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Coordination chemistry of N_6 macrocycles

M. Mitewa and P.R. Bontchev
Department of Chemistry, University of Sofia, 1126 Sofia (Bulgaria)

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CONTENTS

ABSTRACT

The complexation ability of saturated and unsaturated N_6 macrocycles towards different metal ions, synthesis, thermodynamics and structure of the metal complexes (mono- and dinuclear) formed are discussed. The data concerning protonation processes of the saturated azamacrocycles, *i.e.* cyclic polyamines and their ability to react selectively with some anions (host–guest chemistry) are also reviewed.

1. INTRODUCTION

Although the first saturated N_4 macrocycle, namely cyclam, was obtained by Van Alpen [1] in 1937, it was only following the pioneering work of Curtis [2] on the template synthesis of N-containing macrocycles that great interest was shown towards polyazamacrocycles and their metal complexes. Since then the field has been very active owing to their application in analytical practice and industry, for modelling some biosystems, transport processes in the biosphere, stabilization of high oxidation states, selective ion recognition, catalytic and extraction properties etc. [3–5].

Correspondence to: P.R. Bontchev, Department of Chemistry, University of Sofia, 1126 Sofia, Bulgaria.

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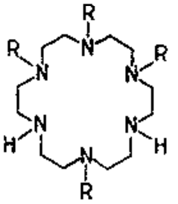
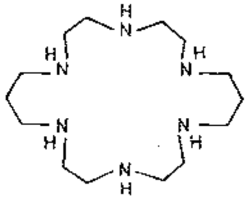
Until now the tetraazamacrocycles have been the most studied [3–6] and much attention was paid to the large (according to Bianchi *et al.* [9] macrocycles with more than six N donor atoms), and also to [3*k*]aneN_k $k=7–12$) [7–10].

The hexaazamacrocyclic ligands (both saturated and unsaturated), being at the border between small and large polyazamacrocycles, exhibit interesting coordination properties and are capable of forming both mononuclear and polynuclear complexes. To the best of our knowledge the literature on the structure of their metal complexes has not been reviewed. Here therefore we summarize the data available on the coordination properties of N_6 macrocyclic ligands, and the thermodynamics and structure of their metal complexes. Only complexes in which the N_6 macrocycles act as a hexadentate ligand will be reviewed.

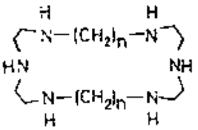
2. SATURATED N_6 MACROCYCLES

Several representatives of this class are known, as follows: for

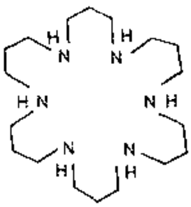




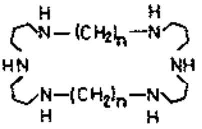
R = H, 1,4,7,10,13,16-hexaazacyclooctadecane ([18]aneN_6) (I) and 1,4,7,11,14,17-hexaazacycloeicosane ([20]aneN_6) (II); for $R=CH_3$; 1,4,7,13-tetramethyl-1,4,7,10,13,16-hexaazacyclooctadecane (I′);



for $n=4$, 1,4,7,12,15,18-hexaazacyclododecosane ([22]aneN_6) (III); for $n=5$, 1,4,7,13,16,19-hexaazacyclotetracosane ([24]aneN_6) (IV); for $n=6$, 1,4,7,14,17,20-hexaazacyclohexacosane ([26]aneN_6) (V); for $n=9$, 1,4,7,17,20,23-hexaazacyclodotriacontane ([32]aneN_6) (VI);



1,5,9,13,17,21-hexaazacyclotetracosane ([25-aneN$_6$) (VII);



for $n=7$, 1,5,9,17,21,25-hexaazacyclodotriacontane ([32]aneN$_6$) (VIII); and for $n=10$, 1,5,9,20,24,28-hexaazacyclooctatriacontane ([38]aneN$_6$) (IX).

2.1. *Metal complexes of [18]aneN$_6$ (hexacyclen) and its derivatives*

The hexaazamacrocyclic ligand hexacyclen (Hex) (I) was first synthesized by Richman and co-workers [11] and shortly after that its Co(III), Ni(II) and Cu(II) complexes were obtained [12,13]. On the basis of spectroscopic data an octahedral structure was proposed for the complexes, the ligand acting as a hexadentate. ^{1}H and ^{13}C nuclear magnetic resonance (NMR) data obtained for Co(Hex)$^{3+}$ indicated the formation of two geometric isomers [13]. Later an octahedral structure for Co(Hex)$^{3+}$ was proven unequivocally [14]. The crystal structure of one of the geometric isomers, namely all-facial [Co(Hex)](NO$_3$)$_3$·H$_2$O, was solved by the X-ray diffraction method (Fig. 1), proving at the same time the flexibility of the ligand. An isomerization process of the Co(III)–Hexacyclen system in basic medium was also studied [15] using ion-exchange high performance liquid chromatography, spectrophotometric and ^{13}C NMR methods.

Later, detailed studies on the complexation ability of Hexacyclen were performed by two research groups: those of Kodama *et al.* [16] and Mitewa *et al.* [17].

Kodama *et al.* studied the complexation constants (together with ΔH and ΔS parameters) of Hexacyclen complexes and compared them with those of its linear analogue 3,6,9,12-tetraazatetradecane 1,14-diamine (X). These authors have shown

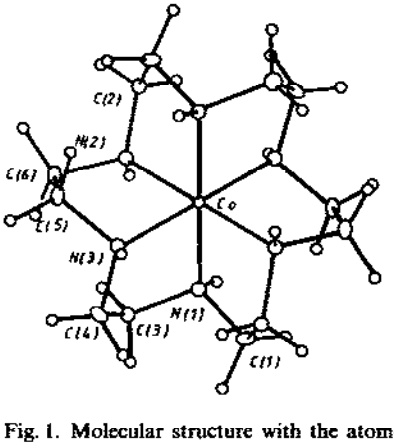
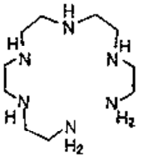
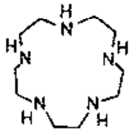


Fig. 1. Molecular structure with the atom-labelling scheme for the fac-[Co(Hex)]$^{3+}$ cation reproduced by permission from ref. 14.

that in contrast to the lower macrocyclic homologues, Hexacyclen shows appreciable affinity for non-polarizable cations (Ca^{2+}, Sr^{2+}, La^{3+}) and even for K^+ like its O-containing "hard" analogue 18-Crown-6. No complexation with Mg^{2+} was observed [16].





Hexacyclen forms more stable complexes with Co(II), Ni(II) and Hg(II) compared with 1,4,7,10,13-pentaazacyclopentadecane (XI) (Table 1) while the formation constants of the Zn(II), Cd(II), Pb(II) and Cu(II) complexes with [15]aneN_5 are higher than those with [18]aneN_6 [10,16]. The higher thermodynamic stability of the Co(II), Ni(II) and Hg(II) complexes with [18]aneN_6 is ascribed to its capability to form octahedral complexes [10]. However, the Cu(II) and Zn(II) complexes of [18]aneN_6 are most probably also octahedral [17,19,20] and yet their formation constants are lower than those of [15]aneN_5. Evidently in these complexes the ligand is not fully coordinated.

Recently Bencini and co-workers [21,22] performed a thermodynamic study on the equilibria between polyazacycloalkanes of the series [3*k*]aneN_k ($k = 3$–11)

TABLE 1

Equilibrium constants for complexation of some cyclic and open-chain polyamine ligands

M^{n+}	Ionic radii[a]	log K_{ML}[b]		
		1,4,7,10,13,16-hexa-azacyclooctadecane (I)	3,6,9,12-tetraaza-tetradecane-1,14-diamine (IX)	1,4,7,10,13-penta-azacyclopentadecane (X)
Co^{2+}	0.72	18.9	13.7	16.8
Ni^{2+}	0.69	19.6	17.4	18.1
Zn^{2+}	0.74	17.8	15.1	19.1
Cu^{2+}	0.72	21.6	22.8	28.3
Cd^{2+}	0.97	17.9	14.1	19.2
Hg^{2+}	1.10	29.1	24.8	28.5
Pb^{2+}	0.84	14.1	9.9	17.3
Ca^{2+}	0.99	2.5	–	–
Sr^{2+}	1.12	3.2	–	–
La^{3+}	1.14	5.7	–	–
K^+	1.33	≈0.8	–	–

[a] According to ref. 18.

[b] According to ref. 16.

with a series of bivalent metal ions. The experimental data showed that for the mononuclear complexes the formation constants of a given metal ion increase in the order N_3–N_5, with the exclusion of Co(II) and Ni(II); for N_6 and N_7 they are slightly lower and sharply decrease for N_8 macrocycles. However, it has also been shown that on increasing the size of the macrocycles the coordination features depend largely on the metal ion, namely its electronic configuration. Some considerations in this respect have been published recently [23].

Data were also reported concerning the high stability of Hexacyclen complexes with lanthanide ions [24].

In another paper [17] the complexation ability of Hexacyclen towards 23 ions with different ionic radii and electronic configurations was studied by means of spectrophotometric and IR methods. The ability of Hexacyclen to coordinate to rather different ions was proven. A series of Hexacyclen complexes were isolated through precipitation with tetraphenylborate (TPB) and their structure in the solid state was investigated by means of IR, electron paramagnetic resonance (EPR), Mössbauer spectroscopy and magnetochemical methods [17,19,25–28] in a broad temperature range (130–400 K).

The magnetochemical ($\mu_{eff} = 2.7\mu_B$) and EPR data (two-component anisotropic EPR spectrum) obtained for $Co(Hex)(TPB)_2$ indicated the formation of a flattened "phthalocyanine-like" structure [26]. In contrast, the results obtained in aqueous solution based only on visible spectral data are in favour of a high-spin octahedral structure [16].

