Control of Metal-ion Size-based Selectivity Through the Structure of the Oxygen-donor Pendant Groups on Lariat Ethers. A Crystallographic and Thermodynamic Study†

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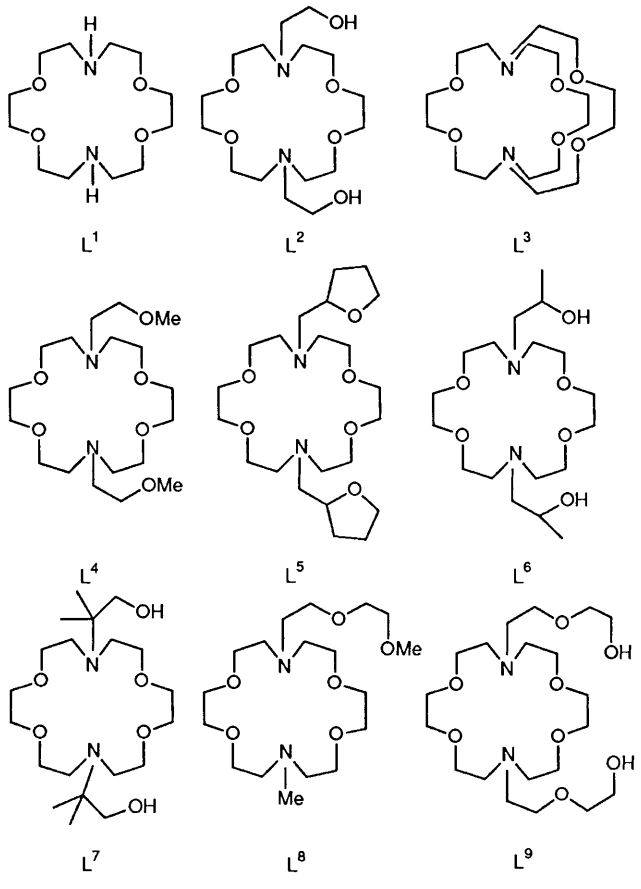
Ligand protonation constants and formation constants of complexes of Cu^{2+}, Cd^{2+}, Ca^{2+}, Sr^{2+}, Pb^{2+} and Ba^{2+} with 7,16-disubstituted 1,4,10,13-tetraoxa-7,16-diazacyclooctadecanes where the substituents are $MeOCH_2CH_2$ (L^4), $\overline{CH_2CH_2CH_2OCHCH_2}$ (tetrahydrofurfuryl, L^5), and $HOCH_2CMe_2$ (L^7) have been determined. Steric and inductive effects alter the selectivities of the ligands such that the stability order for L^4 is $Ba^{2+} > Sr^{2+} > Ca^{2+}$, but the reverse for L^7. The structure of the complex $[KL^7]I$ has been determined: colourless crystals, orthorhombic space group $P_12_12_1$, with $a = 11.507(4)$, $b = 13.222(6)$ and $c = 17.911(4)$ Å, $Z = 4$ and $R = 0.049$. The absolute structure was determined by statistical analysis. The K–L bond lengths of the potassium complexes of L^2 (substituent $HOCH_2CH_2$), L^4 and L^7 vary considerably. The origins of this variation have been analysed using molecular mechanics calculations, and different approaches to modelling the K–O and K–N bonds are discussed.

The co-ordinating properties of 'lariat ethers' such as L^2 have been extensively investigated.[1–3] The presence of the hydroxyethyl 'arms' (pendant donor groups) on the eighteen-membered macrocyclic ring lead to formation constants for L^2 which are intermediate[4] between those of the monomacrocyclic L^1 and the bicyclic cryptand L^3, see Table 1.

The fact that addition of hydroxyethyl arms leads to complex stabilities roughly intermediate between those of the simple macrocycle and the cryptand has interesting implications[4] for the nature of the cryptate effect.[8] This result is also important as a means of producing enhanced selectivity for metal ions, and thermodynamic stabilities of their complexes, approaching those observed for cryptands, but with greater simplicity of ligand synthesis.

In this paper the possibility is explored that structural variation of the oxygen-donor pendant arms might result in further enhancement of the selectivity which is produced by adding hydroxyethyl arms. This enhancement of selectivity is related to the size of the metal ion, as seen in Table 1. Large metal ions show considerable increases in log K_1 on addition of hydroxyethyl arms to L^1 to give L^2, and do so also on adding an ethylene bridge to L^2 to give the cryptand L^3. This effect decreases with decreasing size of the metal ion, and may even become reversed with small metal ions. It has been interpreted[9] in terms of steric destabilisation of the complexes of smaller metal ions, which outweighs the stabilisation produced by the higher basicity than water of the alcoholic and ether oxygen donor. Since virtually all work on ligands of the L^2 type has focused on hydroxyethyl groups as pendant arms, here the effect of increased bulk and rigidity of these pendant groups is explored. The ligands L^4 with pendant 2-methoxyethyl donor groups, L^5 with pendant tetrahydrofurfuryl groups, and L^7 with 2-hydroxy-1,1-dimethylethyl groups were synthesised following the generalised procedures of Gatto and Gokel.[10] The C-methyl groups on L^7 produced marked changes in complex stability, and in order to examine how these methyl groups packed in



complexes of a larger metal ion the crystal structure of the K^+ complex of L^7 was determined. It was found that there was considerable variability in K–L bond lengths in structures reported for the eight-co-ordinate potassium complexes of L^2, L^4 and L^7. Kollman and co-workers[11] have used a united-atom

