Synthesis of the Cage Penta-azamacrobicycloalkane 12,17-Dimethyl-1,5,9,12,17-penta-azabicyclo[7.5.5]nonadecane, its Basicity, and Metal Complex Formation. Crystal Structure of the Copper(II) Perchlorate Complex†

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The synthesis and characterisation of the new penta-azamacrobicycloalkane 12,17-dimethyl-1,5,9,12,17-penta-azabicyclo[7.5.5]nonadecane (L) are described. Its basicity in aqueous solution has been investigated by potentiometric and spectroscopic (^1H, ^{13}C n.m.r.) techniques. The macrocycle L can take up three protons. It behaves as a very strong base (proton sponge) in the first protonation step, as a moderate base in the second step ($\log K_2 = 8.41$), and as very weak base in the last step ($\log K_3 < 2$). The ^1H n.m.r. spectrum of the monoprotonated species HL^+ in CD_3CN shows a broad signal attributable to two deshielded NH protons, which are rapidly exchanged with acidic hydrogens on the n.m.r. time-scale. pH–^{13}C N.m.r. studies have been carried out and a tentative structure for HL^+, in accord with the n.m.r. features, is proposed. A number of metal ions were tested for complex formation with L. According to ^{13}C n.m.r. spectroscopy, there was no evidence of metal co-ordination with Na^+, K^+, Be^{2+}, and Al^{3+}, whereas some weak interaction occurs for Mg^{2+}. A lithium complex is formed at high pH. With the other metal ions, solid complexes were isolated from the reaction of the appropriate metal perchlorate and [HL]Br in boiling methanol. The molecular structure of the complex $[CuL][ClO_4]_2 \cdot H_2O$ has been determined by single-crystal *X*-ray analysis. The compound crystallises in an orthorhombic unit cell (space group $P2_12_12_1$) with lattice constants $a = 17.332(5)$, $b = 15.448(5)$, $c = 9.066(4)$ Å, with $Z = 4$. Least-squares refinement converged at $R = 0.058$ for 1 865 observed reflections. The copper ion is wholly enclosed by the macrobicycle and is five-co-ordinated. The co-ordination geometry is a distorted square pyramid with the secondary nitrogen atom in the apical position. The electronic spectra of the copper, cobalt, and nickel complexes show essentially the same features in the solid state and in solution, and are diagnostic of a distorted square-pyramidal structure.

Diazamacrobicycloalkanes with nitrogen bridgehead atoms have been much studied from the conformational, protonation, and redox points of view.[1,2] Particular interest has been devoted to their polyoxa and polythia derivatives (cryptands).[3,4] Surprisingly, their polyaza derivatives, containing only nitrogen donor atoms, have been much less investigated. To date the only one extensively studied is 1,3,6,8,10,13,16,19-octa-azabicyclo[6.6.6]eicosane (sepulchrate) which, however, has been so far obtained by metal-template synthesis and only as its metal complexes.[5] We report the non-template synthesis of the new penta-azamacrobicycle 12,17-dimethyl-1,5,9,12,17-penta-azabicyclo[7.5.5]nonadecane (L) and a study of both its basicity and metal complex formation.

Experimental

Synthesis of the Derivatives of 12,17-*Dimethyl*-1,5,9,12,17-*penta-azabicyclo*[7.5.5]*nonadecane* (L) (*Scheme*).—(*a*) *Bis*(3-*tosyloxypropyl*)*tosylamine* (**2**). Bis(3-hydroxypropyl)amine was treated with toluene-*p*-sulphonyl chloride in dichloromethane according to the general procedure of Crossland and Servis.[6] Yield *ca.* 45% based on amine; m.p. 79—80 °C (Found: C, 54.4; H, 5.5; N, 2.5. Calc. for $C_{27}H_{33}N_3O_8S_3$: C, 54.4; H, 5.6; N, 2.4%).

(*b*) 12,17-*Dimethyl*-5-*tosyl*-1,5,9,12,17-*penta-azabicyclo*[7.5.5]*nonadecane* (**3**). Finely powdered sodium carbonate (1.40 g, 13 mmol) was added to a solution of compounds (**1**)[7] (2.0 g, 10 mmol) and (**2**) (6.0 g, 10 mmol) in dry reagent-grade methyl cyanide (120 cm^3). The stirred suspension was refluxed for 32 h. Prolonged reaction times resulted in markedly lower yields. The suspension was filtered while hot and the solution was evaporated under reduced pressure to give a yellowish oil. This was dissolved in ethanol (10 cm^3) and precipitated by addition of water to give a white solid, m.p. 115—116 °C (1.40 g, 31%) (Found: C, 61.2; H, 9.3; N, 15.4. Calc. for $C_{23}H_{41}N_5O_2S$: C, 61.2; H, 9.1; N, 15.5%).

