Protonated azacryptate hosts for nitrate and perchlorate

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Encapsulation of nitrate and perchlorate within two protonated cryptate hosts $[H_6L^1]^{6+}$ and $[H_6L^2]^{6+}$, as studied by potentiometric and NMR titration methods, showed dominant 1:1 complexation for both anions. Complexation constants, log K, with $[H_6L^1]^{6+}$ and $[H_6L^2]^{6+}$ are, generally, high at 3.7 and 3.4 for nitrate, and ≈ 3.4 and ≈ 2.5 for perchlorate, respectively. Good geometric complementarity was confirmed in the case of perchlorate and $[H_6L^2]^{6+}$ by an X-ray crystallographic structure determination of the inclusive anion cryptate. For nitrate, there is evidence for 1:2 complexation in the presence of a large excess of anion, relative 1:1 and 1:2 complexation constants being in the approximate ratio $10^3:1$.

Oxoanion co-ordination chemistry, although still in its infancy, is now recognised as an important and developing branch of chemistry,[1] because of potential applications in transport, selectivity, and catalysis which match those by now well developed for cation complexation. The bioinorganic relevance of such chemistry is emphasised by the fact that each positively charged centre in biology is associated with one or more (often oxoanionic) negatively charged centres, which have to be located, transformed and transferred across membranes in the same way as cations.[2] Complexation of anions is however a challenging task on account of their relatively large size and high free energy of solvation, which reduces the chances of successful competition by the co-ordination site of any host provided. In contrast to the obvious manifestations of cation complexation in solution, many anions are relatively silent spectroscopically, which makes anion complexation more difficult to monitor. Among the few techniques generally applicable to the study of anion complexation in solution are potentiometry and NMR spectroscopy, although it must be noted that the results from these solution studies sometimes appear at variance[3] with information obtainable from solid state techniques such as X-ray crystallography.

Polyammonium macrocyclic receptors are among the most widely studied hosts for anions and these studies have often been quantitative, exploiting the host-related technique of pH-metry.[4,5] For oxoanions, stability constants show a charge-dependent increase from monoanions such as perchlorate to di- and tri-anions such as sulfate and phosphate, but stability constants vary with the match between host and guest dimensions;[5] for greatest efficiency the size and shape of the host must be complementary to that of each particular anionic guest. Given that the thermodynamic constants for anion complexation can never be expected to approach the large values commonplace in cation complexation, it can be important to include in the design of ligands a strategy for achieving maximum kinetic stability against dissociation (i.e. unfavourable dissociation kinetics). While carefully designed polychelates have proved useful anion receptors in certain circumstances[6] it is more usual that macrocycles, bicycles or even tricycles[7,8] should be exploited in this role in order to achieve a combination of good kinetic and thermodynamic stability. With macrotricycles the hosts so far synthesized have been restricted

to encapsulation of single halide ions, where a large macrotricyclic effect has been noted.[8] However, in comparison with macrobicyclic hosts, results have often been disappointing because the steric rigidity inherent in the tetrahedral host skeleton used can militate against successful matching of host/guest dimensions.[7]

The hexaprotonated macrobicycle O-bistrenH$_6^{6+}$ {O-bistrenH$_6^{6+}$ = N[(CH$_2$)$_2$NH$_2^+$(CH$_2$)$_2$O(CH$_2$)$_2$NH$_2^+$(CH$_2$)$_2$]$_3$N} is sufficiently flexible to adapt to a range of guest geometries and has been used to good effect in the encapsulation of many anions including oxoanions. pH-Metric techniques have been used to monitor the complexation.[4] However, as no X-ray crystallographic data are available for oxoanion complexes of this host, it is not possible to state whether the complexation is wholly exclusive or whether one or more anions are included in the cryptand cavity.
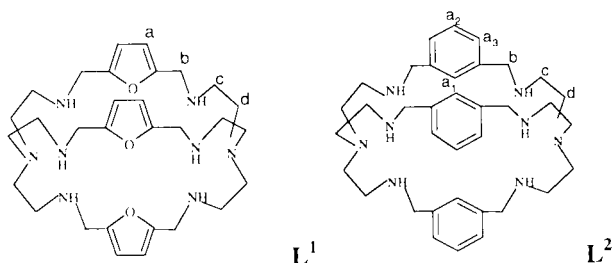
In 1994 we discovered that the series of Schiff-base derived azacryptands which we had been studying[9] over the previous five years as hosts for cations have an effective oxoanion-complexing facility when protonated. Our structure of a perchlorate cryptate of the furan-spaced aminocryptand $[H_6L^1]^{6+}$ was the first structurally characterised example[10] of an inclusive oxoanion cryptate. This structure, together with that of an inclusive hexafluorosilicate cryptate of a related host, demonstrates the importance of good complementarity of fit between the polyammonium host and anionic guests having tetrahedral or octahedral geometry. This implies that our protonated aminocryptand hosts represent effective receptors for complex anions with trigonal symmetry, including the environmentally significant nitrate ion.

