two distinct ways to treat the problem. It is possible to use the (${}^1T_{1g} + {}^1A_{1g}$) band of the parent octahedral complex in conjunction with the unresolved band in the complex to calculate Dt and hence Dq^Z . However, the maxima of the two unresolved bands present under the envelope may be well separated (up to 1000 cm^{-1}), so simply using the peak maximum to represent the (${}^1E_g^a + {}^1A_{1g}$) transition will lead to appreciable error. Alternatively, the "average environment rule"^{97,384,385} may be used to determine the effective contributions of the various ligands. For a $\text{Co}^{\text{III}}\text{L}_5\text{A}$ system the average ligand field strength

$$10Dq^{\text{av}} = E({}^1T_{1g} + {}^1A_{1g}) + C \quad 3.6$$

may be expressed as the contributions of the different ligands

$$Dq^{\text{av}} = \frac{5}{6}Dq^{\text{L}} + \frac{1}{6}Dq^{\text{A}} \quad 3.7$$

Such a treatment has been applied to cobalt(III) complexes of a variety of linear pentamines.⁹⁷ This method requires an estimate of Dq^{A} if the ligand field strength of the ligand L is to be calculated. Clearly the choice of Dq^{A} will have a profound influence on Dq^{L} , and again this relies on the assumption that the field strength of the ligand A is constant for all six-coordinate cobalt(III) complexes. Furthermore, the assumption that all the coordinating groups of a multidentate ligand are equivalent cannot be easily justified. (It is probably quite invalid for the ligands with π -bonding capability³⁸⁶ such as those discussed by Martell,⁹⁷ although for the saturated pentaazamacrocyclic ligands, which have five similar secondary amine donor groups, the treatment has rather more justification). In those cases where the two low energy bands are not resolved, the complexes implicitly have ligand fields with near-octahedral symmetry. For a series of complexes (CoL_5A) where the ligands L are closely related (as are the pentaazamacrocycles) and the sixth donor

group (A) remains unchanged, it can be assumed that the contribution of Dq^A to Dq^{av} will remain nearly constant and changes in the value of Dq^{av} will merely reflect differences in the strength of the ligand field of ligand L. Hence even if the absolute value of Dq^{av} has no value for comparison with other systems, trends within the related compounds can still be discussed.

Ligand field parameters for the complexes are listed in Tables 3.3 and 3.4. Where two low energy peaks are present in the visible spectrum, they have been resolved graphically, and the respective band maxima are used to calculate Dq^{xy} , Dt and Dq^z . For comparison, the ligand field parameters of the chloro complexes are also calculated using equation 3.4 and taking the ratio $C/B = 7.6$.³⁸⁴ It is reassuring that although the two methods of calculating Dq^{xy} for the chloro complexes give values that are quite different ($60\text{--}120\text{ cm}^{-1}$), the relationship throughout the range of macrocyclic complexes retains the same relative order.

In complexes for which only a single low energy band is observed, the ligand field parameters have been calculated using $[\text{Co}([18]\text{aneN}_6)]^{3+}$ as the parent octahedral complex from which Dq^{xy} is derived. For comparison Dq^{av} (the average ligand field of each complex) and the Racah B parameter (where the $(^1E^B + ^1B_2 + ^1A_1)$ level is observed) have been calculated, as well as Dq^L (the net ligand field strength of the macrocycle) for the aquo complexes.

3.3.4.2 Ligand Field Parameters of the Halopentamines

The values of Dq^{xy} , Dt and Dq^z for the different complexes show considerable variation. In complexes with an equatorial tetraazamacrocyclic donor set the value of Dq^{xy} is strongly dependent on the size mismatch between the metal and the macrocyclic cavity.¹⁶⁰ Although there is no

Table 3.3

Ligand Field Parameters of [CoL OH]²⁺
and [CoL H₂O]³⁺ Complexes (cm⁻¹)

CoLX	X=H ₂ O ^a			X=H ₂ O		X=OH ^{-a}		
	Dq ^{XY, b}	Dt	Dq ^Z	Dq ^{Mac, c}	B ^d	Dq ^{XY, b}	Dt	Dq ^Z
L=								
(NH ₃) ₅	2442	5	2425	2556	550	2368	79	2090
tetren	2499	70	2255	2624	462	2421	19	2354
u-datn	2508	80	2228	2635	383	-	-	-
[15]aneN ₅	2531	106	2160	2662	457	2429	10	2395
[16]aneN ₅	2508	80	2228	2635	477	2388	57	2190
[17A]aneN ₅	2384	61	2170	2487	460	2333	119	1915
[17B]aneN ₅	2380	66	2150	2482	486	2314	141	1821
[18A]aneN ₅	2246	219	1478	2321	610	2296	162	1728
[18B]aneN ₅	2360	84	2070	2463	463	2285	175	1674

^a Calculated using [Co([18]aneN₆)]³⁺ (Dq^{XY}=20576 cm⁻¹) as the parent octahedral reference compound.²³⁴

^b Alternatively Dq^{av}.

^c Dq^M = 3/25(Dq^{av}-683)^{97,158}

^d B = E(¹E_g^b + ¹B_{2g} + ¹A_{2g})/16.

Table 3.4
Ligand Field Parameters of Cobalt(III) Halopentamines (cm⁻¹)

[CoLX] ²⁺ L=	X=Br ^{-a}			X=Cl ^{-a}			X=Cl ^{-b}				
	Dq ^{xy}	Dt	Dq ^z	Dq ^{xy}	Dt	Dq ^z	B	C ^C	Dq ^{xy}	Dt	Dq ^z
(NH ₃) ₅	2508	361	1244	2521	307	1446	379	2896	2431	307	1366
u-datn	-	-	-	2463	187	1809	406	3102	2394	187	1738
tetren	2463	295	1429	2463	204	1749	424	3239	2407	204	1693
pyaneN ₅	2545	297	1506	2554	368	1265	480	3667	2541	368	1253
[15]aneN ₅	2476	405	1059	2490	381	1156	394	3010	2411	381	1077
[16]aneN ₅	2526	430	1022	2563	394	1182	357	2727	2456	394	1086
[17A]aneN ₅	2400	307	1324	2468	289	1457	336	2567	2344	289	1333
[17B]aneN ₅	2438	354	1201	2485	332	1323	346	2643	2370	332	1208
[18A]aneN ₅	2075	-	>1500	-	-	-	-	-	-	-	-
[18B]aneN ₅	2285	282	1299	2274	142	1778	419	3201	2214	142	1717

^aCalculated from equations 3.1-3.3.
^bBased on the alternative treatment outlined in ref. 384.
^cC.f. 3800 cm⁻¹, 158

completed ring system in the equatorial plane of the pentaazamacrocyclic complexes, variations in the value of Dq^{xy} may nevertheless be related to the degree of strain experienced by the equatorial N_4 donor set (c.f. the cis-carbonato complexes of the tetraazamacrocyclic complexes which also show a variation of Dq^{av} with ring size, although it is much smaller than the effect observed for the trans-dichloro complexes¹⁶⁰). The nature of the equatorial donor set in cobalt chloropentamine complexes clearly has a marked effect on Dq^{xy} , although in theory the size and number of the chelate rings linking the equatorial amine groups should not affect the value of Dq^{xy} unless severe strain or steric crowding results.

The chelate ring arrangement of the equatorial donor plane is shown in Table 3.5. The values of Dq^{xy} calculated for the halopentamines do not accurately reflect the order of stability of multidentate chelate ring systems. The halo complexes of [16]aneN₅ have the highest Dq^{xy} value in each group, and this is consistent with the known stability of the 5,6,5 chelate ring sequence which is known to be present in the equatorial plane, but the next highest values are those of the [15]aneN₅ complexes, although they have a 5,5,5 chelate ring sequence in the equatorial plane which is more strained than the 5,6,5 and 6,5,6 chelate ring systems¹⁶⁶ that are present in the equatorial plane of the [17B]aneN₅ cobalt(III) complexes. The cumulative ring strain associated with the 6,6,6 arrangement of chelate rings in the equatorial plane is even greater than that associated with the 5,5,5 arrangement^{121,166} and this is seen in the substantially lowered Dq^{xy} of $[Co([18A]aneN_5)Br]^{2+}$. Although the order of chelate rings in the equatorial plane of $[Co([18B]aneN_5)Br]^{2+}$ is not known, it cannot be 6,6,6 and hence a value of Dq^{xy} which is greater than that of the cobalt(III) complex of [18A]aneN₅. The fact that the value of Dq^{xy} is smaller than those for the sixteen or seventeen membered macrocycles with which it has a common equatorial chelate ring arrangement is probably the result of

Table 3.5

Chelate Ring Sequence In
Cobalt(III) Complexes of Pentamines^a

	<u>Chelate Rings in</u> <u>Equatorial Plane</u>	<u>Chelate Rings to</u> <u>Axial Nitrogen</u>
[15]aneN ₅	5,5,5	5,5
[16]aneN ₅	5,6,5	5,5
[17A]aneN ₅	5,6,6	5,5
[17B]aneN ₅ ^{b,c}	α 6,5,6	5,5
	γ 5,5,6	5,6
[18A]aneN ₅	6,6,6	5,5
[18B]aneN ₅	5,6,5	6,6
	5,6,6 ^c	5,6 ^c
	6,5,6	5,6
tetren	5,5,-	5,5
u-datn	5,5,-	5,5,5 ^d
pyaneN ₅	5,5 ^e ,5 ^e	5,5

^aThe numbers refer to the "bite-size" of each chelate ring.

^bTwo different isomers obtained.

^cPostulated to be the most likely isomeric forms.

^dTripodal tertiary amine.

^eChelate rings incorporating an aromatic segment.

increased strain arising from the presence of at least one out-of-plane six-membered chelate ring.

The axial field strengths present a different picture. With the possible exception of γ -[Co([17B]aneN₅)X]²⁺, and [Co([18B]aneN₅)X]²⁺ all the complexes should have the same axial donor field (Table 3.5), comprising a secondary amine group bound to two secondary amines in the equatorial plane via two five-membered chelate rings in a facial arrangement, and a halide bound trans to this group. Yet the values of Dq^Z vary quite dramatically. The values for complexes of [15]aneN₅ and [16]aneN₅ are significantly lower than those of the other pentaazamacrocycles, and the values appear to increase roughly with increasing macrocycle size, but there is no clear relationship with the nature of either the axial or equatorial donor groups. Unlike the trans-dichloro macrocyclic tetramines¹⁶⁰ there is no obvious correlation between Dq^{xy} and Dq^Z . The values of Dq^{xy} for [Co(tetren)Br]²⁺ and [Co([15]aneN₅)Br]²⁺ are 2463 cm⁻¹ and 2476 cm⁻¹ respectively, whereas the corresponding Dq^Z values are 1429 cm⁻¹ and 1059 cm⁻¹ respectively. These represent the two extremes of the observed range of Dq^Z for the bromo complexes, yet there is virtually no difference in Dq^{xy} and both have effectively equivalent axial donor groups. Similar anomalies are also present in the Dq^Z values of the chloro complexes. Clearly the conventional models^{158,384} are inadequate to explain such variations in the values, and this must cast doubt on the significance of the assumptions implicit in the treatment as well as on reported ligand field parameters. Furthermore, the values of Dq^{xy} appear to be dependent on the nature of the monodentate (axial) donor group, so the effect of both axial donor groups is transmitted to the equatorial donor set.

3.3.4.3 Ligand Field Parameters of the Aquo and Hydroxo Complexes

The range of values exhibited by these complexes is much narrower than that of the halo complexes. The values of Dt and Dq^Z generated for the macrocyclic aquo and hydroxo complexes using $[\text{Co}([\text{18}] \text{aneN}_6)]^{3+}$ as the parent octahedral chromophore are expected to have large uncertainties. The values obtained are all of the expected magnitude with the exception of Dt and Dq^Z for $[\text{Co}([\text{18A}] \text{aneN}_5) \text{H}_2\text{O}]^{3+}$ which indicate appreciable distortion and weakening of the axial field.

By contrast with the halo complexes (in which Dq^Z increases with increasing macrocycle size), the hydroxo complexes show a small but steady decline in both axial and equatorial field strength, and a corresponding increase in the tetragonal distortion. It is possible that the smaller hydroxide ion and the relative ease of deprotonation of the amines in base lessen the effect of unfavourable interactions specific to any complex, so the progressive weakening of the donor field can be attributed simply to the increasing size of the macrocycle.

With the exception of $[\text{Co}([\text{18A}] \text{aneN}_5) \text{H}_2\text{O}]^{3+}$, the average ligand field strengths of the aquo complexes show a similar gradual trend, and the values of the Racah B parameter remain invariant ($457 \text{ cm}^{-1} < B < 486 \text{ cm}^{-1}$). The values for the former complex ($B = 610 \text{ cm}^{-1}$, $Dq^{\text{mac}} = 2321 \text{ cm}^{-1}$) are indicative of significant steric crowding and distortion.³⁸⁴ The parameters calculated for the aquo complexes using $[\text{Co}([\text{18}] \text{aneN}_6)]^{3+}$ as the parent octahedral reference are consistent with those calculated using equations 3.6 and 3.7. $[\text{Co}([\text{18A}] \text{aneN}_5) \text{H}_2\text{O}]^{3+}$ shows anomalous behaviour again, with a significantly lower Dq^{xy} than the other complexes. The axial ligand field strength is very considerably weaker ($Dq^Z = 1478 \text{ cm}^{-1}$; average of other macrocyclic complexes $Dq^Z \sim 2156 \text{ cm}^{-1}$) and Dt is correspondingly larger, suggesting that the complex is subject to severe strain.

The most significant differences between the halopentamines and their aquo and hydroxo counterparts is the opposite trends in the axial field strengths and the reversal in the order of the equatorial field strengths of [15]aneN₅ and [16]aneN₅ (which further highlights the significant effect that the axial donors have on the equatorial field strength).

In conclusion, it is quite clear that there is considerable disagreement regarding the correct method of calculating the parameters, and consequently interpretation of the data in terms of structural and bonding features must at best be tentative. The presence of anomalies that are irreconcilable with the original treatment¹⁵⁸ indicates that other factors also contribute to determining the electronic environment of the metal, and highlights the shortcomings of this method in its present form. It appears that the spectral parameters derived using this technique cannot be used as indicators of specific structural characteristics, but only to draw rather general conclusions regarding the degree of strain that is present in the complex as a whole, at least for the more elaborate systems involving a large degree of chelation.

3.3.5 Cobalt(II) Complexes

3.3.5.1 Structure and Spectra

The complexes $[\text{Co}([19]\text{aneN}_5)](\text{ClO}_4)_2$ and $[\text{Co}([20]\text{aneN}_5)](\text{ClO}_4)_2$ have magnetic moments that are typical for high-spin d^7 cations. Their infrared spectra show no evidence for perchlorate coordination, and the single sharp $\nu_{(\text{N-H})}$ peak of each compound confirms that all five amine groups are bound. They behave as typical 1:2 electrolytes in non-aqueous solution and thus they are both five-coordinate, high-spin cobalt(II) complexes.

The enhanced stability of the cobalt(II) state in these complexes (as shown by their resistance to oxidation using methods that were successful for the complexes of smaller macrocycles) has also been noted in a series of complexes $\text{trans-}[\text{Co}([13-16]\text{aneN}_4)\text{Cl}_2]^+$, in which $E_{1/2}(\text{Co}^{3+}/\text{Co}^{2+})$ decreases with increased strain¹⁶⁰ (the largest macrocyclic species- $\text{trans-}[\text{Co}([16]\text{aneN}_4)\text{Cl}_2]^+$ has an $E_{1/2}$ of -0.11 v in acetonitrile). The increased preference of the larger tetraazamacrocyclic complexes for the cobalt(II) cation has been attributed to the better fit of the larger $2+$ cation into the macrocyclic cavity (and the consequent relief from strain). Although the pentaazamacrocyclic complexes do not have the same complete macrocyclic 'girdle' as the equatorially coordinated tetraazamacrocycles, and therefore there is more opportunity to minimize the effect of the cation-macrocycle size mismatch, the increase in the effective size of the macrocyclic cavity with chain size may well lead to the destabilizing of the cobalt(III) state (the $E_{1/2}$ value has been shown to depend on both the equatorial and axial donor fields,^{146,160,164} which change progressively with increasing macrocyclic ring size).

However, the lack of success in the attempted synthesis of cobalt(III) complexes of 3,3,3-tet and the instability of complexes containing large chelate rings (such as 3,4-tri²⁵⁹) suggest that cumulative ring strain also plays a significant part in determining the stability of cobalt(III) complexes. The instability of cobalt(III) complexes of [19]aneN₅ and [20]aneN₅ may well result from cumulative ring strain caused by the successive six-membered chelate rings (four and five respectively) in the macrocycles. Even the complexes of the eighteen membered macrocycles appear to be less stable than those of their smaller analogues. The effect of cumulative ring strain is also evident in the rapid (~minutes) decomposition of [Co([20]aneN₅)](ClO₄)₂ even in neutral aqueous solution. Similarly tetrpn (the linear pentamine analogue of [20]aneN₅) does not form complexes with cobalt that are stable in aqueous solution.

When steric hindrance prevents coordination of a sixth donor group, the cobalt(II) state is often stabilized. A number of five-coordinate cobalt(II) amine complexes have been reported that do not undergo oxygenation even in solution,^{91,95,170-172,286,327,329,348,352,387,388} and the corresponding nickel(II) complexes are generally five-coordinate (although the converse relationship does not necessarily hold^{31,98}). In the case of [19]aneN₅ and [20]aneN₅, both the cobalt(II) and nickel(II) complexes are five-coordinate and it appears that oxygenation of the cobalt(II) complexes and possibly also oxidation by bromine may be prevented by steric considerations.

