

# 1,4,7,10-Tetrakis(2-hydroxyethyl)-1,4,7,10-tetra-azacyclododecane: a Strong Cation Complexer

Solfrid Buøen,<sup>a</sup> Johannes Dale,<sup>a</sup> Per Groth,<sup>a</sup> and Jostein Krane<sup>b</sup>

<sup>a</sup> Kjemisk institutt, Universitetet i Oslo, Oslo 3, Norway

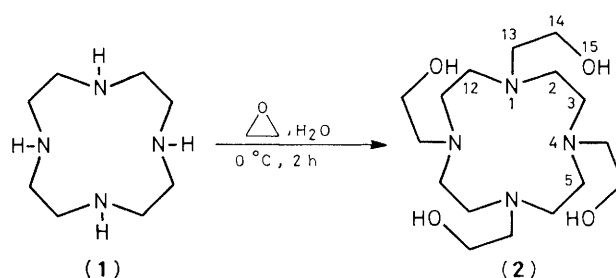
<sup>b</sup> Kjemisk institutt, NLHT, Universitetet i Trondheim, Trondheim, Norway

The title compound uses a varying number of side-arm ligating atoms for the complexation of alkali cations, leading to penta-, hepta-, and octa-co-ordination for Li<sup>+</sup>, Na<sup>+</sup>, and K<sup>+</sup>, respectively, and for tetrahedral encapsulation of a water molecule, while the conformation of the 12-membered ring remains the same.

Amino-ether ligands designed to fit cubic octa-co-ordination of cations the size of Na<sup>+</sup>, Ca<sup>2+</sup>, and La<sup>3+</sup> should include at least one twelve-membered ring, with its predictable and well-defined 'square' conformation,<sup>1</sup> and have amino nitrogen as bridge-heads or branching points. We have already reported examples involving aza-12-crown-4 rings joined by one<sup>2</sup> or by two<sup>3</sup> ethylene bridges, and confirmed the perfect cubic octa-co-ordination of the Na<sup>+</sup> complex of the latter by *X*-ray crystallography.<sup>4</sup>

A similar co-ordination topology might be expected if the tetra-aza-12-crown-4 (1)<sup>5</sup> is provided with 2-hydroxyethyl side-arms to give the tetrapodand (2). Attempts to hydroxyethylate the aza-crown (1) with ethylene oxide failed when it was partially protonated or when NaCl was present, as is the case in standard procedures, the base being liberated *in situ* with NaOH from its tetrahydrochloride. On the other hand, hydroxyethylation of the salt-free base in pure water is remarkably fast, and the product (2) crystallizes directly as the monohydrate, m.p. 90–92 °C, unchanged after drying under high vacuum (Scheme 1).<sup>†</sup>

The complexation properties of (2) were studied in various solvents by titration with dry salt, monitored by <sup>13</sup>C n.m.r. spectroscopy.<sup>7</sup> Alkaline earth metal salts form particularly strong 1:1 complexes as witnessed by a slow-exchange spectrum at room temperature of a 1:1 mixture of complexed and free ligand. For calcium bis(toluene-*p*-sulphonate) in dimethylformamide (DMF) the signals have not coalesced even at 126 °C, implying a decomplexation barrier higher than 20 kcal/mol.<sup>‡</sup> Alkali metal salts also give 1:1 complexes, but ligand exchange is fast at room temperature. The titration curves have sharper bends for Li<sup>+</sup> and Na<sup>+</sup> than for K<sup>+</sup>. Cooling of 1:1 mixtures of complexed and free ligand caused signal splitting for lithium toluene-*p*-sulphonate in DMF (*T*<sub>c</sub> –3 °C, Δ*G*<sup>‡</sup> = 13.5 kcal/mol) and for NaSCN in



Scheme 1

methanol (*T*<sub>c</sub> –5 °C, Δ*G*<sup>‡</sup> ca. 13 kcal/mol). The <sup>13</sup>C n.m.r. signal (in methanol) for the ring carbons moved only moderately upfield (ca. 1 p.p.m.) on complexation, suggesting a similar ring conformation in the hydrate and in the cation complexes. The <sup>13</sup>C n.m.r. signal for the side-chain NCH<sub>2</sub> carbons, on the other hand, was much more sensitive, moving 1.9 p.p.m. upfield in the Li<sup>+</sup> complex and 2.1 p.p.m. downfield in the K<sup>+</sup> complex, Na<sup>+</sup> being intermediate (ca. 0.6 p.p.m. upfield). This suggests more profound conformational differences for the side-arms in these three complexes.