† *Supplementary data available:* see Instructions for Authors, *J. Chem. Soc., Dalton Trans.*, 1991, Issue 1, pp. xviii–xxii.

Non-SI unit employed: cal = 4.184 J, dyn = 10^{-5} N.

Table 1 Formation constants of complexes with macrocyclic ligands

Metal ion	Ionic radius[a]	Log K_1[b]		
		L^1	L^2	L^3
K	1.39	1.8[c]	5.1[c]	10.6[d]
Ba	1.36	3.0	5.3	9.5
Pb^{II}	1.18	6.8	9.2	12.0
Ca	1.00	1.7	4.1	4.5
Cd	0.95	5.3	8.0	6.8
Cu^{II}	0.57	6.1	6.6	6.5

[a] Octahedral radii (Å) for the metal ions, except for Cu^{II} which is square planar, from ref. 5. [b] Formation constants in water from refs. 1 and 6. [c] In methanol, ref. 2. [d] Mean of values reported in methanol in ref. 7.

force field for calculations on complexes of the crown ethers with alkali-metal ions and spherands. It thus seemed that the set of complexes L^2, L^4 and L^7 presented a good test of the ability to predict structure by molecular mechanics (m.m.) calculations using the force field and procedures employed by Kollman and co-workers.[11] In addition to testing the predictive ability of such calculations, the m.m. study was aimed at analysing the effects of steric crowding and rigidity on metal-ion selectivity.

Experimental

Synthesis of Ligands.—7,16-*Bis*(*tetrahydrofurfuryl*)-1,4,10,13-*tetraoxa*-7,16-*diazacyclooctadecane* (L^5). The ligand was synthesised as the NaI complex using the procedure of Gatto and Gokel.[10] The ligand was purified using column chromatography (silica 60; solvent, 1% methanol in dichloromethane), followed by recrystallisation from methanol–dichloromethane, giving the NaI complex as a yellow crystalline material. Yield 16%, m.p. 113–115 °C. ^{1}H NMR ($CDCl_3$): δ 1.7–2.2 (8 H, m, CH_2CH_2), 2.4–3.0 (12 H, m, NCH_2) and 3.4–4.0 (22 H, m, OCH_2 and OCH) (Found: C, 45.30; H, 7.30; N, 4.45. Calc. for $C_{22}H_{42}IN_2NaO_6$: C, 45.50; H, 7.30; N, 4.85%).

7,16-*Bis*(2-*methoxyethyl*)-1,4,10,13-*tetraoxa*-7,16-*diazacyclooctadecane* (L^4). This was synthesised according to the procedure of Gokel and Gatto.[10] Yield 70%.

7,16-*Bis*(1,1-*dimethyl*-2-*hydroxyethyl*)-1,4,10,13-*tetraoxa*-7,16-*diazacycloctadecane* (L^4). The procedure of Gokel and Gatto [10] yielded the ligand as a KI complex, which was obtained as a white crystalline solid after recrystallisation from ethanol–diethyl ether. M.p. 213–216 °C, yield 56%. ^{1}H NMR ($CDCl_3$): δ 1.0 (6 H, s, CH_3), 3.4–3.6 (8 H, t, NCH_2), 3.7–3.8 (20 H, m, OCH_2) and 4.0–4.3 (2 H, br, OH) (Found: C, 42.05; H, 7.85; N, 4.95. Calc. for $C_{20}H_{42}IKN_2O_6$: C, 41.95; H, 7.40; N, 4.90%).

Formation Constant Studies.—These were carried out by glass-electrode potentiometry as described previously[9a] at 25 °C, in 0.1 mol dm^{-3} $NaNO_3$.