(*c*) 12,17-*Dimethyl*-1,5,9,12,17-*penta-azabicyclo*[7.5.5]*nonadecane trihydrobromide monohydrate* (**4**). The tosyl derivative (**3**) (4.0 g) was dissolved in 96% H_2SO_4 (4 cm^3) and heated at 100 °C for 60 h. Ethanol (15 cm^3) was then carefully added to the ice-cold solution while stirring. The dropwise addition of diethyl ether (30 cm^3) precipitated a white material which was washed with cold diethyl ether and dried *in vacuo*. This crude sulphate of L was dissolved in water (10 cm^3). The resulting solution was made strongly alkaline with sodium hydroxide,

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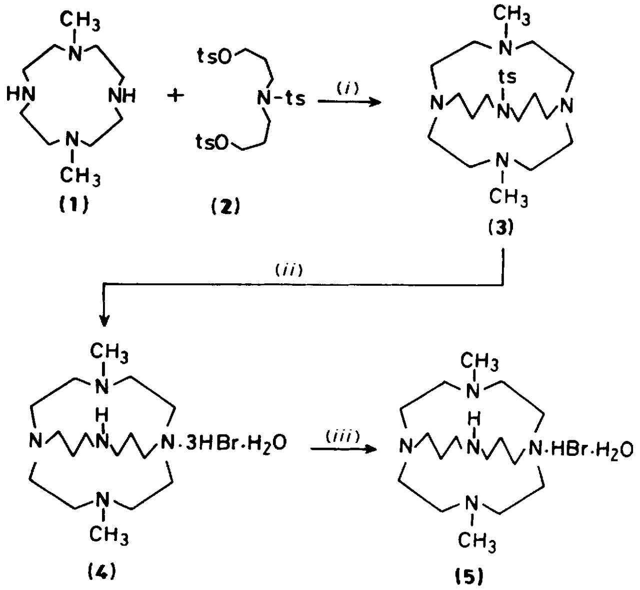
† *Supplementary data available* (No. SUP 56389, 5 pp.): thermal parameters, complete bond lengths and angles. See Instructions for Authors, *J. Chem. Soc., Dalton Trans.*, 1986, Issue 1, pp. xvii—xx. Structure factors are available from the editorial office.



Scheme. ts = Toluene-*p*-sulphonyl. (*i*) $CH_3CN-Na_2CO_3$, reflux for 32 h, yield 31%; (*ii*) (*a*) 96% H_2SO_4, (*b*) NaOH–47% HBr, yield 81%; (*iii*) $NaOH-CH_2Cl_2$

extracted with dichloromethane (4×50 cm^3) and the combined extracts were evaporated to dryness under reduced pressure affording a sticky oil. This was dissolved in ethanol (10 cm^3) and the addition of 47% hydrobromic acid (5 cm^3) gave the desired trihydrobromide monohydrate as a white crystalline powder. This was washed with ethanol and dried *in vacuo*, m.p. 285—290 °C (yield 4.0 g, 81%) (Found: C, 34.9; H, 7.3; N, 12.8. Calc. for $C_{16}H_{40}Br_3N_5O$: C, 34.4; H, 7.2; N, 12.5%).

(*d*) *Bromide and perchlorate of* HL^+. Attempts to isolate the free amine L by dissolving the trihydrobromide (**4**) in concentrated sodium hydroxide solution (up to 10 mol dm^{-3}) and extracting with dichloromethane were unsuccessful. The only product extracted was the monohydrobromide (**5**); m.p. 200 °C (decomp.) (Found: C, 50.2; H, 9.6; N, 18.3. Calc. for $C_{16}H_{36}BrN_5$: C, 50.7; H, 9.6; N, 18.5%). Addition of strong sodium perchlorate solution to the aqueous solution of (**4**) afforded white crystals of the slightly soluble $[HL][ClO_4]$ (Found: C, 48.5; H, 9.4; N, 17.6. Calc. for $C_{16}H_{36}ClN_5O_4$: C, 48.4, H, 9.1; N, 17.6%).

Preparation of Metal Complexes.—$[CuL][ClO_4]_2{\cdot}H_2O$. A solution of $Cu[ClO_4]_2{\cdot}6H_2O$ (0.25 mmol) in methanol (10 cm^3) was added to a solution of [HL]Br (0.25 mmol) in methanol (20 cm^3). The resulting solution was refluxed for 10 min and concentrated to small volume. On standing at room temperature, blue crystals separated which were recrystallised from acetone–diethyl ether (Found: C, 33.4; H, 6.3; N, 12.2. Calc. for $C_{16}H_{37}Cl_2CuN_5O_9$: C, 33.3; H, 6.5; N, 12.1%). Molar conductance, $\Lambda = 189$ Ω^{-1} cm^2 mol^{-1} for a 0.001 mol dm^{-3} aqueous solution at 20 °C.

$[ZnL][ClO_4]_2$. This complex was prepared by the same procedure as for the copper complex but was recrystallised from hot methanol (Found: C, 34.4; H, 6.5; N, 12.6. Calc. for $C_{16}H_{35}Cl_2N_5O_8Zn$: C, 34.2; H, 6.3; N, 12.4%).