The crystal structures of the three alkali metal cation complexes of ligand (2), as well as of the monohydrate, have now been determined by *X*-ray diffraction (Table 1).§ The essential part of these structures, the conformation chosen by the ligand, and its interaction with the cation (or H<sub>2</sub>O), is shown in Figure 1. The complex (2)·2LiCl·2H<sub>2</sub>O [Figure 1(a)] contains one penta-co-ordinated Li cation, involving the cyclic ligand with one side-arm bent in; the other Li cation is tetra-co-ordinated, with contacts not to the nitrogens of any ring, but to rejected side-arm hydroxy-groups and water

<sup>†</sup> A semi-solid, formed among other cyclo-oligomerization products from *N*-(2-hydroxyethyl)aziridine, has been claimed to have this tetrameric structure.<sup>6</sup> No mention has been made of its complexation properties.

<sup>‡</sup> 1 kcal = 4.184 kJ.

§ The details of the *X*-ray analyses will be published in *Acta Chem. Scand.* The atomic co-ordinates for this work are available on request from the Director of the Cambridge Crystallographic Data Centre, University Chemical Laboratory, Lensfield Road, Cambridge CB2 1EW. Any request should be accompanied by the full literature citation for this communication.

Table 1. Crystallographic data for the three alkali metal cation complexes of ligand (2) and of the monohydrate.

Complex	(2)·2LiCl·2H <sub>2</sub> O	(2)·NaSCN	(2)·KSCN	(2)·H <sub>2</sub> O
Space group	<i>P</i> 2 <sub>1</sub> / <i>n</i>	<i>Pna</i> 2 <sub>1</sub>	<i>P</i> 2 <sub>1</sub> / <i>n</i>	<i>P</i> 1̄
<i>a</i> /Å	10.388(6)	24.980(5)	11.015(4)	7.022(2)
<i>b</i> /Å	19.719(5)	9.304(2)	31.863(10)	9.680(3)
<i>c</i> /Å	11.778(12)	9.295(2)	12.988(3)	14.709(5)
α/°	—	—	—	97.38(2)
β/°	91.00(5)	—	94.30(2)	92.10(3)
γ/°	—	—	—	96.99(2)
<i>Z</i>	4	4	8	2
<i>D</i> <sub>m</sub> /g cm <sup>-3</sup>	1.22	1.28	1.25	1.22
<i>D</i> <sub>c</sub> /g cm <sup>-3</sup>	1.29	1.32	1.30	1.24
Observed reflections	2387	1709	5306	2221
<i>R</i> /%	5.4	3.5	6.6	5.6
<i>R</i> <sub>w</sub> /%	3.8	3.0	6.5	4.2

molecules. In the complex (2)·NaSCN [Figure 1(b)] the Na cation is hepta-co-ordinated, making use of only three side-arms, even though octa-co-ordination is observed when two twelve-membered rings are provided, be it separately<sup>1</sup> or by a single ligand.<sup>4</sup> Only in the complex (2)·KSCN [Figure 1(c)] are all four side-arms used to make the K cation octa-co-ordinated; its relative weakness must therefore be due to the

need for still higher co-ordination and to a poor matching of ligand topology to the large size of K<sup>+</sup>.¶ In none of these structures is there any direct anion-cation contact. Ligand

¶ The crystals contain two disordered complexes in the asymmetric unit, and Figure 1(c) shows one of the four independent but essentially identical complexes.