Molecular Mechanics Calculations.—These were carried out using the program MOLBLD 3 of Boyd *et al.*[12] for all calculations. A locally modified version of MOLBLD 3 was used to reproduce the united-atom force field of AMBER employed by Kollman and co-workers,[11] for crown ether complexes of alkali-metal ions. The strain energies reported [11] were satisfactorily reproduced. Kollman and co-workers [11] used partial charges on the oxygens of −0.3 for the free ligands and of −0.6 for the complexes in separate calculations on the crown ethers. We tried both of these charges, and found that the predicted structures (but not the energies) were rather insensitive to the magnitude of the charge. The structure and energies reported in this paper were calculated using partial charges of −0.6 on the nitrogen and oxygen donor atoms when using the Kollman force field. However, because of the somewhat poor ability of the Kollman type of approach to predict structure accurately, an alternative was tried. Rather than representing the interaction between the alkali-metal ion and the donor atoms as a purely electrostatic phenomenon, the force field used previously[9c] for complexes of nickel(II) was employed. Here no charges are placed on atoms, and force constants and ideal bond angles and lengths are used to represent the M–O bond. In this type of approach the M–O bond is, in a sense, being treated as purely covalent. A problem that arises here is how to define the ideal co-ordination geometry around the eight-co-ordinate K^+ ion present in the complexes under consideration. Since the co-ordination geometry is highly irregular, it seemed justified as a first approach to set the L–K–L (L = O or N) angle-bending force constants to zero, and allow the ligand to dictate the L–K–L bond angles and hence the geometry. A further advantage of allowing the ligand to dictate the co-ordination geometry around the metal ion was that this dispensed with the problem of rewriting parts of the program so that it could recognise the three different types of ideal L–K–L angles that would be present in even the most regular eight-co-ordinate structure types, such as cubic. (This problem is analogous to getting the program to distinguish between *cis* and *trans* L–M–L angles in octahedral co-ordination.) This was not satisfactory from the point of view that the N–K–N angles were consistently predicted to be far from 180°, when in the observed structures they are all close to 180°. The admittedly rather arbitrary approach was adopted of introducing an ideal N–K–N angle of 180°, with an accompanying small N–K–N force constant, which produced structures in much closer agreement with those observed.

Crystallography.—Single crystals of $[KL^7]I$ were selected from oscillation and Weissenberg photographs using Cu-Kα radiation. Data were collected at room temperature on an Enraf-Nonius CAD-4 diffractometer using graphite-monochromated Mo-Kα radiation (0.710 73 Å). Cell dimensions were obtained from a least-squares fit of 25 high-θ reflections. An ω–2θ scan mode was used with a scan width of 0.6 + 0.35 tanθ and a variable scan speed. Three standard reflections were monitored and showed no significant variation over the data collection. Absorption and Lorentz polarisation corrections were applied according to the method of North *et al.*[13a] The crystal density was determined using flotation on mixtures of carbon tetrachloride and hexane. The program SHELX [13b] was used for all crystallographic computations. It uses atomic scattering factors corrected for anomalous dispersion for all common atoms. Dispersion corrections for the iodine scattering factors were obtained from the same source.[13c] The absolute structure in the chiral space group was established by parallel refinement of the trial model and its enantiomorph. These converted with R indices of 0.043 and 0.039, defined as $R_g = [w(\Delta F)^2/wF^2]$ with weighting factors based on counting statistics. According to the Hamilton test,[13d] the difference is significant and the lower value indicates the absolute configuration.

Crystal data and data collection parameters are given in Table 3, fractional atomic coordinates in Table 4 and important bond angles and lengths in Table 5. An ORTEP [14] drawing of the complex cation of $[KL^7]I$ is seen in Fig. 2.

Additional material available from the Cambridge Crystallographic Data Centre comprises H-atom coordinates, thermal parameters, and remaining bond lengths and angles.

Results and Discussion

Stability Constants of the Complexes.—The formation constants in Table 2 show how the stability of the complexes varies with the nature of the pendant donor group, all with neutral oxygen donors. For the ligand L^4 the O-methyl group produces a large decrease in complex stability relative to L^2, as much as four log units in log K_1 for Cd^{II}. This illustrates how

Table 2 Complex formation and protonation constants of ligands studied in this work,[a] with some literature values for similar ligands for comparison

Ligand:	L^1 [b]	L^2 [c]	L^4 [d]	L^5 [d]	L^6 [e]	L^7 [d]
Pendant group:	H					
pK_1 [f]	9.08		8.06(1)	7.97(3)		8.60(1)
pK_2	7.94		6.89(1)	7.04(3)		7.96(1)
log K_1(Cu) [g]	6.18	6.6	5.40(4)	5.42(1)	5.97	*h*
log K_1(Cd)	5.25	8.0	3.93(1)	7.03(2)	7.64	6.12(1)
log K_1(Ca)	1.74	4.1	*h*	3.07(1)	3.59	2.97(1)
log K_1(Sr)	2.57		3.23(1)	4.10(1)	4.05	2.69(1)
log K_1(Pb)	6.90	9.2	7.54(1)	8.50(1)	8.57	6.95(1)
log K_1(Ba)	2.97	5.3	3.72(1)	4.50(2)	4.65	2.73(1)

[a] All constants at 25 °C in 0.1 mol dm^{-3} $NaNO_3$. [b] Ref. 15. [c] Ref. 1. [d] This work. [e] Ref. 3. [f] pK_1 and pK_2 are the stepwise protonation constants. [g] log K_1 refers to the equilibrium constant for the process M + L $\rightleftharpoons$ ML, where M is the metal(II) ion and L the ligand in the equilibrium. [h] No evidence of complex formation, so that log $K_1 < 1$.