The cobalt(II) complexes may adopt either trigonal bipyramidal or square pyramidal geometry as the two limiting cases (c.f. 3.2.2.5 and 3.2.2.6). Structural determinations of cobalt(II) complexes with trigonal bipyramidal geometry have been reported^{328,329,343} but square

pyramidal geometry³⁴³ has generally been established for cobalt(II) complexes only when the structure of the nickel(II) complex has been determined, and the two complexes have been shown to be isostructural on the basis of x-ray powder diffraction patterns.^{320,388}

Various authors have developed ligand field interpretations of high-spin five-coordinate cobalt(II) complexes with both geometries.^{343-345,389,390} The spectra of $[\text{Co}([19]\text{aneN}_5)](\text{ClO}_4)_2$ and $[\text{Co}([20]\text{aneN}_5)](\text{ClO}_4)_2$ are quite similar, and it is likely that they both adopt the same geometry. Their spectra differ from those of complexes with trigonal bipyramidal geometry (such as complexes of the tripodal tetramines)^{216,295,347,348,390,391} not only in the positions of the band maxima, but also in their significantly lower extinction coefficients. The similarity of their spectra to those of complexes postulated to have square pyramidal geometry, both in peak position and intensity^{31,170,286} suggest this as their probable geometry. However, assignment of structure on the basis of spectra features alone is at best tentative. Thus the spectra of cobalt(II) complexes with known square pyramidal and trigonal bipyramidal geometry may be very similar.³⁸⁹ Furthermore, if the structures are distorted from the limiting geometries, the spectra become more complex owing to the large number of closely spaced energy bands,^{389,390} and any distinctive spectral features may be the result of factors other than the gross stereochemistry of the complexes. A full structural determination is needed to determine whether these complexes indeed adopt the less common square pyramidal stereochemistry.

3.3.6 Rhodium(III) Complexes

Despite the possibility that up to eleven isomeric forms could exist for most of the cobalt(III) complexes, only a very small number of these were isolated in any case. It seemed appropriate to attempt the synthesis

of some analogous complexes of rhodium(III) (which also forms octahedral low-spin d^6 complexes with amines) in order to compare the behaviour of two related cations differing substantially in size, especially since the metal-macrocycle size relationship has been shown to be a dominant feature of the tetraazamacrocyclic complexes.^{160,166} The reaction with [20]aneN₅ is of particular interest, because the absence of complexes with cobalt(III) has been attributed to the metal-ring size mismatch and the rhodium(III) cation, being larger than cobalt(III), should better be able to accommodate the larger macrocycles without strain.

Synthesis of the yellow chloro complexes proceeds smoothly on heating rhodium(III) chloride with the free macrocyclic ligand in methanol.³⁹² The crude product formed with [16]aneN₅ consisted of at least two isomers, although it was not possible to determine from the spectrum whether they are geometrical isomers or diastereoisomers. However, it is clear that the formation of a single isomer of each cobalt(III) complex of [16]aneN₅ is not due to the steric constraints of the ligand alone. By contrast with the unsuccessful attempts to prepare cobalt(III) complexes of [20]aneN₅, the presence of 31 peaks in the ¹³C n.m.r. spectrum of $[\text{Rh}([20]\text{aneN}_5)\text{Cl}]^{2+}$ indicates that all three possible isomers of this complex had been formed. Clearly the increased radius of the cation results in an easing of the strain and steric crowding caused by disposing five linked six-membered chelate rings around the smaller metal cation. The relationship between the size of the macrocyclic "cavity" and the metal cation appears to be one important factor in determining the stability of the different isomers and complexes. This relationship clearly warrants further investigation for macrocycles lacking the complete equatorial 'girdle' of the tetraazamacrocycles.

3.4 Kinetics of Acid Dissociation of Copper Complexes

3.4.1 Comparison with other Donor Systems

The relatively rapid rates of acid dissociation of the copper(II) pentaazamacrocyclic complexes are in marked contrast to the generally sluggish kinetics observed for the unsubstituted saturated tetraazamacrocyclic complexes.^{54,102,138,175,184-187,219,221,222,229} They more closely parallel the rates of dissociation of the copper(II) complexes of the linear amines or triazamacrocycles.^{173,217,225} Once again, the difference between the closed planar equatorial girdle of a tetraazamacrocycle and a system that does not contain such a closed ring, either because of the donor number (as in the triaza- and pentaazamacrocycles) or the non-cyclic nature of the ligand, is highlighted.

Although the dissociation reactions are all first order in complex concentration (as shown by the linear plots of $\log(A-A_\infty)$ against time and the use of the variable drive mechanism on the stopped-flow to alter the initial concentration of the copper complexes), their acid-dependence is considerably more complex than that of the related linear amine or triazamacrocyclic complexes. In all cases (with the possible exception of $[\text{Cu}([17\text{A})\text{aneN}_5)]^{2+}$) there appear to be at least two protonation reactions involved in the dissociation mechanism. Even where the dependence is apparently linear, the rate law involves terms in $[\text{H}^+]^2$. Furthermore, throughout the series of complexes studied, the relative importance of different parts of the dissociation mechanism changes, and it may even be necessary to invoke a different mechanism for some of the pentaazamacrocyclic complexes (e.g. $[\text{Cu}([16]\text{aneN}_5)]^{2+}$). The differences observed with respect to general-acid catalysis also reflect the different mechanistic factors in force.

The different acid-dependence of the triaza- and pentaazamacrocyclic copper(II) complexes is not surprising. Addition of two protons to the former leaves only one coordinated nitrogen which would clearly dissociate rapidly, whereas diprotonation of a complex with five nitrogen donors leaves three copper-nitrogen bonds and at least one chelate ring intact. Unfortunately, the situation with the acid-dissociation kinetics of tetraazamacrocyclic complexes is not at all clear. Although there have been reports of second-order hydrogen ion dependence at high acid concentration,^{54,181,222} the acid dissociation of tetraazamacrocyclic copper(II) complexes is generally so slow that it has not been possible to study the dissociation in more dilute (0-1 molar) acid. Those complexes that dissociate rapidly have large chelate rings (e.g. the eighteen membered tetraazamacrocycles)²²⁶ or substituents on the nitrogen donors^{54,181,226} which may significantly affect the dissociation pathways, making comparisons meaningless. The linear amines on the other hand are capable of stepwise unravelling from both ends simultaneously with no restrictions on the separation of the cation and the non-bonded nitrogens^{198-200,206,212,393} and this has no analogy among the pentaazamacrocycles.

Another significant difference between the copper(II) complexes of pentaazamacrocycles and of those polyamines with only three or four donor nitrogens is that the first rapid equilibrium protonation reaction forming a species with an unbound protonated nitrogen is likely to be almost complete for the former group, whereas the existence of stable monoprotonated species of other copper(II) amine complexes will only be observed where larger chelate rings or significant strain are present (see Table 3.6). The pK_a^{CuHL} values for L=[15]aneN₅, [16]aneN₅, [17B]aneN₅ and tetren have been reported (Table 3.6) and it is probable that the values for other pentaazamacrocycles will be of the same order of magnitude or

Table 3.6

Acid Dissociation Constants of Copper(II) Complexes

Ligand (L)	pK_a^a	Ref.
[15]aneN ₅	4.33	104
[16]aneN ₅	≤ 5	104
[17B]aneN ₅	4.7	104
tetren	5.18	394
(Htetren) ⁺	3.8	394
(H-[18]aneN ₆) ⁺	4.0	125
[14]ane-1,4,7,10-N ₄	3.08	395
[15]ane-1,4,8,12-N ₄	5.5	187
[16]ane-1,5,9,13-N ₄	2.63	396
2,4-tri	6.14	397
2,3-tri	3.14	317

^aThese represent the reaction $\text{CuHL}^{3+} \xrightleftharpoons{K_a} \text{CuL}^{2+} + \text{H}^+$.

greater, as the number of six-membered chelate rings increases. If this protonation is rapid, then the reaction mixture initially present in the stopped-flow (over the range of hydrogen ion concentrations studied) will effectively be the species CuHL^{3+} exclusively. As there are five coordinated nitrogens in the copper(II) complexes of the pentaazamacrocyclic ligands, one of them will be in an axial site, and it would be expected to be more readily displaced than the other four due to the Jahn-Teller effect.³⁰³ In the discussion of individual complexes it will be seen that it is likely that this first protonation is indeed rapid on the stopped-flow timescale.

The ability of the monoprotinated species, as well as the more highly protonated species to have significant lifetimes is not surprising. Although repulsive forces increase as successive nitrogen atoms become protonated, so does the relief from steric strain, which is also a significant factor in complexes of multidentate ligands. Hence the necessity for the protonation of more than one nitrogen before complete dissociation can take place. This contrasts with the behaviour observed for linear amine complexes of copper(II) for example, where first bond rupture or the first protonation have been reported as rate determining.²¹⁷ Consideration of the formation reactions with cyclic amines shows that for the cyclic triamines, tetramines and pentamines respectively the most highly protonated reactive species are HL^+ , H_2L^{2+} and H_3L^{3+} respectively. Clearly therefore by the principle of microscopic reversibility the (reverse) dissociation reactions of these systems can be expected to involve the CuHL^{3+} , $\text{CuH}_2\text{L}^{4+}$ and $\text{CuH}_3\text{L}^{5+}$ species,¹⁹⁹ as well as less highly protonated species in each case. In macrocyclic systems where acid is not required to assist in the dissociation reactions (and the consequent repulsive effects of protonation are circumvented) the rate determining step has also been shown to occur late in the dechelation process, as for the cyclic polythiaethers, which dissociate several orders of

magnitude more slowly than the linear thiaethers.^{192,193}

The third-order hydrogen ion dependence reported for the acid-dissociation of $[\text{Ni}([\text{18}] \text{aneN}_6)]^{2+}$ ¹⁶⁷ shows that the presence of an additional nitrogen in the framework necessitates a further protonation before dissociation can take place. In effect the species from which dissociation occur in the nickel(II) pentaaza- and hexaazamacrocyclic complexes have the same number of intact metal-nitrogen bonds (although the latter complex has an additional protonated nitrogen). This suggests that the same bond breaking is the important feature in the rate determining step.

It would be of interest to investigate the acid-dependence of the $[\text{Cu}([\text{18}] \text{aneN}_6)]^{2+}$ dissociation. In this complex there would be two axially bound nitrogen atoms that are more loosely held than the four equatorial nitrogens (Jahn-Teller effect). In the titrimetric determination of the stability constant of $[\text{Cu}([\text{18}] \text{aneN}_6)]^{2+}$ the titration curve could only be resolved by invoking the formation of the mono- and diprotonated complexes in the region pH ~3.5. It is possible that the dissociation reaction would thus still only show second order dependence on hydrogen ion concentration (with both axial nitrogens rapidly and completely protonated early in the reaction sequence).

In common with the complexes of many other polyamines,^{80,198,225} the dissociation rate of the copper(II) pentaazamacrocyclic complexes in the absence of acid is extremely slow.¹⁷⁷ From the range of hydrogen ion concentrations investigated in this work, the rate is experimentally indistinguishable from zero, and this is consistent with an estimated value for $[\text{Cu}([\text{15}] \text{aneN}_5)]^{2+}$ ($k_o \sim 6 \times 10^{-21} \text{ s}^{-1}$).¹⁷⁷

3.4.2 Acid Dissociation Kinetics of $[\text{Cu}([\text{15}] \text{aneN}_5)]^{2+}$

The dissociation of this complex shows second order dependence on the hydrogen ion concentration (Table 2.29 and fig. 2.15) in nitrate medium. Hay has studied the acid dissociation kinetics of $[\text{Cu}([\text{15}] \text{aneN}_5)]^{2+}$ in perchloric acid, and also observed second-order dependence on hydrogen ion concentration.¹⁶⁷ He derives a rate expression based on the rapid equilibrium protonation of an apical nitrogen followed by a second equilibrium protonation and the subsequent loss of the ligand (Scheme 12). The second protonation is postulated to involve the lengthening of a copper-nitrogen bond followed by protonation and the replacement of the protonated nitrogen by a solvent molecule in the coordination sphere. However, there is no evidence to support the implication that the two protonated nitrogens are not adjacent. The two possible diprotonated intermediates are shown below (CVII and CVIII).

CVII

CVIII

If the two protonated nitrogens are not adjacent, their mutual repulsion will be minimised, but they will both be held close to the more highly charged copper(2+) cation. If on the other hand two adjacent nitrogen atoms are protonated, the increased mutual repulsion will be offset by their greater separation from the metal cation, owing to the flexibility resulting from the rupture of two adjacent chelate rings. Similar

'unwrapping' involving protonation of adjacent nitrogens has been invoked for the dissociation of linear amine complexes.^{199,206,212,393}

Furthermore, the rate law takes a form that is derived from a mechanism simply involving two equilibrium protonation steps followed by dissociation of the complex (c.f. Scheme 3.7).

$$\text{Rate} = \frac{k_1 K_1 K_2 [\text{CuL}^{2+}] [\text{H}^+]^2}{1 + K_1 [\text{H}^+] + K_1 K_2 [\text{H}^+]^2} \quad 3.8$$

The simplifying assumption

$$K_1 [\text{H}^+] + K_1 K_2 [\text{H}^+]^2 \ll 1 \quad 3.9$$

is used to reduce the rate law to the observed form

$$\text{Rate} = k_1 K_1 K_2 [\text{CuL}^{2+}] [\text{H}^+]^2 \quad 3.10$$

However, the reported value of K_1 ($\sim 2 \times 10^4$)¹⁰⁴ renders the assumption (3.9) invalid throughout the entire range of hydrogen ion concentration studied. It is possible to propose a similar mechanism in which three protonation steps are involved (Scheme 19).

SCHEME 19

The observation that for pentaazamacrocyclic ligands (L), species such as H_3L^{3+} contribute significantly to the rate of complex formation with copper(II)⁹⁰ suggest that the proposed third equilibrium step in Scheme 19 (K_3) is not unreasonable.

The full form of the rate law for this mechanism is

$$\text{Rate} = \frac{k_{1d}K_1[H^+] + k_{2d}K_1K_2[H^+]^2 + k_{3d}K_1K_2K_3[H^+]^3}{1 + K_1[H^+] + K_1K_2[H^+]^2 + K_1K_2K_3[H^+]^3} \cdot [\text{CuL}^{2+}] \quad 3.11$$

dividing through by $K_1[H^+]$

$$\text{Rate} = \frac{k_{1d} + k_{2d}K_2[H^+] + k_{3d}K_2K_3[H^+]^2}{\frac{1}{K_1[H^+]} + 1 + K_2[H^+] + K_2K_3[H^+]^2} \cdot [\text{CuL}^{2+}] \quad 3.12$$

and since $[H^+] > 0.05 \text{ M}$ and $K_1 \sim 10^4$ the expression can be reduced to

$$\text{Rate} = \frac{k_{1d} + k_{2d}K_2[H^+] + k_{3d}K_2K_3[H^+]^2}{1 + K_2[H^+] + K_2K_3[H^+]^2} \cdot [\text{CuL}^{2+}] \quad 3.13$$

which has the same form as the full expression from which Hay derives his expression (having made the implicit assumption that only the $\text{CuH}_2\text{L}^{4+}$ species undergoes dissociation at a significant rate). To derive a rate expression similar to (3.10) the following conditions must hold:

$$K_2[H^+] + K_2K_3[H^+]^2 \ll 1 \quad 3.14$$

$$k_{1d} \ll k_{3d}K_2K_3[H^+]^2 \quad 3.15$$

$$k_{2d} \ll k_{3d}K_3[H^+] \quad 3.16$$

These inequalities, together with the rate law derived from the experimental results of this work (Section 2.5) give limiting values for the various rate and equilibrium constants,

$$k_{3d}K_2K_3 = 0.157(\pm 0.005) \text{ s}^{-1} \quad 3.17$$

$$K_2 \ll 1 \quad K_3 \leq 1 \quad 3.18$$

$$k_{1d} \ll 6 \times 10^{-3} \text{ s}^{-1} \quad k_{2d} \ll 3 \text{ s}^{-1} \quad k_{3d} \gg 0.16 \text{ s}^{-1} \quad 3.19$$

For the copper(II) pentaazamacrocyclic complexes the relationship

$$K_1 \gg K_2 > K_3 \quad 3.20$$

is expected to hold. It has been observed that whereas the value of K_1 for $[\text{Cu}(\text{tetren})]^{2+}$ is similar to that of $[\text{Cu}([15]\text{aneN}_5)]^{2+}$ and $[\text{Cu}([17\text{B}]\text{aneN}_5)]^{2+}$, there is no significant additional protonation of the macrocyclic complexes, in contrast to the significant protonation of $[\text{Cu}(\text{Htetren})]^{3+}$ and $[\text{Cu}(\text{H}-[18]\text{aneN}_6)]^{3+}$ (see Table 3.6). The dissociation rate constants are expected to follow the order

$$k_{1d} < k_{2d} < k_{3d} \quad 3.21$$

and similar relationships have previously been established.^{199,224,226,398} The observed values are all compatible with the various constraints imposed above.

At the two lowest hydrogen ion concentrations, the values of k_{obs} are significantly greater than those calculated from the simplified form of 3.13 (see Table 2.29a), and it is possible that with decreasing hydrogen ion concentration the inequalities 3.15 and 3.16 may no longer be valid. It would be desirable to extend the range of observations below $[\text{H}^+] = 0.1 \text{ M}$. However, at these hydrogen ion concentrations it is no longer possible to use the standard pseudo first order excess method together with spectrophotometric methods as the maximum complex concentration of complex allowable becomes very low, and the absorbance change becomes impracticably small. The use of buffered solutions is one possible answer, but there are often significant kinetic effects caused by the presence of a large excess of buffer. At the lower hydrogen ion concentrations ($\leq 0.05 \text{ M } [\text{H}^+]$) it

appears that the dissociation is not complete, and the reverse reaction presumably becomes significant. Under these conditions, other kinetic techniques (e.g. relaxation) may be more useful.