Nitrate is currently one of the highest priority oxoanion targets for complexation studies. There are serious ecological effects from overuse of nitrate-based fertiliser, and, increasingly, evidence accumulates of the adverse effects to human health of exposure to excessive amounts of nitrate, for example in drinking water, where it may pose a significant health risk and has been implicated in high incidences of lymphomas.[11a,c] A communication[11b] reporting the structure of a dinitrate cryptate of $[H_6L^2]^{6+}$ together with an anomalously large stability constant for the corresponding aqueous solution species has already appeared. One of our first aims in the solution complexation studies of protonated aminocryptand hosts

Table 1 Chemical shifts[a] for free cryptands and their protonated salts[b]

Compound	H_{a1}	H_{a2}	H_{a3}	H_b	H_c		H_d
L^2	7.54 (tr)	7.43 (d)	7.20 (s)	3.62 (s)		2.44 (s)	
$[H_6L^2]^{6+}$	—	7.80 (m)	—	4.26 (s)	3.33 (s)		2.84 (s)
		H_a			H_b	H_c	H_d
L^1		6.35 (s)			3.77 (s)		2.57 (m)	2.90 (d)
$[H_6L^1]^{6+}$		6.77 (s)			4.41 (s)	3.38 (d)	2.90 (d)

[a] In D_2O; ppm from TMS. [b] As bromide.

L^1 L^2

was to establish and verify the nitrate complexation strength of our azacryptate ligands.

Perchlorate monitoring is also becoming increasing important in the USA (and will be mandatory from next year) where levels of this oxoanion are becoming increasingly widespread due to its presence in solid rocket fuel.[11d]

In this paper we report the solution complexation properties, for nitrate and perchlorate ion, of the polyammonium furan- or *m*-xylyl-spaced cryptate hosts $[H_6L^1]^{6+}$ and $[H_6L^2]^{6+}$ as measured both by pH-metric and NMR titration methods.

Results and discussion

The cryptates show NMR protonation shifts which are anion-dependent and can be used to monitor complexation equilibria (Table 1). At ambient temperatures the methylene CH_2 signals are undifferentiated, *i.e.* they fail to resolve into separate pseudo-axial and pseudo-equatorial resonances, and the H_b singlet was selected for NMR monitoring because of its simplicity and its sensitivity to anion complexation. The program EQNMR [12] was used to analyse the behaviour of the signal as a function of oxoanion concentration [in tosylate (toluene-*p*-sulfonate) supporting electrolyte] in order to determine the stoichiometries and stabilities of the complexes formed. The studies were carried out at pH 3 where the host is known [13] to be in its hexaprotonated form.
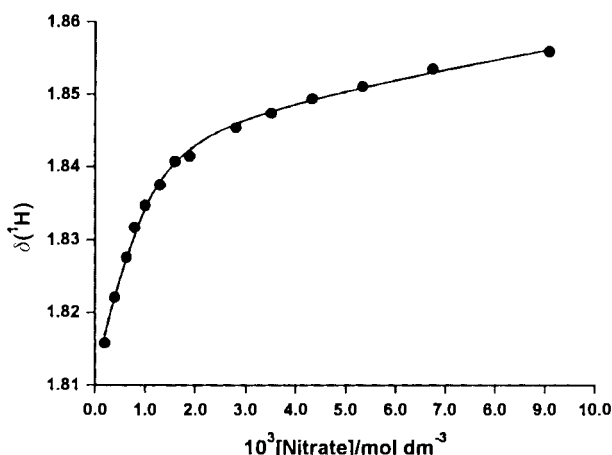
Nitrate complexation

From the dependence of chemical shift on concentration of added nitrate anion to the *m*-xylyl- and furan-spaced protonated cryptates $[H_6L^2]^{6+}$ and $[H_6L^1]^{6+}$, stability constants, log K, of the order of 3–4 calculated on a simple model of 1 : 1 complexation, were indicated. The agreement between the experimental chemical shift data and those calculated using the equilibrium constant together with the chemical shifts of the "free" and complexed ligand was good; nonetheless, some systematic error was evident.

While nitrate binding constants obtained by this analysis were gratifyingly large, near the top end of the range of those recorded for nitrate encapsulation, and a factor of around four times larger than that seen with the superficially similar host [4] O-bistrenH$_6^{6+}$, it is interesting that they provide evidence for predominantly 1 : 1 complex formation in aqueous solution. 1 : 2 Complexation of anions has been reported [14] for large aza-macrocycles and the recent report [11b] of the crystal structure of a hexanitrate complex of $[H_6L^2]^{6+}$ demonstrates encapsulation of a pair of nitrate anions within the cavity of this cryptand in the
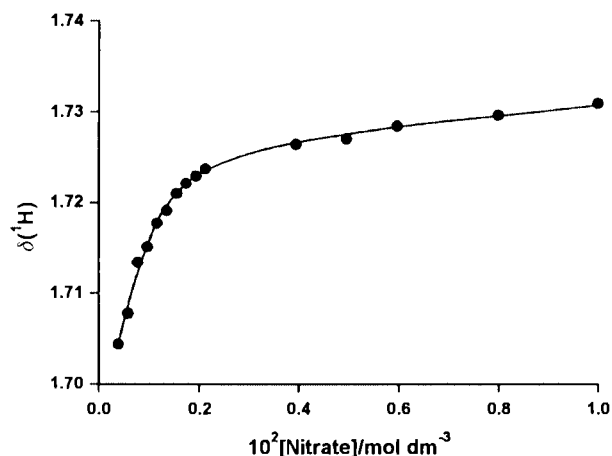
Fig. 1 Plot of δ_H for H_b of L^2 *vs.* [NO$_3^-$] in D_2O. Circles represent experimental points, the solid line shifts calculated using the best-fit parameters assuming simultaneous formation of 1 : 1 and 1 : 2 complexes. Chemical shifts are reported as differences from the δ 2.39 methyl resonance of tosylate.