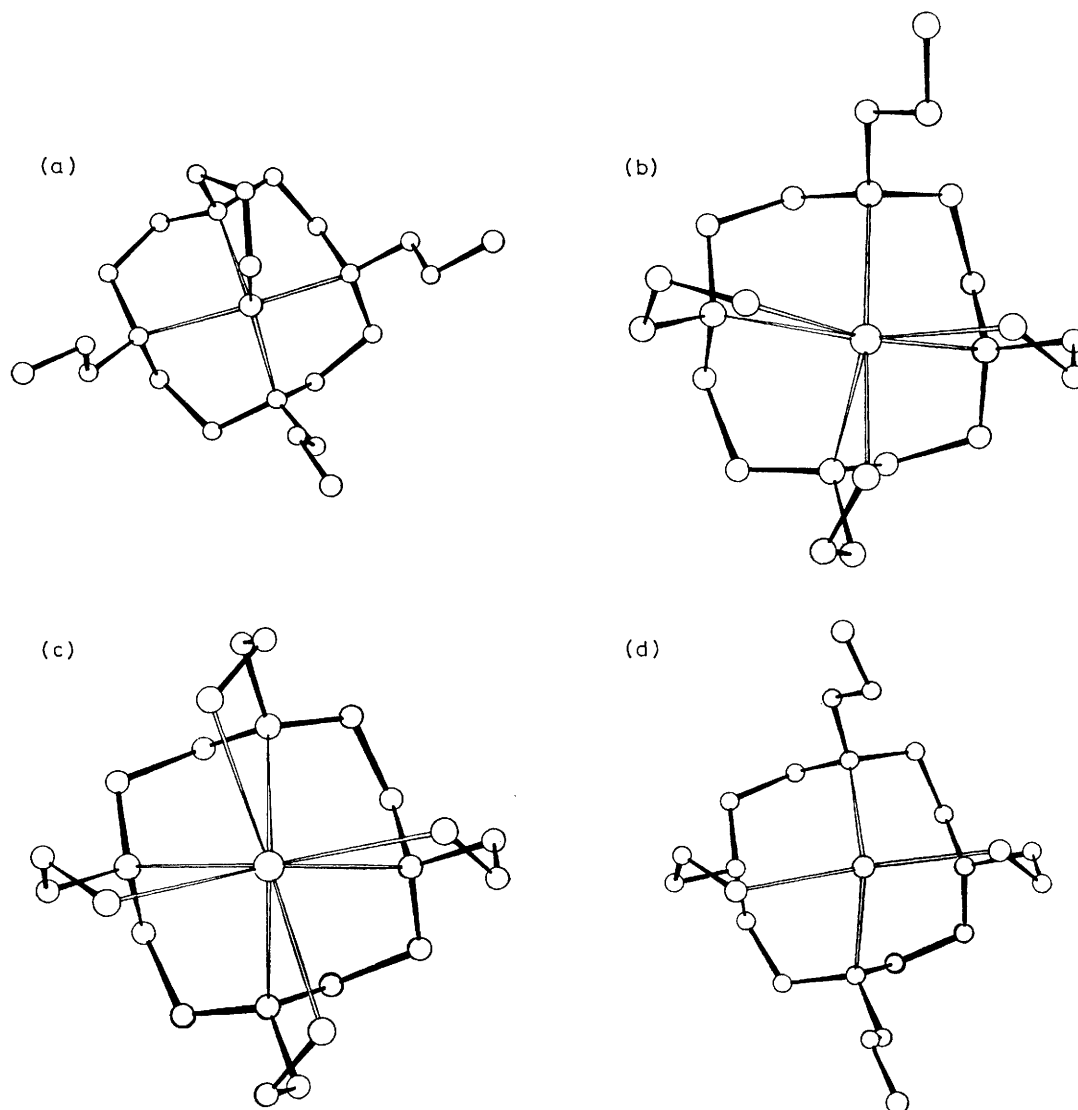


Figure 1. The crystal conformation of the tetrapodand (2) in its complexes with (a) Li<sup>+</sup> in (2)·2LiCl·2H<sub>2</sub>O, (b) Na<sup>+</sup> in (2)·NaSCN, (c) K<sup>+</sup> in (2)·KSCN, and (d) as its monohydrate.