The presence of undissociated acetic acid does not enhance the dissociation rate (see Table 2.29b) indicating the absence of general acid catalysis; this suggests that direct proton attack is not involved in the rate determining step.^{217,226} The apparent absence of direct acid attack is further evidence that the ligand is more flexibly disposed around the metal than is the case for triaza or tetraazamacrocycles. Restriction of the movement of an unbound nitrogen away from the metal has been cited as a requirement for the observation of direct acid attack on a bound or partially bound nitrogen.^{173,211,217,225} After removal of the fifth (apical) nitrogen, the protonated complex can more readily accommodate such metal-nitrogen separation (at least in adjacent sites), more in keeping with the linear amines than with other macrocyclic amines. Presumably in mechanisms involving direct acid attack (e.g. Scheme 11), the rate of acid attack on a coordinated species remains relatively constant (dependent primarily on electrostatic factors) and such a pathway only becomes significant when alternative routes are made less favourable on steric grounds. These steric restrictions are less prevalent in pentaazamacrocycles than among the triaza and tetraazamacrocycles.

There is a significant difference between the rate constant determined in perchlorate and nitrate media (~ a factor of three), and similar medium effects have been observed for other dissociation reactions.^{54,173,225,235,236,399} The exact nature of this dependence clearly warrants further investigation, possibly involving other anions, or mixed media. It also highlights the need for standardising the

conditions (ionic strength, choice of anion) under which such dissociation kinetics are carried out. Thus Barefield reports that the rate of acid dissociation of the nickel(II) complexes of [14]aneN₄ and its N-methylated analogues are very much more resistant to 6M-perchloric acid than to hydrochloric acid.⁵⁴ Kaden reports linear hydrogen ion dependence for the dissociation of $[\text{Cu}([12]\text{aneN}_3)]^{2+}$ in acetic medium ($I=0.5$)¹⁷³ whereas Weatherburn and Graham observe limiting kinetics in nitrate medium ($I=1.0$).²²⁵ However, both these authors report linear hydrogen ion concentration dependence for the dissociation of $[\text{Cu}([9]\text{aneN}_3)]^{2+}$,^{173,225} whereas Shepherd reports limiting kinetics in chloride medium ($I=0.5$).³⁹⁹ (although he also claims $I=0.5$ when $[\text{H}^+]=1.0$ M); furthermore, each study reports significantly different rate constants.

A number of measurements of the dissociation rate of $[\text{Cu}([15]\text{aneN}_5)]^{2+}$ were made with $[\text{H}^+] > 1.0$ M, and the observed rate is greater than that calculated from the rate law (Table 2.29a). However, the values must be treated as semi-quantitative at best, as the ionic strength is no longer constant, and considering the apparently strong dependence on the medium, the possibility that the increased rate is merely a function of the greater nitrate ion concentration cannot be discounted. Also, the mixing was less efficient as solutions with ionic strength 1.00 and 4.00 respectively were being mixed in the stopped-flow; this would also be expected to cause a small amount of local heating, resulting in an apparent rate enhancement. Clearly it would be necessary to redetermine the rate at lower hydrogen ion concentrations in solutions of greater ionic strength in order to meaningfully incorporate the values for $[\text{H}^+] > 1.0$ M.

Hay has observed second order hydrogen ion concentration dependence for the dissociation of $[\text{Ni}([15]\text{aneN}_5)]^{2+}$, with an observed

rate constant ~15 times greater than that of the copper(II) complex.¹⁶⁷ Although such reversals have been reported for at least one tetraaza-macrocyclic complex,⁴⁰⁰ in almost all cases the copper(II) complex dissociates more rapidly than the analogous nickel(II) complex. It would be necessary to measure the activation parameters for the dissociation of both complexes to determine the cause of this reversed order, and it would certainly cast more light on the mechanism of the dissociation reaction.

3.4.3 Acid Dissociation Kinetics of $[\text{Cu}([\text{16}] \text{aneN}_5)]^{2+}$

The acid dissociation kinetics of $[\text{Cu}([\text{16}] \text{aneN}_5)]^{2+}$ shows considerably more complex behaviour than that of $[\text{Cu}([\text{15}] \text{aneN}_5)]^{2+}$ (Table 2.30, fig. 2.16). Initially the dissociation shows second order dependence on hydrogen ion concentration, but at higher acid concentration, the reaction shows a tendency towards limiting kinetics. The observed rate constant takes the form

$$k_{\text{obs}} = \frac{13.9 [\text{H}^+]^2}{1 + 4.9 [\text{H}^+]^2} \quad 3.22$$

If the mechanism follows the form described in Scheme 19, a rate expression such as 3.12 can be derived. The value of K_1 has been estimated as $\sim 10^5$,¹⁰⁴ so presumably the dissociation initially involves the monoprotonated species in which the apical copper-nitrogen bond has already been broken, and the nitrogen is fully protonated. Two successive protonation equilibria must therefore be involved, and once again it appears that the rates of dissociation of the monoprotonated and diprotonated species (k_{1d} and k_{2d} respectively) can be neglected. The form of the derived rate law is thus

$$\text{Rate} = \frac{k_{3d} K_2 K_3 [\text{H}^+]^2}{1 + K_2 [\text{H}^+] + K_2 K_3 [\text{H}^+]^2} \cdot [\text{CuL}^{2+}] \quad 3.23$$

It is possible to include a term in $[\text{H}^+]$ in the denominator of 3.22 but the coefficient would be small (<0.01) and this is incompatible with the expected relative magnitudes of K_2 and K_3 . If 3.22 and 3.23 are equivalent then $K_2 \lesssim 0.01$ and $K_2 K_3 = 4.9$, which would require that $K_3 \gtrsim 500$; clearly, successive protonation equilibria must diminish, so such a value is untenable, and the behaviour must be more complex than that described in Scheme 19. The limiting kinetics at higher hydrogen ion concentration (fig. 2.16) must result from a shift of the rate determining step. The limiting rate ($\sim 2.8 \text{ s}^{-1}$) is of the same order as values observed by Graham²²⁵ and Weatherburn²¹⁷ for the rate determining chelate ring opening in some copper(II) complexes of triazamacrocycles and linear amines containing at least one six-membered chelate ring. The $[\text{Cu}([\text{16}] \text{aneN}_5)]^{2+}$ complex contains one six-membered chelate ring (in contrast to $[\text{Cu}([\text{15}] \text{aneN}_5)]^{2+}$) and Weatherburn notes²¹⁷ that in linear amine systems containing a six-membered chelate ring, acid-independence was observed at lower hydrogen ion concentration than for those with only five-membered chelate rings. It is possible therefore that behaviour similar to that of $[\text{Cu}([\text{16}] \text{aneN}_5)]^{2+}$ would be observed for $[\text{Cu}([\text{15}] \text{aneN}_5)]^{2+}$ at higher acid concentrations than those investigated.

There was no evidence for an enhanced rate of dissociation in $0.5 \text{ M } [\text{H}^+]$ containing undissociated acetic acid. This absence of general-acid catalysis further highlights the similarity to $[\text{Cu}([\text{15}] \text{aneN}_5)]^{2+}$, particularly as the other complexes that were tested for general-acid catalysis showed a rate enhancement.

3.4.4 Acid Dissociation Kinetics of $[\text{Cu}([\text{17A}] \text{aneN}_5)]^{2+}$

The behaviour of this complex is quite different from that of all the other pentaazamacrocyclic complexes examined. Over the range ($0.05 \text{ M} \leq [\text{H}^+] \leq 0.75 \text{ M}$) the rate showed a strictly linear dependence on hydrogen ion concentration (fig. 2.17), with no indication of curvature to suggest either limiting kinetic behaviour or second order hydrogen ion dependence.

Measurements in the range ($1.0 \text{ M} \leq [\text{H}^+] \leq 3.0 \text{ M}$) show a positive deviation from linear behaviour (Table 2.31a, fig. 2.17). However, the ionic strength was no longer unity, and the two reactant solutions being mixed in the stopped-flow were not of equal ionic strength, so it is not possible to state unequivocally that the increased rate is the result of a higher order hydrogen ion dependence, rather than simply a function of increased ionic strength, nitrate ion concentration or local heating (see section 3.4.2). Furthermore, it is not possible to fit these latter points together with those at $I=1.00$ to a more complex (yet still realistic) function of hydrogen ion concentration. (The following discussion will only relate to measurements obtained on the solutions with $I=1.00$).

The acid-dependence at different temperatures all show intercepts that are experimentally indistinguishable from zero (Table 2.32, fig. 2.17 and the observed first-order rate constant at 25.0°C is $34 (\pm 2) \text{ s}^{-1}$. Unlike the smaller pentaazamacrocycles, the acid dissociation rate of $[\text{Cu}([\text{17A}] \text{aneN}_5)]^{2+}$ is greater in acetic or monochloroacetic acid than that expected, based on hydrogen ion concentration alone (Table 2.31b). The dissociation rate appears to depend linearly on the general-acid concentration, but as the measurements were not carried out in an excess of mineral acid (as for the copper(II) complexes of $[\text{15}] \text{aneN}_5$ and $[\text{16}] \text{aneN}_5$), the solutions also contained free acetate (or monochloroacetate) which may in part be responsible for the rate enhancement.

Although a value of K_1 (the first protonation equilibrium), has not been determined for $[\text{Cu}([17\text{A})\text{aneN}_5)]^{2+}$, there is no reason to suppose that it is significantly different from the similar values reported for the other macrocyclic pentamine complexes (see Table 3.6), hence again it seems probable that there is initially a rapid and complete conversion to the monoprotonated complex. The dissociation mechanism may be as simple as a second protonation equilibrium followed by an acid-independent dissociation.

Scheme 20

Both this mechanism or one similar to that proposed by Weatherburn and Graham²¹³ (Scheme 11) would involve non-linear behaviour (limiting kinetics) but it is possible that the range of hydrogen ion concentration studied is simply not large enough to reach the region where the chelate ring opening rate becomes limiting. In Scheme 20 this requires that $K_2[\text{H}^+] \ll 1$ over the range of hydrogen ion concentration studied. The latter mechanism (Scheme 11) requires that $k_{24}[\text{H}^+]$ (k_{24} is the rate of protonation of the unbound nitrogen) is always less than k_{21} (the chelate ring closure rate); although this is indeed observed and readily explained for copper(II) complexes of the smaller triazamacrocycles²²⁵ it is harder to envisage for the rather more flexible pentaazamacrocycles. (In fact it has recently been reported that the acid dissociation of $[\text{Cu}([9]\text{aneN}_3)]^{2+}$ also shows limiting kinetics,³⁹⁹ although a number of serious inconsistencies in this paper mean that the observation should be treated with some reservations). The rate law derived for the copper(II) complexes of $[17\text{B})\text{aneN}_5$ and $[18-20]\text{aneN}_5$ (see section 3.4.5) can also be applied

$$k_{\text{obs}} = \frac{k_{2d}[\text{H}^+] + k_{3d}K_3[\text{H}^+]^2}{\frac{1}{K_2} + [\text{H}^+] + K_3[\text{H}^+]^2} \quad 3.24$$

with the constraints

$$k_{2d} \ll k_{3d}K_3[\text{H}^+] \quad 3.25$$

$$\frac{1}{K_2} \ll [\text{H}^+] \quad 3.26$$

$$K_3[\text{H}^+] \ll 1 \quad 3.27$$

At 25.0°C this gives rise to the following limiting values

$$K_2 \gg 20 \quad K_3 \ll 1 \quad 3.28$$

$$k_{2d} \ll 2 \text{ s}^{-1} \quad k_{3d} \gg 34 \text{ s}^{-1} \quad 3.29$$

(This amounts to a situation where there are two rapid initial protonation reactions followed by an equilibrium protonation and dissociation). These values are not unreasonable, but it would be necessary to extend the range of observations to both higher and lower hydrogen ion concentration to confirm that there is not simply a linear acid-dependence and a completely different mechanism from that observed for the other complexes.

The activation parameters for the acid dissociation of $[\text{Cu}(\text{[17A]aneN}_5)]^{2+}$ have been determined, using the variation of the observed rate constant over the range $6^\circ\text{C} \leq t \leq 35^\circ\text{C}$ (see Table 2.32, fig. 2.18), and the following values were obtained

$$E_a = 51.3(\pm 0.6) \text{ kJ mol}^{-1}$$

$$\Delta H_{298}^\ddagger = 48.8(\pm 0.6) \text{ kJ mol}^{-1}$$

$$\Delta S_{298}^\ddagger = -52(\pm 3) \text{ J K}^{-1} \text{ mol}^{-1}$$

The value of $\Delta H_{298}^\ddagger$ suggests that the breaking of a copper-nitrogen bond may be the rate determining step (c.f. $\Delta H_{298}^\ddagger = 40 \text{ kJ mol}^{-1}$ for the $\text{Cu}^{2+}\text{-NH}_3$ bond rupture⁴⁰¹). This is of the same order as those

reported for the copper(II) complexes of macrocyclic triamines and various linear amines,^{217,225} while the corresponding values for the more labile copper(II) tetraazamacrocyclic complexes are significantly greater (see Table 3.7). Likewise $\Delta S_{298}^{\ddagger}$ of $[\text{Cu}([\text{17A}] \text{aneN}_5)]^{2+}$ has a similar sign and magnitude to values reported for copper(II) complexes of some triazamacrocyclic and linear polyamine complexes. The values for the tetraazamacrocyclic complexes vary significantly (see Table 3.7). The negative $\Delta S_{298}^{\ddagger}$ of $[\text{Cu}([\text{17A}] \text{aneN}_5)]^{2+}$ arises as a result of either conformational changes, or (more likely) from an associative rate determining step. Weatherburn and Graham speculate on the possible factors contributing to the value and sign of $\Delta S_{298}^{\ddagger}$ of the copper(II) triazamacrocycles,²²⁵ but conclude only that it is probably related to the coordination number of the intermediate, and reflects the association of a solvent molecule during the activation process.

The different rate laws that are observed for the copper(II) complexes of the pentaazamacrocycles and the amines studied by Graham and Weatherburn indicates that the dissociation mechanisms are different, but the similarity of the activation parameters suggests that the rate determining steps may well be similar.

It would be worthwhile to measure the acid dissociation rate of $[\text{Ni}([\text{17A}] \text{aneN}_5)]^{2+}$ to determine whether the reversal of rates observed for $[\text{15}] \text{aneN}_5$ is general for the pentaazamacrocycles. Certainly there is nothing striking in the activation parameters of $[\text{Cu}([\text{17A}] \text{aneN}_5)]^{2+}$ so perhaps the effect is manifested in the activation parameters of the nickel(II) complexes, or is specific to the smallest member of the series.

Table 3.7

Activation Parameters of Copper(II)-Amine Complexes

Complex ^a	k_H (s ⁻¹)	$\Delta H_{298}^\ddagger$ (kJ mol ⁻¹)	$\Delta S_{298}^\ddagger$ (J K ⁻¹ mol ⁻¹)	Ref
[Cu(NH ₃)(H ₂ O) ₅] ²⁺	2.0×10 ⁴	40	-29	401
[Cu(2,3-tri)] ²⁺	3.5	62	-17	217
[Cu(3,2,3-tet)] ²⁺	9.7	43	-58	217
[Cu([9]aneN ₃)] ²⁺	51	34	-68	225
[Cu([10]aneN ₃)] ²⁺	17	43	-78	225
[Cu([11]aneN ₃)] ²⁺	5.6	45	-79	225
[Cu(TMC)] ²⁺ ^b	0.0224	85.2	8.8	224
[Cu([18]-dieneN ₄)] ²⁺ ^c	0.004	77.1	-32	226
[Cu([17A]aneN ₅)] ²⁺	34	48.8	-52	d

^aSolvent molecules omitted for clarity.

^bTMC = N,N',N'',N'''-(2-cyanoethyl)₄-[14]ane-1,4,8,11-N₄.

^c[18]-dieneN₄ = Me₆-[18]-1,10-diene-1,5,10,14-N₄.

^dThis work.

3.4.5 Acid Dissociation Kinetics of $[\text{Cu}([\text{17B}] \text{aneN}_5)]^{2+}$ and $[\text{Cu}([\text{18-20}] \text{aneN}_5)]^{2+}$

These complexes all show similar acid-dependence in the range studied ($0.05 \text{ M} \leq [\text{H}^+] \leq 0.75 \text{ M}$) (Tables 2.33 to 2.37, figs 2.19 to 2.23). The plots appear to be linear for complexes of $[\text{17B}] \text{aneN}_5$ and $[\text{18A}] \text{aneN}_5$, and for $[\text{18B}] \text{aneN}_5$ and $[\text{19}] \text{aneN}_5$ when $[\text{H}^+] \geq 0.10 \text{ M}$. However, if the linear acid-dependence is extrapolated to zero hydrogen ion concentration, in accord with a rate expression of the form,

$$k_{\text{obs}} = k_{\text{O}} + k_{\text{H}}[\text{H}^+] \quad 3.30$$

then in each case the value obtained for k_{O} would correspond to a dissociation half-life of less than one second in neutral solution. This is contrary to the observed behaviour, and the acid-dependence must resemble that of the complexes of $[\text{19}] \text{aneN}_5$ and $[\text{20}] \text{aneN}_5$ which show linear dependence at higher hydrogen ion concentration but curve towards $k_{\text{obs}} = 0 \text{ s}^{-1}$ as the hydrogen ion concentration tends to zero. The behaviour cannot be fitted to an expression of the form typical for many of the linear and cyclic polyamine copper(II) complexes, where linear hydrogen ion dependence and a limiting rate at high $[\text{H}^+]$ lead to an observed rate constant of the form^{217,225,399}

$$k_{\text{obs}} = \frac{a[\text{H}^+]}{b+c[\text{H}^+]} \quad 3.31$$

For such a rate law the plot of k_{obs}^{-1} vs $[\text{H}^+]^{-1}$ is linear, with slope b/a and intercept c/a . Such plots are curved for these copper(II) complexes (with the possible exception of $[\text{Cu}([\text{20}] \text{aneN}_5)]^{2+}$ - vide infra), and the fact that this mechanism is not operative is also borne out by the observation that the observed rate does not reach a limiting value, but increases linearly with hydrogen ion concentration. It is in fact possible to fit

the data for $[\text{Cu}([20]\text{aneN}_5)]^{2+}$ to such an expression, as the pattern of acid-dependence has not become clear over the range of hydrogen ion concentration studied; however, values of the observed rate constant at $[\text{H}^+] \geq 1.0 \text{ M}$ are still increasing and it also seems unlikely that this single complex would behave differently from the others. An equally good (if not better) fit can be obtained for $[\text{Cu}([20]\text{aneN}_5)]^{2+}$ by invoking the same rate expression as for the other macrocyclic complexes in this group. This expression takes the form

$$k_{\text{obs}} = \frac{a[\text{H}^+] + b[\text{H}^+]^2}{c + [\text{H}^+]} \quad 3.32$$

where the values of a , b and c are given in Table 3.8.