Very interesting experimental data were obtained for Hexacyclen complexes with Cu(II) [19], Ni(II) [27] and Fe(II) [25].

Temperature-dependent EPR parametres and μ_{eff} values were observed for $Cu(Hex)(TPB)_2$ in the temperature range 100–300 K, changing their character at 240–250 K [19]. These data were interpreted in terms of a temperature-variable structure for the complex. It was concluded that up to 240 K a structure with coordination number 4 is realized, being most probably distorted planar. Above 250 K the realization of a distorted octahedral structure (XII) was suggested on the basis of the corresponding magnetochemical and EPR data and their dependence on temperature.

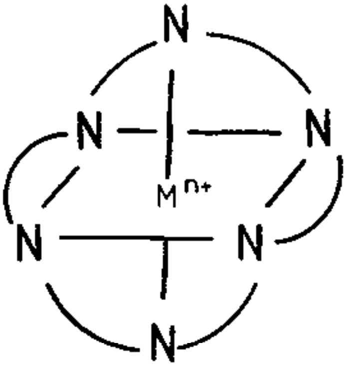
Data indicating temperature-dependent structures were also obtained for Hexacyclen complexes of Ni(II) and Fe(II) [25,27]. On the basis of the EPR data (the presence of free radical signals in the spectra of both $Ni(Hex)(TPB)_2$ and $Fe(Hex)(TPB)_2$), the changes in structure were ascribed to thermally controlled intramolecular reverse electron transfers and the following equilibria:

$$|\mathrm{Ni}''\text{–}\mathrm{L}| \rightleftarrows |\mathrm{Ni}'\text{–}\mathrm{L}^{\cdot}| \qquad (1)$$

$$|\mathrm{Fe}''\text{–}\mathrm{L}| \rightleftarrows |\mathrm{Fe}'''\text{–}\mathrm{L}^{\cdot}| \qquad (2)$$

Additional ^{57}Fe Mössbauer and magnetochemical data obtained in the temperature range 100–380 K were also in agreement with these assumptions.

For the Ni(Hex)(TPB)$_2$ complex a distorted octahedral structure was assumed (XII) [27] showing a two-component anisotropic EPR spectrum typical of octahedral Ni(II) species [29], while for Fe(Hex)(TPB)$_2$ a planar structure with an intermediate spin state ($S=1$) was proposed based on magnetochemial and Mössbauer data [25].



Experimental data concerning the structure of Hexacyclen complexes of Ni(II) [30,31] and Cu(II) [32,33] in solution showed octahedral structures on the basis of visible electronic and kinetic data [30]. Kinetic data for the acid-catalysed dissociation of Ni(Hex)$^{2+}$ were also reported [31].

Detailed electrochemical (CV), spectroscopic and EPR studies of Cu(Hex)$^{2+}$ in a series of organic solvents again led to octahedral coordination [32,33].

Hexacyclen is capable of stabilizing some unusual oxidation states such as Mn(III) [28], Ni(III) [30] and Ni(I) [34(a)].

Using elemental analysis, IR, EPR and magnetochemical data the reaction of Mn(III) with Hexacyclen is shown to form the dimeric Mn(II,III) complex Mn$_2$(Hex)$_2$(TPB)$_5$ in which the macrocycle serves as a bridging ligand [28]. The structure is also temperature dependent, probably because of internal ligand-to-metal charge transfer.

The Ni(III)–Hexacyclen complex was obtained only in solution by anodic or chemical oxidation (NOBF$_4$ in dry acetonitrile) of the Ni(II)–Hexacyclen complex [30]. Its EPR parameters (anisotropic two-component EPR spectrum with $g_\parallel > g_\perp$) were reported and consequently a tetragonally compressed octahedral structure was assumed. Electrochemical data were also obtained, namely values for the half-wave potential $E_{1/2}$ of the Ni(Hex)$^{2+}$–Ni(Hex)$^{3+}$ couple. The comparison of the $E_{1/2}$ value for the latter system with those of other saturated N$_4$ and N$_5$ macrocyclic nickel complexes has shown that the best cavity for stabilizing Ni(III) is that of [14]aneN$_4$, the Hexacyclen being also suitable although to a smaller extent [30]. Our recent attempt to isolate (by precipitation) the Ni(III)–Hex complex in the solid state failed [34(b)].

Attempts to obtain Cu(III)–Hex by chemical oxidation of the corresponding Cu(II) complex (with $S_2O_8^{2-}$ in water medium or with $NOBF_4$ in acetonitrile) resulted only in the formation of a short-lived Cu(III) species. Its formation was proven spectrophotometrically and by EPR (disappearance of the $Cu(Hex)^{2+}$ EPR signal). These intermediate species could not be stabilized and are further reoxidized leading to formation of dimeric Cu(II) complexes as shown by EPR measurements [34(b)].

In contrast, the Ni(I)–Hexacyclen complex was obtained as a precipitate (with AsF_6^-) and studied in the solid state [34(a)]. It was prepared by dissolving $NiCl_2 \cdot 4H_2O$ and Hexacyclen in acetonitrile, resulting in $Ni(Hex)^{2+}$ formation as a first step. The latter was reduced with $NaBH_4$. A violet compound was obtained showing a three-component EPR signal, typical of Ni(I) complexes (d^9 configuration) [34(a)]. On the basis of visible, IR, EPR spectral data and magnetochemical measurements, a distorted octahedral structure was proposed.

Two dimeric Pd(II) complexes with Hexacyclen were synthesized ($[Pd_2(Hex)Cl_2](ClO_4)_2$ [35] and $[Pd_2(Hex)Br_2]Br_2 \cdot 4H_2O$ [36]) and their structures were solved by X-ray diffraction analysis (Figs. 2 and 3). Crystallographic data for $[Pd_2(Hex)Br_2]Br_2 \cdot 4H_2O$ showed stacking along the *a* axis and the existence of a channel-type interaction between one of the bromide ions and lattice H_2O molecules [36].

In both cases Hexacyclen acts as a dipodal ligand — it occupies three coordination sites of every Pd^{2+} ion, and at the fourth site halide ion is coordinted. The Pd–Pd distance in both cases is about 3 Å.

Some data (spectroscopic and potentiometric) concerning the formation of mono- and dinuclear Pd(II) complexes with Hexacyclen have also been reported [35(a)]. Both complex species $[Pd(Hex)^{2+}]$ and $[Pd_2(Hex)Cl_2]^{2+}$ are very stable, the logarithms of the corresponding formation constants being 29.2 and 51.8 respec-

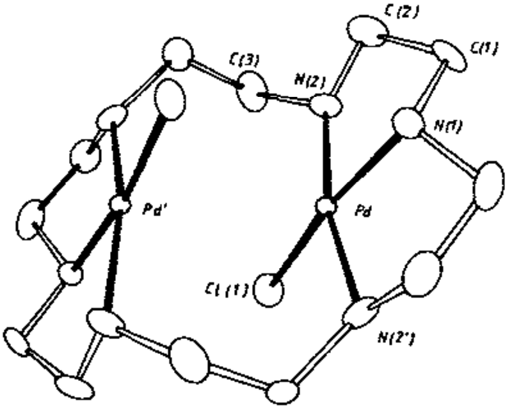


Fig. 2. Molecular structure with the atom-labelling scheme for the complexed cation $[(Pd_2\text{-}[18]aneN_6)Cl_2]$ reproduced by permission from ref. 35(a).

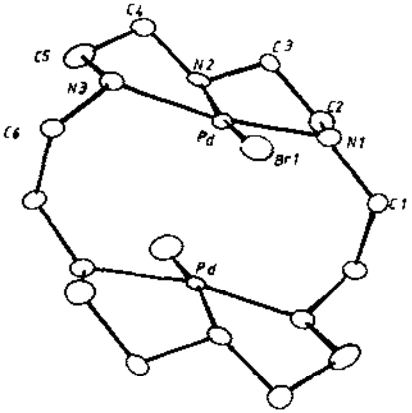
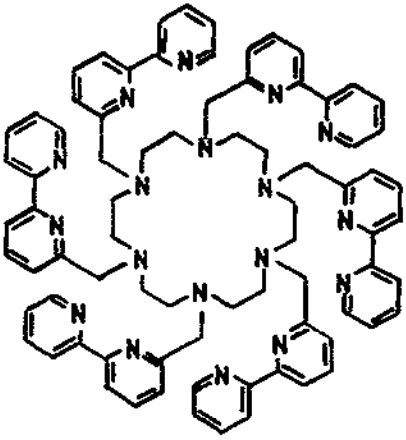


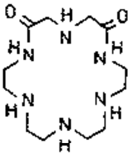
Fig. 3. Molecular structure with the atom-labelling scheme for [Pd_2[18]aneN_6]Br_2^{2+} reproduced by permission from ref. 36.

tively. The extremely high stability constant of the dimeric complex is combined with a marked kinetic inertness towards acid dissociation [35(a)]. Evidence for the inertness of [Pd_2(Hex)Br_2]$^{2+}$ towards oxidative addition of small molecules across the Pd–Pd unit and towards the electrochemical or γ irradiation initiation of reduction or oxidation processes have also been reported [36]. Data concerning the substitution kinetics of the complex with different halide ligands were also presented [36].

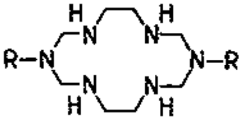
A very brief communication concerning the synthesis of substituted Hexacyclen (XIII) and its ability to form mononuclear, dinuclear or trinuclear transition metal complexes has been published [37]. Some results concerning their potential use as catalysts for multielectronic reactions (water oxidation, CO_2 reduction etc.) were provided [37].