$[ML]Br[ClO_4]$ (M = Co *or* Ni). An equimolar solution of $M[ClO_4]_2{\cdot}6H_2O$ (0.25 mmol) and [HL]Br in methanol (10 cm^3) was refluxed for 24 h and evaporated to small volume under reduced pressure. On standing the complexes separated and were recrystallised twice from hot methanol. Yield *ca.* 20% [Found: C. 35.9; H, 6.9; N, 13.2 (for the cobalt complex). C, 35.9; H, 6.9; N, 13.3 (for the nickel complex). Calc. for $C_{16}H_{35}BrClMN_5O_4$: C, 35.9; H, 6.6; N, 13.1%]. Molar conductances, Λ (Co) = 190 and Λ (Ni) = 195 Ω^{-1} cm^2 mol^{-1} for 0.001 mol dm^{-3} aqueous solutions at 20 °C.

E.M.F. Measurements.—The potentiometric titrations were carried out in 0.5 mol dm^{-3} KNO_3 (C. Erba, ACS grade) at 25 °C by using apparatus that has already been described.[8] The computer program SUPERQUAD[9] was used to process data and calculate the basicity constants.

Spectroscopy.—Proton-decoupled ^{13}C n.m.r. spectra were recorded with a Varian FT-80A spectrometer operating at 20.0 MHz using deuterium oxide–water (1:1 v/v) as solvent; chemical shifts are reported in p.p.m. from $SiMe_4$ with dioxane as secondary reference standard [δ (dioxane) = δ ($SiMe_4$) + 67.4] (Table 1). Hydrogen-1 n.m.r. spectra were recorded in the pulse Fourier-transform mode with a Varian CFT-20 spectrometer or with a Perkin-Elmer R32 instrument (90 MHz) in continuous wave; chemical shifts are reported in p.p.m. from $SiMe_4$.

The electronic spectra were recorded on a Perkin-Elmer Lambda 9 spectrophotometer.

Crystallography.—*Crystal data*. $C_{16}H_{37}Cl_2CuN_5O_9$, M = 577.9, orthorhombic, space group $P2_12_12_1$, a = 17.332(5), b = 15.448(5), c = 9.066(4) Å, U = 2 427.4 $Å^3$, Z = 4, D_c = 1.581 g cm^{-3}, $\lambda(Mo\text{-}K_\alpha)$ = 0.710 69 Å, $\mu(Mo\text{-}K_\alpha)$ = 11.31 cm^{-1}, $F(000)$ = 1 212.

Data collection. A parallelepiped crystal of $[CuL][ClO_4]_2{\cdot}H_2O$ having dimensions $0.43 \times 0.10 \times 0.10$ mm was chosen for data collection. Cell parameters were determined from the setting angles of 25 reflections, measured accurately on a Philips PW 1 100 automatic diffractometer, using Mo-K_α radiation. The intensities were collected, on the same diffractometer, in the range $6 \leqslant 2\theta \leqslant 50°$ by using graphite-monochromated Mo-K_α radiation and the ω—2θ scan technique. Variable scan widths of $(0.70 + 0.30 \tan \omega)°$ were used with a scan speed of 0.08° s^{-1}. The background counting time was half the peak time for each side. Three standard reflections were measured every 120 min, but no systematic loss of intensity was noted during the data collection. Standard deviations of the intensities were calculated as described elsewhere,[10] using a value for the instability factor K of 0.03. The 1 865 independent reflections having $I \geqslant 3\sigma(I)$ (from a total of 2 065 reflections) were considered observed and used in the structure analysis. An absorption correction was applied using a numerical method.[11] The intensities were also corrected for Lorentz and polarisation effects. Atomic scattering factors were taken from ref. 12 for non-hydrogen atoms and from ref. 13 for hydrogen atoms. Corrections for anomalous dispersion effects were also applied:[14] the application of the $\Delta f''$ corrections allowed the determination of the absolute structure.

Structure determination and refinement. The structure was solved by the heavy-atom method which gave the positions of the chlorine and copper atoms. Successive F_o Fourier syntheses gave the positions of all non-hydrogen atoms. The structure was then refined by use of full-matrix least squares using the SHELX program.[10] The function minimised was $\Sigma w(|F_o| - |F_c|)^2$, where the weights w where assigned according to the expression $w = 1/\sigma^2(F_o)$. The hydrogen atoms of L were introduced in calculated positions with an overall thermal parameter U of 0.05 $Å^2$, and were not refined. Their positions were varied in every cycle on the basis of the shift in the carbon atoms (C–H fixed at 1.08 Å). According to SHELX, the hydrogen atoms of the methyl group are fixed in staggered configuration. Anisotropic thermal parameters were used for copper and for chlorine and oxygen atoms of the perchlorate anions, whereas the other atoms were refined isotropically. The absolute structure was determined by performing cycles on the two possible configurations; that which gave the lower R factor and standard deviations was considered the correct one. The final conventional R was 0.058 (for the other configuration R was 0.062); $R' = [\Sigma w(|F_o| - |F_c|)^2/\Sigma w|F_o|^2]^{\frac{1}{2}} = 0.057$. The final ΔF Fourier synthesis did not show any unusual features. The final values of the atomic co-ordinates are in Table 2.