Table 3.8

Coefficients of the Rate Constant $k_{\text{obs}} = \frac{a[\text{H}^+] + b[\text{H}^+]^2}{c + [\text{H}^+]}$			
Complex	a	b	c
$[\text{Cu}([17\text{B}]\text{aneN}_5)]^{2+}$	23	62	0.005
$[\text{Cu}([18\text{A}]\text{aneN}_5)]^{2+}$	8	41	0.010
$[\text{Cu}([18\text{B}]\text{aneN}_5)]^{2+}$	0.9	13.6	0.007
$[\text{Cu}([19]\text{aneN}_5)]^{2+}$	136	70	0.020
$[\text{Cu}([20]\text{aneN}_5)]^{2+}$	70	19	0.030

The values of the coefficient c have a considerable uncertainty as they reflect the tailing towards zero with decreasing hydrogen ion concentration (i.e. generally the region $[\text{H}^+] \leq 0.05 \text{ M}$) and there are few points in this region to fix the value. For $[\text{Cu}([17\text{B}]\text{aneN}_5)]^{2+}$ and $[\text{Cu}([18\text{A}]\text{aneN}_5)]^{2+}$ the values of c are effectively the maximum values based on the lack of curvature at the lowest hydrogen ion concentration studied.

Without resorting to buffered solutions it was not possible to investigate the region of curvature of the acid-dependence. In order to preserve the pseudo first order conditions, a considerable excess of acid is required. Each pentaazamacrocyclic can accept up to five protons (once the complex has dissociated) so the normal tenfold excess of acid is insufficient. Hence the complex concentration must be no more than 1/50th of the hydrogen ion concentration, and in the region where curvature is observed ($\leq 0.10 \text{ M } [\text{H}^+]$) the absorbance change on dissociation would be very small, and the uncertainties correspondingly large. The problem is compounded by the short path length on the stopped-flow spectrophotometer ($\sim 2 \text{ mm}$). Use of a stopped-flow with a longer path length would obviate this problem, and enable the hydrogen ion concentration to be reduced by an order of magnitude. The alternative is to use buffer solutions, but these would interfere with the acid-dissociation rate. General acid catalysis is observed for at least some of these complexes (*vide infra*), so the presence of a large excess of a weak acid would lead to considerable complications.

Although the form of the rate expression as written in (3.32) is such that $k_{\text{obs}} = 0$ when $[\text{H}^+] = 0$, in common with other copper(II) polyamine systems there is an acid-independent pathway (e.g. $[\text{Cu}(\text{[18]-diene N}_4)]^{2+} \dagger$ $k_{\text{O}} = 8 \times 10^{-4} \text{ s}^{-1}$ ²²⁶; $[\text{Cu}(\text{Me}_3\text{-[12]aneN}_3)]^{2+} \dagger$ $k_{\text{O}} = 1.8 \times 10^{-4} \text{ s}^{-1}$ ²²⁵, at 25.0°C) but the value is expected to be negligibly small compared with the acid-dependent terms over the range of hydrogen ion concentration in this study.

The simplest mechanism that can account for this kinetic behaviour again involves the presence of three species in equilibrium, each of which is capable of undergoing dissociation (Scheme 19) giving rise to an

[†] See appendix.

expression of the form 3.11. Although the values of K_1 have not been determined for these pentaazamacrocyclic copper(II) complexes, they are expected to be at least as large as those determined for [15]aneN₅, [16]aneN₅ and [17B]aneN₅ (Table 3.6), and probably even larger due to the increased number of six-membered chelate rings. Consequently the species CuHL^{3+} should initially be fully formed at all hydrogen ion concentrations investigated and a simpler form of the rate law will be sufficient (3.13). As has previously been pointed out, k_{1d} can be neglected, and if

$$K_2 K_3 [\text{H}]^2 \ll K_2 [\text{H}^+] + 1 \quad 3.33$$

the expression reduces to

$$\text{Rate} = \frac{k_{2d} K_2 [\text{H}^+] + k_{3d} K_2 K_3 [\text{H}^+]^2}{1 + K_2 [\text{H}^+]} \cdot [\text{CuL}^{2+}] \quad 3.34$$

$$\text{or} \quad \text{Rate} = \frac{k_{2d} [\text{H}^+] + k_{3d} K_3 [\text{H}^+]^2}{\frac{1}{K_2} + [\text{H}^+]} \cdot [\text{CuL}^{2+}] \quad 3.35$$

The inequality (3.33) is certainly satisfied if

$$K_2 K_3 [\text{H}^+]^2 \ll K_2 [\text{H}^+] \quad 3.36$$

which can be reduced to

$$K_3 \ll 1 \quad 3.37$$

over the range of hydrogen ion concentration investigated.

As $K_1 \sim 10^5$ and $K_2 \sim 30$ to 200 (derived from $1/c$ in Table 3.8) this condition (3.37) is not unreasonable. Although first protonation equilibria have been reported for some complexes (Table 3.6 and refs. therein), successive protonation constants have seldom been observed, or are significantly smaller.^{394,398}

The ratio b/a in Table 3.8 falls in the range $(0.3 < \frac{b}{a} \leq 15)$; from 3.34 it can be seen that this ratio corresponds to $(k_{3d}/k_{2d})K_3$. As $K_3 \ll 1$, the ratio $k_{3d}/k_{2d} \gg 1$. Once again this is not inconsistent with

our knowledge of the relative magnitudes of successive dissociation rate constants. 199,224,226,398

It is probable that at even higher hydrogen ion concentrations the inequality expressed by 3.33 would no longer be valid, and the acid-dependence curves would flatten out, in which case a value for k_{3d} could be obtained from the limiting rate of the dissociation reaction. To examine the dissociation kinetics at higher hydrogen ion concentrations, it would be necessary to use a higher ionic strength throughout the range; for the more rapidly dissociating complexes it would be necessary to work at lower temperatures to keep within the limits of the stopped-flow timescale.

The various equilibrium and rate constants obtained for the different complexes are listed in Table 3.9.

Table 3.9

Acid Dissociation Reactions-Derived Parameters ^a			
Complex	K_2 ^b	k_{2d} (s ⁻¹)	$K_3 k_{3d}/k_{2d}$ ^c
Cu([17B]aneN ₅) ²⁺	200	23	2.7
Cu([18A]aneN ₅) ²⁺	100	8	5.1
Cu([18B]aneN ₅) ²⁺	140	0.9	15
Cu([19]aneN ₅) ²⁺	50	136	0.51
Cu([20]aneN ₅) ²⁺	30	70	0.27

^a Derived from $k_{\text{obs}} = \frac{k_{2d}[\text{H}^+] + k_{3d}K_3[\text{H}^+]^2}{\frac{1}{K_2} + [\text{H}^+]}$

^b approximate only

^c k_{3H}/k_{2d} in the alternative treatment (vide infra)

An alternative reaction scheme

Scheme 21

gives a rate expression of the same form

$$\text{Rate} = \frac{k_{2d} [\text{H}^+] + k_{3H} [\text{H}^+]^2}{\frac{1}{K_2} + [\text{H}^+]} \cdot [\text{CuL}^{2+}] \quad 3.38$$

In this mechanism, the species $\text{CuH}_2\text{L}^{4+}$ can undergo an acid-dependent dissociation as well as the normal acid-independent pathway; there is no equilibrium reaction between $\text{CuH}_2\text{L}^{4+}$ and $\text{CuH}_3\text{L}^{5+}$, the latter species dissociates rapidly. The only effective change is in the interpretation of the coefficient of the $[\text{H}^+]^2$ term in the rate law (3.35). Thus the values of b in Table 3.8 represent k_{3H} , and the ratio b/a (corresponding to the column headed $K_3 k_{3d}/k_{2d}$ in Table 3.9) represents the relative rates of the acid-independent and acid-dependent dissociation of $\text{CuH}_2\text{L}^{4+}$. The ratio is less than unity for the copper(II) complexes of the two largest macrocycles, and greater than unity for the others, and it is not difficult to envisage that as the number of six-membered chelate rings increases, the relative importance of the two pathways changes.

The $[\text{Cu}([\text{18B}] \text{aneN}_5)]^{2+}$ complex was investigated for general acid catalysis (as it was the slowest to dissociate), and in solutions of constant hydrogen ion concentration, there was a linear dependence on the acetic acid concentration. This is in marked contrast to $\text{Cu}([\text{15}] \text{aneN}_5)]^{2+}$, $[\text{Cu}([\text{16}] \text{aneN}_5)]^{2+}$ and the copper(II) complexes of linear polyamines²¹⁷ which did not show general-acid catalysis. The rate expression for the dissociation of $[\text{Cu}([\text{18B}] \text{aneN}_5)]^{2+}$ takes the form

$$k_{\text{obs}} = \frac{0.9[\text{H}^+] + 13.6[\text{H}^+]^2}{0.007 + [\text{H}^+]} + 3.0[\text{HOAc}] \quad 3.39$$

The reaction of $[\text{Cu}([20]\text{aneN}_5)]^{2+}$ with acetic acid was investigated in order to elucidate the behaviour at low hydrogen ion concentration. This system also showed enhanced kinetic behaviour, the rate being dependent not only on the hydrogen ion concentration, but also on the concentration of the acetic acid. It is not possible to determine the exact nature of the relationship as there was also free acetate ion in the solution (unlike the previous case there was no excess of mineral acid present to suppress hydrolysis).

The relative magnitudes of the two rate steps (corresponding to the terms in $[\text{H}^+]$ and $[\text{H}^+]^2$ in the numerator of (3.32)) reflect the changing importance of the acid dissociations involving one and two proton pathways respectively, but there is no obvious pattern in their values. The trend does not appear to follow the expected stability of the complexes, nor the number of five- and six-membered chelate rings in each structure. Presumably the relative stability of the intermediate protonated species is important, but without further information on the site of successive protonations or activation parameters for the various processes, speculation would be meaningless.

It is quite clear however, that although the same mechanism can be applied to all these copper(II) complexes, as well as those of $[15]\text{aneN}_5$ and $[17\text{A}]\text{aneN}_5$, and possibly to $[\text{Cu}([16]\text{aneN}_5)]^{2+}$, the relative importance of different parts of the reaction mechanism can be profoundly altered simply by altering the number or even the order of the five- and six-membered chelate rings in the macrocycle.

References

1. "Coordination Chemistry of Macrocyclic Compounds", (Melson, G.A., ed.), Plenum Press, New York, (1979).
2. Hodgson, G.W., and Baker, B.L., Chem. Geol., (1967), 2, 187-198;
Moore, J.W., and Dunning, H.N., Ind. Eng. Chem., (1955), 47, 1440-1444.
3. Goedkin, V.L., Chapter 10 in ref. 1 and references therein.
4. Hoffman, B.M., and Petering, D.H., Proc. Natl. Acad. Sci. U.S.A., (1970), 67, 637-643; Hsu, G.C., Spilburg, C.A., Bull. C. and Hoffman, B.M., *ibid.*, (1972), 69, 2122-2124;
Chien, J.C.W., and Dickinson, L.C., *ibid.*, (1972), 69, 2783-2787.
5. Collman, J.P., Acc. Chem. Res., (1977), 10, 265-272.
6. Miyoshi, K., Tanaka, H., Kimura, E., Tsuboyama, S., Murata, S., Shimizu, H., and Ishizu, K., Inorg. Chim. Acta, (1983), 78, 23-30.
7. "Synthetic Multidentate Macrocyclic Compounds", (Izatt, R.M., and Christensen, J.J., ed.), Academic Press, New York, (1978).
8. Lehn, J-M., Pure Appl. Chem., (1978), 50, 871-892.
9. Pedersen, C.J., J. Am. Chem. Soc., (1967), 89, 2495-2496; 7017-7036.
10. Lamb, J.D., Izatt, R.M., Christensen, J.J., and Eatough, D.J., in ref. 1, pp.180-210.
11. Neupert-Laves, K., and Dobler, M., Helv. Chim. Acta, (1975), 58, 432-442.
12. Phillies, G.D.J., Asher, I.M., and Stanley, H.E., Science, (1975), 188, 1027-1029.
13. Lehn, J-M., Acc. Chem. Res., (1978), 11, 49-57.
14. Lehn, J-M., and Sauvage, J.P., J. Am. Chem. Soc., (1975), 97, 6700-6707.
15. Lehn, J-M., and Simon, J., Helv. Chim. Acta, (1977), 60, 141-151;
Fischer, J., Mellinger, M., Weiss, R., Inorg. Chim. Acta, (1977), 21, 259-263.
16. Graf, E., and Lehn, J-M., J. Am. Chem. Soc., (1975), 97, 5022-5024.
17. Graf, E., and Lehn, J-M., J. Am. Chem. Soc., (1976), 98, 6403-6405;
Metz, B., Rosalky, J.M., and Weiss, R., J. Chem. Soc., Chem. Commun., (1976), 533-534.
18. Dye, J.L., Yemen, M.R., DaGue, M.G., and Lehn, J-M., J. Chem. Phys., (1978), 68, 1665-1670.

19. Bell, T.W., Lein, G.M., Nakamura, H., and Cram, D.J., *J. Org. Chem.*, (1983), 48, 4728-4734, and refs therein; Cram, D.J., and Cram, J.M., *Acc. Chem. Res.*, (1978), 11, 8-14, and refs therein.
20. Van Alphen, J., *Rec. Trav. Chim. Pays-Bas*, (1936), 55, 835-840
c.f. *C.A.*, (1937), 31, 1007².
21. Bosnich, B., Poon, C.K., and Tobe, M.L., *Inorg. Chem.*, (1965), 4, 1102-1108.
22. Bosnich, B., Tobe, M.L., and Webb, G.A., *Inorg. Chem.*, (1965), 4, 1109-1112.
23. Curtis, N.F., *J. Chem. Soc.*, (1960), 4409-4413; Curtis, N.F., and House, D.A., *Chem. and Ind.*, (1961), 42, 1708-1709; Curtis, N.F., Curtis, Y.M., and Powell, H.K.J., *J. Chem. Soc. (A)*, (1966), 1015-1018.
24. Thompson, M.C., and Busch, D.H., *J. Am. Chem. Soc.*, (1964), 86, 3651-3656.
25. Melson, G.A., and Busch, D.H., *Proc. Chem. Soc.*, (1963), 223-224; Melson, G.A., and Busch, D.H., *J. Am. Chem. Soc.*, (1965), 87, 1706-1710.
26. Cuellar, E.A., Stojakovic, D.R., and Marks, T.J., *Inorg. Synth.*, (1980), 20, 97-100, and refs therein.
27. Marks, T.J., and Stojakovic, D.R., *J. Am. Chem. Soc.*, (1978), 100, 1695-1705.
28. Busch, D.H., *Rec. Chem. Prog.*, (1964), 25, 107-126.
29. Barefield, E.K., *Inorg. Chem.*, (1972), 11, 2273-2274; Barefield, E.K., Wagner, F., and Hodges, K.D., *ibid.*, (1976), 15, 1370-1377; Barefield, E.K., Wagner, F., Herlinger, A.W., and Dahl, A.R., *Inorg. Synth.*, (1975), 16, 220-225.
30. Curtis, N.F., and Hay, R.W., *J. Chem. Soc., Chem. Commun.*, (1966), 524-525; Tait, A.M., and Busch, D.H., *Inorg. Synth.*, (1978), 18, 2-9; Tait, A.M., and Busch, D.H., *Inorg. Nucl. Chem. Lett.*, (1972), 8, 491-496.
31. Martin, J.W.L., Johnston, J.H., and Curtis, N.F., *J. Chem. Soc., Dalton Trans.*, (1978), 68-76.
32. House, D.A., and Curtis, N.F., *J. Am. Chem. Soc.*, (1962), 84, 3248-3250; Curtis, N.F., and Milestone, T.N., *Aust. J. Chem.*, (1975), 28, 275-283.
33. Blight, M.M., and Curtis, N.F., *J. Chem. Soc.*, (1962), 1204-1207; Curtis, N.F., Swann, D.A., Waters, T.N., and Maxwell, I.E., *J. Am. Chem. Soc.*, (1969), 91, 4588-4589.