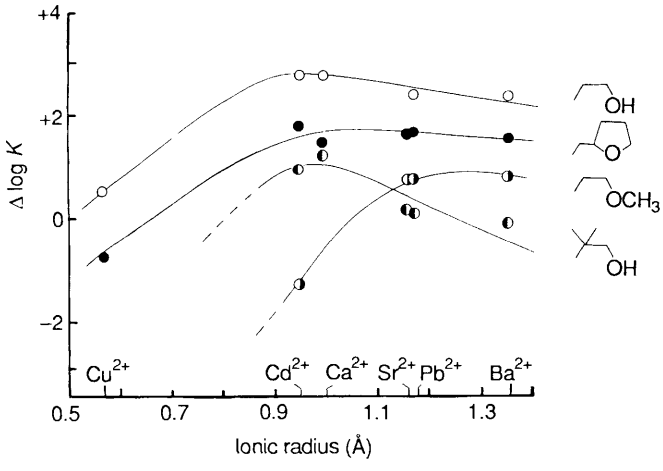


Fig. 1 The change in complex stability, Δ log *K*, which occurs for a variety of metal ions, on change in nitrogen substituents from hydrogen to the groups indicated, plotted as a function of the ionic radius [5] of the metal ions

steric hindrance produced by methyl groups on oxygen donor atoms may make ligands such as L^8 unsuitable analogues for comparison [16] with L^3 as a measure of the thermodynamic cryptate effect with some metal ions. In contrast, the furfuryl group produces an increase in steric efficiency in L^5 as compared with the simple ether donor oxygen of L^4, and the drops in log K_1 for L^5 relative to L^2 are quite small. It has long been known [17] that placement of methyl groups on the ethylene bridges of a chelate ring has a much less adverse steric effect than placement on the donor atoms so as to give O- or N-methyl groups. Accordingly, the drop in log K_1 in passing from L^2 to L^6 is quite small.

The effect of added methyl groups to ligands, whether on C, O or N, has two opposing contributions to complex stability.[4] These are the inductive effects which act to increase the basicity of the donor atoms, and steric effects which act to decrease complex stability by distortion of bond lengths and angles in the complex away from the ideal values. In general, the inductive effects increase linearly with added methyl groups of the same kind, *e.g.* a series of N-methyls, or a series of methyls on the α-carbon. In contrast, steric effects increase geometrically with increasing numbers of methyl substituents, so that where initially inductive effects might predominate these are eventually outweighed by the more rapidly increasing steric effects as methyl substitution proceeds. Thus, addition of a single C-methyl group to each of the pendant donor groups of L^2 to give L^6 has a negligible effect on complex stability, since the adverse steric effects and favourable inductive effects appear to be nearly balanced. However, addition of two methyl groups to each pendant donor group of L^2 to give L^7 has a dramatic effect on complex stability. An important additional factor here is the placement of the two methyls on each pendant donor group on L^7 adjacent to the nitrogen rather than the oxygen donors, as is the case for L^6.

The effect of the structure of the pendant donor group is analysed more closely in Fig. 1 Here the change in complex stability, Δ log *K*, that occurs for each metal ion on changing the substituent on the nitrogen from hydrogen (L^1) to 2-hydroxyethyl (L^2), 2-methoxyethyl (L^4), tetrahydrofurfuryl (L^5), or 2-hydroxy-1,1-dimethylethyl (L^7) has been plotted against the ionic radius [5] of each metal ion. Octahedral radii for all metal ions are used except for Cu^{II}, where the square-planar radius is used. It has previously been found [3,4,9] that the response of the formation constants of metal ions to addition of neutral oxygen donor groups is strongly related to metal-ion radius, so that the same type of analysis is employed here in Fig. 1. Fig. 1 shows gentle peaks in the curves of Δ log *K versus* ionic radius. A possible interpretation [18] of such peaks is that they arise from a change in balance of steric *versus* inductive effects. At larger ionic radii inductive effects are dominant, and metal ions respond better to increased inductive effects as the metal ions decrease in size and hence increase in polarising power. At the peak in the curve the balance changes so that steric effects begin to outweigh inductive effects, and further decreases in metal-ion size bring drops in Δ log *K*. The positions of the peaks in the curve of Δ log *K versus* ionic radius may thus be interpreted in terms of the change in the balance between steric and inductive effects. For the sterically efficient 2-hydroxyethyl (L^2) and tetrahydrofurfuryl (L^5) substituents steric effects become dominant at fairly small metal radii, with the peaks occurring at about 1.0 Å. For the sterically inefficient 2-methoxyethyl substituent (L^4) steric effects predominate at much larger metal radii, with the peak occurring at about 1.3 Å. The two methyls on the carbon adjacent to the nitrogen donor of L^7 results in a peak at about 1.0 Å, but the slope of the curve at larger metal ionic radii is much steeper, sharpening up the selectivity for the smaller, more strongly polarising, Cd^{2+} and Ca^{2+} ions. It seems reasonable to interpret this behaviour in terms of a better response to inductive effects through the nitrogen donor than through an oxygen donor. What is perhaps a little strange is that the relatively small Cd^{2+} ion is able to tolerate the high levels of steric strain expected from the four C-methyl groups close in to the nitrogen donor atom, and in order to understand this the crystal structure of the potassium complex of L^7 was examined.