Results and Discussion

Protonation.—In the solid state mono- and tri-protonated salts of L are obtained, no higher protonated species being isolated. In aqueous solution this polyamine can take up to three hydrogen ions. It behaves as a very weak base in the third protonation step [log $K_3 < 2$ for the stepwise equilibria $H_{(i-1)}L^{(i-1)+} + H^+ \rightleftharpoons H_iL^{i+}$] and as moderate base in the second protonation step (log $K_2 = 8.41$). The first proton cannot be removed even in strongly alkaline solution. Indeed, the ^{13}C n.m.r. spectra of HL^+ in neat water and in 3 mol dm^{-3} KOH solution are exactly the same. No changes in these spectra are observed after 1 week. Six sharp signals are found, four of which integrate for two carbons and two for four carbons (Figure 1). The assignment of the peak at 43.5 p.p.m. to methyl carbons is confirmed by the 'attached proton test' technique,[15] whereas the central carbons d of the propylenic chains are assigned to the highest-field peak at 27.1 p.p.m. A tentative assignment of the remaining signals can be obtained from the successive protonation steps and is shown in Figure 1.

The ^1H n.m.r. spectrum of $[HL][ClO_4]$ in D_2O shows a complicated multiplet pattern between 1.5 and 3.0 p.p.m. where the signal of the methyl groups is easily recognisable at 2.28 p.p.m. The same pattern is found in CD_3CN and $CDCl_3$ where a broad signal is present at 9.3 p.p.m. (full-width at half-height *ca.* 90 Hz), integrating for two protons, which is attributable to NH protons. This signal disappears upon adding 2 equivalents of CH_3OH or water, presumably due to excessive linewidth, thus indicating intermediate or fast proton exchange on the n.m.r. time-scale.

The occurrence of only six signals in the ^{13}C n.m.r. spectrum points to a C_{2v} symmetry for HL^+, possibly time averaged among lower-symmetry conformers and/or tautomers. Also, the ^1H n.m.r. spectrum indicates equivalence of the two NH hydrogens on the n.m.r. time-scale. A tentative structure, in accord with these n.m.r. features, is shown diagrammatically in Figure 2. Such a structure could account for the exceptionally high basicity for the first protonation step with this amine, each of the two NH hydrogens being involved in hydrogen bonds with tertiary nitrogens within the cyclic framework. Furthermore, it could account also for the very fast proton exchange with 'external' active hydrogens, which is quite unusual with bicyclic diamines,[1,2] bulky substituted 1,8-diaminonaphthalenes,[16] and small cryptands.[3] Actually, in Figure 2 the NH hydrogen atoms are rather unscreened and readily accessible by solvent molecules since they lie on the 'surface' and not 'inside' the cavity of the macrobicycle.

Of course, tautomeric structures related to that in Figure 2 could also account for the above mentioned features, provided fast exchange occurs on the n.m.r. time-scale. Such tautomers could have a protonated tertiary nitrogen and a secondary amino group, both involved in a similar framework of hydrogen bonds. However, no i.r. band attributable to an unprotonated secondary amine group (3 500—3 300 cm^{-1}) is present in the spectrum above 3 100 cm^{-1} both in CH_2Cl_2 solution and in the solid state.

The successive protonation steps result in marked changes in the ^{13}C n.m.r. spectra (Figure 1). When the number of protons, $n = 2$, two sets of six signals are present. One set, integrating for about 80% of the total carbon, belongs to one or more isomers in fast exchange with HL^+ and H_3L^{3+} on the n.m.r. time-scale. On the contrary, the second set (accounting for the remaining 20%) belongs to one or more isomers which exchange slowly, on the n.m.r. time-scale, with all of the above species. This set reaches its greatest intensity at $n = 2$. The large downfield shift found for the carbons c of the predominant species contrasts with the usual upfield shifts occurring on protonation.[17] This suggests large configurational changes in the second protonation step accompanying the partial disruption of the hydrogen-bond framework.

The value of the second protonation constant (log $K_2 = 8.41$) is slightly smaller than those found for the second protonation step of secondary amino groups of polyazacycloalkanes.[18] The addition of the third proton to the macrocycle L is difficult and the equilibrium constant cannot be accurately measured in the useful pH range (log K_3 estimated as <2). This behaviour can be ascribed to the electrostatic repulsions among the positive charges in the protonated macrocycle.