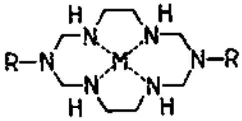
Dioxo[18]aneN_6 (XIV), a ligand combining the coordinative properties both of saturated macrocyclic polyamines and of peptides, has been synthesized and its complexation with the biologically harmful Hg(II) studied by Kodama and Kimura [38]. The data showed that complexation is connected with displacement of one amide proton and formation of a relatively stable ($\log K = 9.64$) complex with a metal-to-ligand ratio $[Hg(H_{-1}L]^+$ of 1:1.



By means of the template condensation of ethylenediamine, formaldehyde and alkylamines in the presence of Ni(II) or Cu(II) salts, the corresponding 14-membered hexaazamacrocycles XV and XVI



were prepared [39(a)]: for $R = CH_3$, 1,8-dimethyl-1,3,6,8,10,13-hexaazacyclotetradecane (XV); for $R = C_2H_5$, 1,8-diethyl-1,3,6,8,10,13-hexaazacyccotetradeycane (XVI). (All attempts to obtain the unsubstituted 14-membered macrocycle XV′ (R = H, 1,3,6,8,10,13-hexaazacyclotetradecane) failed [39(a)]; this was ascribed to the instability of methylenediamine chains containing free secondary nitrogen.) Based on their spectroscopic (electronic, IR, ^1H and ^{13}C NMR) and electrochemical (CV) properties four-coordinate square–planar Ni(II) and Cu(II) complexes are apparently formed, similar to those of tetraaza macrocyclic ligands:

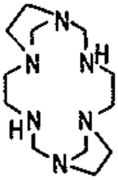


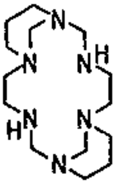
An equilibrium between diamagnetic square–planar and paramagnetic octahedral species of the type

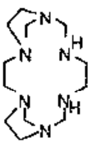
$$[Ni(L)]^{2+} + 2H_2O \overset{K}{\rightleftharpoons} [Ni(L)(H_2O)_2]^{2+} \tag{3}$$

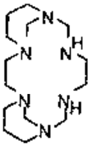
was found to exist in aqueous solutions. Thermodynamic data for the equilibrium are reported. The $\Delta H°$ and $\Delta S°$ values for the square–planar⇄octahedral conversion of Ni(II) complex with XV were found to be much more negative in comparison with those for the Ni(II) complex with XVI.

Ni(II) and Cu(II) complexes with the 14-membered N_6 macrocyclic ligands with diazafused rings (1,3,6,9,11,14-hexaazatricyclo-[$12.2.1.1^{6,9}$]octadecane(A) (XVII), 1,3,6,10,12,15-hexaazatricyclo-[$13.3.1.1^{6,10}$]eicosane(B) (XVIII), 1,3,6,8,11,14-hexaazatricyclo-[$12.2.1.1^{8,11}$]octadecane(A′) (XVII′), 1,3,6,8,12,15-hexaazatricyclo-[$13.3.1.1^{8,12}$]eicosane (B′) (XVIII′)) were obtained (template synthesis) by Suh and co-workers and their structure (Figs. 4–6) and spectroscopic, electrochemical and thermodynamic properties were studied in detail [39(b),39(c)].









The presence of two diazafused rings in the ligand molecules significantly affects their coordination mode. Crystallographic data showed the formation of square–planar structures, similar to those of 14-membered tetraazamacrocyclic ligands. In addition, the spectroscopic properties and the Ni–N bond distances were found to be significantly affected by small-ring moieties fused to the macrocycle although the same macrocyclic frameworks were retained.

Thermodynamic and electrochemical (CV) data obtained for both Ni(II) complexes showed that the macrocyclic cavity of the B′ ligand is more flexible than that of the A′ ligand [39(c)].

A recent paper [39(d)] reported the preparation of Ni(I) complexes with the 14-membered N_6 macrocycles with diazafused rings (XVII, XVIII) by Na(Hg) reduction of the corresponding Ni(II) complexes in nitrogen atmosphere (solvent, acetonitrile). The oxidation state +1 was proven by means of electronic and EPR spectroscopic data. The ClO_4^- salt of the Ni(I) complex with XVII′ was obtained as single crystals and its structure solved by X-ray diffraction. The four-coordinate complexes obtained exhibited anisotropic axial $g_{\parallel}$ and $g_{\perp}$ values or rhombic g_1, g_2 and g_3 values. X-ray data showed square–planar geometry for the complex and a set of two Ni–N distances similar to those of many other Ni(I) complexes [39(d)].

The extraction properties of Hexacyclen towards different metal ions (more than 15) were studied [40]. The ions Ag(I), Hg(II), Cu(II), Pt(II) and Pd(II) can be quantitatively extracted and separated from Fe(III) and some other metal ions.

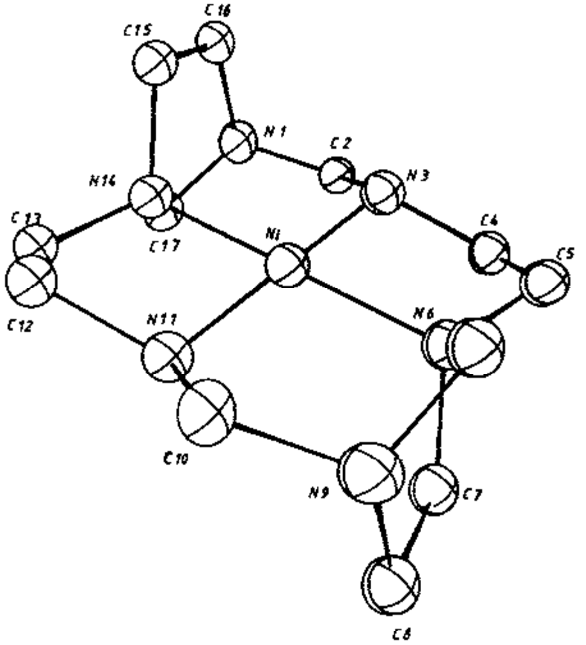


Fig. 4. Molecular structure of the cation of $[Ni(A)]Cl_2 \cdot 2H_2O$ with the atomic numbering scheme, reproduced with permission from ref. 39(b).

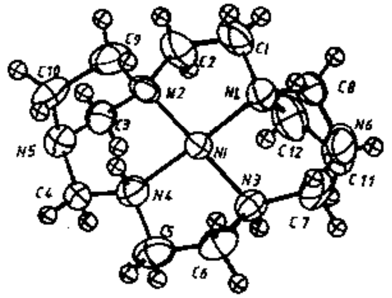


Fig. 5. Molecular structure and the atomic labelling scheme for $[NiA](ClO_4)_2$ reproduced by permission from ref. 39(c).

2.2. Metal complexes of saturated macrocyclic ligands with a greater cavity

Only a few metal complexes with such ligands have been studied [36,41–45]. The most interesting feature of these macrocycles is their capability to form polynuclear complexes.

A dinuclear Pd(II) complex was synthesized with $[20]aneN_6$ (II) and its structure solved by X-ray diffraction analysis [36] (Fig. 7). In a similar fashion to the corresponding dinuclear complex with Hexacyclen, each palladium ion is

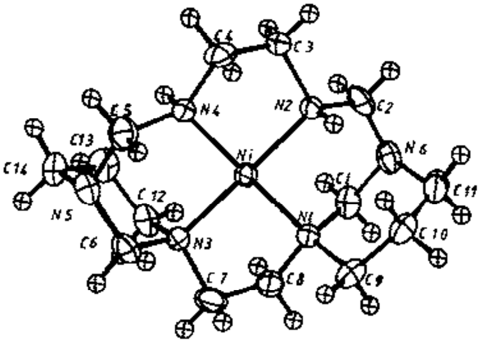


Fig. 6. Molecular structure and the atomic labelling scheme for $[NiB](ClO_4)_2 \cdot 1/2H_2O$ reproduced by permission from ref. 39(c).

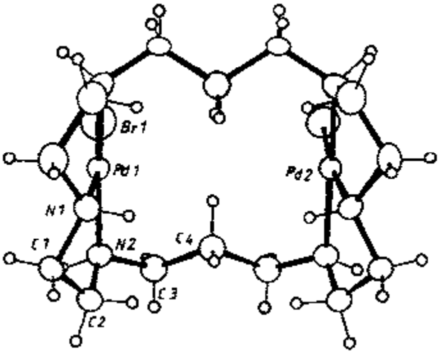
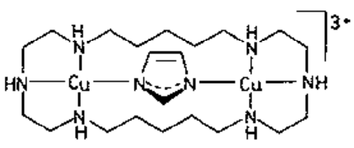


Fig. 7. Molecular structure and the atom-labelling scheme for the $Pd_2([20]aneN_6) \cdot Br_2^{2+}$ cation reproduced by permission from ref. 36.

coordinated to three N atoms of the ligand, the fourth coordination site being occupied by Br^-. The crystallographic data showed the Pd–Pd distance between the Pd_2 units as being 4.601 Å [36].

Dinuclear Cu(II) complexes with a series of N_6 macrocycles are also known [41–43]. Coughlin and co-workers obtained imidazolate-bridged dicopper(II) complexes with 1,4,7,13,16,19-hexaazacyclotetracosane ($[24]aneN_6$) (IV) and studied its structure, magnetochemcial, EPR and thermodynamic properties [41–43]. The thermodynamic data obtained have shown on a high stability of the dicopper(II) complex (XIX) formed [41,43].

The crystal structure by an analogous complex with two methylimidazole molecules coordinated to each Cu(II) centre was solved by X-ray analysis [42] (Fig. 8). The data confirmed the insertion of the imidazolate-bridged dicopper core into the macrocycle cavity, resulting in formation of distorted trigonal bipyramidal geometry (coordination number 5) for both Cu(II) centres [42].