The Structure of [KL^7]I.—An ORTEP drawing of the structure of the complex cation is seen in Fig. 2. Important bond lengths and angles are listed in Table 5. In Table 6 are shown for comparison the average K–O and K–N bond lengths in the macrocyclic ring, and the K–O bond lengths to the oxygens of the pendant arms, for the potassium complexes of L^2,[19] L^4[20] and L^7 (this work). Also included are the K–L bond lengths for these complexes predicted by us using the force field of Kollman and co-workers.[11,21] What is of interest in Table 5 is the large variation in the metal–ligand bond lengths of these potassium complexes. As would be expected from the idea that the methoxy groups on L^4 produce the most steric crowding at the donor oxygen of the pendant arms, followed by the two methyl groups on each arm of L^7, with the hydroxyethyl arms of L^2 producing the least steric crowding, the bond lengths K–O to the oxygens of the pendant groups increase in the order 2.72 (L^2), 2.79 (L^7) and 2.86 Å (L^4). The K–O bond lengths to the oxygens of the ring show no strong trends. What is surprising is

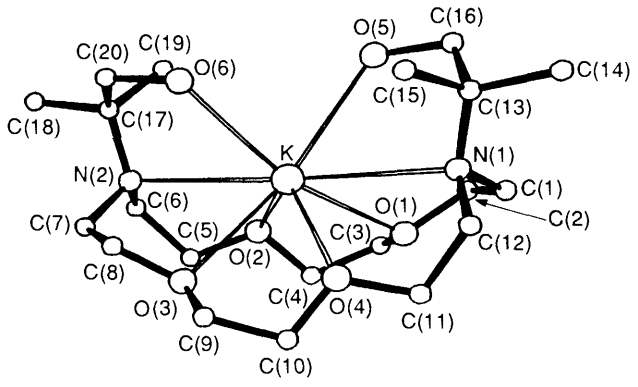


Fig. 2 ORTEP[14] drawing of the complex cation $[KL^7]^+$ showing the numbering scheme, and the *anti* conformation of the pendant groups

Table 3 Crystal data for the potassium complex $[KL^7]I$

Formula	$C_{20}H_{42}IKN_2O_6$
Crystal colour	White
M	572.558
Crystal dimensions/mm	0.70 × 0.60 × 0.35
Crystal system	Orthorhombic
Space group	$P_12_12_1$
Cell dimensions:	
a/Å	11.507(4)
b/Å	13.222(6)
c/Å	17.911(4)
U/Å^3	2725.17
Z	4
D_m/g cm^{-3}	1.39
D_c/g cm^{-3}	1.40
$F(000)$	1184
θ range/°	$2 < \theta < 30$
h, k, l Ranges	−6 to 6, 0–18, 0–25
Scan speed range/° min^{-1}	0.9–5.5
No. reflections measured	4435
No. unique data	3698
R_{int}	0.0665
No. data used $[F > 3\sigma(F_o)]$	2484
μ/cm^{-1}	12.54
Transmission factor range	68.3–100.0
Residual density (maximum, minimum)/e Å^{-3}	0.72, −0.90
R_g (see text)	0.039
Final R	0.049

Table 4 Fractional atomic coordinates (× 10^4, × 10^5, for I and K) for the complex $[KL^7]I$

Atom	X/a	Y/b	Z/c
I	17 491(5)	42 505(5)	34 355(4)
K	45 408(15)	7 495(16)	4 657(10)
N(1)	4 760(6)	−682(6)	−860(4)
N(2)	4 424(6)	2 130(5)	1 842(4)
O(1)	4 438(6)	1 519(6)	−976(4)
O(2)	4 391(6)	2 855(5)	287(4)
O(3)	2 433(5)	936(6)	1 239(4)
O(4)	2 617(5)	−407(5)	21(4)
O(5)	6 717(6)	27(5)	18(3)
O(6)	5 449(7)	125(5)	1 842(4)
C(1)	4 911(10)	−74(7)	−1 519(6)
C(2)	5 264(10)	991(7)	−1 424(6)
C(3)	4 582(11)	2 601(8)	−997(6)
C(4)	3 891(10)	3 054(7)	−419(6)
C(5)	3 769(9)	3 339(8)	871(6)
C(6)	4 408(9)	3 203(6)	1 590(6)
C(7)	3 319(9)	1 909(8)	2 222(6)
C(8)	2 734(9)	935(10)	2 003(6)
C(9)	1 643(9)	131(8)	1 068(6)
C(10)	1 553(9)	−15(9)	270(7)
C(11)	2 602(8)	−614(9)	−755(6)
C(12)	3 628(8)	−1 231(7)	−925(6)
C(13)	5 750(8)	−1 346(8)	−660(6)
C(14)	6 011(9)	−2 117(8)	−1 276(6)
C(15)	5 507(9)	−1 854(7)	99(6)
C(16)	6 859(8)	−702(7)	−557(6)
C(17)	5 495(9)	1 903(7)	2 282(5)
C(18)	5 563(9)	2 492(8)	3 010(6)
C(19)	6 570(7)	2 055(8)	1 794(6)
C(20)	5 497(9)	772(8)	2 499(6)