For H_3L^{3+} only one set of five peaks is found at room temperature, the reduction in the number of signals being due to coincidence of the two lowest-field peaks (Figure 1). The methyl and 54.1 p.p.m. signals look very broad whereas the other peaks are rather sharp; at 70 °C the former two signals become sharper. This suggests intermediate exchange, on the n.m.r. time-scale, among tautomers or conformers differing mainly in the

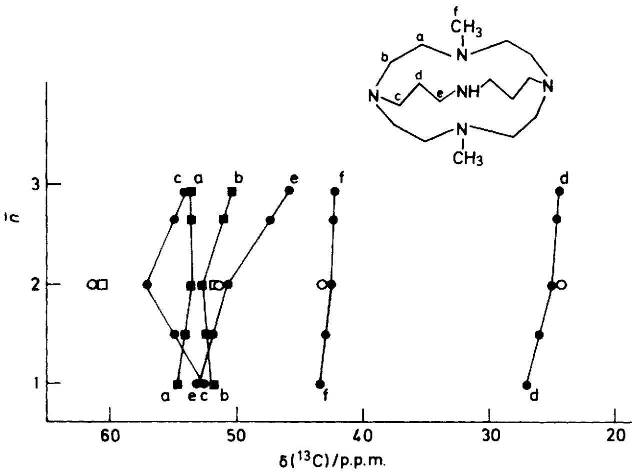


Figure 1. Carbon-13 chemical shifts for $[H_nL]^{n+}$ *vs.* $\bar{n}$, the mean number of protons; signals integrating for two carbons (●, ○) and for four carbons (■, □). The open circles refer to the 20% species (see text)

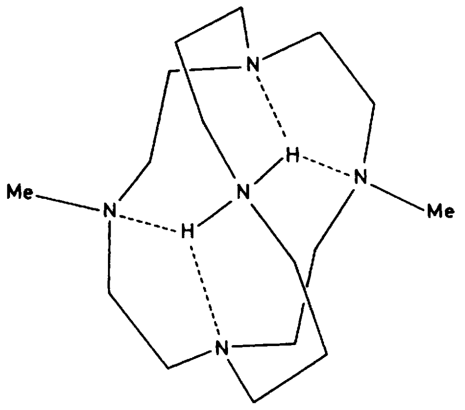


Figure 2. Proposed structure for $[HL]^+$

methylated nitrogens and their adjacent atoms. Accordingly, the peak at 54.1 p.p.m. is assigned to the carbon atoms a. On the other hand, since the unusual configurational constraints due to the intramolecular hydrogen-bridge framework should be released in H_2L^{2+} and H_3L^{3+}, it seems reasonable to attribute the peaks at 54.0 and 45.9 p.p.m. for the latter cation to carbon atoms c and e, respectively. Indeed, similar chemical shift differences (4—7 p.p.m.) are usually found between tertiary and secondary amines or their protonated forms.[17,19]

Complex Formation.—A number of metal ions including Li^+, Na^+, K^+, Be^{2+}, Mg^{2+}, Al^{3+}, Co^{2+}, Ni^{2+}, Cu^{2+}, and Zn^{2+} were tested for complex formation with L. According to ^{13}C n.m.r. spectroscopy, there was no evidence of metal co-ordination for Na^+, K^+, Be^{2+}, and Al^{3+}, whereas some kind of weak interaction occurs for Mg^{2+}, as suggested by the moderate upfield and downfield shifts (0.6 to −0.3 p.p.m.) of the HL^+ signals. With the other metal ions (except lithium), solid complexes were isolated from the mixture of the appropriate metal perchlorate and [HL]Br in boiling methanol, using reaction times ranging from 10 min for copper to 24 h for cobalt and nickel. For the diamagnetic ions dramatic variations in the ^{13}C spectra are found (see Table 1).

In order to confirm the ability of L to encapsulate the heavier 3*d* metal ions, an *X*-ray crystal structure analysis of $[CuL][ClO_4]_2 \cdot H_2O$ has been carried out. The structure consists of discrete $[CuL]^{2+}$ cations, $[ClO_4]^-$ anions, and interposed water molecules. The copper ion is wholly enclosed by the macrobicycle, and adopts a five-co-ordinated geometry (Figure 3) which is best described as a distorted square pyramid with the secondary nitrogen atom in the apical position.

Bond distances and angles are in Table 3. The copper–nitrogen distances are within the range expected for five-co-ordinated amine–copper complexes (mean 2.067 Å). Bond angles in the co-ordination polyhedron are in the range 85.2—86.3° for the basal atoms, and are clearly imposed by the bites of the five-membered chelate rings. The two angles spanned by the longer propylenic chains are 100.1 and 101.4°, which are normal for square-pyramidal co-ordination. The remaining two angles, not subtended by chelate rings, are 106.7 and 118.9°. These rather high values can be accounted for by intramolecular repulsions between the propylenic chains and the N(3) methyl group (118.9°), on the one hand, and those between the N(4) methyl and the H atom of the NH group, on the other. In conclusion, the internal constraints of this macrobicyclic ligand, with five- and six-membered chelate rings, favour a square-pyramidal arrangement. Four diastereoisomers are in principle possible for a square-pyramidal complex of this macrocycle. Indeed, the methyl groups and the hydrogen atom of the secondary amine can each assume two different configurations, a unique one occurring for the bridgehead nitrogens. The present copper complex occurs as diastereoisomer (i). It may be recalled that two diastereoisomeric configurations of the nitrogen atoms have been found for the *cis*-octahedral

