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Selectivity for dinegative *versus* mononegative oxoanionic guests within a cryptand host

Beatrice M. Maubert,[ab] **Jane Nelson,**[ab] **Vickie McKee,**[c] **Raewyn M. Town**[a] **and Ibolya Pál**[a]

[a] *School of Chemistry, Queen's University Belfast, UK BT9 5AG*
[b] *Open University, Milton Keynes, UK MK7 6AA*
[c] *Department of Chemistry, University of Loughborough, UK LE11 3TU*

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In the structures of three new oxoanion cryptates (M = Cr(VI), Se(VI) and SSO_3^{2-}) of a protonated azacryptate host: $H_6L(MO_4^{2-})(ClO_4)_4$ the dinegative anion invariably occupies the crypt, providing evidence of selectivity with respect to the mononegative analogue; solution studies support this observation.

Coordination chemistry of oxoanions now approaches the priority attached to cation coordination, because of the many applications which may attend a successful outcome.[1,2] Thus, as many oxoanions are environmental targets on account of the high aqueous and low organic solubility that leaves them pervasive and persistent pollutants in surface water,[1] a host ligand capable of altering their solubility would be of considerable interest; while for other oxoanions used as redox agents, the possibility of redox properties tunable *via* encapsulation is an attractive prospect. Anions are of considerable importance in biology, especially in relation to the oxoanion condensation and hydrolysis which drives the energetics of so many biochemical processes.[3] For yet other oxoanions, the objective may be to use host ligation to transport a radiochemically active anion to a specific biomedical target. So, in anion as in cation coordination chemistry, the target properties are specificity, efficient transport, and catalysis.

Some years ago we discovered that the azacryptand ligands which we have exploited in transition and main group cation coordination chemistry[4] make good hosts for anions when protonated.[5] We have since established[6] stability constants in the order of log $K \approx 3$ for mononegative oxoanions encapsulated within these hosts. This implies, given the significantly greater stability constants expected for dinegative anions, that these protonated azacryptate systems should represent effective hosts for multiply charged oxoanions of trigonal or tetrahedral geometry. One of the essential properties of an anion host is the ability to select for a particular guest on the basis of charge and/or geometry; to extend our work toward examination of such selectivity we have synthesised cryptates of tetrahedral dinegative oxoanions including three with particular environmental/ biological significance: CrO_4^{2-}, SeO_4^{2-} and SSO_3^{2-}.

Chromate is of particular concern environmentally given its status as a recognised carcinogen, and the high local concentrations arising from use in particular industrial processes.[7] The very soluble selenate anion similarly shows high local concentrations associated with mining processes. Although selenium is an essential element at low concentration, it is toxic at higher levels being a suspected mutagen (teratogen) and growth inhibitor.[8] The third anion, thiosulfate, contains the labile sulfane sulfur atom which is believed to have natural regulatory functions; it is now believed that deficiency in sulfur metabolism can be related to disease states such as cancer, virus infection and immunodeficiency,[9] so the chemistry and biochemistry of sulfane sulfur-containing species currently attracts increasing attention.

We have generated crystals of three oxoanion cryptates, $[H_6L^1(MO_4)](ClO_4)_4 \cdot nH_2O$ (**1**: M = Cr, **2**: M = Se and **3**: SSO_3^{2-}) involving encapsulated dinegative oxoanions.† The cryptates **1**–**3** were made by treatment of the perchlorate salt of $[H_6L^1]^{6+}$, **4**,‡ with the potassium or sodium salt of the dinegative oxoanion. Irrespective of the relative starting concentrations of mono- and di-negative anion in the synthesis mixture, the MO_4^{2-} ion was invariably found encapsulated within the cryptate cavity. In preliminary synthetic experiments we have shown that the dinegative anion cryptate is still obtained at a perchlorate : dianion ratio of 100 : 1. In contrast, in preliminary experiments where the differently sized mononegative anions perrhenate and perchlorate are allowed to compete for the cavity site, no selectivity was exhibited, and the product obtained reflected the proportion of anions in the synthetic starting mixture.[10]