Table 5 Important bond lengths (Å) and angles (°) for the complex cation $[KL^7]^+$

K–N(1)	3.048(7)	K–N(2)	3.071(7)
K–O(1)	2.778(7)	K–O(2)	2.808(7)
K–O(3)	2.804(6)	K–O(4)	2.807(6)
K–O(5)	2.798(7)	K–O(6)	2.801(7)
N(1)–K–N(2)	177.0(2)	N(1)–K–O(1)	60.4(2)
N(1)–K–O(3)	120.7(2)	N(1)–K–O(2)	122.2(2)
N(1)–K–O(4)	60.3(2)	N(1)–K–O(6)	118.1(2)
O(1)–K–O(2)	61.9(2)	O(1)–K–O(3)	113.0(2)
O(1)–K–O(4)	84.4(2)	O(1)–K–O(5)	84.1(2)
O(1)–K–O(6)	160.3(2)	O(5)–K–O(6)	79.5(2)
K–N(1)–C(1)	107.6(5)	K–N(1)–C(12)	106.8(5)
K–N(1)–C(13)	104.0(5)	C(1)–N(1)–C(13)	115.9(8)

that the K–N bond lengths show (Table 5) a strong inverse relationship to the K–O(arm) bond lengths, ranging in length from 3.10 to 2.94 Å. To try to understand these trends in K–L bond lengths, and the variation in formation constants of the complexes of these ligands, molecular mechanics calculations were undertaken.

Molecular mechanics (*m.m.*) *Calculations*.—The average K–N, K–O(arm) and K–O(ring) bond lengths, as determined crystallographically,[19,20] and predicted by the force field of Kollman and co-workers.[11,21] together with the calculated strain energies, are given in Table 6. Kollman and co-workers have used their m.m. parametrisation of the crown ether, cryptand and spherand complexes of the alkali-metal ions with great success in rationalising the energetics of formation of these complexes, but have not explored the ability of the force field to reproduce the structures of such complexes. It is thus of interest to compare the m.m. predicted, and observed, K–L bond lengths. Table 6 shows that some features of the structures are reproduced, such as the fact that the presence of sterically crowding O-methyl groups on L^4 leads to lengthening of the K–(arm) bonds, with an accompanying compression of the K–N bonds. However, some features are badly reproduced, with the K–N bond length in the L^7 complex being predicted to be 3.32 Å as compared with an observed value (this work) of 3.06 Å. Another surprising fact was that the energy of the *anti* form of the complex with L^4, observed in the crystal structure,[20] was calculated to be higher than that of the non-observed *cis* form. An advantage of the approach of Kollman and co-workers is that it does not prescribe the type of co-ordination geometry or number which the potassium should have. The geometry is produced by electrostatic repulsion between the partial charges on the oxygens, any number of which may be co-ordinated. Some co-ordinated oxygens may even become non-co-ordinating during the course of refinement.[11] It is thus not surprising that such a generalised model should not be as good at reproducing structural details as the type of model where the M–L bonds are generated specifically[22] using ideal bond lengths, and force constants. To see how well such an approach might work for potassium complexes, a model for potassium was employed in which ideal K–N and K–O bond lengths as well as K–L force constants were obtained. These apply,

Table 6 Bond lengths (Å) and angles (°) involving the donor atoms and the potassium ion, observed and calculated from molecular mechanics, and calculated strain energies (kcal mol^{-1}), in the complexes of K^+ with L^2,[a] L^4[b] and L^7[c]

Bond length or angle		$[KL^2]^+$	$[KL^7]^+$	$[KL^4]^+$ *anti*	$[KL^4]^+$ *cis*
K–O(arm),	obs.	2.72	2.80	2.86	
	calc.[d]	2.84	2.80	2.80	
	calc.[e]	2.85	2.83	2.86	
K–(O-ring)	obs.	2.84	2.80	2.83	
	calc.[d]	2.84	2.80	2.69	
	calc.[e]	2.92	2.89	2.83	
K–N	obs.	3.10	3.06	2.94	
	calc.[d]	3.06	3.11	2.89	
	calc.[e]	3.28	3.32	2.97	
N–K–N	obs.	176.4	177.0	176.9	
	calc.	177.2	180.0	175.9	
Total strain energy					
Boyd[d]		7.39	13.86	8.53	6.00
Kollman[e]		14.46	25.45	9.21	5.87

[a] Refs. 9 and 10. [b] Ref. 20. [c] This work. [d] Calculated with force field of Kollman and co-workers.[11,21] [e] Calculated using force field in ref. 22, plus constants reported in Table 7.