34. Curtis, N.F., and Reader, G.W., *J. Chem. Soc. (A)*, (1971), 1771-1777.
35. Funke, L.A., and Melson, G.A., *Inorg. Chem.*, (1975), 14, 306-308;
Jäger, E.G., *Zeit. für Anorg. und Allgem. Chemie*, (1969), 364,
177-191.
36. Lindoy, L.F., *Chem. Soc. Revs.*, (1975), 4, 421-441, and refs therein.
37. Grimsley, P.G., Lindoy, L.F., Lip, H.C., Smith, R.J., and Baker, J.T.,
Aust. J. Chem., (1977), 30, 2095-2098; Armstrong, L.G.,
Grimsley, P.G., Lindoy, L.F., Lip, H.C., Norris, V.A., and
Smith, R.J., *Inorg. Chem.*, (1978), 17, 2350-2352.
38. Black, D.StC., and Lane, M.J., *Aust. J. Chem.*, (1970), 23, 2039-2053;
Black, D.StC., and Kortt, P.W., *ibid.*, (1972), 25, 281-288.
39. Black, D.StC., and Hartshorn, A.J., *Coord. Chem. Rev.*, (1972-1973),
9, 219-274.
40. Coughlin, P.K., Dewan, J.C., Lippard, S.J., Watanabe, E., and
Lehn, J-M., *J. Am. Chem. Soc.*, (1979), 101, 265-266;
Coughlin, P.K., Lippard, S.J., Martin, A.E., Bulkowski, J.E.,
ibid., (1980), 102, 7616-7617; Comarmond, J., Plumeré, P.,
Lehn, J-M., Agnus, Y., Louis, R., Weiss, R., Kahn, O., and
Morgenstern-Badarau, I., *ibid.*, (1982), 104, 6330-6340;
Pilkington, N.H., and Robson, R., *Aust. J. Chem.*, (1970),
23, 2225-2236.
41. Creaser, I.I., Harrowfield, J.MacB., Herlt, A.J., Sargeson, A.M.,
Springborg, J., Geue, R.J. and Snow, M.R., *J. Am. Chem. Soc.*,
(1977), 99, 3181-3182; Sargeson, A.M., *Chem. in Britain*,
1979, 15, 23-27.
42. Gahan, L.R., Hambley, T.W., Sargeson, A.M., and Snow, M.R.,
Inorg. Chem., (1982), 21, 2699-2706.
43. Curtis, N.F., personal communication.
44. Goedkin, V.L., and Peng, S-M., *J. Chem. Soc., Chem. Commun.*, (1973),
62-63.
45. Keypour, H., and Stotter, D.A., *Inorg. Chim. Acta*, (1979), 33,
L149-L150.
46. Karn, J.L., and Busch, D.H., *Nature*, (1966), 211, 160-162;
Rich, R.L., and Stucky, G.L., *Inorg. Nucl. Chem. Lett.*, (1965),
1, 61-64; Prince, R.H., Stotter, D.A., and Woolley, P.R.,
Inorg. Chim. Acta, (1974), 9, 51-54; Keypour, H., and
Stotter, D.A., *Inorg. Chim. Acta*, (1976), 19, L48;
Lindoy, L.F., Tokel, N.E., Anderson, L.B., and Busch, D.H.,
J. Coord. Chem., (1971), 1, 7-16.
47. Curry, J.D., and Busch, D.H., *J. Am. Chem. Soc.*, (1964), 86, 592-594;
Nelson, S.M., and Busch, D.H., *Inorg. Chem.*, (1969), 8, 1859-1863;
Alexander, M.D., Van Heuvelen, A., and Hamilton, Jr., H.G.,
Inorg. Nucl. Chem. Lett., (1970), 6, 445-448.

48. Cook, D.H., Fenton, D.E., Drew, M.G.B., McFall, S.G., and Nelson, S.M., J. Chem. Soc., Dalton Trans., (1977), 446-449;
Drew, M.G.B., Bin Othman, A.H., McFall, S.G., McIlroy, P.D.A., and Nelson, S.M., J. Chem. Soc., Dalton Trans., (1977), 1173-1180;
Fenton, D.E., Cook, D.H., and Nowell, I.W., J. Chem. Soc., Chem. Commun., (1977), 274-275.
49. Rakowski, M.C., Rychek, M., and Busch, D.H., Inorg. Chem., (1975), 14, 1194-1200.
50. Lotz, T.J., and Kaden, T.A., Helv. Chim. Acta, (1978), 61, 1376-1387.
51. Kaden, T.A., Coord. Chem., --Invited Lect. Int. Conf., 20th, (1979) (Pub. 1980), 71-9, (Banerjee, D., ed.), Pergamon, Oxford, England.
52. Drew, M.G.B., Rodgers, A., McCann, M., and Nelson, S.M., J. Chem. Soc., Chem. Commun., (1978), 415-416.
53. Nelson, S.M., McCann, M., Stevenson, C., and Drew, M.G.B., J. Chem. Soc., Dalton Trans., (1979), 1477-1481.
54. Wagner, F., and Barefield, E.K., Inorg. Chem., (1976), 15, 408-417.
55. Baldwin, D.A., Pfeiffer, R.M., Reichgott, D.W., and Rose, N.J., J. Am. Chem. Soc., (1973), 95, 5152-5158;
Tait, A.M., and Busch, D.H., Inorg. Synth., (1978), 18, 22-30.
Jackels, S.C., Farmery, K., Barefield, E.K., Rose, N.J., and Busch, D.H., Inorg. Chem., (1972), 11, 2893-2901.
56. Green, M., Smith, J., and Tasker, P.A., Inorg. Chim. Acta, (1971), 5, 17-24; 65-69.
57. Armstrong, L.G., and Lindoy, L.F., Inorg. Chem., (1975), 14, 1322-1326.
58. Hankovszky, O.H., Hideg, K., Lloyd, D., and McNab, H., J. Chem. Soc., Perkin Trans., I, (1979), 1345-1350.
59. Thompson, J.B., U.S. Patent 3,485,818 (1969).
60. Jaźwiński, J., and Kolinski, R.A., Tetrahedron Lett., (1981), 22, 1711-1714.
61. Bergstedt, L., and Widmark, G., Acta Chem. Scand., (1970), 24, 2713-2723.
62. House, D.A., and Garner, C.S., Inorg. Chem., (1966), 12, 2097-2102.
63. Stetter, H., and Mayer, K-H., Chem. Ber., (1961), 94, 1410-1416.
64. Koyama, H., and Yoshino, T., Bull. Chem. Soc. Jpn., (1972), 45, 481-484.
65. Richman, J.E., and Atkins, T.J., J. Am. Chem. Soc., (1974), 96, 2268-2270.

66. Stetter, H., and Roos, E-E., *Chem. Ber.*, (1954), 87, 566-571.
67. Atkins, T.J., Richman, J.E., and Oettle, W.F., *Org. Synth.*, (1978), 58, 86-98.
68. Nonoyama, M., *Trans. Met. Chem.*, (1976), 1, 70-74.
69. Smith, W.L., Ekstrand, J.D., and Raymond, K.N., *J. Am. Chem. Soc.*, (1978), 100, 3539-3544.
70. Sugimoto, M., Nonoyama, M., Ito, T., and Fujita, J., *Inorg. Chem.*, (1983), 22, 950-954; 955-960.
71. Bencini, A., Fabbrizzi, L., and Poggi, A., *Inorg. Chem.*, (1981), 20, 2544-2549.
72. This work.
73. Royer, D.J., Grant, G.J., Van Der Veer, D.G., and Castillo, M.J., *Inorg. Chem.*, (1982), 21, 1902-1908.
74. Dietrich, B., Hosseini, M.W., Lehn, J-M., and Sessions, R.B., *J. Am. Chem. Soc.*, (1981), 103, 1282-1283.
75. Margulis, T.N., Zompa, L.J., *J. Chem. Soc., Chem. Commun.*, (1979), 430-431.
76. Angley, M.E., Dwyer, M., Lincoln, S.F., and Searle, G.H., *Inorg. Chim. Acta*, (1980), 45, L91-L93.
77. Martin, A.E., Ford, T.M., and Bulkowski, J.E., *J. Org. Chem.*, (1982), 47, 412-415.
78. Martin, A.E., and Bulkowski, J.E., *J. Org. Chem.*, (1982), 47, 415-418.
79. Mason, S.F., and Peacock, R.D., *Inorg. Chim. Acta*, (1976), 19, 75-77.
80. Graham, P.G., PhD Thesis, V.U.W., (1982).
81. Graham, P.G., Weatherburn, D.C., *Aust. J. Chem.*, (1983), 36, 2349-2354.
82. Snyder, H.R., and Heckert, R.E., *J. Am. Chem. Soc.*, (1952), 74, 2006-2009.
83. Kossai, R., Simonet, J., and Jeminet, G., *Tetrahedron Lett.*, (1979), 12, 1059-1062.
84. Schmidtchen, F.P., *Chem. Ber.*, (1980), 113, 864-874.
85. Birch, A.J., and Smith, H., *Quart. Rev.*, (1958), 12, 17-33.

86. Kovacs, J., and Ghatak, U.R., *J. Org. Chem.*, (1966), 31, 119-121.
87. Cuvigny, T., and Larchevêque, M., *J. Organomet. Chem.*, (1974), 64, 315-321.
88. Ji, S., Gortler, L.B., Waring, A., Battisti, A., Bank, S., Clossen, W.D., and Wriede, P., *J. Am. Chem. Soc.*, (1967), 89, 5311-5312.
89. Gold, E.H., and Babad, E., *J. Org. Chem.*, (1972), 37, 2208-2210.
Čásenský, B., and Macháček, J., *Inorg. Synth.*, (1978), 18, 149-152.
90. Kodama, M., and Kimura, E., *J. Chem. Soc., Dalton Trans.*, (1978), 104-110.
91. Machida, R., Kimura, E., and Kodama, M., *Inorg. Chem.*, (1983), 22, 2055-2061.
92. Ansell, C.W.G., Lewis, J., Liptrot, M.C., Raithby, P.R., and Schröder, M., *J. Chem. Soc., Dalton Trans.*, (1982), 1593-1601, and refs. therein.
93. Gahan, L.R., Lawrence, G.A., and Sargeson, A.M., *Aust. J. Chem.*, (1982), 35, 1119-1131.
94. Buckingham, D.A., Marzilli, P.A., Maxwell, I.E., and Sargeson, A.M., *J. Chem. Soc., Chem. Commun.*, (1969), 473-474.
95. Dei, A., *Inorg. Chim. Acta*, (1975), 12, 79-83.
96. Timmons, J.H., Harris, W.R., Murase, I., and Martell, A.E., *Inorg. Chem.*, (1978), 17, 2192-2197.
97. Pickens, S.R., and Martell, A.E., *Inorg. Chem.*, (1980), 19, 15-21; 21-26 and refs. therein.
98. Phillip, A.T., Mazurek, W., and Casey, A.T., *Aust. J. Chem.*, (1971), 24, 501-511.
99. Cabbiness, D.K., and Margerum, D.W., *J. Am. Chem. Soc.*, (1969), 91, 6540-6541.
100. Myers, R.T., *Inorg. Chem.*, (1978), 17, 952-958;
Munro, D., *Chem. in Brit.*, (1977), 13, 100-105;
Chung, C-S., *Inorg. Chem.*, (1979), 18, 1321-1324.
101. Hinz, F.P., and Margerum, D.W., *Inorg. Chem.*, (1974), 13, 2941-2949.
102. Kodama, M., and Kimura, E., *J. Chem. Soc., Chem. Commun.*, (1975), 326-327.
103. Paoletti, P., *Pure Appl. Chem.*, (1980), 52, 2433-2439, and refs. therein.
104. Kodama, M., and Kimura, E., *J. Chem. Soc., Dalton Trans.*, (1978), 1081-1085, and refs. therein.

105. Fabbrizzi, L., Paoletti, P., and Clay, R.M., *Inorg. Chem.*, (1978), 17, 1042-1046.
106. Fabbrizzi, L., Micheloni, M., and Paoletti, P., *J. Chem. Soc., Dalton Trans.*, (1979), 1581-1584.
107. Clay, R.M., Corr, S., Keenan, G., and Steele, W.V., *J. Am. Chem. Soc.*, (1983), 105, 2070-2071.
108. Micheloni, M., Paoletti, P., and Sabatini, A., *J. Chem. Soc., Dalton Trans.*, (1983), 1189-1191.
109. Anachini, A., Fabbrizzi, L., and Paoletti, P., *J. Chem. Soc., Chem. Commun.*, (1977), 244-245.
110. Anachini, A., Fabbrizzi, L., Paoletti, P., and Clay, R.M., *Inorg. Chim. Acta*, (1977), 22, L25-L27.
111. Anachini, A., Fabbrizzi, L., Paoletti, P., and Clay, R.M., *J. Chem. Soc., Dalton Trans.*, (1978), 577-583.
112. Clay, R.M., Micheloni, M., Paoletti, P., and Steele, W.V., *J. Am. Chem. Soc.*, (1979), 101, 4119-4122.
113. Micheloni, M., and Paoletti, P., *Inorg. Chim. Acta*, (1980), 43, 109-112.
114. Fabbrizzi, L., Micheloni, M., and Paoletti, P., *Inorg. Chem.* (1980), 19, 535-538.
115. Fabbrizzi, L., *Advances in Molecular Relaxation and Interaction Processes*, (1980), 18, 109-113.
116. Martin, L.Y., De Hayes, L.J., Zompa, L.J., and Busch, D.H., *J. Am. Chem. Soc.*, (1974), 96, 4046-4048.
117. Loehlin, J.H., and Fleischer, E.B., *Acta Crystallogr., Sect. B*, (1976), 32, 3063-3066; Smierciak, R., Passariello, J., and Blinn, E.L., *Inorg. Chem.*, (1977), 16, 2646-2648.
118. Clay, R.M., Murray-Rust, P., Murray-Rust, J., *Acta Crystallogr., Sect. B.*, (1979), 35, 1894-1895.
119. Fawcett, T.G., Rudich, S.M., Toby, B.H., Lalancette, R.A., Potenza, J.A., and Schugar, H.J., *Inorg. Chem.*, (1980), 19, 940-945; Duggan, M., Ray, N., Hathaway, B., Tomlinson, G., Brint, P., and Pelin, K., *J. Chem. Soc., Dalton Trans.*, (1980), 1342-1348.
120. Fabbrizzi, L., Mealli, C., and Paoletti, P., *J. Chem. Res. (S)*, (1979), 170-171.
121. Weatherburn, D.C., Billo, E.J., Jones, J.P., and Margerum, D.W., *Inorg. Chem.*, (1970), 9, 1557-1559.

122. Fabbrizzi, L., Paoletti, P., and Lever, A.B.P., *Inorg. Chem.* (1976), 15, 1502-1506.
123. Lever, A.B.P., Paoletti, P., and Fabbrizzi, L., *Inorg. Chem.*, (1979), 18, 1324-1329.
124. Paoletti, P., and Vacca, A., *J. Chem. Soc.*, (1964), 5051-5057.
125. Kodama, M., Kimura, E., and Yamaguchi, S., *J. Chem. Soc., Dalton Trans.*, (1980), 2536-2538.
126. Jonassen, H.B., Bertrand, J.A., Groves, Jun., F.R., and Stearns, R.I., *J. Am. Chem. Soc.*, (1957), 79, 4279-4282.
127. Busch, D.H., *Acc. Chem. Res.*, (1978), 392-400, and refs. therein.
128. Fleischer, E., and Hawkinson, S., *J. Am. Chem. Soc.*, (1967), 89, 720-721; Nelson, S.M., McFall, S.G., Drew, M.G.B., Bin Othman, A.H., and Mason, N.B., *J. Chem. Soc., Chem. Commun.*, (1977), 167-168; Nelson, S.M., McFall, S.G., Drew, M.G.B., and Bin Othman, A.H., *J. Chem. Soc., Chem. Commun.*, (1977), 370-371.
129. Lewis, J., O'Donoghue, T.D., and Raithby, P.R., *J. Chem. Soc., Dalton Trans.*, (1980), 1383-1389.
130. Barefield, E.K., and Mocella, M.T., *Inorg. Chem.*, (1973), 12, 2829-2832; Olson, D.C., and Vasilevskis, J., *Inorg. Chem.*, (1971), 10, 463-470.
131. Martin, L.Y., Sperati, C.R., and Busch, D.H., *J. Am. Chem. Soc.*, (1977), 99, 2968-2981.
132. Jørgensen, C.K., *Acta Chem. Scand.*, (1955), 9, 1362-1377.
133. Hediger, M., and Kaden, T.A., *Helv. Chim. Acta*, (1983), 66, 861-870.
134. Fabbrizzi, L., Micheloni, M., Paoletti, P., Poggi, A., and Lever, A.B.P., *J. Chem. Soc., Dalton Trans.*, (1981), 1438-1441.
135. Bombieri, G., Forsellini, E., Del Pra, A., Cooksey, C.J., Humanes, M., and Tobe, M.L., *Inorg. Chim. Acta*, (1982), 61, 43-49.
136. Lever, A.B.P., Walker, I.M., and McCarthy, P.J., *Inorg. Chim. Acta*, (1980), 44, L143-L145.
137. Millar, M., and Holm, R.H., *J. Am. Chem. Soc.*, (1975), 97, 6052-6058.
138. Olson, D.C., and Vasilevskis, J., *Inorg. Chem.*, (1969), 8, 1611-1621.

139. Lovecchio, F.V., Gore, E.S., and Busch, D.H., J. Am. Chem. Soc., (1974), 96, 3109-3118.
140. Bossu, F.P., and Margerum, D.W., Inorg. Chem., (1977), 16, 1210-1214.
141. Curtis, N.F., and Cook, D.F., J. Chem. Soc., Chem. Commun., (1967), 962-963.
142. Barefield, E.K., and Busch, D.H., J. Chem. Soc., Chem. Commun., (1970), 522-523.
143. Gore, E.S., and Busch, D.H., Inorg. Chem., (1973), 12, 1-3.
144. Sabatini, L., and Fabbrizzi, L., Inorg. Chem., (1979), 18, 438-444.
145. Fabbrizzi, L., Inorg. Chim. Acta, (1979), 36, L391-L393.
146. Tait, A.M., Lovecchio, F.V., and Busch, D.H., Inorg. Chem., (1977), 16, 2206-2212.
147. Fabbrizzi, L., J. Chem. Soc., Chem. Commun., (1979), 1063-1065.
148. Nicholson, R.S., and Shain, I., Anal. Chem., (1964), 36, 706-723.
149. Hathaway, B.J., and Billing, D.E., Coord. Chem. Revs., (1970), 5, 143-207.
150. Hathaway, B.J., J. Chem. Soc., Dalton Trans., (1972), 1196-1199.
151. Bianchini, C., Fabbrizzi, L., Paoletti, P., and Lever, A.B.P., Inorg. Chem., (1975), 14, 197-199.
152. Paoletti, P., Fabbrizzi, L., and Barbucci, R., Inorg. Chem., (1973), 12, 1961-1962.
153. Sugiura, Y., Ishizu, K., and Miyoshi, K., J. Antibiotics, (1979), 32, 453-461.
154. Drew, M.G.B., and Hollis, S., Inorg. Chim. Acta, (1978), 29, L231-L232.
155. Henrick, K., and Tasker, P.A., Inorg. Chim. Acta, (1980), 47, 47-58.
156. Billo, E.J., Inorg. Nucl. Chem. Lett., (1974), 10, 613-617.
157. Lotz, T.J., and Kaden, T.A., J. Chem. Soc., Chem. Commun., (1977), 15-16.
158. Wentworth, R.A.D., and Piper, T.S., Inorg. Chem., (1965), 4, 709-714; 1524-1526.
159. Wainwright, K.P., J. Chem. Soc., Dalton Trans., (1983), 1149-1152.