Table 1. Carbon-13 n.m.r. chemical shifts (p.p.m.) of some derivatives of L[a]

$[HL]^{+b}$	27.1 (1), 43.5 (1), 52.0 (2), 52.7 (1), 53.0 (1), 54.7 (2)
$[LiL]^{+b}$	28.1 (2), 40.4 (1), 43.7 (1), 51.9 (2), 53.2 (2), 53.3 (2), 55.0 (2), 57.6 (2), 59.4 (2)
$[Mg^{2+}]/[HL]^{+c}$	26.8 (1), 43.6 (1), 52.2 (2), 52.4 (1), 53.6 (1), 54.6 (2)
$[ZnL]^{2+b}$	26.5 (2), 41.9 (1), 45.0 (1), 52.3 (2), 52.9 (2), 53.4 (2), 54.8 (2), 56.8 (2), 59.8 (2)

[a] Spectra recorded at 36 °C. Relative intensities in parentheses. [b] In 1 mol dm^{-3} NaOH solution. [c] In 2 mol dm^{-3} NH_3–0.5 mol dm^{-3} NH_4Br.

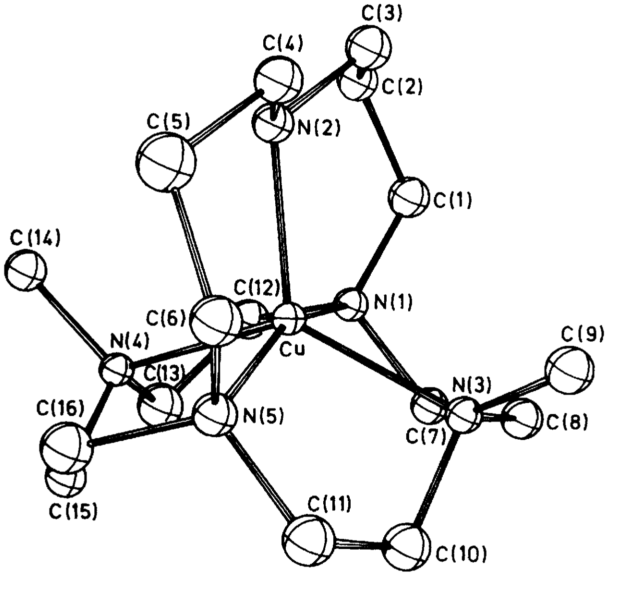


Figure 3. ORTEP drawing of the structure of $[CuL]^{2+}$ with the atom labelling scheme

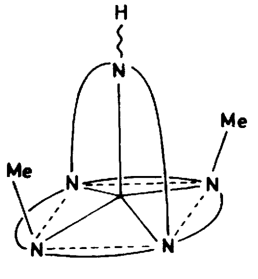
Table 2. Atomic co-ordinates (× 10^4), with estimated standard deviations in parentheses, for $[CuL][ClO_4]_2 \cdot H_2O$

Atom	*x*	*y*	*z*
Cu	1 683(1)	2 568(1)	1 857(1)
N(1)	2 615(5)	1 766(5)	1 821(12)
N(2)	1 158(5)	2 217(6)	−120(10)
N(3)	2 475(5)	3 569(5)	1 853(12)
N(4)	1 233(5)	1 740(6)	3 498(10)
N(5)	927(6)	3 469(6)	2 641(11)
C(1)	2 865(7)	1 458(9)	376(14)
C(2)	2 227(7)	1 194(8)	−677(15)
C(3)	1 736(7)	1 904(8)	−1 239(14)
C(4)	659(7)	2 906(8)	−743(16)
C(5)	79(8)	3 234(9)	347(16)
C(6)	409(7)	3 864(8)	1 482(14)
C(7)	3 238(7)	2 281(7)	2 543(14)
C(8)	3 261(7)	3 182(7)	1 880(15)
C(9)	2 458(8)	4 233(9)	657(15)
C(10)	2 236(8)	3 974(9)	3 286(17)
C(11)	1 419(7)	4 165(8)	3 312(18)
C(12)	2 434(7)	1 004(8)	2 790(14)
C(13)	1 927(8)	1 265(9)	4 079(17)
C(14)	666(7)	1 098(7)	2 979(15)
C(15)	888(6)	2 340(7)	4 569(13)
C(16)	421(8)	3 013(9)	3 759(15)
Cl(1)	8 389(2)	1 725(2)	3 224(4)
Cl(2)	4 895(2)	−80(2)	2 993(5)
O(1)	8 768(6)	1 710(10)	1 878(13)
O(2)	7 665(6)	1 323(8)	3 134(15)
O(3)	8 839(6)	1 325(9)	4 307(12)
O(4)	8 238(9)	2 558(8)	3 597(16)
O(5)	5 618(8)	210(9)	2 676(17)
O(6)	4 410(10)	−271(12)	1 822(18)
O(7)	4 911(8)	−699(10)	4 067(19)
O(8)	4 537(11)	629(14)	3 394(31)
O_w	8 604(6)	4 290(7)	3 821(13)