**Fig. 2** Plot of δ_H for H_b of L^1 *vs.* [NO$_3^-$] in D_2O. Details as in Fig. 1.

solid state. Preliminary numbers of around log K_1 = 3.0 mol^{-1} l for the formation of 1 : 1 and log K_2 = 2.4 mol^{-2} l^2 for 1 : 2 nitrate complexes of $[H_6L^2]^{6+}$ were indicated,[11b] although no experimental details were supplied. We accordingly allowed our model to include formation of the 1 : 2 complex for both protonated hosts as shown in Figs. 1 and 2. The fit to the data noticeably improved on inclusion of this species, although log K values for 1 : 2 nitrate complexation are tiny: of the order only of 0.2 (*i.e.* $K \approx$ 1.5–2 mol^{-2} l^2), implying that a vanishingly small proportion of 1 : 2 complex is present at equilibrium under the conditions of our NMR experiments (Fig. 3). This analysis of the equilibrium was confirmed by repeating the experiment using a large excess of nitrate and separately evaluating the constant for 1 : 2 nitrate complexation; this refined the estimate of K_2 as 1.87 ± 0.73 mol^{-1} l for $[H_6L^2]^{6+}$ (Fig. 4). The analysis requires assumption of a much larger shift in the H_b resonance position for 1 : 2 complexation (*i.e.* 0.44 and 1.54 ppm respect-

Table 2 Protonation constants, log K, in various media

(a) For L^2

	0.1 mol dm^{-3} NaOTs[a]	0.1 mol dm^{-3} Et$_4$NClO$_4$[13]	0.1 mol dm^{-3} NaClO$_4$[a]	0.1 mol dm^{-3} KNO$_3$[b]	0.1 mol dm^{-3} NaNO$_3$[a]
log K_1	10.5 ± 0.1	9.8 ± 0.3	10.0 ± 0.1	9.92	10.27 ± 0.08
log K_2	9.34 ± 0.05	9.17 ± 0.06	9.1 ± 0.1	9.26	9.43 ± 0.09
log K_3	8.59 ± 0.08	8.5 ± 0.2	8.2 ± 0.1	8.75	8.57 ± 0.09
log K_4	7.1 ± 0.2	7.21 ± 0.04	7.29 ± 0.05	7.67	7.69 ± 0.05
log K_5	6.2 ± 0.1	6.9 ± 0.1	6.72 ± 0.04	7.16	6.7 ± 0.1
log K_6	5.22 ± 0.04	6.70 ± 0.05	6.54 ± 0.1	6.59	6.4 ± 0.2
Σ log K	46.95 ± 0.6	48.3 ± 0.8	47.9 ± 0.5	49.35	49.11 ± 0.7

(b) For L^1

	0.1 mol dm^{-3} NaOTs[a]	0.1 mol dm^{-3} NaClO$_4$[a]	0.1 mol dm^{-1} NClO$_4$[13]	0.1 mol dm^{-3} NaNO$_3$[a]
log K_1	9.7 ± 0.1	8.95 ± 0.07	9.2 ± 0.3	9.3 ± 0.1
log K_2	8.91 ± 0.03	8.6 ± 0.1	8.7 ± 0.2	8.65 ± 0.03
log K_3	8.18 ± 0.03	7.81 ± 0.02	8.0 ± 0.2	7.97 ± 0.05
log K_4	6.78 ± 0.1	6.91 ± 0.02	6.6 ± 0.1	6.95 ± 0.07
log K_5	5.99 ± 0.01	6.1 ± 0.1	5.93 ± 0.03	6.6 ± 0.1
log K_6	4.63 ± 0.03	5.8 ± 0.1	5.76 ± 0.06	5.9 ± 0.1
Σ log K	44.23 ± 0.2	44.2 ± 0.05	44.2 ± 0.9	45.46 ± 0.5