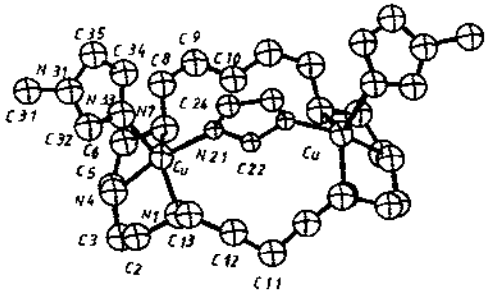


Fig. 8. Molecular structure and the atom-labelling scheme for $[Cu_2(im)(Meim)_2L]^{3+}$ (L = 1,4,7,13,16,19-hexaazacyclotetracosane, im ≡ imidazole, Meim ≡ methylimidazole), reproduced by permission from ref. 42.

The preparation, spectroscopic (UV-visible, EPR) properties and crystal structure of a dicopper(II) complex with 1,5,9,13,17,21-hexaazacyclotetracosane ([24]aneN_6) (VII) have also been reported (Fig. 9) [44]. This dinuclear complex is not stabilized by bridging ligands. The two Cu(II) ions lie in the macrocyclic ligand cavity with square-pyramidal coordination. The square base is described by two N atoms and two bromide ligands, the third N atom defining the apical position [44]. The ligand itself was formed as a byproduct in the synthesis of [12]ane$N_3 \cdot 3HBr$.

The complexation of Cu(II) with 1,4,7,12,15,18-hexaazacyclododecosane ([22]aneN_6) (III) and 1,4,7,14,17,20-hexaazacyclohexacosane ([26]aneN_6) (V) was studied potentiometrically, and together with the mononuclear species, three other dinuclear complexes are formed [45]. On the basis of EPR and electrochemical data the complex of [22]aneN_6 is described as a very stable hydroxo-bridged dinuclear

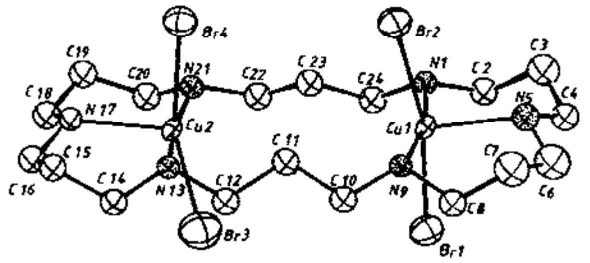


Fig. 9. Molecular structure and the atom-labelling scheme for $Cu_2([24]aneN_6)Br_4$, reproduced by permission from ref. 44.

species. On the contrary no bridged Cu^{2+}–Cu^{2+} unit exists in the [26]aneN_6 dinuclear complex as the macrocyclic cavity is much larger.

Recently the interaction of silica-gel-bound N_6 polyazamacrocycle with different cations was studied [46] and the results showed that in general the size-based selectivity is enhanced by the attachment to a solid support via a donor atom, *e.g.* it introduces some degree of rigidity to the otherwise rather flexible Hexacyclen molecule.

2.3. Coordination properties of saturated polyazamacrocycles towards anions (host–guest chemistry)

During the last decade coordination of anions by crown ethers has been of current interest [47–49] due mostly to the biological significance of this process. Earlier data have already been thoroughly summarized [10,47] and for that reason they will only be briefly overviewed.

The stepwise protonation of saturated hexaazamacrocyclic ligands has been studied in depth [10,16,47,50,51] with results summarized by Bianchi *et al.* [10].

With respect to their basicity the saturated N_6 macrocyclic ligands (similarly to N_4 macrocycles) may be divided into two groups: conformationally-restrained macrocyclic systems [16] containing only $-CH_2-CH_2-$ chains, *e.g.* [18]aneN_6 (they exhibit the highest N-basicity constants for the first three protons and rather low constants for the fourth, fifth and sixth protons [10,47]; this grouping of constants is explained by electrostatic repulsion between the positively charged NH_2 groups in the macrocycle [10] and with H bonding between NH_2^+ and the neighbouring N atom [52] (Fig. 10); and conformationally non-restrained macrocyclic systems containing $-CH_2-CH_2-CH_2-$ groups, *e.g.* [24]aneN_6, exhibiting protonation characteristics of linear polyamines [47].

The newly synthesized 1,4,7,13-tetramethyl-1,4,7,10,13,16-hexaazacyclooctadecane (I′) [51(b)] behaves as a tetraprotic base in contrast to Hexacyclen, which forms an appreciable amount of the fully protonated species H_6L^{6+} [10]. In the octadecane case, similar to Hexacyclen, a sharp decrease is observed in basicity

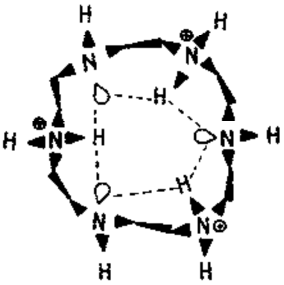


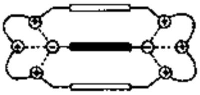
Fig. 10. Proposed conformation and hydrogen-bonding for Hexacyclen in the triprotonated form.

between the third and fourth stepwise protonation constants. On the other hand methylation of the nitrogen atoms leads to a lowering of basicity at each protonation step.

Using an in-depth NMR study (^{1}H and ^{13}C NMR together with two-dimensional (2D) ^{1}H–^{1}H COSY and ^{1}H–^{13}C HETCORR experiments) an order for protonation of the different N atoms has been suggested.

The polyprotonated N_6 macrocyclic systems proved to be excellent receptors for simple anions (Cl^-, SO_4^{2-}, ClO_4^-, CO_3^{2-} etc.) [10,47,53–57], complex anions ($M(CN)_6^{n-}$) [10,49,58,59], carboxylate anions [10,47,60–63], nucleotide anions (AMP^{2-}, ADP^{3-}, ATP^{4-}) [10,47,61,64,65] and catechol [47,66], the last being of great biological importance. Kimura and co-workers have proposed structures for the 1:1 complexes of Hexacyclen with HPO_4^{2-}, ATP and catechol [47,64,66].

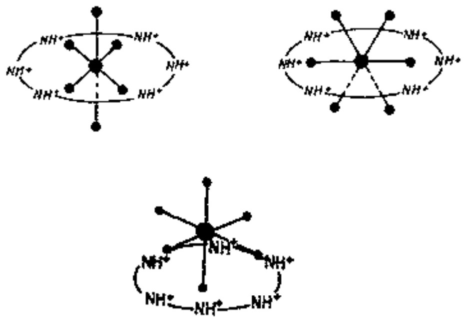
In this respect Hosseini and Lehn [62,63] observed a remarkable linear molecular recognition process to proceed between the fully protonated forms of 1,5,9,17,21,25-hexaazacyclodotriacontane ([32]aneN_6) (VIII) and 1,5,9,20,24,28-hexaazacyclooctatriacontane ([38]aneN_6) (IX) as well as of a tetraprotonated form of 1,4,7,17,20,23-hexaazacyclodotriacontane ([32]aneN_6) (VI) (the latter being ditopic receptors) with dicarboxylate substrates $^-OOC–R–COO^-$ including amino acids and dipeptide dicarboxylates of biological importance.



Several features of the ditopic coreceptors should be mentioned: the existence of the protonated forms mentioned above in the neutral pH range; the strong complex formation with dicarboxylate anions in aqueous solution (the most stable complexes are those of the hexaprotonated forms, thereby indicating predominant electrostatic interactions); remarkable complexation selectivity (both the high stability and selectivity result from incorporation of two binding centres in the macrocycle on one side and the best fit between the dicarboxylate length and site separation of the receptor); a pronounced macrocyclic effect on both the stability and selectivity of binding.

Some data concerning the catalytic properties of protonated N_6 macrocyclic polyamines [67,68] and photochemical behaviour of ion pairs containing $M(CN)_6^{n-}$ and protonated N_6 macrocycle [69] were also reported. The interaction of the $M(CN)_6^{n-}$ (M = Fe(II), Fe(III), Co(III)) species with some protonated hexaazamacrocycles (VI–IX) is assumed in fact to be complexation in the second coordination sphere, *i.e.* formation of supramolecular species (XX) (incorporation of $Co(CN)_6^{3-}$ into a protonated N_6 macrocycle).

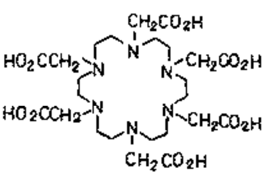
In a recent paper, Hosseini [49] reviewed the thermodynamic properties, electrochemical and photochemical reactivity of these supramolecular complexes. It

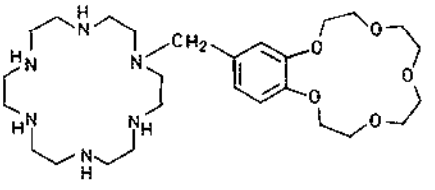


was shown that: (i) the redox properties of the supermolecular complexes are strongly affected by both the structure of the macrocyclic molecule and its degree of protonation; (ii) the supermolecular formation resulted in stabilization of the lower oxidation state (+2); (iii) the magnitude of the redox potential shifts due to complexation depends more strongly on the macrocycle structure than on the nature of the central metal ion; (iv) the supermolecular formation resulted in specific modification of the photoactivity of the M(CN)$_6^{n+}$ species.

Recently Santos and Drew [70] reported a theoretical study of the Hexacyclen steric structure and its interaction with neutral and anionic species resulting in formation of 1: host–guest complexes. Applying molecular mechanics and semiempirical quantum mechanical methods they calculated the possible conformations of the Hexacyclen molecule, its triprotonated form and the structure of ion pairs of $H_3[[18]aneN_6]^3$ with CO_3^{2-}, H_4SiO_4 and H_3BO_3. The intermolecular H bonding was considered to be the driving force for ion pairing. The heats of formation, atomic charge distribution and binding energies were given.