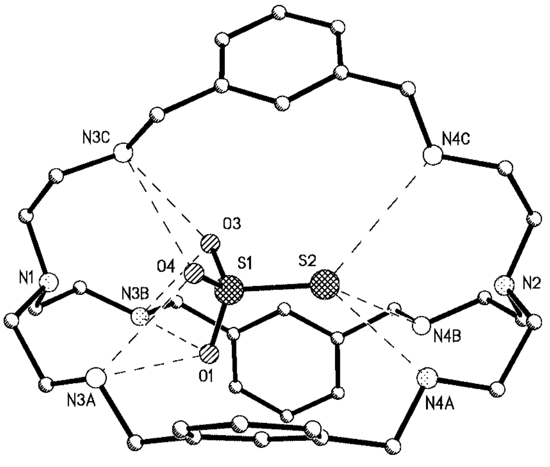

Fig. 1 The $[(H_6L^1)(S_2O_3)]^{4+}$ cation. Hydrogen bonds are shown as dashed lines.

The dimensions of the bound chromate and selenate anions are very similar and these are significantly larger than in the analogous bound perchlorate ion[6] in **4** (mean M–O distances for **1**, **2** and **4** are 1.624, 1.637 and 1.468 Å, respectively). The mean S–O distance in thiosulfate (1.476 Å) is comparable to that of perchlorate but the long S–S bond (1.994(1) Å) and the larger radius of the sulfur atom mean that there are significant differences in the binding of these two anions. Notably, each of the guest anions forms a larger number of direct hydrogen bonds to the host crypt than was the case for the encapsulated perchlorate (**4**), they also show different host–guest geometry.

Fig. 1 shows the binding of $S_2O_3^{2-}$ within the H_6L^1 cavity. The cation has approximate three-fold symmetry, although the conformation of the cryptand strand including N3C and N4C is different from the other two. In contrast to the other anions in this series, thiosulfate is able to use all four of its acceptor sites to bind directly to all six protonated amines. The anion is bound by six NH···O and three NH···S interactions (Table 1). This suggests a good fit between host and guest although the presence of a few rather long H-bonds implies the fit is not optimal.

The encapsulated anions in **1** and **2** are bound in almost

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Table 1 Hydrogen bonds between encapsulated anion and cryptand

	1	2	3
O1	2.766(8) N3B 2.841(9) N3A	2.820(6) N3A 2.924(6) N3B	3.059(4) N3B 3.214(5) N3A
O2/S2	2.950(9) N4B 3.214(10) N4A	2.927(6) N4A 3.116(6) N4B	3.298(3) N4B 3.455(3) N4A 3.491(3) N4C
O3			2.852(4) N3C 2.957(4) N3B
O4	2.75(3) N3C 2.75(4) N3C′	2.653(12) N3C 2.913(13) N3C′	2.861(4) N3A 3.087(4) N3C

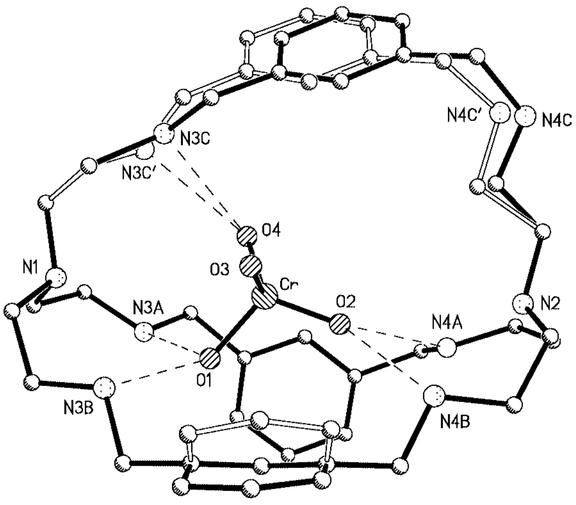

Fig. 2 $[(H_6L^1)(CrO_4)]^{4+}$ showing the disorder in the cryptand.