[a] This work, analysis via SUPERQUAD. [b] Reference 20, no error limits supplied.
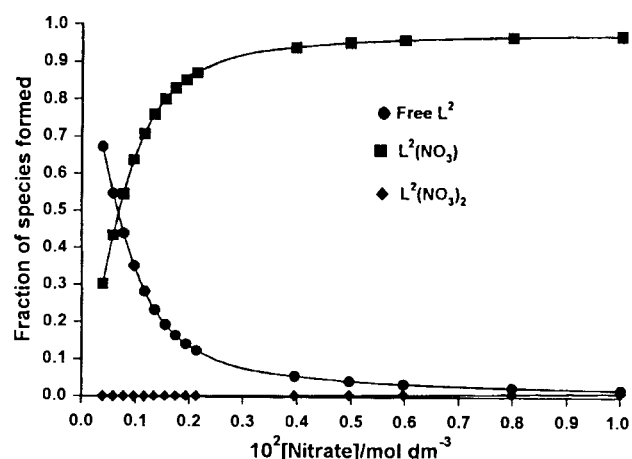
Fig. 3 Fraction of species present as a function of $[NO_3^-]$ in the L^2–NO_3^- system.
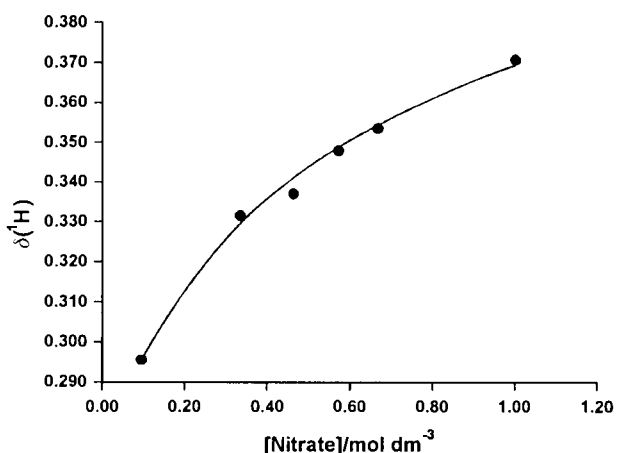
Fig. 4 Plot of δ_H for H_b of L^2 vs. $[NO_3^-]$ in D_2O using a large excess of nitrate. Circles represent experimental points, the solid line shifts calculated using the best-fit parameters assuming formation of only the 1 : 2 complex.

ively for $[H_6L^2]^{6+}$ and $[H_6L^1]^{6+}$) than for 1 : 1 complexation (0.03 ppm for both hosts) which suggests a significant alteration of conformation and thus disposition of the aromatic ring current on accommodation of the second nitrate guest. This conform-

Table 3 Complexation constants, log K_1, for different anions with ligands $[H_6L^2]^{6+}$ and $[H_6L^1]^{6+}$

Ligand	NMR[a] (NO$_3^-$)	pH[b] (NO$_3^-$)	NMR[a] (ClO$_4^-$)	pH[b] (ClO$_4^-$)
$[H_6L^2]^{6+}$	3.74 ± 0.09	3.73 ± 0.06	3.53 ± 0.04	3.25 ± 0.06
$[H_6L^1]^{6+}$	3.63 ± 0.09	3.35 ± 0.07	2.66 ± 0.13	2.29 ± 0.04

[a] Using EQNMR. [b] From analysis of data in Table 2.

ational effect appears to be more important for $[H_6L^1]^{6+}$, in keeping with studies on cascade complexation[15] where the furan-spaced host appears to offer a more sterically constrained cavity than other 1,5 linked cryptands. The log K values for 1 : 1 complexation in the two ligand systems (see Table 3) are barely significantly different, although the value is marginally higher for $[H_6L^2]^{6+}$.

We have also estimated equilibrium constants for oxoanion encapsulation by analysis of the results of pH-metric titrations carried out in e.g. nitrate vs. tosylate supporting electrolyte, assuming no interference from supporting electrolyte in the latter case. Table 2 lists the protonation constants obtained in various supporting electrolytes. The difference in K values across the various media, in particular K_5 and K_6, reflects the contribution of anion complexation to the equilibria of the more highly protonated species. For $[H_6L^2]^{6+}$ a nitrate binding constant log K of 3.73 ± 0.06 (vs. tosylate) was obtained. Table 3 compares the complexation constants evaluated potentiometrically with those obtained using the EQNMR program. There was no evidence for formation of the 1 : 2 species under the potentiometric conditions (consistent with the NMR results above).

All K values reported are conditional constants relative to those for tosylate medium (the notional standard for anion complexation). Given the different nature of the titrations employed, exact agreement between the potentiometric and NMR titration data may not be expected. In potentiometry pH is monitored as alkali is added incrementally to a solution of host plus anion, while in NMR the chemical shift of a solution of the host is monitored as increments of anion are added at constant pH. While NMR is not generally considered a very sensitive technique for the determination of equilibrium constants, under the experimental conditions of the present work it is likely to provide a more reliable measure of the constants for
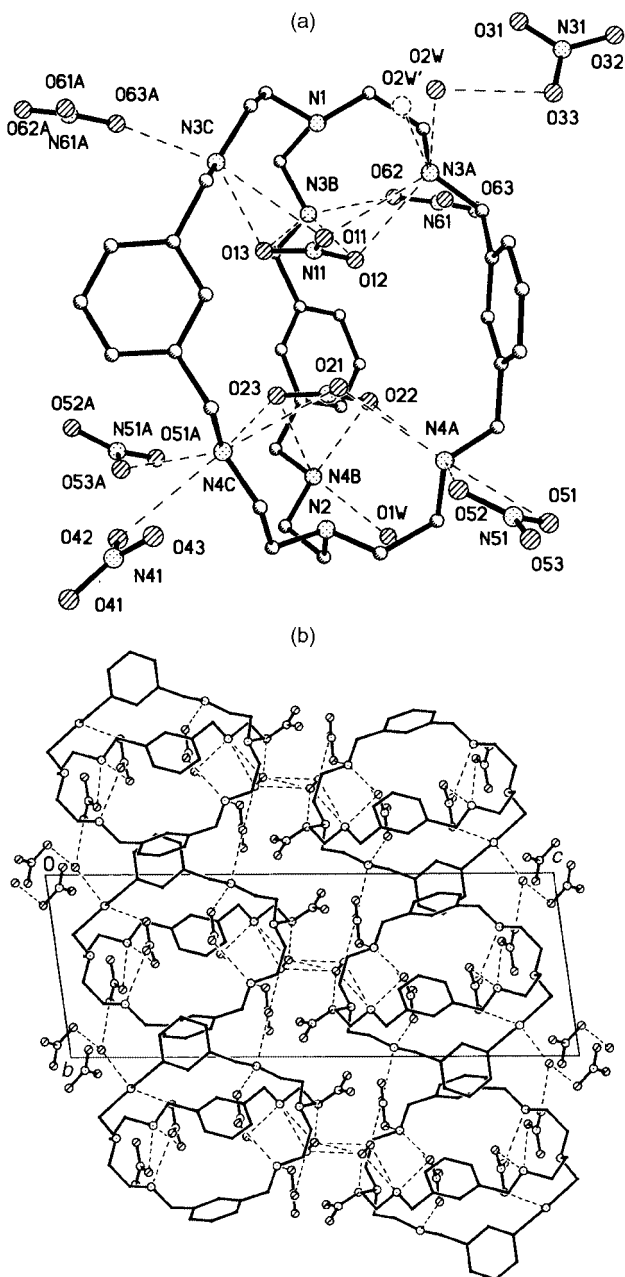
Fig. 5 (a) Illustration of hydrogen bonding interactions involving encapsulated nitrate, cryptand NH⁺ and associated waters in compound **3**. (b) Packing diagram showing the hydrogen bond network in **3**.