Kimura [47] has studied the dissolution of $Ca_3(PO_4)_2$ with Hexacyclen at 37°C in a neutral medium (pH 7), a model for Calculi dissolution. At the same time a Hexacyclen derivative, namely [18]aneN$_6$-hexaacetic acid (XXI) was designed to combine the anion-binding properties of [18]aneN$_6$ with the cation complexation ability of ethylenediaminetetraacetic acid and tested as a litholytic agent [47]. Some speculations on the mechanism of the process *in vitro* were also reported.

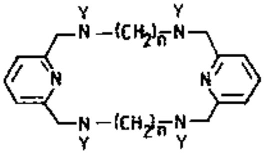




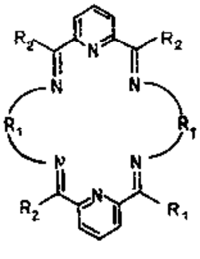
A ditopic receptor molecule containing benzo-15-crown-5 and Hexacyclen (XXII) was synthesized [71] and its ability to form stable 1 : 1 complexes with amino acids, peptides and dopamine was studied. It was assumed that the amino acids and peptides participate as zwitterionic molecules, the anionic carboxylate being coordinated to the protonated Hexacyclene moiety and the primary ammonium cation to the crown ether. A scheme for dopamine binding was also proposed. This supposition is supported by the fact that the dopamine interaction with this ditopic receptor is much stronger than that of dopamine with [18]ane$N_6 \cdot 3H^+$ alone while its interaction with the monotopic guest catechol (with the [18]ane$N_6 \cdot 3H^+$ moiety) is not enhanced by attachment of the crown ether moiety [71(b)].

3. UNSATURATED N_6 MACROCYCLES

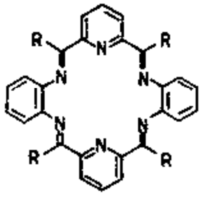
The unsaturated macrocycles can be divided into three groups depending on the degree of unsaturation: (i) macrocycles containing two pyridine rings ($n=2$, $Y=H$ (XXIII); $n=2$, $Y=CH_3$ (XXIII′); $n=4$, $Y=H$ (XXIV); $n=5$, $Y=H$ (XXV));



(ii) macrocyclic Schiff bases containing two pyridine rings ($R_1=CH_2CH_2$: $R_2=CH_3$



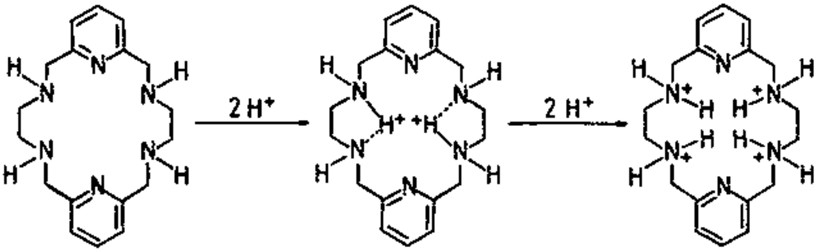
(XXVI); $R_1=CH_2CH_2$: $R_2=H$ (XXVII); $R_1=(CH_2)_3$: $R_2=H$ (XXVIII); $R_1=(CH_2)_4$: $R_2=H$ (XXIX); $R_1=(CH_2)_5$: $R_2=CH_3$ (XXX); $R_1=(CH_2)_6$: $R_2=CH_3$ (XXXI)) and (iii) macrocyclic Schiff bases containing two pyridine and two phenylene rings ($R=CH_3$ (XXXII); $R=H$ (XXXIII)).



3.1. Macrocycles containing two pyridine rings

The partially substituted N_6 macrocycle 3,6,12,15-tetramethyl-18-N(2,6)-pyridino,N-1.2.1|$_2$-corronand-6 (XXIII′) [72] was prepared as a result of non-template synthesis from 2,6-bis(chloromethyl)pyridine treated with *N,N′*-dimethylenediamine (solvent dimethylformamide) in the presence of K_2CO_3 or Cs_2CO_3. It forms octahedral complexes with Cu(II) and Co(II) similar to those of Hexacyclen (Fig. 11). The deviations from regular octahedral stereochemistry are, as usual, greater for the Cu(II) complex. The expected Jahn–Teller effect is observed (equatorial Cu–N bonds average 2.107 Å, axial Cu–N bonds average 2.298 Å).

The unsubstituted macrocycle py$_2$[18]dieneN$_6$ (XXIII) was prepared very recently via $NaBH_4$ reduction of the Ba^{2+} complex of the corresponding macrocyclic Schiff base (XXVI) [72(b)]. By means of potentiometric and ^1H NMR titrations it was shown that only the saturated amine groups are protonated in approximately two proton steps ($\log K_1 = 9.13$; $\log K_2 = 8.32$, $\log K_3 = 6.12$; $\log K_4 = 5.24$). The following scheme (XXXIII′) is proposed.



The potentiometric study of the metal binding properties showed on 1 : 1 metal-to-ligand formation even when the metal ion was in excess. The formation constants follow the order $Ca^{2+} < La^{3+} < Mn^{2+}$ $Cd^{2+} < Cu^{2+} < Zn^{2+}$ similar to the corresponding Hexacyclen complexes. Comparing the formation constants of Hexacyclen and py$_2$[18]dieneN$_6$ complexes mentioned above the partially unsaturated ligand is shown to exhibit excellent coordination properties with the filled-shell Ca^{2+}, Zn^{2+} and La^{3+} ions forming even more stable complexes than those of Hexacyclen.

It is proposed that the smaller ions form octahedral complexes, while the larger ones are planar.

22- and 24-membered hexaaza macrocycles (XXIV, XXV) were also synthesized and their complexation abilities towards metal ions and anions (after protonation) were studied [73]. Earlier, their ability to form dinuclear copper complexes was demonstrated [74]. Some preliminary results concerning their catalytic activity in phosphoryl-transfer processes were also mentioned [73].

The protonation constants of py$_2$[22]dieneN$_6$ (XXIV) [73(b)] are similar to those of py$_2$[18]dieneN$_6$ with only the amine nitrogens protonated ($\log K_1 = 9.1$;

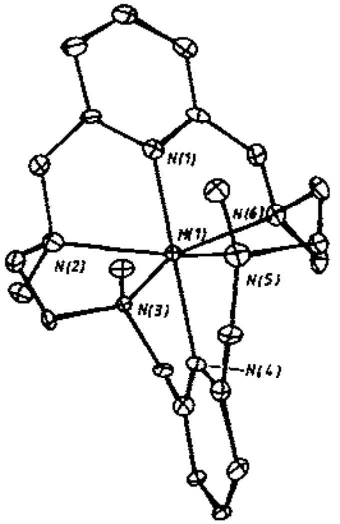


Fig. 11. Molecular structure and the atom-labelling scheme of the Co(II) complex with 3,6,12,15-tetramethyl-18[(2,6)-pyridino,N-1.2.1]$_2$-coronand-6 reproduced by permission from ref. 72.

log $K_2 = 8.3$; log $K_3 = 7.1$; log $K_4 = 3.7$). The ligand forms stable mononuclear complexes with Co(II), Ni(II), Zn(II), Cd(II) and Pb(II) and both mono- and dinuclear complexes with Cu(II) and Ag(I). The corresponding formation constants were determined. The molecular structure of the dinuclear Cu(II) complex ($Cu_2(L)(N_3)_4$) is briefly reported, the Cu–Cu distance being 4.790 Å.

In conclusion the structural data have shown a high degree of ligand flexibility (despite the presence of two pyridine rings) allowing octahedral structure to be realized.

3.2. Macrocyclic Schiff bases containing two pyridine rings

By means of [2+2] template condensation of 2,3-diacetylpyridine or 2,6-pyridinedicarboaldehyde with α and ω primary diamines, metal complexes of N_6 Schiff base macrocycles (XXVI–XXXI) were obtained [75–85]. The syntheses were realized in the presence of template ions, namely the large alkaline earths, Pb^{2+} and lanthanide ions only, resulting in the formation of mononuclear complexes with the 18-membered macrocycle. The Mg^{2+} ion and transition metal ions (Mn^{2+}–Zn^{2+}), Ag^+ and Cd^{2+} were ineffective as templates in the process of [2+2] Schiff base condensation [75,76].

The X-ray data [76,80,82] have shown unambiguously that all six N atoms of the macrocycle are coordinated to the metal ions (Figs. 12–17). In view of the high degree of conjugation realized in the 18-membered N_6 macrocycles, planarity of the

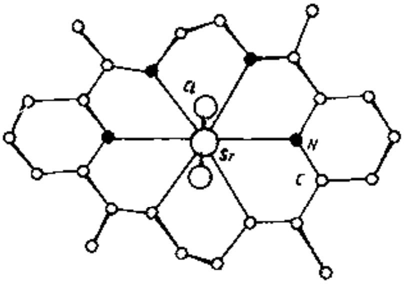


Fig. 12. Molecular structure and atom-labelling scheme for $Sr(L)Cl_2$ (L = XXVI) reproduced by permission from ref. 75.

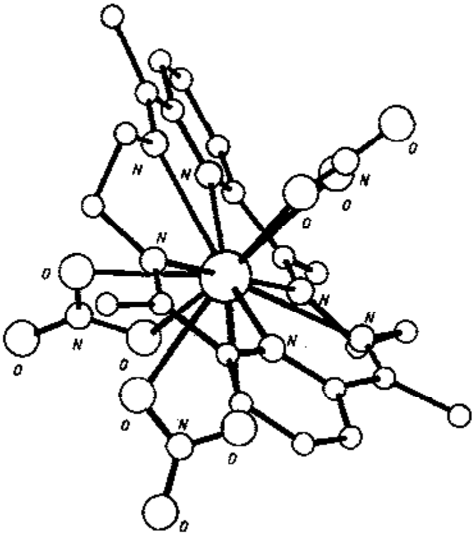


Fig. 13. Molecular structure and atom-labelling scheme for $[La(L)](NO_3)_3$ (L = XXVI) reproduced by permission from ref. 76.

ligand molecule might be expected [78]. The first X-ray data obtained for the Sr^{2+} and Pb^{2+} macrocyclic complexes [75] have indeed shown that the geometry of the ligand molecule might be considered to a first approximation as being nearly planar (Fig. 12). At the same time these results indicated a degree of flexibility allowed by the=N–CH_2–CH_2–N= linkage. However, the complex molecules usually consist of two planar secftions (saddle shape), the interplanar angle depending on the ion dimensions as shown by Arif *et al.* [85] (Figs. 15–17).