160. Hung, Y., Martin, L.Y., Jackels, S.C., Tait, A.M., and Busch, D.H., J. Am. Chem. Soc., (1977), 99, 4029-4039.
161. Collman, J.P., and Schneider, P.W., Inorg. Chem., (1966), 5, 1380-1384.
162. Poon, C.K., and Tobe, M.L., J. Chem. Soc. (A), (1968), 1549-1555.
163. Urbach, F.L., in ref. 1, pp. 372-373.
164. Rillema, D.P., Endicott, J.F., and Papaconstantinou, E., Inorg. Chem., (1971), 10, 1739-1746.
165. Poon, C.K., and Tobe, M.L., J. Chem. Soc., (A), (1967), 2069-2075.
166. Hung, Y., and Busch, D.H., J. Am. Chem. Soc., (1977), 99, 4977-4984.
167. Hay, R.W., Bembi, R., Moodie, T., and Norman, P.R., J. Chem. Soc., Dalton Trans., (1982), 2131-2136.
168. Long, K.M., and Busch, D.H., Inorg. Chem., (1970), 9, 505-512.
169. Tait, A.M., and Busch, D.H., Inorg. Chem., (1976), 15, 197-203.
170. Micheloni, M., Paoletti, P., Bürki, S., and Kaden, T.A., Helv. Chim. Acta, (1982), 65, 587-594.
171. Steinmann, W., and Kaden, T.A., Helv. Chim. Acta, (1975), 58, 1358-1366.
172. Nonoyama, M., J. Inorg. Nucl. Chem., (1977), 39, 550-552.
173. Riedo, T.J., and Kaden, T.A., Helv. Chim. Acta, (1979), 62, 1089-1096.
174. Kodama, M., and Kimura, E., J. Chem. Soc., Dalton Trans., (1977), 1473-1478.
175. Cabbiness, D.K., and Margerum, D.W., J. Am. Chem. Soc., (1970), 92, 2151-2153.
176. Lin, C-T., Rorabacher, D.B., Cayley, G.R., and Margerum, D.W., Inorg. Chem., (1975), 14, 919-925.
177. Tabushi, I., and Fujiyoshi, M., Tetrahedron Lett., (1978), 25, 2157-2160.
178. Kaden, T.A., Helv. Chim. Acta, (1970), 53, 617-622.
179. Kaden, T.A., Helv. Chim. Acta, (1971), 54, 2307-2312.
180. Buxtorf, R., and Kaden, T.A., Helv. Chim. Acta, (1974), 57, 1035-1042.

181. Hertli, L., and Kaden, T.A., *Helv. Chim. Acta*, (1974), 57, 1328-1333.
182. Shultz-Grunow, P., and Kaden, T.A., *Helv. Chim. Acta*, (1978), 61, 2291-2296.
183. Luegger, A.P., Hertli, L., and Kaden, T.A., *Helv. Chim. Acta*, (1978), 61, 2296-2306.
184. Kodama, M., and Kimura, E., *J. Chem. Soc., Dalton Trans.*, (1976), 116-120.
185. Kodama, M., and Kimura, E., *J. Chem. Soc., Chem. Commun.*, (1975), 891-892.
186. Kodama, M., and Kimura, E., *J. Chem. Soc., Dalton Trans.*, (1976), 1720-1724.
187. Kodama, M., and Kimura, E.J., *Chem. Soc., Dalton Trans.*, (1976), 2341-2345.
188. Kodama, M., and Kimura, E., *J. Chem. Soc., Dalton Trans.*, (1977), 2269-2276.
189. McDowell, L.A., and Johnston, H.L., *J. Am. Chem. Soc.*, (1936), 58, 2009-2014.
190. Wilkins, R.G., *Acc. Chem. Res.*, (1970), 3, 408-416.
191. Ochrymowycz, L.A., Mak, C-P., and Michna, J.D., *J. Org. Chem.*, (1974), 39, 2079-2084.
192. Jones, T.E., Zimmer, L.L., Diaddario, L.L., Rorabacher, D.B., and Ochrymowycz, L.A., *J. Am. Chem. Soc.*, (1975), 97, 7163-7165.
193. Diaddario, L.L., Zimmer, L.L., Jones, T.E., Sokol, L.S.W.L., Cruz, R.B., Yee, E.L., Ochrymowycz, L.A., and Rorabacher, D.B., *J. Am. Chem. Soc.*, (1979), 101, 3511-3520.
194. Moss, D.B., Lin, C-T., and Rorabacher, D.B., *J. Am. Chem. Soc.*, (1973), 95, 5179-5185.
195. Dalley, N.K., Smith, J.S., Larson, S.B., Matheson, K.B., Christensen, J.J., and Izatt, R.M., *J. Chem. Soc., Chem. Commun.*, (1975), 84-85; DeSimone, R.E., and Glick, M.D., *J. Am. Chem. Soc.*, (1976), 98, 762-767; Dalley, N.K., Larsen, S.B., Smith, J.S., Matheson, K.L., Izatt, R.M., and Christensen, J.J., *J. Heterocycl. Chem.*, (1981), 18, 463-467.
196. Kowalak, A., Kustin, K., Pasternack, R.F., and Petrucci, S., *J. Am. Chem. Soc.*, (1967), 89, 3126-3130.

197. Kodama, M., Yatsunami, T., and Kimura, E., *Inorg. Chem.*, (1980), 19, 1600-1602, and refs. therein.
198. Margerum, D.W., Cayley, G.R., Weatherburn, D.C., and Pagenkopf, G.K., In "Coordination Chemistry", Vol.2, A.C.S. Monograph 174, (Martell, A.E., ed.), Am. Chem. Soc., (1978), pp.52-220.
199. Margerum, D.W., Rorabacher, D.B., and Clarke, Jr., J.F.G., *Inorg. Chem.* (1963), 2, 667-677.
200. Shepherd, R.E., Hodgson, G.M., and Margerum, D.W., *Inorg. Chem.*, (1971), 10, 989-994.
201. Schwindinger, W.F., Fawcett, T.G., Lalancette, R.A., Potenza, J.A., and Schugar, H.J., *Inorg. Chem.*, (1980), 19, 1379-1381; Bereman, R.D., Churchill, M.R., Schaber, P.M., and Winkler, M.E., *Inorg. Chem.*, (1979), 18, 3122-3125.
202. Zompa, L.J., and Margulis, T.N., *Inorg. Chim. Acta*, (1978), 28, L157-L159.
203. Rorabacher, D.B., and Melendez-Cepeda, C.A., *J. Am. Chem. Soc.*, (1971), 93, 6071-6076.
204. Turan, T.S., and Rorabacher, D.B., *Inorg. Chem.*, (1972), 11, 288-295.
205. Turan, T.S., *Inorg. Chem.*, (1974), 13, 1584-1590.
206. Melson, G.A., and Wilkins, R.G., *J. Chem. Soc.*, (1963), 2662-2672.
207. Ahmed, A.K.S., and Wilkins, R.G., *J. Chem. Soc.*, (1959), 3700-3708.
208. Ahmed, A.K.S., and Wilkins, R.G., *Proc. Chem. Soc.*, (1959), 399-400.
209. Ahmed, A.K.S., and Wilkins, R.G., *J. Chem. Soc.*, (1960), 2895-2900.
210. Ahmed, A.K.S., and Wilkins, R.G., *J. Chem. Soc.*, (1960), 2901-2906.
211. Read, R.A., and Margerum, D.W., *Inorg. Chem.* (1981), 20, 3143-3149.
212. Kemp, T.J., Moore, P., and Quick, G.R., *J. Chem. Soc., Dalton Trans.*, (1979), 1377-1383.
213. Read, R.A., and Margerum, D.W., *Inorg. Chem.*, (1983), 22, 3447-3451.
214. Lever, A.B.P., and Mantovani, E., *Inorg. Chim. Acta*, (1971), 5, 429-433.
215. Kleft, J.A., and Nakamoto, K., *Inorg. Chim. Acta*, (1968), 2, 225-229.
216. Lincoln, S.F., and Hubbard, C.D., *J. Chem. Soc., Dalton Trans.*, (1974), 2513-2516.
217. Weatherburn, D.C., *Aust. J. Chem.*, (1983), 36, 433-439.
218. Cox, B.G., and Schneider, H., *J. Am. Chem. Soc.*, (1980), 102, 3628-3630.

219. Liang, B-F., and Chung, C-S., *Inorg. Chem.*, (1983), 22, 1017-1021.
220. Ekstrom, A., Lindoy, L.F., and Smith, R.J., *Inorg. Chem.*, (1980), 19, 724-727.
221. Barefield, E.K., and Wagner, F., *Inorg. Chem.*, (1973), 12, 2435-2439.
222. Cabbiness, D.K., PhD. Thesis, Purdue University (1970),
Diss. Abstr. Int. B (1970), 31, 1773-1774.
223. Kallianou, C.S., Kaden, T.A., *Helv. Chim. Acta*, (1979), 62,
2562-2568.
224. Hay, R.W., and Bembi, R., *Inorg. Chim. Acta*, (1982), 65, L227-L230.
225. Graham, P.G., and Weatherburn, D.C., *Aust. J. Chem.*, (1981), 34,
291-300.
226. Hay, R.W., and Bembi, R., *Inorg. Chim. Acta*, (1982), 62, 89-97.
227. Timmons, J.H., Rudolf, P., Martell, A.E., Martin, J.W.L., and
Clearfield, A., *Inorg. Chem.*, (1980), 19, 2331-2338.
228. Clay, R., Murray-Rust, J., and Murray-Rust, P., *J. Chem. Soc.*,
Dalton Trans., (1979), 1135-1139.
229. Liang, B-F, and Chung, C-S., *Inorg. Chem.*, (1981), 20, 2152-2155.
230. Murphy, L.J., and Zompa, L.J., *Inorg. Chem.*, (1979), 18, 3278-3281.
231. Childers, R.F., and Wentworth, R.A.D., *Inorg. Chem.*, (1969), 8,
2218-2220.
232. Zompa, L.J., and Margulis, T.N., *Inorg. Chim. Acta*, (1980),
45, L263-L264.
233. Zompa, L.J., *Inorg. Chem.*, (1978), 17, 2531-2536.
234. Hay, R.W., Jeragh, B., Lincoln, S.F., and Searle, G.H.,
Inorg. Nucl. Chem. Lett., (1978), 14, 435-440.
235. Sokol, L.S.W.L., Ochrymowycz, L.A., and Rorabacher, D.B.,
Inorg. Chem., (1981), 20, 3189-3195.
236. Margerum, D.W., in "A.C.S. Symposium Series 198", (Rorabacher, D.B.,
and Endicott, J.F., ed.), A.C.S., Washington, (1982), pp.3-38.
237. "C.R.C. Handbook of Chemistry and Physics", (Weast, R.C., ed.)
C.R.C. Press, Ohio.
238. "Classics in Coordination Chemistry", Parts I-III (Kaufmann, G.B., ed.),
Dover, New York, (1968, 1976, 1978) .
239. Brown, D.R., *Progr. Inorg. Chem.*, (1973), 18, 177-286.
240. Mitchell, P.R., In *Method. Chim.* (1976), 8, 307-344, and refs. therein.
(Niedenzu, K., and Zimmer, H., ed.), Academic Press, New York.

241. Bjerrum, J., and McReynolds, J.P., *Inorg. Synth.* (1946), 2, 216-221.
242. Bailar, Jr., J.C., and Work, J.B., *J. Am. Chem. Soc.*, (1945), 67, 176-179.
243. Schlessinger, G., *Inorg. Synth.*, (1960), 6, 173-175.
244. Hung, Y., *Inorg. Synth.*, (1980), 20, 105-114; Pearson, K.H., Howell, Jr., W.R., Reinbold, P.E., and Kirschner, S., *Inorg. Synth.*, (1973), 14, 57-60.
245. Bennett, L.E., *Inorg. Chem.*, (1970), 9, 1941-1942.
246. Bauer, H.F., and Drinkard, W.C., *J. Am. Chem. Soc.*, (1960), 2, 5031-5032; Bauer, H.F., and Drinkard, W.C., *Inorg. Synth.*, (1966), 8, 202-204.
247. Mori, M., Shibata, M., Kyuno, E., and Adachi, T., *Bull. Chem. Soc. Jpn.*, (1956), 29, 883-886.
248. Crayton, P.H., *Inorg. Synth.*, (1963), 7, 207-213.
249. Ha, F.C., House, D.A., Blunt, J.W., *Inorg. Chim. Acta*, (1979), 33, 269-279.
250. Searle, G.H., and Hambley, T.W., *Aust. J. Chem.*, (1982), 35, 2399-2411.
251. Alexander, M.D., and Spillert, C.A., *Inorg. Chem.*, (1970), 9, 2344-2346.
252. Muto, M., and Nakao, C., *Acta Chem. Scand., Ser. A*, (1982), 36, 89-92.
253. Hay, R.W., Bembi, R., *Inorg. Chim. Acta*, (1982), 64, L199-L201.
254. Cahn, R.S., Ingold, C., and Prelog, V., *Angew. Chem., Int. Ed. Engl.*, (1966), 5, 385-415.
255. Commission on the Nomenclature of Inorganic Chemistry, *Inorg. Chem.*, (1970), 9, 1-5; *Pure and Appl. Chem.*, (1971), 28, 75-83.
256. Sargeson, A.M., and Searle, G.H., *Inorg. Chem.*, (1965), 4, 45-52. *ibid.*, (1967), 6, 787-796.
257. Snow, M.R., Buckingham, D.A., Marzilli, P.A., and Sargeson, A.M., *J. Chem. Soc., Chem. Commun.*, (1969), 891-892.
258. Buckingham, D.A., Marzilli, P.A., and Sargeson, A.M., *Inorg. Chem.*, (1967), 6, 1032-1041.

259. House, D.A., Gainsford, A.R., and Blunt, J.W., *Inorg. Chim. Acta*, (1982), 57, 141-149; Dong, L.S., Gainsford, A.R., and House, D.A., *Inorg. Chim. Acta*, (1978), 30, 271-280.
260. Yoshikawa, Y., and Yamasaki, K., *Coord. Chem. Revs.*, (1979), 28, 205-229.
261. Searle, G.H., *Aust. J. Chem.*, (1977), 30, 2625-2637.
262. Nonoyama, M., *Inorg. Chim. Acta*, (1978), 29, 211-215.
263. Yoshikawa, Y., *Chem. Lett.*, (1978), 109-112.
264. Yoshikawa, Y., Toriumi, K., Ito, T., and Yamatera, H., *Bull. Chem. Soc. Jpn.*, (1982), 55, 1422-1424.
265. Yoshikawa, Y., and Yamaski, K., *Bull. Chem. Soc. Jpn.*, (1973), 46, 3448-3452; Yoshikawa, Y., *Bull. Chem. Soc. Jpn.*, (1976), 49, 159-162; Sato, S., and Saito, Y., *Acta Crystallogr., Ser. B.*, (1975), 31, 2456-2460.
266. Sakakibara, K., Yoshikawa, Y., and Yamatera, H., *Bull. Chem. Soc. Jpn.*, (1979), 52, 2725-2726.
267. Searle, G.H., and Angley, M.E., *Inorg. Chim. Acta*, (1981), 49, 185-192.
268. House, D.A., and Garner, C.S., *Inorg. Chem.*, (1967), 6, 272-276.
269. Snow, M.R., *J. Chem. Soc., Dalton Trans.*, (1972), 1627-1634.
270. Snow, M.R., *J. Am. Chem. Soc.*, (1970), 92, 3610-3617.
271. Lager, S., Bang, O., and Woldbye, F., *Acta Chem. Scand.*, (1973), 27, 2663-2664.
272. Searle, G.H., and Hambley, T.W., *Aust. J. Chem.*, (1982), 35, 1297-1309.
273. Brubaker, G.R., and Johnson, D.W., *Inorg. Chem.*, (1982), 21, 2223-2226.
274. Brubaker, G.R., and Johnson, D.W., *Inorg. Chim. Acta*, (1982), 62, 141-148.
275. Sancilio, F.D., Druding, L.F., and Lukaszewski, D.M., *Inorg. Chem.*, (1976), 15, 1626-1629.
276. Forsberg, J.H., Kubik, T.M., Moeller, T., and Gucwa, K., *Inorg. Chem.*, (1971), 10, 2656-2660.
277. Israel, M., Rosenfield, J.S., and Modest, E.J., *J. Med. Chem.*, (1964), 7, 710-716.
278. Dominguez, X.A., Lopez, I.C., and Franco, R., *J. Org. Chem.*, (1961), 26, 1625.