anion association as only the hexaprotonated host species is considered. However the greater sensitivity of the potentiometric approach can allow the contribution of other protonated species to anion association to be assessed. Nevertheless surprisingly good agreement between the two techniques was obtained. Analysis of the potentiometric data revealed no evidence for anion association with ligands in protonation states lower than six.

We have also studied by pH-metric methods the complexation of nitrate by the furan-linked aminocryptand $[H_6L^1]^{6+}$ (Table 3). Once more we note sizeable complexation constants, log K_1, of 3.35 ± 0.07 for nitrate, relative to tosylate, which are just significantly lower, given error limits, than those obtained with the EQNMR method.

The generally good agreement of results from NMR and potentiometric methods emphasises the conclusion that under both sets of experimental conditions the 1:2 complex is not present in significant amount. In order to try to rationalise the differences between our results and the earlier report[11b] which indicates significant dinuclearity in both solid state and solu-
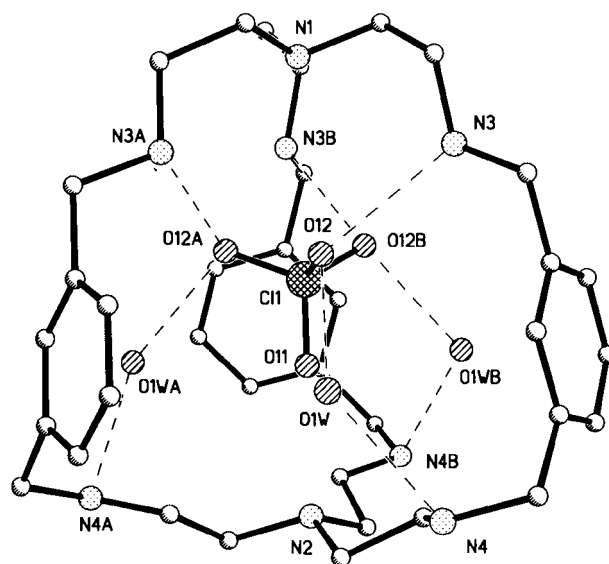

Fig. 6 Illustration of hydrogen bonding interactions involving encapsulated perchlorate, cryptand NH⁺ and associated waters in compound **1**.

tion, we decided to obtain the structure of a crystal isolated from solution of the ligand in 0.1 mol dm⁻³ HNO₃ left to evaporate slowly in air, in case this might reveal the existence of an alternative, *e.g.* mononitrate cryptate structure. However, this structure **3** (Fig. 5a) turned out to be a dinitrate cryptate identical with that communicated in preliminary fashion[11b] by Bowman-James and co-workers, leading to the conclusion that in this $[H_6L^2]^{6+}$ system anion nuclearity in the solid state cryptate differs from that normally applying in aqueous solution. The hydrogen-bonding network (Fig. 5b) involved in retention of nitrate anions includes water molecules and runs through the whole structure apart from the areas occupied by aromatic rings; the shortest hydrogen-bonds actually operate between NH⁺ and the water which tethers exclusive nitrate anions (Table 4).