The coordination numbers of the lanthanide ion complexes are rather high (greater than 10) (even the unusual coordination number 11 has been observed [85] (Fig. 16)) obtained via coordination of other mono- and bidentate ligands.

Some speculations concerning the mechanism of template synthesis were

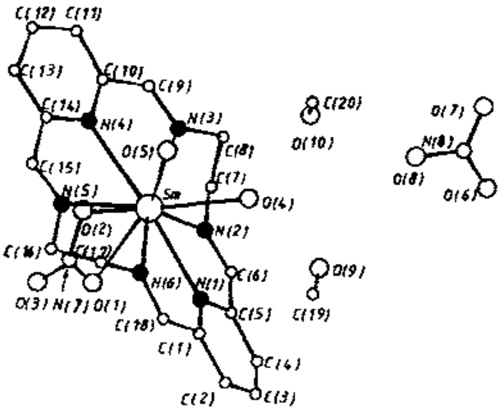


Fig. 14. Molecular structure and atom-labelling scheme for $[Sm(L)(NO_3)(OH)(H_2)]\cdot NO_3\cdot 2CH_3OH$ (L=XXVI), reproduced by permission from ref. 80.

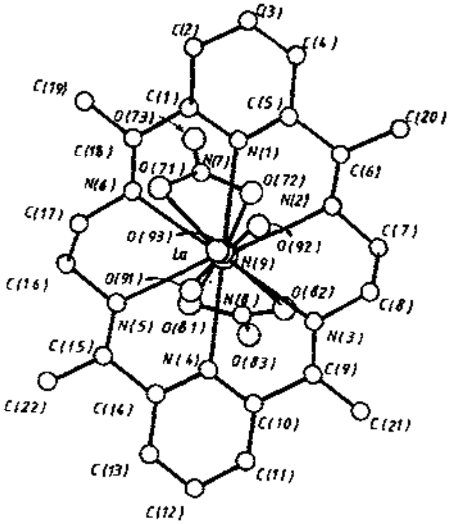
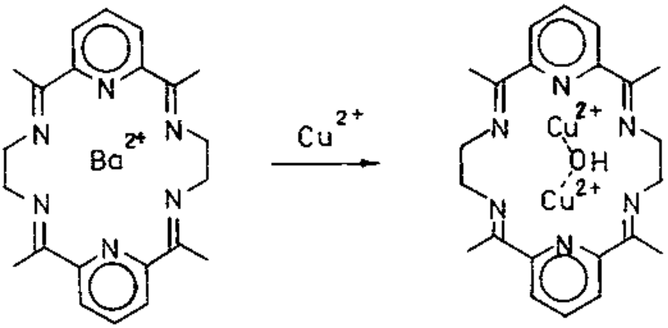


Fig. 15. Molecular structure with atom-labelling scheme for $[La(L)(NO_3)_3]$ (L=XXVI) reproduced by permission from ref. 85.

reported by Nelson [78]. In addition the lanthanide ion complexes formed with 18-membered N_6 macrocyclic Schiff bases are characterized by a unique inertness towards ligand substitution reactions and a remarkable thermal stability (the macrocyclic cavity is stable up to 240°C [83]).

Another very important feature of these complexes is their ability to participate in transmetallization (metal exchange) reactions resulting for example in formation of dinuclear Cu(II) complexes [78,81] according to:



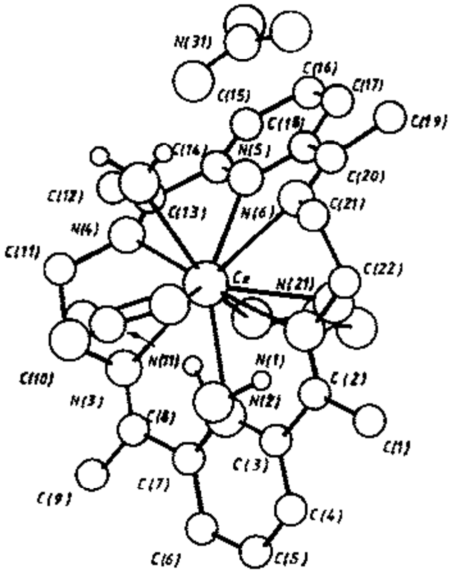


Fig. 16. Molecular structure with atom-labelling scheme for $[Ce(L)(NO_3)_2(H_2O)]NO_3 \cdot H_2O$ (L = XXVI), reproduced by permission from ref. 85.

Drew *et al.* [79] have shown that, depending on the reaction conditions, the 2,6-diacetylpyridine reaction with diethylenetriamine in methanol and in the presence of perchlorate or nitrate salts of alkaline earths ions resulted in formation of two different products: at ambient temperature an open-chain N_7 Schiff base is formed (XXXIV) and at reflux for 1–4 h the cyclic N_6 Schiff base (XXXV) could be obtained. In the case of the first [1+2] condensation reaction all alkaline earths ions were effective template ions, while in the "high temperature" [2+2] condensation resulting in formation of the macrocycle (XXXV) Ba^{2+}, Sr^2 and Ca^{2+} were effective template ions Mg^{2+} is ineffective.

The X-ray structure of this Ba^{2+} complex (Fig. 18) shows planarity of the N_6

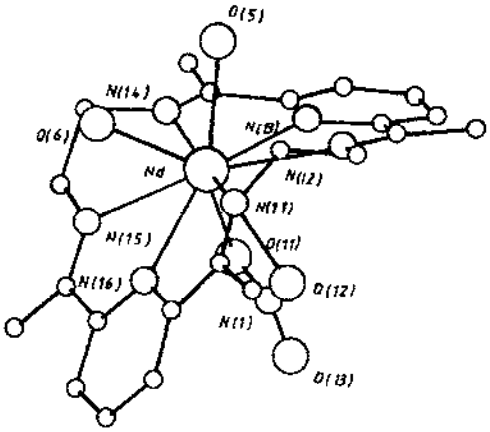


Fig. 17. Molecular structure with atom-labelling scheme for the $[Nd(L)(NO_3)(H_2O)]^{2+}$ ion (L = XXVI), reproduced by permission from ref. 85.

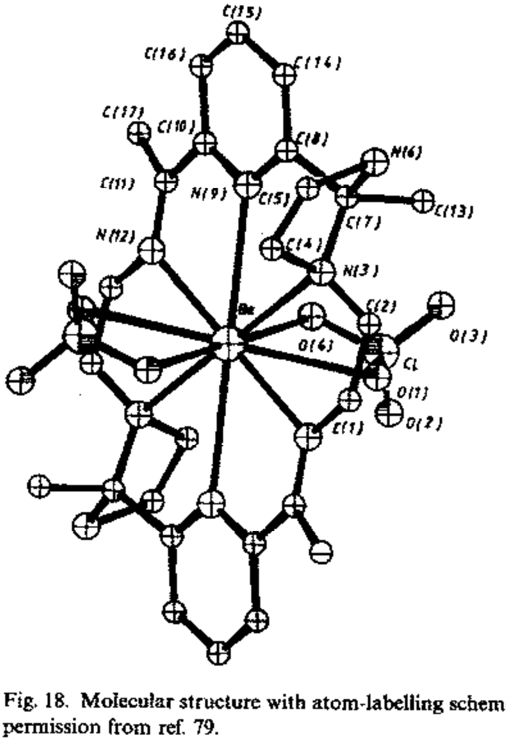
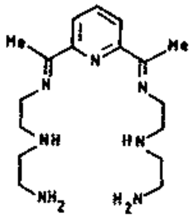
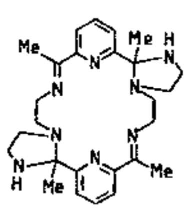


Fig. 18. Molecular structure with atom-labelling scheme for $[Ba(L)(ClO_4)_2]$ (L = XXXV), reproduced by permission from ref. 79.

ring system, with only the imidazoline rings and $-CH_3$ groups being out of plane.

The complexes with the open-chained ligand are intermediates in the formation of the macrocyclic complexes with the 18-membered cycle (XXXV) [72].





The ability of this type of macrocycle to participate in a reversible ring expansion–contraction process [18]⇄[24] was experimentally proven [79]. Treatment of the Sr^{2+} complex with $AgClO_4$ or $Cu(ClO_4)_2$ led to the corresponding dinuclear complexes of the N_8 macrocycle [79].

Mononuclear complexes of the lanthanide group ions with the larger 20-membered Schiff base macrocycle (XXVIII) were all obtained by a template condensation [81]. All lanthanide ions serve as template agents, most probably because an increased flexibility of the macorcycle as an extended bridge unit ($-CH_2-CH_2-CH_2-$ instead of $-CH_2-CH_2-$) is present in this molecule.

In contrast, with the smaller Cu(II) ion a hydroxo-bridged dicopper(II) complex is formed [81(b)] and its electrochemical (CV) characteristics were studied. In a recent paper some observations on the formation of a mononuclear Mn(II) complex with the same ligand and its ability to accommodate two manganese ions in higher oxidation states are reported very briefly [81(c)].

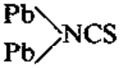
The preparation and structure of a dimeric Mn^{2+} complex with the 22-membered Schiff base macrocycle (XXIX) was also reported [81(c)]. The complex $(Mn_2(L)(NCS)_4)$ (L≡XXIX) (NCS≡CNS≡thiocyanate) was obtained as a result of transmetallization reaction from the corresponding Ba^{2+} complex (synthesized from diformylpyridine and 1,3-diaminobutane on a Ba^{2+} template in excess of NCS^- ions. On the basis of IR data two of the thiocyanate ions serve as bridging ligands, rather surprisingly with the N atom only (1,1-NCS), the other two being terminal.