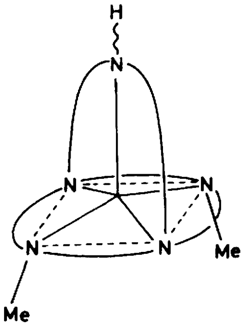
Table 3. Selected bond distances (Å) and angles (°), with estimated standard deviations in parentheses

Cu–N(1)	2.035(7)	C(2)–C(3)	1.479(13)	C(7)–C(8)	1.516(12)	C(12)–C(13)	1.516(15)
Cu–N(2)	2.082(8)	C(3)–N(2)	1.506(12)	C(8)–N(3)	1.488(12)	C(13)–N(4)	1.504(12)
Cu–N(3)	2.068(7)	N(2)–C(4)	1.483(12)	N(3)–C(9)	1.493(13)	N(4)–C(14)	1.475(11)
Cu–N(4)	2.111(7)	C(4)–C(5)	1.499(14)	N(3)–C(10)	1.500(14)	N(4)–C(15)	1.469(11)
Cu–N(5)	2.039(8)	C(5)–C(6)	1.528(14)	C(10)–C(11)	1.448(14)	C(15)–C(16)	1.509(14)
N(1)–C(1)	1.459(12)	C(6)–N(5)	1.511(12)	C(11)–N(5)	1.501(13)	C(16)–N(5)	1.514(13)
C(1)–C(2)	1.517(14)	N(1)–C(7)	1.493(12)	N(1)–C(12)	1.502(12)		

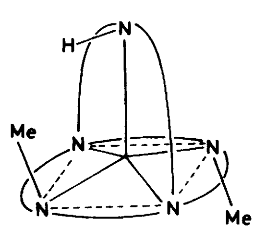
N(1)–Cu–N(2)	100.1(3)	C(1)–N(1)–C(7)	110.6(7)	Cu–N(4)–C(14)	115.4(6)	C(2)–C(3)–N(2)	112.9(9)
N(1)–Cu–N(3)	85.9(3)	C(1)–N(1)–C(12)	109.4(7)	Cu–N(4)–C(15)	103.6(5)	N(2)–C(4)–C(5)	112.5(9)
N(1)–Cu–N(4)	86.3(3)	C(7)–N(1)–C(12)	108.2(8)	C(13)–N(4)–C(14)	108.5(7)	C(4)–C(5)–C(6)	114.1(9)
N(1)–Cu–N(5)	158.5(3)	Cu–N(2)–C(3)	111.9(6)	C(13)–N(4)–C(15)	113.7(8)	C(5)–C(6)–N(5)	115.7(9)
N(2)–Cu–N(3)	118.9(3)	Cu–N(2)–C(4)	113.3(6)	C(14)–N(4)–C(15)	111.3(7)	N(1)–C(7)–C(8)	109.5(8)
N(2)–Cu–N(4)	106.7(3)	C(3)–N(2)–C(4)	111.2(8)	Cu–N(5)–C(6)	114.5(6)	C(7)–C(8)–N(3)	110.6(8)
N(2)–Cu–N(5)	101.4(3)	Cu–N(3)–C(8)	107.9(5)	Cu–N(5)–C(11)	105.4(6)	N(3)–C(10)–C(11)	111.7(10)
N(3)–Cu–N(4)	134.4(3)	Cu–N(3)–C(9)	120.1(6)	Cu–N(5)–C(16)	106.8(6)	C(10)–C(11)–N(5)	113.7(9)
N(3)–Cu–N(5)	85.2(3)	Cu–N(3)–C(10)	97.3(6)	C(6)–N(5)–C(11)	109.2(8)	N(1)–C(12)–C(13)	111.3(8)
N(4)–Cu–N(5)	86.0(3)	C(8)–N(3)–C(9)	107.8(8)	C(6)–N(5)–C(16)	108.0(8)	C(12)–C(13)–N(4)	108.9(9)
Cu–N(1)–C(1)	116.7(6)	C(8)–N(3)–C(10)	114.0(8)	C(11)–N(5)–C(16)	113.0(8)	N(4)–C(15)–C(16)	109.4(8)
Cu–N(1)–C(7)	104.0(5)	C(9)–N(3)–C(10)	109.7(7)	N(1)–C(1)–C(2)	115.8(9)	C(15)–C(16)–N(5)	109.6(8)
Cu–N(1)–C(12)	107.5(6)	Cu–N(4)–C(13)	104.3(6)	C(1)–C(2)–C(3)	115.9(9)		



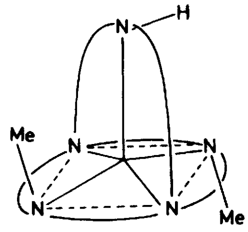
(i)



(ii)



(iii)



(iv)