279. Jonassen, H.B., Frey, F.W., and Schaafsma, A., J. Phys. Chem., (1957), 61, 504-505.
280. Kotelko, B., Acta Pol. Pharm., (1967), 24, 475-481.
c.f. C.A. (1968), 69: 2943h.
281. "Organic Chemistry", Grundon, M.F., and Henbest, H.B., Oldbourne, London, (1969), p.135.
282. "Reagents for Organic Synthesis", Volume 1, Feiser, L.F., and Feiser, M., Wiley, New York, (1967), p.1179-1180.
283. Hay, R.W., and Norman, P.R., J. Chem. Soc., Dalton Trans., (1979), 1441-1445.
284. Ponticelli, G., and Diaz, A., Ann. Chim. (Rome), (1971), 61, 46-53.
285. Portanova, R., Di Bernardo, P., Cassol, A., Tondello, E., and Magon, L., Inorg. Chim. Acta, (1974), 8, 233-240.
286. Basak, A.K., and Kaden, T.A., Helv. Chim. Acta, (1983), 66, 2086-2092.
287. Splinter, R.C., Harris, S.J., and Tobias, R.S., Inorg. Chem., 1968, 7, 897-902.
288. Diehl, H., Clark, H., and Willard, H.H., Inorg. Synth., (1939), 1, 186-188.
289. Schlessinger, G.G., Inorg. Synth., (1967), 9, 160-163.
290. Duffy, D.L., House, D.A., and Weil, J.A., J. Inorg. Nucl. Chem., (1969), 31, 2053-2058.
291. This experiment was performed by Mr M. Sim; an aqueous solution of $[\text{Co}([^{17}\text{B}]\text{aneN}_5)\text{H}_2\text{O}]^{3+}$ was treated with sodium meta-bisulphite and subsequently neutralized, yielding the desired product.
292. Linhard, M., and Weigel, M., Z. Physik. Chem., (1957), 11, 308-317.
293. "Gmelins Handbuch der anorganischen Chemie", Kobalt. Teil B, Vol. 58, Verlag Chemie, Germany (1964), p404.
294. Colmar, R.I., Schwartz, F.W., J. Am. Chem. Soc., (1932), 54, 3204-3212.
295. Dei, A., Morassi, R., J. Chem. Soc.(A), (1971), 2024-2027.
296. Main, P., Lessinger, L., Woolfson, M.M., Germain, G., and Decleraq, J.P., (1977), MULTAN 77, A system of computer programs for the automatic solution of crystal structures from x-ray diffraction data, Univ. of York, England and Louvain, Belgium.

297. Sheldrick, G.M., Shelx-76 Program for Crystal Structure Determination, University of Cambridge, England.
298. International Table for X-ray Crystallography (1974), Volume IV, Birmingham, Kynoch Press.
299. "Basic Reaction Kinetics and Mechanisms", Avery, H.E., MacMillan Press, London, (1974), 65-67.
300. Sarneski, J.E., Surprenant, H.L., Molen, F.K., and Reilley, C.N., Anal. Chem., (1975), 47, 2116-2124, and refs. therein.
301. Salomaa, P., Acta Chem. Scand., (1956), 10, 306-310.
302. Yatsunami, T., Sakonaka, A., and Kimura, E., Anal. Chem., (1981), 53, 477-480.
303. "Advanced Inorganic Chemistry", Cotton, F.A., Wilkinson, G., Wiley & Sons, New York, (1980).
304. Wester, D., and Palenik, G.J., J. Am. Chem. Soc., (1974), 96, 7565-7566.
305. "Infrared and Raman Spectra of Inorganic and Coordination Compounds", Nakamoto, K., Wiley-Interscience, New York, (1978).
306. Rosenthal, M.R., J. Chem. Educ., (1973), 50, 331-335.
307. Parkovic, S.F., and Meek, D.W., Inorg. Chem., (1965), 4, 1091-1098.
308. Brown, D.S., Lee, J.D., Melsom, B.G.A., Hathaway, B.J., Proctor, I.M., and Tomlinson, A.A.G., J. Chem. Soc., Chem. Commun., (1967), 369-371.
309. McWhinnie, W.R., J. Inorg. Nucl. Chem., (1964), 26, 21-24; Proctor, I.M., Hathaway, B.J., and Nicholls, P., J. Chem. Soc.(A), (1968), 1678-1684.
310. Addison, C.C., Logan, N., Wallwork, S.C., and Garner, C.D., Quart. Rev., (1971), 25, 289-322.
311. Curtis, N.F., and Curtis, Y.M., Inorg. Chem., (1965), 4, 804-809.
312. Geary, W.J., Coord. Chem. Rev., (1971), 7, 81-122.
313. Kennedy, B.P., and Lever, A.B.P., J. Am. Chem. Soc., (1973), 95, 6907-6913.
314. Lever, A.B.P., and Mantovani, E., Inorg. Chem., (1971), 4, 817-826.
315. Jahn, H.A., Teller, E., Proc. Royal Soc., (1937), A161, 220-235.
316. Bosnich, B., Gillard, R.D., McKenzie, E.D., and Webb, G.A., J. Chem. Soc. (A), (1966), 1331-1339; Hancock, R.D., McDougall, G.J., and Marsicano, F., Inorg. Chem., (1979), 18, 2847-2852.

317. Barbucci, R., Fabbrizzi, L., and Paoletti, P., *Inorg. Chim. Acta*, (1973), 7, 157-160.
318. Gibson, J.G., and McKenzie, E.D., *J. Chem. Soc., Dalton Trans.*, (1974), 989-992.
319. Paoletti, P., Walser, R., Vacca, A., and Schwarzenbach, G., *Helv. Chim. Acta*, (1971), 54, 243-265.
320. Gibson, J.G., and McKenzie, E.D., *J. Chem. Soc.(A)*, (1971), 1029-1038.
321. DeSimone, R.E., Blinn, E.L., and Mucker, K.F., *Inorg. Nucl. Chem. Lett.*, (1980), 16, 23-26; Brennan, T.F., Davies, G., El-Sayed, M.A., El-Shazly, M.F., Rupich, M.W., and Yeidis, M., *Inorg. Chim. Acta*, (1981), 51, 45-48; Marongiu, G., Lingafelter, E.C., and Paoletti, P., *Inorg. Chem.*, (1969), 8, 2763-2767; Estes, E.D., Estes, W.E., Hatfield, W.E., and Hodgson, D.J., *Inorg. Chem.*, (1975), 14, 106-109; Balvich, J., Fivizzani, K.P., Parkovic, S.F., and Brown, J.N., *Inorg. Chem.*, (1976), 15, 71-74.
322. Cannas, M., Carta, G., and Marongiu, G., *J. Chem. Soc., Dalton Trans.*, (1974), 553-555.
323. Tomlinson, A.A.G., and Hathaway, B.J., *J. Chem. Soc. (A)*, (1968), 1685-1688.
324. Hathaway, B.J., Tomlinson, A.A.G., *Coord. Chem. Rev.*, (1970), 5, 1-43.
325. Procter, I.M., Hathaway, B.J., and Nicholls, P., *J. Chem. Soc. (A)*, (1968), 1678-1684.
326. Jain, P.C., and Lingafelter, E.C., *J. Am. Chem. Soc.*, (1967), 89, 6131-6136.
327. DiVaira, M., and Orioli, P.L., *Inorg. Chem.*, (1967), 6, 955-957.
328. DiVaira, M., and Orioli, P.L., *Acta Crystallogr., Sect. B*, (1968), 24, 595-599.
329. Shafer, J.L., and Raymond, K.N., *Inorg. Chem.*, (1971), 10, 1799-1802.
330. Huang, C-L., Li, C-M., and Lu, C-H., *Acta Chem. Sinica*, (1966), 32, 162-168. c.f. *C.A.* (1966), 65:4758c.
331. Devoto, G., and Ponticelli, G., *J. Inorg. Nucl. Chem.*, (1975), 37, 1153-1157.
332. Vacca, A., and Paoletti, P., *J. Chem. Soc.(A)*, (1968), 2378-2383.
333. Drew, M.G.B., Nelson, J., and Nelson, S.M., *J. Chem. Soc., Dalton Trans.*, (1981), 1685-1690.
334. Lever, A.B.P., *Coord. Chem. Rev.*, (1968), 3, 119-140.

335. Rowley, D.A., and Drago, R.S., *Inorg. Chem.*, (1968), 7, 795-800.
336. Lever, A.B.P., London, G., and McCarthy, P.J., *Can. J. Chem.*, (1977), 55, 3172-3189.
337. Nonoyama, M., *Inorg. Chim. Acta*, (1976), 20, 53-58.
338. Renfrew, R.W., Jamison, R.S., and Weatherburn, D.C., *Inorg. Chem.* (1979), 18, 1584-1589.
339. Manch, W., and Fernelius, W.C., *J. Chem. Educ.*, (1961), 38, 192-201.
340. Sacconi, L., *Trans. Metal Chem.*, (1968), 4, 199-298.
341. Kalligeros, G.A., and Blinn, E.L., *Inorg. Chem.*, (1972), 11, 1145-1148.
342. Lever, A.B.P., Walker, I.M., and McCarthy, P.J., *Spectrosc. Lett.*, (1979), 12, 739-752.
343. Morassi, R., Bertini, I., and Sacconi, L., *Coord. Chem. Rev.*, (1973), 11, 343-402.
344. Furlani, C., *Coord. Chem. Rev.*, (1968), 3, 141-167.
345. Wood, J.S., *Prog. Inorg. Chem.*, (1972), 16, 227-486.
346. Ciampolini, M., *Inorg. Chem.*, (1966), 5, 35-40.
347. Ciampolini, M., and Speroni, G.P., *Inorg. Chem.*, (1966), 5, 45-49.
348. Ciampolini, M., and Gelsomini, J., *Inorg. Chem.*, (1967), 6, 1821-1825.
349. Cristini, A., Ponticelli, G., and Diaz, A., *J. Chem. Soc., Dalton Trans.*, (1972), 1361-1363.
350. Mazurek, W., Phillip, A.T., Hoskins, B.F., and Whillans, F.D., *J. Chem. Soc., Chem. Commun.*, (1970), 184-185.
351. Ponticelli, G., and Preti, C., *J. Chem. Soc., Dalton Trans.*, (1972), 708-712.
352. Ciampolini, M., and Nardi, N., *Inorg. Chem.*, (1966), 5, 41-44.
353. "Absolute Configuration of Metal Complexes", Hawkins, C.J., Wiley Interscience, New York, (1971).
354. Appleton, T.G., and Hall, J.R., *Inorg. Chem.*, (1970), 9, 1807-1814.
355. Gray, G.A., *Anal. Chem.*, (1975), 47, 546A-564A.
356. The $[\text{Co}(\text{[18A]aneN}_5)\text{Br}]\text{Br}_2$ complex has been the subject of ^{13}C CP/MAS n.m.r. and it has been shown that the proton spin magnetisation recovers at a rate consistent with relaxation by traces of paramagnetic impurities; this results in the near equal T_1 values for all the carbon atoms ($T_1 = 0.28$ ms for $\text{CH}_2\text{-N}$; $T_1 = 0.34$ ms for $\text{C-CH}_2\text{-C}$). R.A. Newman, personal communication.

357. Searle, G.H., Lincoln, S.F., Keene, F.R., Teague, S.G., and Rowe, D.G.,
Aust. J. Chem., (1977), 30, 1221-1228.
358. Searle, G.H., Keene, F.R., and Lincoln, S.F., Inorg. Chem., (1978),
17, 2362-2369.
359. Searle, G.H., and Keene, F.R., Inorg. Chem., (1972), 11, 1006-1011.
360. Buckingham, D.A., Cresswell, P.J., Dellaca, R.J., Dwyer, M.,
Gainsford, G.J., Marzilli, L.G., Maxwell, I.E., Robinson, W.T.,
Sargeson, A.M., and Turnbull, K.R., J. Am. Chem. Soc., (1974),
96, 1713-1725.
361. Juranić, N., Čelap, M.B., Vučelić, D., Malinar, M.J., and
Radivojčša, P.N., Inorg. Chim. Acta, (1977), 25, 229-232;
Inorg. Chem., (1980), 19, 802-805.
362. Gainsford, A.R., and House, D.A., Inorg. Chim. Acta, (1969),
3, 33-40.
363. Gainsford, A.R., and House, D.A., Inorg. Chim. Acta, (1972), 6, 227-244.
364. Gainsford, A.R., and House, D.A., Inorg. Chim. Acta, (1969), 3, 367-372.
365. Gainsford, A.R., and House, D.A., Inorg. Chim. Acta, (1971), 5, 544-546.
366. Jackson, W.G., Begbie, C.M., and Randall, M.L., Inorg. Chim. Acta,
(1983), 70, 7-12.
367. Buckingham, D.A., Clark, C.R., and Lewis, T.W., Inorg. Chem., (1979),
18, 2041-2043.
368. Buckingham, D.A., Marzilli, P.A., and Sargeson, A.M., Inorg. Chem.,
(1969), 8, 1595-1604.
369. Poon, C.K., and Tobe, M.L., Inorg. Chem., (1968), 7, 2398-2404.
370. Ahmed, E., and Tobe, M.L., Inorg. Chem., (1976), 15, 2635-2639.
371. "Concepts and Models of Inorganic Chemistry", Douglas, B.E.,
McDaniel, D.H., and Alexander, J.J., Wiley, New York, p366.
372. Taylor, S.G., Snow, M.R., and Hambley, T.W., Aust. J. Chem., (1983),
36, 2359-2368.
373. Ireland, P.R., House, D.A., and Robinson, W.T., Inorg. Chim. Acta,
(1970), 4, 137-140.
374. House, D.A., Ireland, P.R., Maxwell, I.E., and Robinson, W.T.,
Inorg. Chim. Acta, (1971), 5, 397-405.
375. Barefield, E.K., Carrier, A.M., and Vanderveer, D.G., Inorg.
Chim. Acta, (1980), 42, 271-275.
376. Gainsford, A.R., House, D.A., and Robinson, W.T., Inorg. Chim. Acta,
(1971), 5, 595-604.

377. House, D.A., and Blunt, J.W., *Inorg. Chim. Acta*, (1981), 49, 193-198.
378. Buckingham, D.A., Edwards, J.D., and McLaughlin, G.M., *Inorg. Chem.*, (1982), 21, 2770-2787.
379. House, D.A., *Coord. Chem. Rev.*, (1977), 23, 223-322, and refs. therein.
380. "Mechanisms of Inorganic Reactions", Basolo, F., and Pearson, R.G., Wiley, New York, (1967).
381. Cooksey, C.J., and Tobe, M.L., *Inorg. Chem.*, (1978), 17, 1558-1562, and refs. therein.
382. Huan, T.K., Mulvihill, J.N., Gainsford, A.R., and House, D.A., *Inorg. Chem.*, (1973), 12, 1517-1523, and refs. therein.
383. Piper, T.S., and Carlin, R.L., *J. Chem. Phys.*, (1960), 33, 1208-1211.
384. Lever, A.B.P., in "A.C.S. Symposium Series 62", (Gould, R.F., ed.) A.C.S., Washington, (1967), 430-451.
385. Bostrup, O., and Jørgensen, C.K., *Acta Chem. Scand.*, (1957), 11, 1223-1231.
386. Lever, A.B.P., Nelson, S.M., and Shepherd, T.M., *Inorg. Chem.*, (1965), 4, 810-813.
387. Timmons, J.H., Clearfield, A., Martell, A.E., and Niswander, R.H., *Inorg. Chem.*, (1979), 18, 1042-1047.
388. Averill, D.F., Legg, J.I., and Smith, D.L., *Inorg. Chem.*, (1972), 11, 2344-2349.
389. Ciampolini, M., and Bertini, I., *J. Chem. Soc.(A)*, (1968), 2241-2244.
390. Banci, L., Bencini, A., Benelli, C., Gatteschi, D., and Zanchini, C., *Structure and Bonding*, (1982), 52, 37-86.
391. Interrante, L.V., and Shafer, J.L., *Inorg. Nucl. Chem. Lett.*, (1968), 4, 411-417.
392. Bounsall, E.J., and Koprach, S.R., *Can. J. Chem.*, (1970), 48, 1481-1491.
393. Vitiello, J.D., and Billo, E.J., *Inorg. Chem.*, (1980), 19, 3477-3481.
394. "Stability Constants of Metal-Ion Complexes; Supplement No.1, Part II (Organic Including Macromolecule Ligands)", (compiled by Martell, A.E.), Special Publication No.25, The Chemical Society, London, (1971), p.546.
395. Micheloni, M., Paoletti, P., Poggi, A., and Fabbriizzi, L., *J. Chem. Soc., Dalton Trans.*, (1982), 61-65.

- 396. Gallori, E., Martini, E., Micheloni, M. and Paoletti, P.,
J. Chem. Soc., Dalton Trans., (1980), 1722-1725.
- 397. Gold, M., and Powell, H.K.J., J. Chem. Soc., Dalton Trans., (1976),
230-233.
- 398. Raycheba, J.M.T., and Margerum, D.W., Inorg. Chem., (1980), 19,
497-500.
- 399. Siddiqui, S., and Shepherd, R.E., Inorg. Chem., (1983), 22,
3726-3733.
- 400. Passariello, J., and Blinn, E.L., 170th Meeting of ACS in Chicago, 1975.
- 401. Sokol, L.S.W.L., Fink, T.D., and Rorabacher, D.B., Inorg. Chem.,
(1980), 19, 1263-1266.

Appendix 1

Abbreviations

The linear amines are named by specifying the number of methylene linkages between successive nitrogens and finally specifying the number of nitrogen atoms (using the prefixes tri, tet, pent, hex). Thus a tetramine $\text{H}_2\text{N}(\text{CH}_2)_a\text{NH}(\text{CH}_2)_b\text{NH}(\text{CH}_2)_c\text{NH}_2$ would be named a,b,c -tet.