Table 7 Force-field parameters for the potassium ion in eight-co-ordination complexes to neutral oxygen and nitrogen donors, to be used in conjunction with those employed previously[22] for the organic parts of the complex

Bond	Ideal length (Å)	Force constant mdyn Å^{-1}
K–N	3.03	0.2
K–O	2.89	0.2
Angle*	**Ideal value (°)**	**Force constant mdyn Å rad^{-1}**
K–N–H	109.5	0.1
K–N–C	109.5	0.1
K–O–C	109.5	0.1
K–O–H	109.5	0.1
N–K–N	180.0	0.2

* The L–K–L (L = N or O) angles are not specified, and the co-ordination geometry around the potassium atom is generated by van der Waals forces between the co-ordinated N and O atoms, as discussed in the text.

however, only to eight-co-ordinate potassium, and predict bonds that are too long for six-co-ordinate complexes. No geometry around potassium was defined, and this was generated by van der Waals forces between the donor atom, as in previous parametrisations for cobalt(III).[23] The additional force constants required for incorporation of eight-co-ordinate potassium into the m.m. model described previously[22] are seen in Table 7. Although the geometry around the K was not defined, it was found necessary to include a N–K–N angle-bending force constant in order to constrain the N–K–N angles to be close to the observed values of about 180°. Without this angle-bending constant, N–K–N angles of as low as 157° were predicted. The K–N and K–O bond lengths and N–K–N angles predicted by this force field are given in Table 6. As might be expected for the more narrowly defined force field, the predicted bond lengths are in better agreement with experimental values, and, in particular, K–N bond lengths are predicted in reasonable agreement with observed values, and are not too long by almost 0.3 Å as obtained with the model of Kollman and co-workers.

The tendency of the Kollman model to predict excessive lengthening of the K–N bonds, as compared with the small

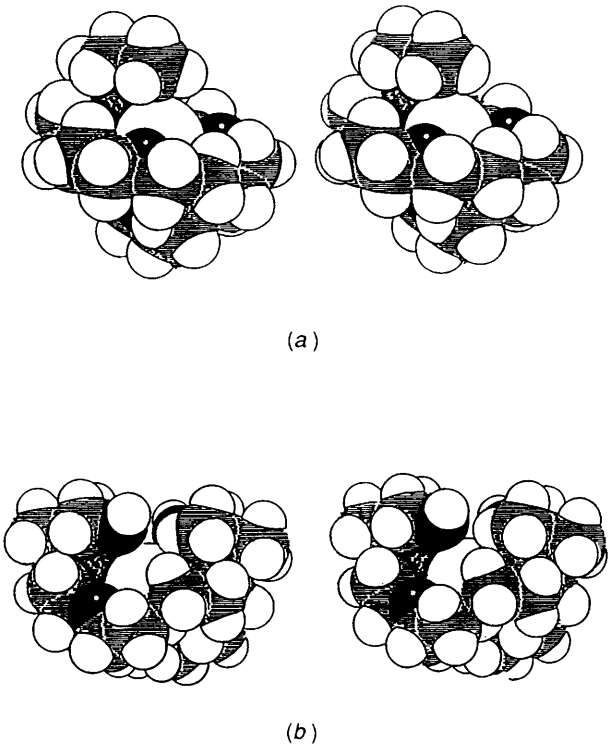


Fig. 3 Space-filling stereoviews of (*a*) the complex cation of $[KL^4]^+$ and (*b*) of $[KL^7]^+$, drawn using the program ALCHEMY.[24] The structures were generated using the AMBER force field of Kollman and co-workers[11] in the program MOLBLD 3 of Boyd *et al.*[12] The drawings show the level of steric crowding by the addition of O- or C-methyl groups to the pendant groups of these complexes.

stretching predicted by the Boyd type of parametrisation, may relate to the way the K–L bonds are modelled. In the Kollman model the donor atoms are preventing from collapsing into the potassium ion by a non-bonded repulsion term in r^{12}, where r is the internuclear separation between the potassium and the donor atoms. In the Boyd approach, compression of the K–L bonds is prevented only by the term in $(r^0 - r)^2$, so that it is easier to compress the K^+ here than in the Kollman model. It is thus seen that where the potassium is constrained to lie in the too-small cavity of the *anti* form of L^4, the Boyd parametrisation predicts some compression of the metal ion, which is not evidenced in the crystal structure. In contrast, in the Kollman approach, K–L bond elongation is prevented only by an electrostatic attraction term which has the form q_iq_j/r, as compared to the $(r^0 - r)^2$ term in the Boyd approach (q_i and q_j are the charges on atoms i and j). The result of this is that it is much easier in the Kollman approach to stretch bonds out to unrealistic values than it is in the Boyd approach.