Perchlorate complexation

During this work we obtained X-ray quality crystals of the hexaperchlorate, **1**, of $[H_6L^2]^{6+}$. The complex (Fig. 6) crystallises in the chiral cubic space group $P2_1$ 3. The cryptand lies on a 3-fold axis as do three perchlorate anions; the asymmetric unit also contains one full occupancy perchlorate anion. The protonated cryptand acts as host for one perchlorate guest which is hydrogen-bonded to three symmetry-related amines at one end of the cage {O(12)···N(3) 2.790(5) Å} and indirectly to the other set of amines *via* water molecules {O(12)···O(1W) 2.782(5) Å and O(1W)···N(4) 2.712(6) Å}. The perchlorate oxygen atom lying on the 3-fold axis does not appear to be involved in hydrogen bonding but is surprisingly close to the bridgehead nitrogen atom {O(11)···N(2) 2.559(4) Å}. The relatively strong hydrogen-bonding network involving the other three oxygen atoms is responsible for the unsymmetric "Easter egg" shape of the host. The combination of amino NH⁺··· anion O⁻ hydrogen bonding and remnant hydration shell interactions that we observe here is frequently found in oxoanion cryptate systems.[10,16] Molecular dynamics simulations[17] on the similar polyether (2,2,2) cryptand system (4,7,13,16,21,24-hexaoxa-1,10-diazabicyclo[8.8.8]hexacosane) indeed predict such remnant hydration to be important in solute–solvent interactions. All but one of the exclusive perchlorate anions in **1** are also hydrogen bonded to NH⁺, and there is a one-dimensional chain connecting the protonated host molecules *via* hydrogen-bonded NH⁺···OClO···NH⁺ bridges.

While estimates of binding constants (log $K \leq 1$)[5a] for perchlorate measured potentiometrically with O-bistrenH₆⁶⁺

Table 4 Hydrogen bonds distances (Å) and angles (°)

(*a*) For compound **1**

D–H···A	d(D–H)	d(H···A)	d(D···A)	DHA
N(3)–H(3A)···O(42)#1	0.92	2.07	2.953(6)	159.7
N(3)–H(3B)···O(12)	0.92	1.88	2.790(5)	170.7
N(3)–H(3B)···O(12)#2	0.92	2.58	3.028(5)	110.5
N(4)–H(4A)···O(32)	0.92	2.26	2.975(6)	133.8
N(4)–H(4A)···O(41)#3	0.92	2.37	2.992(6)	124.8
N(4)–H(4B)···O(1W)	0.92	1.83	2.712(6)	159.3
O(1W)–H(1WA)···O(12)	1.08	1.75	2.782(5)	159.8
O(1W)–H(1WB)···O(43)#4	0.92	2.26	3.049(6)	142.6

Symmetry transformations used to generate equivalent atoms: #1 $x + \frac{1}{2}, -y + \frac{3}{2}, -z$; #2 $-y + \frac{3}{2}, -z + 1, x - \frac{1}{2}$; #3 $z, x + 1, y - 1$; #4 $-z + \frac{1}{2}, -x + 1, y - \frac{1}{2}$.

(*b*) For compound **3**

D–H···A	d(D–H)	d(H···A)	d(D···A)	DHA
N(3A)–H(3A1)···O(2W)#1	0.96	1.85	2.769(3)	159.2
N(3A)–H(3A1)···O(2W′)#1	0.96	1.86	2.730(3)	148.2
N(3A)–H(3A2)···O(11)	0.89	2.02	2.8819(15)	162.8
N(3A)–H(3A2)···O(12)	0.89	2.31	3.0244(15)	137.2
N(4A)–H(4A1)···O(21)	0.94	1.90	2.8415(14)	175.4
N(4A)–H(4A1)···O(22)	0.94	2.35	2.9882(15)	124.5
N(4A)–H(4A2)···O(52)	0.92	1.89	2.8058(15)	175.1
N(3B)–H(3B1)···O(12)	0.88	1.97	2.8384(16)	170.4
N(3B)–H(3B1)···O(13)	0.88	2.39	3.0386(16)	130.4
N(3B)–H(3B2)···O(62)#2	0.95	1.91	2.8582(16)	171.9
N(4B)–H(4B1)···O(1W)	0.93	1.77	2.6632(16)	159.6
N(4B)–H(4B2)···O(22)	0.89	1.99	2.8595(15)	164.1
B(4B)–H(4B2)···O(23)	0.89	2.33	3.0350(16)	136.0
N(3C)–H(3C1)···O(63)	0.93	1.92	2.8209(15)	162.1
N(3C)–H(3C2)···O(13)	0.91	1.98	2.8781(16)	169.5
N(3C)–H(3C2)···O(11)	0.91	2.28	2.9518(15)	129.8
N(4C)–H(4C1)···O(23)	0.92	1.99	2.8968(16)	170.9
N(4C)–H(4C1)···O(21)	0.92	2.33	2.9814(15)	127.5
N(4C)–H(4C2)···O(53)#3	0.88	2.11	2.8992(15)	149.2
N(4C)–H(4C2)···O(42)#4	0.88	2.48	3.0580(18)	123.8
O(1W)–H(1WA)···O(53)#5	0.94	1.91	2.8467(16)	171.5
O(1W)–H(1WA)···O(52)#5	0.94	2.64	3.2076(16)	119.0
O(1W)–H(1WB)···O(41)#6	0.93	1.99	2.8877(17)	161.8
O(1W)–H(1WB)···O(42)#6	0.93	2.47	3.1837(17)	133.4
O(2W)···O(33)			2.697(3)	
O(2W)···O(62)			2.941(3)	
O(2W)···O(2W)#7			2.773(5)	
O(2W)···O(2W′)#7			2.887(3)	

Symmetry transformations used to generate equivalent atoms: #1 $x - 1, y, z$; #2 $x, y - 1, z$; #3 $x + 1, y, z$; 4 $x, y + 1, z$; #5 $x + 1, y - 1, z$; #6 $-x + 2, -y, -z$; #7 3 $- x, 1 - y, 1 - z$.