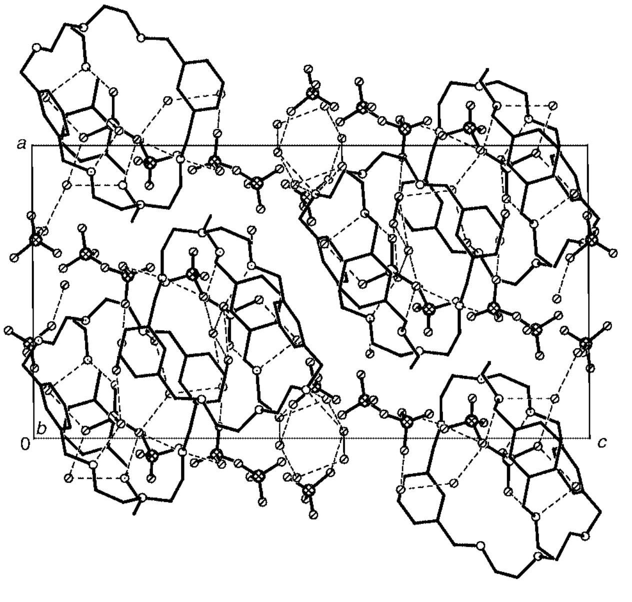

Fig. 3 Packing diagram for $[(H_6L^1)(SeO_4)](ClO_4)_4 \cdot 8.5H_2O$. The minor components of disordered species have been omitted for clarity.

identical fashion, the chromate complex is shown in Fig. 2. The arrangement is less symmetric than for either the perchlorate or thiosulfate analogs. One of the protonated amines is not involved in bonding to the central anion and this section of the cryptand is disordered. Lattice water and perchlorate oxygen atoms take up the remaining hydrogen-bonding sites on both cryptand and encapsulated anion, generating rings and chains running through the crystal lattice (Fig. 3). Full tables of these interactions can be calculated from the CIF.

The vibrational spectrum indicates no more than slight alteration in bond order following encapsulation; thus in **2** the strong SeO_4^{2-} ν_3 absorption appears at 857 cm^{-1} compared with 877 cm^{-1} for the potassium salt in the same medium (KBr disc). In **1** ν_3 together with the normally IR-forbidden ν_1 appear as a medium intensity 878, 800 cm^{-1} doublet compared to the strong 890 and weak 847 cm^{-1} absorption seen in the potassium salt, intensification of ν_1 reflecting the low symmetry siting of the anion. In the thiosulfate cryptate, **3** where the intense $\nu_{as}(SO_3)$ absorption is obscured by ν_3 of ClO_4^-, sharp peaks can be seen at 991 cm^{-1} due to the symmetric (SO_3) stretching mode (ν_s) and at 661 cm^{-1} ν_1(S–S) which are close to ν_1 and ν_2 frequencies in the sodium salt of the free anion (999 and 667 cm^{-1} respectively).

Before examining solution properties of these anion complexes, we wished to establish the integrity of the anion cryptate in solution. As the protonation and condensation equilibria of free aqueous chromate ion are well-known, one ready way of investigating this is to examine the response of the chromate cryptate to pH change. At the pH of the solution from which the chromate cryptate was isolated, equilibrium favours the dinuclear $Cr_2O_7^{2-}$ oxoanion as well as the monoprotonated hydrogen chromate ion from which it derives, over CrO_4^{2-}, so isolation of the chromate cryptate, **1**, in the mononuclear unprotonated form was unexpected. In aqueous solution the spectroscopically estimated $CrO_4^{2-} : HCrO_4^-$ ratio in the presence of cryptand is enhanced four times compared with that in its absence; alteration of pH from 5.85 to 5.45 by adding NaOAc–HOAc buffer decreases this ratio by only 50% in the cryptated system *versus* 300% when no cryptand is present. The tendency of chromate ion to remain in the unprotonated state and thus within the cryptate testifies to kinetic stability against decomplexation, a property of importance in many applications.

It is of interest that the strongly oxidising chromate ion is able to coexist, at least in the short term, with the potentially oxidizable aminocryptand host, L^1. Although the cryptate **1** is stable indefinitely in the solid state, there is evidence of its slow decomposition in aqueous solution, noticeable over 1–2 hours. The more strongly oxidising permanganate ion decolourised immediately on contact with this ligand while the more weakly oxidising perrhenate ion was unaffected. Given the redox-active nature of many of the encapsulated anions it will be of interest to discover whether encapsulation is associated with any alteration of redox potential.

We are currently undertaking the determination, by both potentiometric and NMR titration methods,[6] of aqueous complexation constants of dinegative anions by L^1, and will describe these results in detail shortly.[11] Preliminary results using the NMR method indicate log K values around 4.0 ± 0.1 for SeO_4^{2-} and SSO_3^{2-} (*versus* the normal tosylate standard[6]) confirming the implication of structural and synthetic data that the protonated host shows selectivity for dinegative *versus* mononegative oxoanions. The slow decomposition of the chromate cryptate over the time scale of our experiments means that we are at present unable to report a reliable complexation constant for that system.

