Solid-state and solution complexation of cobalt(iii) sepulchrate by a water-soluble calix[6]arene host

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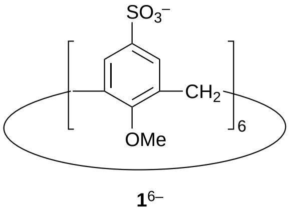
A calix[6]arene hexasulfonate host forms a stable 1 : 1 complex with cobalt(III) sepulchrate in aqueous media while a 2 : 1 guest : host stoichiometry is observed in the solid state.

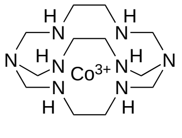
Calixarenes are versatile hosts for inclusion complexation due to their flexible cavities, availability in various sizes, and rugged skeletons amenable to diverse functionalization.[1] Various calixarene complexes involving metal ions[2] and organic molecules[3] have been reported. We have also recently reported on ferrocene and viologen complexes involving calixarene hosts.[4]

In 1977 Sargeson and coworkers reported the facile preparation of the caged metal-ion complex cobalt(iii) sepulchrate (**2**$^{3+}$).[5a] The unusual stabilization of certain metal-ion oxidation states as well as other structural and electronic properties exhibited by this and related complexes prompted numerous investigations.[5] Several prominent examples are the incorporation of sepulchrate complexes in photochemical water-splitting systems,[6a–c] the attachment of sepulchrates to protein backbones to study electron-transfer reactions,[6d] and the recent incorporation of sepulchrate in an electrochemical sensor for H_2 and H_2S.[6e] The literature also contains several reports of ion-pairing interactions involving sepulchrates and relatively simple anions, but the corresponding association constants are rather low (*e.g.* K = 100 dm^3 mol^{-1} for SO_4^{2-} at I = 0.01).[7] Here we report on the complexation of cobalt sepulchrate by sulfonated calix[6]arene host **1**$^{6-}$.† While second-sphere coordination of metal-ion complexes is a well known phenomenon,[8] to the best of our knowledge, this is the first report on the complexation of metal-ion sepulchrates.

The strong interaction between **1**$^{6-}$ and **2**$^{3+}$ was immediately apparent upon preparing a dilute solution of the two compounds in D_2O for NMR analysis. A precipitate appeared which was assumed to be a complex since both compounds are extremely water soluble. Elemental analysis of the dried precipitate revealed a 2 : 1 stoichiometry (**2**$^{3+}$: **1**$^{6-}$) with no counter ions. This ratio makes the complex electrically neutral, thus explaining its low solubility in water. Since the interaction seemed to be largely driven by electrostatics, further studies were conducted in aqueous 0.2 m NaCl in order to be able to use larger concentrations of the compounds without precipitation. A ^{1}H NMR spectroscopic binding study performed in D_2O (0.2 m NaCl) gave a binding constant of 1 600 dm^3 mol^{-1}. This is one of the stronger binding constants reported for a calixarene complex, the strongest ones being around 10^4 dm^3 mol^{-1},[3] and the value would surely be much higher in pure water where there is no electrolyte to shield the charges from each other. The NMR chemical shift data perfectly fit a 1 : 1 binding model and, therefore, the interaction in high ionic strength media seems to be bimolecular. The direction (to higher field) and magnitude of the complexation induced shifts on the sepulchrate proton resonances ($\Delta\delta_{comp}$ −0.45 ppm) both suggest that the sepulchrate is at least partially included by the anionic calixarene host.



1^{6-}



2^{3+}

Solution flow calorimetry (in 0.2 m NaCl) was used to corroborate the NMR binding results and to gain insight into the thermodynamic parameters involved.‡ The resulting calorimetric data gave values of −1.0 kcal mol^{-1} (1 cal = 4.184 J) for $\Delta H°$ and 3.4 kcal mol^{-1} for $T\Delta S°$ at 298 K. This translates into a $\Delta G°$ of −4.4 kcal mol^{-1} or K = 1 770 dm^3 mol^{-1} (again the data perfectly fit a 1 : 1 complex stoichiometry). Not only is this in excellent agreement with our NMR data, but it points to a large entropic driving force for complexation. Even though there is a large favourable enthalpic change in bringing two such highly charged species together, this is cancelled by the unfavourable enthalpy associated with unsheathing them from their solvation spheres. The return of these water molecules to the bulk, however, carried with it a substantially favourable and uncompensated entropic change which drives the complexation process.

Crystals suitable for X-ray crystallographic analysis grew from the flow calorimetry effluent solution that was left standing for a few weeks. The unit cell consists of four sepulchrate and two calixarene units along with several water molecules but no counter ions (see Fig. 1).§ This confirms the electroneutral termolecular stoichiometry of the complex in the solid state suggested by the elemental analysis. Interestingly, the calixarene molecules exhibit a configuration similar to that reported for the solid state structure of the pure unmethylated calixarene analogue even though the intramolecular hydrogen bonds involving the partially deprotonated phenolic groups, which are detected in the latter,[2b] are not possible in **1**$^{6-}$. To our knowledge, this is the first reported crystal structure for calixarene **1**$^{6-}$.

The crystal structure shows the calixarene to be in a rather disorganized conformation with four of the sulfonate groups pointing outwards from the central cavity, one pointing up and the other down. The closest atomic distances between the two ionic components are between the sepulchrate's secondary amine protons and the sulfonate oxygen atoms (dotted lines) on the calixarene. Since hydrogen bonding and electrostatic interactions would be much stronger with the sulfonate groups than with the methoxy groups, these, along with the lack of inclusion complexation, seem to be the main organizing features dominating the structural organization of the solid state lattice. Indeed, the lattice seems to be a net of these ionic/hydrogen bonds with each calixarene bonded to two in-plane sepulchrates through single hydrogen bonds and to one sepulchrate above or below through a bifurcated hydrogen bond. No inclusion complexation is apparent from the crystal structure suggesting the interaction to be mainly ionic in nature. While this does not rule out the possibility of inclusion complexation in solution, it poses interesting questions about the nature of the stable 1 : 1 complex detected in 0.2 M NaCl. The 2 : 1 complex stoichiometry could become prevalent in low ionic strength media, at high concentration, or in a crystal lattice due to packing forces, thus explaining our solid-state data.