The crystal structure of the thiocyanato methoxo-bridged dimeric complex $Mn_2(L)(NCS)_3(OCH_3)$ [81(c)] confirmed the pariticipation of bridging NCS^- through only the nitrogen atom. The two Mn^{2+} ions are crystallographically equivalent and are six coordinate (to three N atoms from the macrocycle, one terminal NCS^- and to the bridging NCS^- and OCH_3 groups). The Mn–Mn distance is long enough (3.418 Å) so that no magnetic interaction could be observed. The macrocyclic molecule is folded allowing all six N atoms to be coordinated.

The same authors [81(c)] reported some preliminary results concerning the preparation and magnetic properties of another dimeric Mn(III) complex with the same ligand ($[Mn_2(L)(OCH_3)_4]\,[Mn(NCS)_4]$).

Larger N_6 macrocyclic 24- and 26-membered Schiff bases (XXX, XXXI) were also prepared by template condensation of 2,6-diacetylpyridine and

1,5-diaminohexane or 1,6-diaminoheptane respectively in the presence of $Pb(CNS)_2$ [84]. These N_6 macrocyclic Schiff bases were binucleating ligands. X-ray analysis of the dimeric Pb(II) complex with XXX showed that NCS– again serves as bridging ligand with the N atom only, forming



$$\begin{matrix}\text{Pb}\\ \text{Pb}\end{matrix}\!>\!\text{NCS}$$

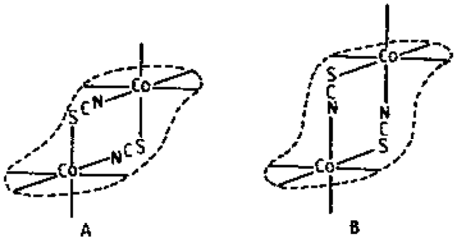
linkage (Fig. 19). It is evident that both Pb(II) ions are four coordinate, every PbN_3 moiety being planar. In this case too the macrocyclic molecule is folded similarly to the 22-membered macrocycle XXIX as in the dimeric Mn(II) complex [81(c)].

The other dinuclear Pb(II) complex with the larger cavity ligand (XXXI) most likely possesses only a weakly N-bonded bridge [84].

By means of transmetallization reactions homodinuclear complexes of Co(II) with the same ligands (XXX, XXXI) were obtained as well as heterodinuclear ones (Pb″–Mn″; Pb″–Ni″; Pb″–Fe″) with the 24-membered macrocycle (XXX) [84].

The formation of the heterodinuclear complexes was proven by means of fast-atom bombardment mass spectra.

In contrast to the dimeric Pb(II) complex, in these cases the NCS^- ions are acting as normal –NCS– bridges proven by means of IR, molecular mechanics calculation and X-ray data ($PbMn(L)(NCS)_4$; L = XXX). Evidently for these complexes of metal ions with lower dimensions the 24- and 26-membered macrocyclic cavity is capable of accommodating them with normal –NCS– bridging. For the Co″–Co″ complex two possible forms of the bridge (equatorial (A) and axial (B))



are accepted (XXXV′) the first being preferred for the complex with smaller cavity (XXX) and the second for that with the greater cavity (XXXI).

Magnetochemical and EPR investigations performed on the dicobalt(II) and dicopper(II) complexes showed some peculiarities: the realization of a spin cross-over complex of dicobalt(II) with the smaller macrocycle (XXX) (a low spin complex below 83 K and a high spin complex at temperatures above 83 K); the realization of six-coordinate high spin dicobalt(II) complexes with the larger macrocycle (XXX) (its geometry is equatorially compressed tetragonal); the presence of a weak anti-ferromagnetic interaction in the dicopper(II) complex with the smaller macrocycle

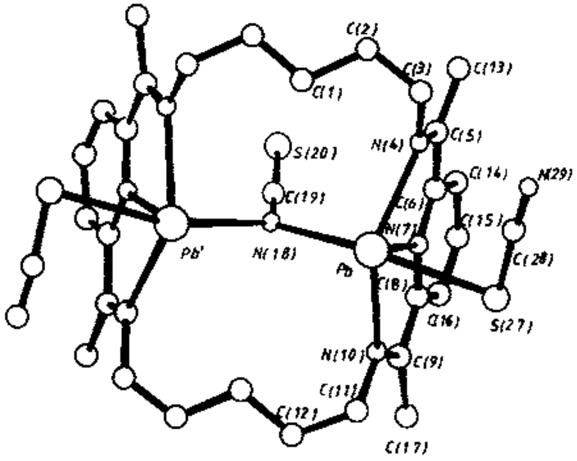


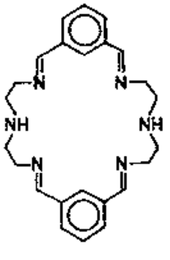
Fig. 19. Molecular structure with atom-labelling scheme for $[Pb_2L(NCS)_3]^+$ (L = XXX) reproduced from ref. 84.

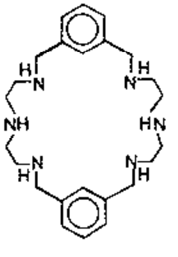
(XXX) and the absence of any in the analogous complex with the greater macrocycle (XXXI).

Recently the catalytic behaviour of the lanthanide ion (Sa^{3+}, Eu^{3+}, Gd^{3+}, Tb^{3+}, Lu^{3+}) complexes of XXVI in the ribose nucleic acid transesterification process (pH 7; T = 37°C) was demonstrated [86], the Eu^{3+} complex being one of the most effective catalysts.

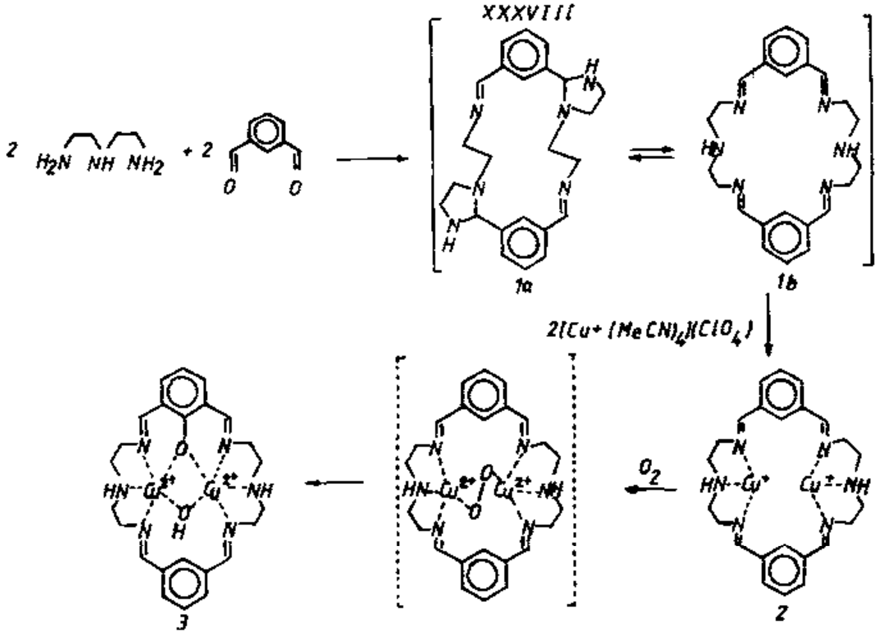
In connection with recent studies on the tyrosynase model system, another 24-membered unsaturated N_6 macrocycle (XXXVI) was obtained [87,88] as well as its reduced form (XXXVII) [88]. The unsaturated N_6 macrocycle containing two benzene rings (which might also be considered as a macrocyclic tetra Schiff base) was obtained in high yield by a 2:2 dipodal condensation of *m*-phthalaldehyde and diethylenetetramine [88]. The saturated macrocycle was obtained by reduction thereof with $NaBH_4$ [88].

Using X-ray diffraction analysis it was shown that the condensation reaction results in the formation of two isomers of the 18-membered macrocycle (1a) (XXXVIII) (Fig. 20). Addition of Cu(I) complex under anaerobic conditions leads





to formation of a dinuclear copper(I) insertion complex of the 24-membered macrocycle (XXXVIII, 2) thus causing ring expansion. In the presence of oxygen one of the benzene rings is hydroxylated accompanied with oxidation of both Cu(I) ions. The formation of the dinuclear Cu(II) complex (3) was proven by means of ^1H NMR spectroscopic and mass spectral data. In replacing Cu(I) with $Co(ClO_4)_2$, no complex formation was observed [88].



The experimental data above show that, although the unsaturated N_6 macrocycles of this type (tetra Schiff bases) might be obtained as a result of non-template reactions, they are stabilized as N_6 macrocycles by complexation with metal ions.

Potentiometric studies of the complexation of Cu(II) with the saturated N_6 macrocycle XXVII were performed [88]. Both mono- and dinuclear complexes are formed.

3.3. Macrocyclic Schiff bases containing two pyridine and two phenylene rings

The template condensation of 2,6-diacetylpyridine or 2,6-diformylpyridine with *o*-phenylenediamine again resulted in formation of 18-membered conjugated N_6 macrocyclic Schiff bases (XXXII, XXXIII) [78,89–96]. In these cases Ca^{2+}, Sr^{2+}, Ba^{2+}, La^{2+} and Pb^{2+} serve as templating agents (XXXVIII′) in contrast to Mg^{2+} and first-row transition metal ions, which are too small to be bonded to all six nitrogen atoms.