The preliminary evidence presented here for kinetic stabilization and selectivity of dinegative *versus* mononegative anionic guests augurs well for the future development of anion sequestering agents based on these promising hosts.

Acknowledgements

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Notes and references

† The three data sets were collected at 150 K and each structure was solved by direct methods and refined against F^2 using the SHELXTL package.[12] All three diffract weakly (**1** and **3** were collected on line 9.8 of the SRS at Daresbury). The crystal data indicate that the structures of **1**, **2** and **3** are close to isomorphous. They differ in the extent of

disorder present (which can be related to the host–guest fit) and the apparent difference in hydration is probably due to a lack of definition in the disordered structures; the apparent occupancy of the water sites decreases as the extent of disorder increases. In **3** two of the perchlorate anions show some disorder of the oxygen atoms. In **2** one strand of the cryptand is disordered over two conformations, three of the perchlorates are disordered and the lattice water molecules have been modelled as four full-occupancy sites and ten partial ocupancy sites. In **1** two strands of the cryptand show disorder, three perchlorates are disordered, water molecules modelled as four full occupancy and six half-occupancy sites. Restraints were applied to the geometry of the perchlorate anions (SAME) and to the ADPs of the disordered sections (ISOR, DELU). The combination of very small crystals, weak data and severe disorder limits the precision of this structure, although the main features have been unambiguously established. Hydrogen atoms bonded to carbon and nitrogen were inserted at calculated positions; hydrogen atoms of solvate water molecules were located for **3** and not further refined, those for **1** and **2** were not included in the refinement.

CCDC reference numbers 159484, 159485 and 161207. See http://www.rsc.org/suppdata/dt/b1/b101832i/ for crystallographic data in CIF or other electronic format.

1 $[(H_6L^1)(CrO_4)](ClO_4)_4{\cdot}7H_2O$, $C_{36}H_{73.50}Cl_4CrN_8O_{27}$, FW 1244.33, $a = 14.321(3)$, $b = 14.050(3)$, $c = 27.431(5)$ Å, $\beta = 90.372(4)°$, $V = 5519.5(17)$ Å^3, monoclinic $P2_1/n$, $Z = 4$, $\mu = 0.492$ mm^{-1}, 29246 reflections collected, 10467 independent, $R_{int} = 0.0785$, $R1 = 0.1412$, $wR2 = 0.3779$ $[I > 2\sigma(I)]$, $R1 = 0.2048$, $wR2 = 0.4034$ (all data).

2 $[(H_6L^1)(SeO_4)](ClO_4)_4{\cdot}8.5H_2O$, $C_{36}H_{77}Cl_4N_8O_{28}Se$, FW 1298.82, $a = 14.476(1)$, $b = 13.9235(9)$, $c = 27.5511(18)$ Å, $\beta = 90.3820(10)°$, $V = 5552.9(6)$ Å^3, monoclinic $P2_1/n$, $Z = 4$, $\mu = 0.963$ mm^{-1}, 53095 reflections collected, 9787 independent, $R_{int} = 0.0586$, $R1 = 0.0742$, $wR2 = 0.2071$ $[I > 2\sigma(I)]$, $R1 = 0.0983$, $wR2 = 0.2303$ (all data).

3 $[(H_6L^1)(S_2O_3)](ClO_4)_4{\cdot}11H_2O$, $C_{36}H_{82}Cl_4N_8O_{30}S_2$, FW 1313.02, $a = 14.6926(4)$, $b = 13.7829(4)$, $c = 28.5979(2)$ Å, $\beta = 91.140(1)°$, $V = 5790.1(2)$ Å^3, monoclinic $P2_1/n$, $Z = 4$, $\mu = 0.371$ mm^{-1}, 30687 reflections collected, 10904 independent, $R_{int} = 0.0557$, $R1 = 0.0669$, $wR2 = 0.0881$ $[I > 2\sigma(I)]$, $R1 = 0.0881$, $wR2 = 0.2081$ (all data).

‡ **CAUTION:** perchlorates should be treated with care because they are potentially explosive and must not be subject to friction or heating in the solid state. However under the conditions of the experimental procedures described here we experienced no problems.

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