(the only other perchlorate cryptate to be investigated in this way to date) are an order of magnitude smaller than those obtained for nitrate, and this weak co-ordination has been used to justify the use of perchlorate as reference supporting electrolyte in anion binding studies, we have good crystallographic evidence for efficient encapsulation of perchlorate in both of our cryptand hosts. The geometric complementarity between trigonal host and tetrahedral anion leads to enhanced receptor properties as confirmed by evaluation of binding constants not much smaller than those measured for nitrate complexation. Tables 2 and 3 include perchlorate binding constants for $[H_6L^2]^{6+}$ evaluated by EQNMR and potentiometry respectively as 3.53 ± 0.04 and 3.25 ± 0.06. As with the nitrate–L^1 system, the EQNMR analysis gives a value just marginally higher than does potentiometric analysis. The analysis of perchlorate ion encapsulation by $[H_6L^2]^{6+}$ is an excellent fit to the 1:1 model and thus provides no evidence for the existence of anion nuclearity different from one. For $[H_6L^1]^{6+}$ we see the smallest binding constants for perchlorate. The potentiometric technique gives a binding constant of 2.29 ± 0.04, while the EQNMR result is again higher at

2.66 ± 0.13. The greater discrepancy noted between the two techniques in this relatively weakly complexing system is not surprising given the higher errors particularly in the EQNMR determination.

The crystal structure of the perchlorate cryptate of L^1, **2**, which exhibits disorder over two orientations at 180° to each other, illustrates a looser fit [10] for the perchlorate ion than is revealed in the present work for the L^2 analogue, where the fit is so neat that no disorder can exist. This presumably explains the lower binding constant observed.

Structural comparisons of anion cryptates of $[H_6L^2]^{6+}$ and $[H_6L^1]^{6+}$ emphasise the role of hydrogen bonding between protonated cryptand host and *external* oxoanions, with or without water intermediacy, in contributing to the stabilisation of the oxoanion cryptate structure. Although the co-operative effect of several weaker interactions results in stabilisation of the inclusive oxoanion site it is instructive that the shortest hydrogen-bond contacts in all cases are to water (Table 4). In the $[H_6L^2]^{6+}$ perchlorate structure **1** and its $[H_6L^1]^{6+}$ analogue **2** the shortest hydrogen-bonds are between NH^+ and water tethered to the inclusively bonded anion, while in the dinitrate

structure of $[H_6L^2]^{6+}$ **3** the externally directed $NH^+ \cdots water \cdots$ nitrate hydrogen-bonds are shortest. In extrapolation of X-ray crystallographic information to the solution phase, where most projected applications operate, it is thus crucially important to remember that thermodynamic parameters are governed by the properties of the entire system.

Conclusion

Comparison of the binding constants obtained by two different methods shows that the protonated aminocryptands studied represent good hosts for the oxoanions nitrate and perchlorate. The advantage over the previously studied cryptand host, O-bistren, is twofold in that the cost is significantly lower while the affinity for oxoanions is significantly higher. The hypothesis, based on an X-ray crystallographic structure determination,[11b] that the 1(L):2(NO$_3$) complex is an appreciable solution species is not borne out by our measurements which show the 1:2 complex to be a very minor constituent unless nitrate is present in large (>100-fold) excess.

Perchlorate binding in the solid state is illustrated by the X-ray crystallographic structure of an inclusive perchlorate cryptate where both hydration and hydrogen bonding interactions contribute to the stability. Structural data are here in agreement with EQNMR studies implying that the 1:1 complex is the only solution species.

One moral to be drawn from this work is that the evidence of X-ray crystallography may not validly be extrapolated to solution equilibria involving anions, as solubility effects can easily lead to crystallisation of minor constituents of the equilibrium mixture. It is thus important that solution properties of any proposed anion sequestration system should be thoroughly studied.

Experimental

Ligands L^1 and L^2 were prepared as described elsewhere.[13] These were used for synthesis of cryptates as described below.

Syntheses

$[H_6L^2(ClO_4)][ClO_4]_5 \cdot 3H_2O$ 1. 5 cm^3 conc. HClO$_4$ were added to an ethanolic solution of 0.2 g L^2 dissolved in the minimum of EtOH and stirred for 30 minutes. A white precipitate was filtered off and recrystallised from 5:1 MeOH–water. The solution was left to stand for about a week until colourless crystals appeared. This recrystallised product was obtained in about 15% yield. IR/cm^{-1}: ClO$_4^-$, v_3 1100, (br)vs; v_4 624ms (sh); v_1 926mw; v_2 456mw. +ve ES-MS: clusters centred about m/z 400, $[LH_4(ClO_4)_2]^{2+}$; 350, $[LH_3(ClO_4)]^{2+}$; 599.6, $[LH^+]$; and 699.5, $[LH_2(ClO_4)]^+$. −ve ES-MS: m/z 800, $[LH(ClO_4)_2]^-$; and 897.4, $[LH_2(ClO_4)_3]^-$.