The macrocyclic amines are named using the system described by Melson¹; where the positions of the nitrogen atoms in the macrocyclic ring have not been specified, only dimethylene and trimethylene linkages are present, and the placement of the nitrogen atoms in the macrocycle is unambiguous (e.g. [15]aneN₄ rather than [15]ane-1,4,8,12-N₄). But where ambiguity could arise, the ring numbering has been specified (e.g. [14]ane-1,4,8,11-N₄ and [14]ane-1,4,7,11-N₄). Only the seventeen- and eighteen-membered pentaazamacrocycles are subject to such ambiguity, and they are named as shown on p262 (cf structures LXXII-LXXIX).

Ar	aromatic
B.M.	Bohr Magneton
bn	butane-2,3-diamine
Br	broad
Bzo ₂ [20]dieneatoN ₅	dibenzo[b,o][1,5,9,13,17]pentaazacycloeicosa-[4,13]-diene
CMe ₄ en	2,3-dimethylbutane-2,3-diamine
cyclam	[14]ane-1,4,8,11-N ₄ (IV)
cyclen	[12]aneN ₄
d	doublet
datn	1,4-bis(2-aminoethyl)-1,4,7-triazacyclononane (XXXIV)
diethanolamine	$\text{HO}(\text{CH}_2)_2\text{NH}(\text{CH}_2)_2\text{OH}$
a,b-diol	$\text{HO}-(\text{CH}_2)_a\text{NH}(\text{CH}_2)_b-\text{OH}$
DMF	N,N-dimethylformamide
DMSO	dimethylsulphoxide
dpt	3,3-tri
en	ethane-1,2-diamine
3,2,3-gly	[14]-2-ene-1,4,8,11-N ₄ (XXIII)

glyoxal	ethanedial
HCBD	hexachlorobutadiene
HClOAc	monochloroacetic acid (ClCH_2COOH)
hexacyclen	[18]ane N_6
i	intense
isocyclam	[14]ane-1,4,7,11- N_4
m	multiplet (^{13}C n.m.r.); medium (i.r.)
M	mol dm^{-3}
Me_4daes	bis(2-dimethylaminoethyl)sulphide
Me_5dien	$\text{N,N,N',N'',N'''}-\text{Me}_5-2,2\text{-tri}$
cis- Me_6 [18]diene N_4	cis-2,4,4,11,11,13- Me_6 -[18]-1,13-diene-1,5,10,14- N_4 (LXIV)
trans- Me_6 [18]diene N_4	trans-2,4,4,11,13,13- Me_6 -[18]-1,10-diene-1,5,10,14- N_4 (LXIII)
Me_3 [12]ene N_3	2,4,4- Me_3 -[12]-1-ene-1,5,9- N_3
Me_4 [14]-hexaenato N_4	5,7,12,14- Me_4 -[14]-2,5,7,9,12,14-hexaene-1,4,8,11- N_4
Me_2pyo -[14]-triene	2,12- Me_2 -3,7,11,17-tetraazabicyclo[11.3.1]-heptadeca-1(17),2,11,13,15-pentaene (LI)
Me_7tetren	$\text{N,N,N',N''N''',N''''',N''''''}-\text{Me}_7-2,2,2,2\text{-pent}$
2,2- Me_2tn	2,2- Me_2 -propane-1,3-diamine
Me_6tren	tris(2-dimethylaminoethyl)amine
Me_6trien	$\text{N,N,N',N'',N''',N''''}-\text{Me}_6-2,2,2\text{-tet}$
Ms	methanesulphonyl
pentaethylene hexamine	2,2,2,2,2-pent
penten	$\text{N,N,N',N''}-\text{tetra-(2-aminoethyl)ethane-1,2-diamine}$
ptetraen	$\text{N,N,N',N''}-\text{tetra-(2-aminoethyl)propane-1,3-diamine}$
pyane N_5	2,13-dimethyl,3,6,9,12,18-pentaazabicyclo-[12,3,1]-octadeca-1(18),14,16-triene (XXIX)
s	singlet
sh	shoulder
S/N	signal to noise ratio
sp	sharp
t	triplet
TC-[18]ane N_6	1,4,7,10,13,16-tri-(R,R)-cyclohexano[b,h,n]-hexaazacyclooctadecane
cis,cis-tach	cyclohexane-r-1,s-3,s-5-triamine
3,22,3-tet	$\text{N,N'}\text{-bis(3-aminopropyl)piperazine}$
tet a	5,7,7,12,14,14- Me -1,4,8,11- N_4 (a isomer)
tet a	5,7,7,12,14,14- Me -1,4,8,11- N_4 (b isomer)

tetraethylene pentamine	2,2,2,2-pent (LXXXI)
tetren	2,2,2,2-pent (LXXXI)
tetrpn	3,3,3,3-pent (LXXX)
TMC	N,N',N'',N'''-tetra(2-cyanoethyl)-[14]-ane-1,4,8,11-N ₄
TMS	tetramethyl silane
tosyl,tosylated	see Ts
tpen	N,N,N'-tris[2-(2'-pyridyl)ethyl]ethane-1,2-diamine (XL)
tp _t	3,3',3''-triaminotripropylamine
tren	2,2',2''-triaminotriethylamine; tris(2-aminoethyl)amine
trenen	4-(2-aminoethyl)-1,4,7,10-tetraazadecane (XXXVI)
trien	2,2,2-tet
triethylene tetramine	2,2,2-tet
trpn	tris(3-aminopropyl)amine
Ts	<i>p</i> -toluenesulphonyl
vi	very intense
w	weak

Appendix 2

Stpflo-Basic and Fortran Listings

```

10 REM STOPPED FLOW PROGRAM
20 DIM C(20),A(20),P(20),D(20),D1(20),T1(20),C1(20),X(20)
30 DIM T(20),C2(20),Y(20)
40 DIM T2(20),TC(20),AD(20),DI(20),CA(20)
40 PRINT "INPUT DATA"
50 PRINT "INPUT EXPERIMENT TITLE"
55 INPUT T#
60 PRINT " INPUT RUNCODE"
70 INPUT R#
80 PRINT "INPUT OSCILLOSCOPE MILLIVOLT SETTING"
90 INPUT S
100 PRINT "INPUT OSCILLOSCOPE TIME SETTING"
110 INPUT T8
120 PRINT " INPUT TEN TURN POT SETTINGS ....WATER LAST"
130 INPUT T6,T7
140 PRINT "INPUT NO OF POINTS"
150 INPUT N
160 PRINT "INPUT DISTANCES ",N"POINTS REQUIRED"
170 FOR I=1 TO N
180 INPUT C(I):NEXT I
181 PRINT "ANY ERRORS? (Y OR N)":INPUT Z#
182 IF Z#="N" GOTO 200
183 INPUT "ENTER CORRECTIONS POINT NUMBER AND DISTANCE":I,C
189 C(I)=C
191 INPUT "FURTHER CORRECTIONS (Y OR N)":Z#
192 IF Z#="N" GOTO 200 ELSE GOTO 183
200 REM CALCULATE TIME INTERVALS
210 T3=(T6/T7)*100.0
220 FOR I = 1 TO N
230 IF I=1 GOTO 260
240 D(I)=D(I-1) +T3
250 GOTO 270
260 D(1) =T3
270 NEXT I
280 REM CONVERT CM TO ABSORBANCE
290 FOR J=1 TO N
300 T1(J)=C(J)*69.50 +T5
310 T2(J) = T1(J)/100.
320 A(J)=-LOG(T2(J))/LOG(10)
321 NEXT J
330 A9 = A(N)
340 FOR I =1 TO (N-1)
350 X(I)=A9- A(I)
360 IF X(I) =0 GOTO 365
364 GOTO 369
365 LPRINT "BAD DATA"
366 GOTO 130
367 X(I) = ABS(X(I))
370 Y(I) = LOG(X(I))
380 NEXT I
400 M=0.0
410 A1=B1=C1=A2=B2=0.0
411 G1=B2=B4=B5=0
420 R7=0
430 FOR J=1 TO (N-1)

```

```

431 M=M+1
440 A1=A1+D(J)
450 B1=B1+Y(J)
460 A2=A2+D(J)*D(J)
470 B2=B2+Y(J)*Y(J)
480 C1=C1+D(J)*Y(J)
490 NEXT J
500 S1=(M*C1-A1*B1)/(M*A2-A1*A1)
510 S2=(A2*B1-A1*C1)/(M*A2-A1*A1)
520 REM S1 IS THE SLOPE AND S2 THE INTERCEPT
530 D1=M*S1-A1*B1
540 Z1=M*A2-A1*A1*(M+B2-B1*B1)
550 Z2=SQR(ABS(Z1))
560 R=Z1/Z2
570 FOR J=1 TO (N-1)
580 YC(J)=S1*D(J)+S2
590 AD(J)=Y(J)-YC(J)
600 DI(J)=AD(J)
610 CA(J)=YC(J)
620 R2=R2+AD(J)*AD(J)
630 R2=R2*(2.0-M)/(M*A2-A1*A1)
640 S3=SQR(R2)
650 S4=SQR(M*S3)
660 S5=SQR(A2*S3)
670 LPRINT "STOPPED FLOW RUN ",T#
680 LPRINT "PICTURE" R#
690 LPRINT "MILLIVOLTS=" S,"TIMESETTING="T#
700 LPRINT "REFERENCE LINE=" T5,"NUMBER OF POINTS="N
710 LPRINT "TIME","DISTANCE","ABSORBANCE","LOG(A-AINF)","CALCY","DIFF"
720 FOR I=1 TO (N-1)
730 LPRINT D(I),C(I),A(I),Y(I),YC(I),AD(I)
740 NEXT I
750 LPRINT "ABSORBANCE AT INFINITY=" A(N)
760 LPRINT "RATE CONSTANT=",S1,"STD. DEV.=",S4
770 LPRINT "INTERCEPT =", S2, " STD. DEV.=", S5
780 LPRINT "CORRELATION COEFFICIENT =",R
790 LPRINT:PRINT
800 END

```

Computer program used to calculate rate constants.⁸⁰

The Fortran VS program listed below was used to analyse the kinetic data from the stopped-flow experiments. Transmittance changes were recorded as an oscilloscope trace over a 3V (100% T) range. For the small changes measured in this study, a "bias" voltage was applied to offset the photomultiplier signal, so that the oscilloscope screen represented a 2 - 10% transmittance range (60 - 300mV full scale deflection). Transmittance values are read as distances on the enlarged copy of the oscilloscope trace (see Chap. II.C.).

The data is read in from an input file (FILE 5) which includes, for each set of kinetic runs, the runcode, which automatically increments by 1 each run, the oscilloscope voltage and time settings, and the bias voltages for the experiment and for the full 100% scale, and for each run, the transmittance points in centimetres including the final value after the reaction has gone to completion.

The program converts the transmittance values into absorbances and calculates linear least squares fits of plots of $-\ln|A_t - A_\infty|$ or $-|A_t - A_\infty|^{-1}$ against time, from which the rate constant k_{obs} and the initial absorbance A are obtained.

```

CHARACTER*72 ATITLE
DIMENSION TIME(50),CM(50),AB(500),PROD(50),DIV(50),DIF(50),Y(50),
* T(50),TTEMP(50),X(50),A(15,5),AVER(1,5),YCOR(50)
COMMON TIME,CALCY(50),Y
REAL INDENT,ISTEP
38 FORMAT(I5)
39 FORMAT(/70P,7H SENS= ,F5.1,4H MV ,5X,10H TIMESET= ,F5.3,5H SEC ,5X
*7H TREF= ,F6.2,3H % ,5X,9H NPOINT= ,I2,/)
40 FORMAT(/5X,'THIS SET OF DATA HAS POINTS EQUAL TO A(INFIN)')
47 FORMAT(5H DIV.,4X,4H TIME,5X,3H CM.,5X,' %T',6X,4H ABS.,6X,2H KT,4X,
* 6H CALCY ,4X,4H DIF //
*(F5.1,F9.3,2F8.2,4F9.4))
48 FORMAT(/2X,6H INFIN.,6X,2F8.2,F9.4)
52 FORMAT(/20X,8H(K/SEC)=,F10.3,5X,10H STD.DEV.=,F10.3/
*18X,10H INTERCEPT=,F10.3,5X,10H STD.DEV.=,F10.3/
*16X,12H ABS.EXTRAP.=,F11.4// '*** CORRELATION COEFF= ',F7.4)
300 FORMAT(/,1H1,25X,' CODE IS:',I5)
400 FORMAT(A72)
410 FORMAT(I2)
420 FORMAT(I5,F5.1,F5.3,F5.1,F5.1)
430 FORMAT(I2,F2.1,15F5.2)
445 FORMAT(1H1,25X,' PSEUDO FIRST ORDER REACTIONS',/
* 1X, A72)
544 FORMAT(1H1,25X,' SECOND ORDER EQUAL REACTIONS',/
* 1X, A72)

DATA INPUT
16 READ(5,400) ATITLE
READ(5,410) IFLAG
IF (IFLAG.GT.0) GO TO 695
WRITE(6,445) ATITLE
GO TO 696
695 WRITE(6,544) ATITLE
696 CONTINUE
17 READ(5,420) NPOINT,SENS,TIMSET,TREF,TTREF
TREF = (TREF/TTREF)*100
18 READ(5,430) NPOINT,ISTEP,(CM(J),J=1,NPOINT)
IF (NPOINT.EQ.0.0) GO TO 69
IF (NPOINT.EQ.1.0) GO TO 17

CALCULATE TIME INTERVAL
DO 26 J=1,NPOINT
IF(J.EQ.1) GO TO 22
323 DIV(J)=J*ISTEP
TIME(J)=(((J-1)*ISTEP)/2.0)*TIMSET
GO TO 23
22 TIME(1)=0.0
DIV(1)=ISTEP
23 CONTINUE

CONVERT CM TO ABSORBANCE
SCALE OF OSCILLOSCOPE EXPANDED 2*
2CM=1 DIVISION OF OSCILLOSCOPE
100%=3 VOLTS
1MV=1/30%
T(J)= + CM(J)*SENS/60.0 + TREF
A + SIGN IS USED FOR CONVENIENCE.MOST POINTS ARE LOWER THAN TREF
TTEMP(J)=T(J)/100.0
26 AB(J)=- (ALOG10(TTEMP(J)))

CALCULATE APPROPRIATE KINETIC DATA
ABFIN=AB(NPOINT)
N=NPOINT - 1
DO 36 J=1,N
X(J)=ABFIN - AB(J)
IF(X(J)) 801,800,801
801 IF(IFLAG) 598,598,699
598 Y(J)=ALOG(ABS(X(J)))
GO TO 36
699 Y(J)=ABS(1/(X(J)))
36 CONTINUE
CALL LLSF (TIME,Y,N,YINT,SINT,SLOPE,SSLOPE,CALCY,DIF,R)
IF(IFLAG) 594,594,595
594 B=EXP(YINT)
GO TO 596

```

```

595 B=1/YINT
596 CONTINUE
IF (AB(NPOINT).LT,AR(1)) ABYINT=AB(NPOINT) + B
IF (AB(NPOINT).GT,AR(1)) ABYINT=AB(NPOINT) - B

```

OUTPUT SECTION

```

WRITE(6,300) KODE
WRITE(6,39) SENS,TIMSET,TREF,NPOINT
WRITE(6,47) (DIV(J),TIME(J),CM(J),T(J),AB(J),Y(J),CALCY(J),
* DIF(J),J=1,N)
WRITE(6,48) CM(NPOINT),T(NPOINT),AB(NPOINT)
WRITE(6,52) SLOPE,SSLOPE,YINT,SINT,ABYINT,R
GO TO 54
800 WRITE(6,38) KODE
WRITE(6,39) SENS,TIMSET,TREF,NPOINT
WRITE(6,40)

```

CLEAR ALL DATA BUFFERS

```

54 DO 66 N=1,NPOINT
DIV(N)= 0.0
TIME (N) =0.0
CM (N) =0.0
AB (N) =0.0
TIME (N) =0.0
TTEMP(N) = 0.0
X (N) =0.0
66 Y (N) =0.0
KODE = KODE + 1
GO TO 18
69 CONTINUE
25 CONTINUE
END

```

SUBROUTINE LINEAR LEAST SQUARES FIT TO DATA

```

SUBROUTINE LLSF(X,Y,N,YINT,SINT,SLOPE,SSLOPE,CALCY,DIF,R)
DIMENSION X(N),Y(N),CALCY(N),DIF(N),YCALC(50),ADIF(50)
M=0
SUMX=0.0
SUMY=0.0
SUMXY=0.0
SUMXX=0.0
SUMYY=0.0
RESID=0.0

```

SUMMING TERMS

```

DO 5 J=1,N
M=M+1
SUMX =SUMX + X(J)
SUMY =SUMY + Y(J)
SUMXX = SUMXX + X(J)*X(J)
SUMYY = SUMYY + Y(J)*Y(J)
5 SUMXY = SUMXY + X(J)*Y(J)

```

SLOPE AND INTERCEPT

```

DENOM = SUMX*SUMX-M*SUMXX
SLOPE = (SUMX*SUMY-M*SUMXY)/DENOM
YINT = +(SUMX*SUMXY-SUMY*SUMXX)/DENOM
Z1 = M*SUMXY-SUMX*SUMY
Z2 = (M*SUMXX-SUMX*SUMX)*(M*SUMYY-SUMY*SUMY)
Z2 = SQRT(Z2)

```

C CORRELATION COEFF. R, PERFECT FIT TO A STRAIGHT LINE INDICATED BY R=1.0
C THE MAXIMUM VALUE.

```

R=Z1/Z2
R=ABS(R)

```

```

DO 7 J=1,N
YCALC(J) = SLOPE*X(J) + YINT
ADIF(J) = Y(J)-YCALC(J)
DIF(J) = ADIF(J)
CALCY(J) = YCALC(J)
7 RESID = RESID + ADIF(J)*ADIF(J)

```

STANDARD DEVIATIONS

```

SIG = RESID/(2.0-M)/DENOM
SSLOPE = SQRT(M*SIG)
SINT = SQRT(SUMXX*SIG)
RETURN
END

```