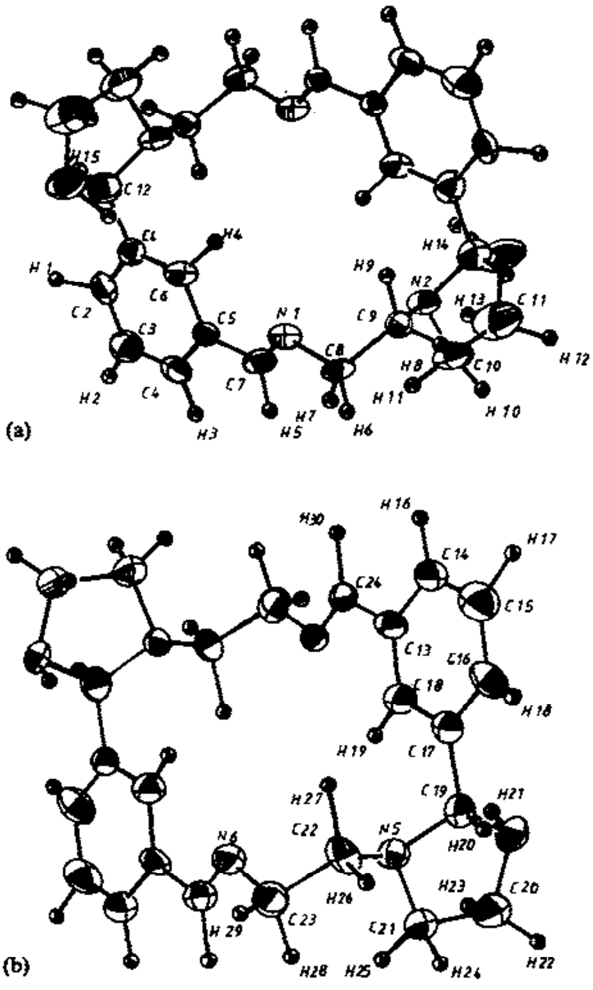
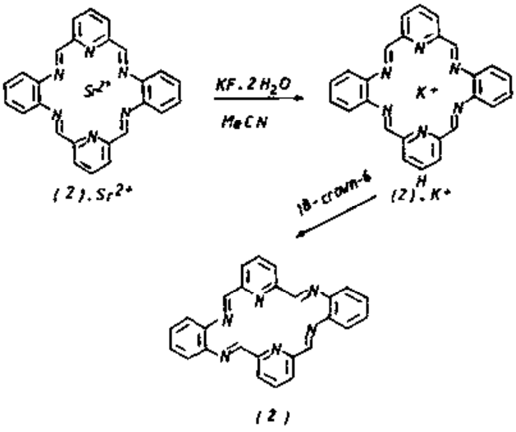


Fig. 20. Structural views of molecules A (top) and B (bottom) together with the atom-labelling scheme of the 18-membered macrocycle XXXVIII reproduced from ref. 88.

Earlier a brief communication was published [89] about the synthesis of the free macrocyclic ligand (XXXII) (condensation of 2,6-diacetyl pyridine and *o*-phenylenediamine in the presence of catalytic amounts of sulphuric acid (without template ions) and its ability to accommodate two Cu(II) ions.

A theoretical study on the geometry of this macrocycle was performed (before its synthesis) [97] predicting a cavity radius of 2.8 Å and the fact that only large metal ions will be accommodated in the cavity without causing considerable distortions from its D_{6h} symmetry. Later, X-ray structural data confirmed in general these predictions. The crystal data showed that the bond lengths vary from 2.65 to 2.85 Å for Pb–N [90] and Sr–N [96] (Figs. 21 and 22). Two different molecules (A and



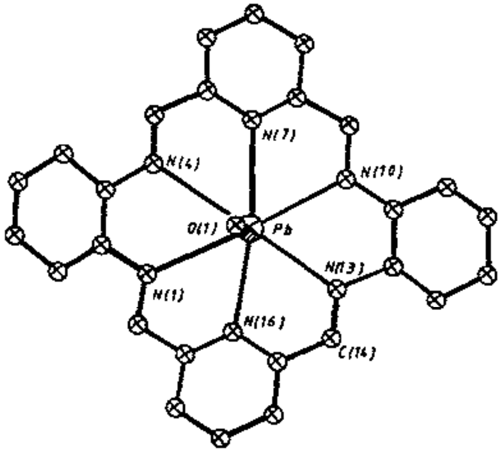


Fig. 21. Molecular structure with atom-labelling scheme for $[Pb(L)(H_2O)]^{2+}$ (L = XXXIII) reproduced from ref. 90.

B) of $Sr(L)(CF_3SO_3)_2$ (L = XXXIII) were obtained (Fig. 21) differing slightly in their coordination spheres. In both the metal ion is bonded to all six N atoms; the Sr–N bonds, however; differ in length (2.65–2.82 Å in molecule A and 2.73–2.76 Å in molecule B). In both cases the Sr^{2+} is nine coordinate, but in molecule A it is bonded to two triflate anions, one via two oxygen atoms and the other through an oxygen atom only. In molecule B the two triflate ions are bonded to Sr^{2+} via one oxygen atom and a water molecule is also coordinated.

Despite the rigidity of the macrocycle molecule in the complexes it is not strictly planar, but saddle shaped, the four imino N atoms forming a plane with the metal ion disposed on one side of the plane and the two pyridine nitrogen atoms on the other. In all cases the coordination number is greater than 6.

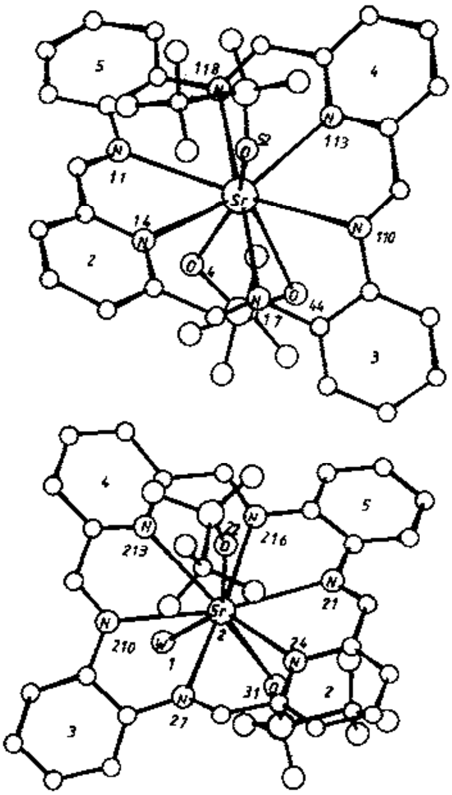


Fig. 22. Molecular structures with atom- and ring-labelling scheme for molecules A (top) and B (bottom) of $Sr(L)(CF_3SO_3)_2$ (L = XXXIII) reproduced from ref. 96.

Two peculiarities should be noted: (a) the sandwich-type structure of the Ba^{2+} complex (coordination of two macrocyclic ligands) with coordination number 12 [90] (most probably because of its greater dimensions, Ba^{2+} cannot be accommodated in the fixed cavity of the rigid macrocycle); (b) parallel formation of two complex molecules of Sr^{2+} with slightly different coordination spheres (Fig. 22).

Bell and Guzzo [94] succeeded in obtaining the free ligand (XXXIII) and have studied its structure using X-ray diffraction analysis. The experimental data show a significant difference in the structure of the free ligand (Fig. 23) and the complexed macrocycle. The conformation of the free macrocycle might be approximated as elliptical, while the complexed one is circular. Thus complexation of the free ligand is accompanied with a conformational change.

In addition to template ion (Ca^{2+}, Sr^{2+}, Pb^{2+}) complexes Cd^{2+}, K^+ and Na^+ complexes were also synthesized by means of transmetallalization reactions [90,96]. The first was obtained by treatment of the Ba^{2+} complex with Cd^{2+}, while the K^+ and Na^+ complexes were obtained by treatment of the Sr^{2+} complex with KF or

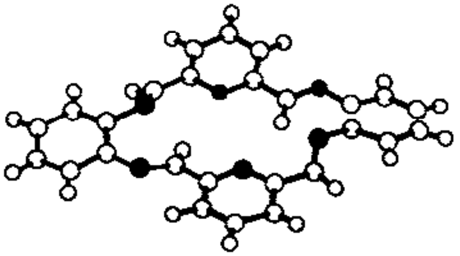
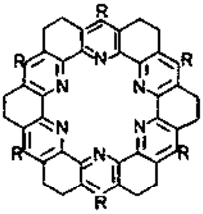


Fig. 23. Molecular structure of the free fully unsaturated macrocycle XXXIII reproduced by permission from ref. 94.

$NaCF_3SO_3$ respectively [92,94–96]. X-ray data for the Cd^{2+} complex [90] showed that it is isostructural with the Pb^{2+} complex.

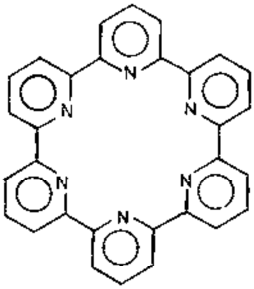
A general scheme for the sequential synthesis of the Sr^{2+} and K^+ complexes, and the free ligand was proposed by Bell and Guzzo [94]. On the basis of ^1H NMR data the stability constants of K^+ and Na^+ complexes were also evaluated [94].

Recently Bell *et al.* [98] have synthesized Na^+ and K^+ complexes with tri-*n*-butyl torand (XXXIX). The ^1H NMR data indicate stronger binding of Na^+ and K^+ trifluoromethanesulphonate with this planar "open-face" ligand than with encapsulating macrocycles such as [2.2.1]- and [2.2.2]-cryptands.



The corresponding stability constants were also evaluated.

Another hexaazamacrocycle (XL) (Sexipyridine) has been obtained [99] as a result of a five-step synthesis in the absence of a template ion, but to the best of our knowledge no data concerning its coordination ability have been reported.



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