$[H_6L^2(NO_3)_2][NO_3]_4 \cdot 2H_2O$ 3. 0.05 g L^2 was dissolved in 5 cm^3 0.1 mol dm^{-3} HNO$_3$ and left to stand at RT uncovered in air. Crystals appeared in around a week as square colourless blocks in about 20% yield. IR/cm^{-1}: NO$_3^-$, v_3 (br, structured) 1360; (max.),1454, 1320 (br)vs; $v_1$1008ms (sh); v_2 802, 765mw. +ve ES-MS: clusters centred about m/z 331.8, $[LH_2(NO_3)]^{2+}$; 363.3 $[LH_4(NO_3)_2]^{2+}$; 394.4, $[LH_5(NO_3)_3]^{2+}$; 599.5, $[LH]^+$; 662.5, $[LH_2(NO_3)]^+$; 725.4, $[LH_3(NO_3)_2]^+$; and 788.4 $[LH_4(NO_3)_3]^+$. −ve ES-MS: 723.4, $[LH(NO_3)_2]^-$; 786.4, $[LH_2(NO_3)_3]^-$; and 849.4, $[LH_3(NO_3)_4]^-$.

NMR

NMR spectra were recorded at 500 MHz in D$_2$O. Each NMR tube contained a 1 ml solution of ligand [10^{-3} mol dm^{-3}], from a stock solution of hexaprotonated cryptand salt, with sufficient HOTs (Ts = toluene-p-sulfonyl) to keep the pH at ≈3; the ionic strength was adjusted to 0.1 mol dm^{-3} with NaOTs. Successive

additions of NaNO$_3$ were made and in no case precipitation occurred. The shift recorded for the H$_b$ methylene peak (calibrated relative to the tosylate resonance at δ 2.39) during the addition gave the input data for the EQNMR program which were used to determine the anion complexation constant.

Potentiometry

All potentiometric titrations were performed at 25 °C under nitrogen, using carbonate-free NaOH and millimolar ligand concentrations. The protonation constants were determined from titrations of a ligand solution containing a small excess of HOTs in the presence of sufficient NaOTs to maintain ionic strength at 0.1 mol dm^{-3}. The oxoanion binding constants were then determined from titrations of ligand solutions containing a small excess of the appropriate oxyacid in the presence of oxoanion salt (ionic strength 0.1 mol dm^{-3}). To avoid Cl$^-$ ingress the calomel reference electrode was jacketed with an 0.01 mol dm^{-3} solution of the appropriate electrolyte. Before and after each set of titrations, the glass electrode was calibrated as an [H$^+$] probe by titration of $ca.$ 0.1 mol dm^{-3} standard HCl solution with standard KOH. Stability constants were calculated with the program SUPERQUAD[18] (average of at least 4 different titrations in each case). For calculation of the oxoanion binding constants, the protonation constants were fixed at their values determined in tosylate medium and an additional constant was included and refined for 1:1 ligand–anion association.

X-Ray crystallography

Data for $[H_6L^2(ClO_4)][ClO_4]_5 \cdot 3H_2O$ **1** were collected using a Siemens P4 diffractometer with Mo-Kα radiation. Data for $[H_6L^2[NO_3]_2][NO_3]_4 \cdot 2H_2O$ **3** were collected on line 9.8 of the Synchrotron radiation source at Daresbury CLRC. The structures were solved by direct methods and refined by full matrix least squares on F^2, using all the independent reflections.

The non-hydrogen atoms were refined with anisotropic atomic displacement parameters and hydrogen atoms were inserted at calculated positions, except for those on the full-occupancy water molecules, which were located and not further refined and those on the disordered water in $[H_6L^2[NO_3]_2][NO_3]_4 \cdot 2H_2O$, which were not included. All programs used in the structure solution and refinement are contained in the SHELX 97 package[19] and the data collection and refinement details are summarised in Table 5.

Table 5 Crystal data and structure refinement for compounds **1** and **3**

	1	3
Empirical formula	$C_{36}H_{66}Cl_6N_8O_{27}$	$C_{36}H_{64}N_{14}O_{20}$
Formula weight	1255.67	1013.01
T/K	153(2)	150(2)
Wavelength, λ/Å	0.71073	0.69230
Crystal system	Cubic	Triclinic
Space group	$P2_13$	$P\bar{1}$
a/Å	17.443(2)	10.1676(8)
b/Å	17.443(2)	10.3453(8)
c/Å	17.443(2)	25.510(2)
$\alpha/°$		80.453(2)
$\beta/°$		84.666(2)
$\gamma/°$		62.182(2)
V/Å^3	5307.5(12)	2339.9(3)
Z	4	2
μ/mm^{-1}	0.419	0.118
Reflections collected	6903	21993
Independent reflections	3141	11319
	[R(int) = 0.0487]	[R(int) = 0.0364]
Data/restraints/parameters	3141/0/232	11319/0/640
Final $R1$, $wR2$ [$I > 2\sigma(I)$]	0.0554, 0.1196	0.0441, 0.1238
(all data)	0.0795, 0.1307	0.0582, 0.1272
Absolute structure parameter	0.07(10)	

CCDC reference number 186/2040.

See http://www.rsc.org/suppdata/dt/b0/b003249m/ for crystallographic files in .cif format.

Acknowledgements

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