Table 2. Torsion angle<sup>a</sup> sets (in degrees) each comprising a ring monomer unit of (2) and its attached side-arm.<sup>b</sup>

Complex	Number of units averaged	Ring			Side-chain	
		C(5)N(4)-C(3)C(2)	N(4)C(3)-C(2)N(1)	C(3)C(2)-N(1)C(12)	C(2)N(1)-C(13)C(14)	N(1)C(13)-C(14)O(15)
(2)·2LiCl·2H <sub>2</sub> O	1 <sup>c</sup>	-160	61	86	82	51
	3 <sup>d</sup>	-163	54	80	84	-174
(2)·NaSCN	3 <sup>c</sup>	-162	61	78	78	60
	1 <sup>d</sup>	-162	60	75	77	-177
(2)·KSCN	4 <sup>c</sup>	-163	65	72	85	72
(2)·H <sub>2</sub> O	2 <sup>c</sup>	-164	62	74	84	68
	2 <sup>d</sup>	-156	69	69	81	-176

<sup>a</sup> Estimated standard deviations are less than 1° except for the KSCN complex where it is less than 2°. <sup>b</sup> A side-arm is defined as belonging to that ring unit whose corner carbon [C(2) in this numbering scheme] adjoins the common nitrogen [N(1)]. <sup>c</sup> Unit(s) with side-arm bent in. <sup>d</sup> Units with rejected side-arm.

(2) can thus be considered a sensitive probe for the optimal co-ordination number of  $\text{Li}^+$  and  $\text{Na}^+$ .

The hydrate structure [Figure 1(d)] provides the missing link, the use of two side-arms. The water molecule is completely encapsulated, tetrahedrally, donating two hydrogen bonds to two diametric ring nitrogens and receiving two hydrogen bonds from side-arms attached to the other two nitrogens.

The most striking structural feature is the recurrence of the same familiar ring conformation<sup>1</sup> in all four structures. The values of the torsion angles (Table 2) vary only slightly as a natural consequence of the adjustment of the donor-acceptor distances, and the modest upfield displacement of ring-carbon  $^{13}\text{C}$  n.m.r. signals is thus explained. Also the side-arms follow a single pattern predictable by conformational analysis of rotational isomers about the  $\text{N}(1)\text{—C}(13)$  bond; they invariably bend off towards the ring 'corner.'<sup>1</sup> When the side-arm is rejected, the  $\text{C—C}$  bond is *anti-*, and when it co-ordinates to the cation (or water molecule) it is *gauche* with the same helicity as the corner bonds of the ring (*cf.* the cage complex given in refs. 3 and 4). Accommodation to the varying size of the cation occurs mainly by adjustment of this *gauche* torsion angle (Table 2). It is difficult to correlate these structural results with the observed variations in  $^{13}\text{C}$  n.m.r.

chemical shift for the  $\text{NCH}_2$  carbon. The numerical value of the  $\text{C—C}$  *gauche* torsion angle shows a clear trend, but then the  $\text{OCH}_2$  carbon signal should also vary as strongly, which it does not. However, the ratio between used and rejected side-arms need not be the same in solution and in the crystal.

Further n.m.r. studies at such low temperatures that side-arm site exchange becomes frozen, are clearly needed.

Received, 21st June 1982; Com. 710

## References

- 1 For a review, see: J. Dale, *Isr. J. Chem.*, 1980, **20**, 3.
- 2 M. J. Calverley and J. Dale, *J. Chem. Soc., Chem. Commun.*, 1981, 684.
- 3 M. J. Calverley and J. Dale, *J. Chem. Soc., Chem. Commun.*, 1981, 1084.
- 4 P. Groth, *Acta Chem. Scand., Ser. A*, 1981, **35**, 717.
- 5 J. E. Richman and T. J. Atkins, *J. Am. Chem. Soc.*, 1974, **96**, 2268.
- 6 G. E. Ham in 'Polymeric Amines and Ammonium Salts,' ed. E. J. Goethals, Pergamon Press, 1980, p. 1.
- 7 For details *cf.* M. J. Calverley and J. Dale, *Acta Chem. Scand., Ser. B*, 1982, **36**, 241.