Our experimental force field based on the Boyd model makes the same prediction as that of Kollman and co-workers, namely that the *anti* conformer of the L^4 complex, observed in the crystal structure, is of higher energy than is the non-observed *cis* structure. This may be due to packing forces in the crystal. The calculations on the *anti* form highlight the fact that the potassium ion is a bit too large for the eighteen-membered macrocyclic ring here. In the *cis* conformer the potassium lies above the macrocyclic ring, and so experiences no compressive forces. In the *anti* conformer, however, the potassium lies in the plane of the donor atoms, and there is a tendency towards compression, as indicated by the m.m. calculations. The low steric strain for the L^4 complexes indicated by both force fields in Table 6 suggests that the crowding in the potassium complex is not large. This is borne out by inspection of space-filling drawings of the complex, seen in Fig. 3(*a*). In contrast to our expectations, the co-ordination around the potassium is not

crowded, and the O-methyl group does not clash strongly with any other groups. The low steric strain calculated for this complex is thus reasonable, and one would suggest that destabilisation of complexes of larger metal ions such as Ba^{2+} or Pb^{2+} with L^4 results because of co-ordination of solvent molecules to give co-ordination numbers higher than eight, at least in solution. In support of this, Ba^{2+} was recently found[25] to be eleven-co-ordinate, with a co-ordinated water molecule.

The steric strain calculated for the potassium complex with L^7 is very high. One cannot, of course, directly compare strain in different molecules, but the strain observed in the L^7 complexes is much higher than one would expect simply from the addition of extra methyl groups. There is here van der Waals repulsion between the C-methyl groups of L^7 and the rest of the ligand in the potassium complex, as also seen in the space-filling drawing in Fig. 3(*b*). One would, however, expect this steric hindrance to become more severe as the metal ions becomes smaller. The fact that the medium-sized Cd^{2+} shows enhanced complex stability with L^7 relative to larger metal ions such as Ba^{2+} can best be explained in terms of the inductive effects of the C-methyl groups on the basicity of the nitrogen donor atoms, in this case not outweighed by adverse steric effects. A metal ion such as Cd^{2+} is a stronger Lewis acid than Ba^{2+}, and so should respond more strongly to inductive effects. An additional factor is that smaller metal ions such as Cd^{2+} may have lower co-ordination numbers than larger metal ions such as Ba^{2+}, and so actually be less sterically crowded.

A referee has commented that Kollman and co-workers[26] have reported a modification to their force field in which the charges on the atoms are obtained by *ab initio* calculation, and that this might improve the ability of the AMBER type of force field to predict structural features of crown ether complexes more accurately. Undoubtedly this will improve the energies predicted by this approach, but in view of our experience that the structural features are largely insensitive to the charge used it seems doubtful that this aspect would be improved. The poorer agreement between calculated and observed structural features found for the AMBER model appears to derive from the way in which the bonds are modelled. The M–L bond lengths are too easily stretched in the AMBER model for reasons already discussed. At the same time the reproduction of M–O–C bond angles tends to be poor because there are no force constants associated with these angles that would tend to make them the ideal value of 109.5°, as in the case with the Boyd model. This relates to the placement of the charge on the donor atom itself, whereas a more realistic representation would be to offset the charge onto the lone pair of the donor atom, which could then favour a K–O–C bond angle of 109.5°. The AMBER model of crown ether complexes of alkali-metal ions has as major advantages the ability to vary co-ordination number, and the prediction of energies of interaction of alkali-metal ions with crown ethers, which account very well for aspects of their chemistry such as the selectivity that they display towards metal ions of different sizes. It must be stressed that the work reported here on the type of model where the K–L bonds are represented by ideal bond lengths and angles, and their associated force constants, is only exploratory, and aimed at seeing how well such an approach would work for alkali metal ions. We believe that the results suggest that for structural analysis such an approach might be quite useful.

Conclusion

The added pendant groups on the nitrogens of the diaza crowns studied differ in their effects on complex stability. The 2-hydroxyethyl group is sterically considerably more efficient than the other groups examined. The 2-methoxyethyl group leads to high levels of steric crowding with a general drop in complex stability, which is more serious for smaller metal ions. The 2-hydroxy-1,1-dimethylethyl group leads to steric crowding in complexes, but the inductive effects of the C-methyl groups appear to dominate steric effects, so that the effect on complex stability is opposite to that of the 2-methoxyethyl group. The tetrahydrofurfuryl group is more sterically efficient than 2-methoxyethyl, but not as efficient as 2-hydroxyethyl, and simply produces a uniform lowering in complex stability relative to the 2-hydroxyethyl pendant group. Selectivity for medium-sized metal ions such as Cd^{2+} or Ca^{2+} can be promoted by the presence of 2-hydroxy-1,1-dimethylethyl substituents.

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