Table 4. Electronic spectra for some metal complexes of L*

[CoL]Br[ClO$_4$]	Solid:	12 600, 15 700, 17 800 (sh), 19 800 (sh), 21 400, 29 000 (sh)
	Aqueous solution:	12 500 (6.3), 15 800 (sh), 18 000 (sh), 20 300 (sh), 21 200 (21.8), 27 000 (sh)
[NiL]Br[ClO$_4$]	Solid:	7 900, 10 900, 14 200 (sh), 16 800, 26 000
	Aqueous solution:	7 850 (5.9), 11 000 (3.4), 14 000 (sh), 16 700 (34.3), 22 000 (sh), 25 950 (50.5)
[CuL][ClO$_4$]$_2$·H$_2$O	Solid:	10 500, 14 450, 32 300
	Aqueous solution:	10 370 (105), 14 550 (343), 32 960 (4 400)

* Wavenumbers (cm^{-1}) with absorption coefficients (ε/dm^3 mol^{-1} cm^{-1}) in parentheses.

complexes of the 12-membered monocycle 1,7-dimethyl-1,4,7,10-tetra-azacyclododecane.[7,20]

In aqueous solution this copper complex exhibits essentially the same stereochemistry as occurs in the solid state. Indeed, its electronic spectrum does not differ significantly from that in the solid state, both being diagnostic of a distorted square-pyramidal structure (Table 4). We note the great inertness of the complex toward strong acid solutions: [CuL][ClO$_4$]$_2$ in 10 mol dm^{-3} HClO$_4$ at 50 °C for 3 d showed no detectable decomposition.

The electronic spectra of the cobalt and nickel complexes show essentially the same features both in the solid state and in solution in methyl cyanide or 1 mol dm^{-3} HCl (Table 4). These spectra are consistent with a high-spin distorted square-pyramidal configuration for both complexes.[21] Such a five-co-ordinate structure is also in agreement with the electrical conductivity data, which are typical of 2:1 electrolytes in aqueous solution. The robustness of these complexes is shown by the absence of any detectable change in their absorption spectra on standing for several days in strong acidic media.

Some features of the zinc complex can be determined from its ^{13}C n.m.r. spectra which consists of nine sharp signals at room temperature in dimethyl sulphoxide or water (Table 1). They are similar, independent of the solvent and of the nature of the anions. The methyl carbons give rise to two signals, each integrating for one carbon atom, which are shifted by *ca.* 2.5 p.p.m. upfield and downfield with respect to that of HL$^+$. This spectrum is indicative of time-averaged C_s symmetry for the zinc(II) species, the zinc atom and the nitrogen atoms of the NMe and NH groups lying in the symmetry plane. Each of the four diastereoisomers (i)—(iv) has this symmetry, but only one of them is apparently present.

The zinc complex is also very inert toward strong acidic media; its ^{13}C n.m.r. spectrum does not change in 3 mol dm^{-3} HCl for a few days. After 90 d at room temperature the amount of H$_3$L^{3+} formed is *ca.* 20%, the chemical shifts of the remaining zinc complex being unchanged. These findings suggest encapsulation of the zinc ion by the macrobicycle involves all five nitrogens, no further solvent or anion being co-ordinated to the metal ion.

Such a high kinetic inertness towards acidic decomposition is in marked contrast with the relatively fast formation of the $[CuL]^{2+}$ and $[ZnL]^{2+}$ complexes in neutral or strongly alkaline solution. The reaction between an aqueous solution of MCl_2 (M = Cu or Zn; 0.3 cm^3, 0.002 mol dm^{-3}) and an alkaline solution (0.5 mol dm^{-3} KOH) of the monoprotonated ligand HL^+ (2 cm^3, 0.001 mol dm^{-3}) was followed calorimetrically using an LKB batch microcalorimeter. The reaction was considered completed within *ca.* 35 min. With the copper complex the completion of reaction was also monitored spectrophotometrically.

The lithium ion reacts with HL^+ only at high pH values. In 1 mol dm^{-3} KOH the formation of a lithium complex appears to be complete as shown by the occurrence of a nine-line ^{13}C n.m.r. spectrum (Table 1). This resembles that of the zinc complex and suggests C_s symmetry. With a 1:2 lithium to HL^+ molar ratio the above nine-line pattern occurs along with the six-line pattern due to HL^+. The two patterns integrate for the same amounts of carbon, thus suggesting a 1:1 metal-to-ligand ratio for the lithium species. The signals of both patterns are sharp, indicating slow exchange rates between the two species on the n.m.r. time-scale. By decreasing the KOH concentration a reversible decrease in the intensities of the signals of the $[LiL]^+$ complex was observed with a concomitant increase in those of HL^+. In a 0.1 mol dm^{-3} KOH and 0.1 mol dm^{-3} HL^+ solution, half formation of the lithium complex occurs with an excess of lithium. The amount of this excess up to 10-fold does not apparently affect the rate of complex formation. Upon adding an excess of HCl (1 mol dm^{-3}) the ^{13}C spectrum showed only signals due to H_3L^{3+}, indicating destruction of the lithium complex within the recording time.

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