The role of the ionic strength of the solvent in mitigating complexation was explored by titrating a 2 : 1 mixture of **1**$^{6-}$ and **2**$^{3+}$ (0.33 mM **2**$^{3+}$, 0.05 M NaCl) in an NMR tube with a 5 M NaCl solution containing the same 2 : 1 mixture of the two compounds. Fig. 2 shows the chemical shift response of the sepulchrate proton resonances as the ionic strength is changed. That the sepulchrate is totally shielded from the calixarene at high NaCl concentrations is shown by the fact that the sepulchrate's proton resonances reach the same chemical shift that they exhibit in the absence of calixarene, thus further proving that its interaction with **1**$^{6-}$ is driven by electrostatic forces.

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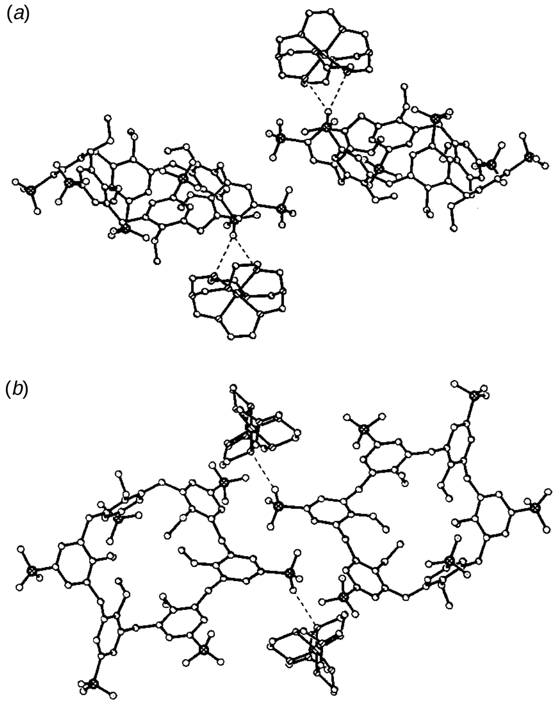

Fig. 1 X-Ray crystal structure of the unit cell of the **1**$^{6-}$–**2**$^{3+}$ solid-state complex. (*a*) Edge-on view through the plane of the calix[6]arenes showing the two sepulchrate units above and below the plane, omitting the two in-plane sepulchrates. (*b*) View orthogonal to the plane of the calixarenes showing the two in-plane sepulchrate units, omitting the above and below sepulchrates for clarity. Water molecules were also omitted for clarity.

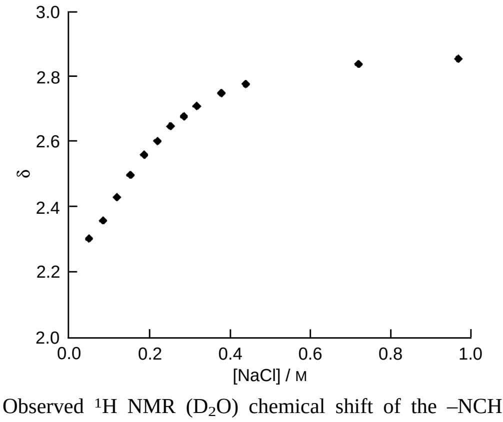

Fig. 2 Observed ^{1}H NMR (D_2O) chemical shift of the –NCH_2CH_2N– sepulchrate proton resonance in a 2 : 1 solution of **1**$^{6-}$ and **2**$^{3+}$ as a function of NaCl concentration

Footnotes

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† **1**$^{6-}$ was synthesized according to ref. 3(*d*) and used as its sodium salt; **2**$^{3+}$ was synthesized according to ref. 5(*b*) and used as the chloride salt.

‡ Details of the calorimetric experiments were as previously described.[9]

§ *Crystal data*. Enraf-Nonius CAD-4 four-circle diffractometer, Mo-Kα radiation (λ = 0.710 73 Å), graphite monochromator, T = 293 K, empirical absorption correction, direct methods, blocked least-squares refinement, Co and SO_3 group anisotropic, H at idealized positions riding on attached atom [B = 1.3B(attached)], water molecules refined with partial occupancy based on initial common temperature factor refinement. $C_{72}H_{124.5}Co_2N_{16}O_{35.25}S_6$, M = 2088.63, triclinic, space group $P1$, a = 18.182(2), b = 20.730(3), c = 28.982(6) Å, α = 107.45(1), β = 105.48(1), γ = 90.13(1)°, U = 10002.6(28) Å^3, Z = 4, D_c = 1.387 g cm^{-3}, μ(Mo-Kα) = 5.33, $2\theta_{max}$ = 44°, ω scan, crystal dimensions *ca.* 0.24 × 0.28 × 0.32 mm, 23 250 unique reflections, $R(R_w)$ = 0.0673 (0.1707) for 8412 reflections with $I > 2\sigma(I)$ or 0.1421 (0.1857) for all data, 13337 variables. Atomic coordinates, bond lengths and angles, and thermal parameters have been deposited at the Cambridge Crystallographic Data Centre (CCDC). See Information for Authors, Issue No. 1. Any request to the CCDC for this material should quote the full literature citation and the reference number 182/427.

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