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# Metal−Organic Anion Receptors: Arranging Urea Hydrogen-Bond Donors to Encapsulate Sulfate Ions

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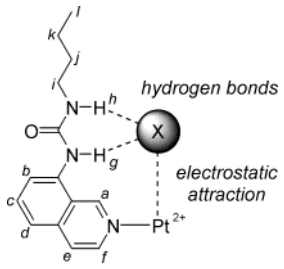
Selective synthetic receptors for the sulfate anion are relatively rare.[1] Pflugrath and Quiocho's crystal structure of sulfate bound within the sulfate binding protein revealed that Nature uses seven hydrogen bonds from neutral donor groups to selectively complex the anion within the protein.[2] Synthetic receptors for anions frequently incorporate a combination of (i) hydrogen bond donor groups, (ii) a positively charged component for effective electrostatic interactions, and (iii) a suitable framework onto which these structural components can be assembled. Strategies to bind sulfate have followed these general principles and have involved the formation of multiple hydrogen bonds between the anion and receptor, resulting in strong complexation either by neutral receptors or by receptors that employ hydrogen bonds in combination with electrostatic interactions.[3] Other approaches have included binding sulfate as a component of a transition metal sulfate ion pair.[4] We recently reported the anion binding properties of platinum(II) tetranicotinamide receptors and introduced a loose analogy between these receptors and the calix[4]arenes in that both classes of receptor are capable of adopting similar "cone", "partial cone", "1,2-alternate", or "1,3-alternate" conformations.[5] Unfortunately, in these first-generation systems, rotation around the platinum−pyridine bond was fast on the NMR time scale, even in the presence of an anionic guest, and therefore the conformation adopted in solution could not be determined unambiguously. Herein, we report a new metal−organic anion receptor containing urea[6] functionalized *iso*-quinoline ligands that exhibits remarkably strong binding of sulfate by completely encapsulating the anion in a "cone" conformation in both solution and the solid state.




Receptor $[Pt(L)_4]^{2+}$, **1** was prepared as the tetrafluoroborate salt by refluxing *cis*-$[PtCl_2(EtCN)_2]$ with 2 equiv of $AgBF_4$ and 4 equiv of L = 8-(*n*-butylurea)*iso*-quinoline in acetonitrile for 24 h. The easily handled, white solid is extremely robust; no evidence of reaction with oxygen or strong donor solvents was observed. The solubility of $\mathbf{1}[BF_4]_2$ limited studies of anion interactions to relatively polar solvents such as a mixture of 35% $MeNO_2$-$d_3$ and 65% DMF-$d_7$ or DMSO-$d_6$. Negligible interactions with triflate, perrhenate, and nitrate were observed in the former solvent mixture.

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***Table 1.*** Stability Constants $K_a$ ($M^{-1}$), at 298 K, between $PtL_4(BF_4)_2$ and Various Putative Anionic Guests in DMSO-$d_6$

| anion[a] | conformation | $K_a$ ($M^{-1}$) | |
|---|---|---|---|
| $Cl^-$ | 1,2 or 1,3-alternate | $K_1$ 11693 | $K_2$ 2223 |
| $Br^-$ | 1,2 or 1,3-alternate | $K_1$ 1364 | $K_2$ 450 |
| $I^-$ | 1,2 or 1,3-alternate | $K_1$ 1431 | $K_2$ 52 |
| $H_2PO_4^-$ | cone | $>10^5$ [b] | |
| $SO_4^{2-}$ | cone | $>10^5$ [b] | |

[a] As $[n\text{Bu}_4\text{N}]^+$ salts except $SO_4^{2-}$ which was added as $K_2SO_4$ (the effects of ion pairing have been ignored. In the case of a $K^+$ salt this effect would likely decrease the observed affinity of the receptor for an anion relative to a $[n\text{Bu}_4\text{N}]^+$ salt). [b] Estimated value − saturation is seen on addition of one equivalent of the anion.

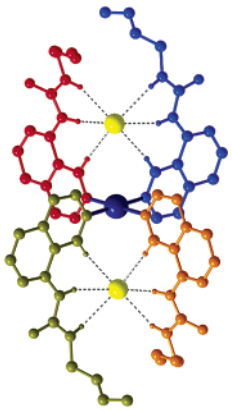

***Figure 1.*** Ball-and-stick representation of the receptor chloride complex. The four urea ligands are colored red, green, orange, and blue, the Pt(II) center is dark blue, and the anions, yellow.

The results of $^1$H NMR titration studies with a variety of other anions (Table 1) show that even in a competitive solvent (DMSO-$d_6$) substantial interactions and selectivity could still be observed.[7]

There are two distinct types of receptor−anion interactions. First for the halide ions, chloride, bromide, and iodide titration curves using NH resonances were best fit to 1:2 receptor:anion interaction. This implies that, although all four urea groups could surround a single anion in a cone conformation when the anion was the limiting reagent, it is likely a 1,2- or 1,3-alternate conformation and trends toward a neutral $[Pt(L)_4][X]_2$ complex prevail at higher anion concentrations. As was observed for our nicotinamide receptors,[5] the binding curves appear somewhat sigmoid in nature, inferring allosteric behavior, but all $K_1$ values are greater than their $K_2$ counterparts, reflecting the reduction in electrostatic interactions upon the first anion binding.

Isolation and subsequent crystallization of the adduct $[Pt(L)_4][Cl]_2$ gave X-ray-quality crystals[8] and allowed a determination of the receptor conformation in the solid state at a 1:2 receptor:anion ratio. Figure 1 shows that the receptor adopts the 1,2-alternate conformation in which two pairs of adjacent urea groups form


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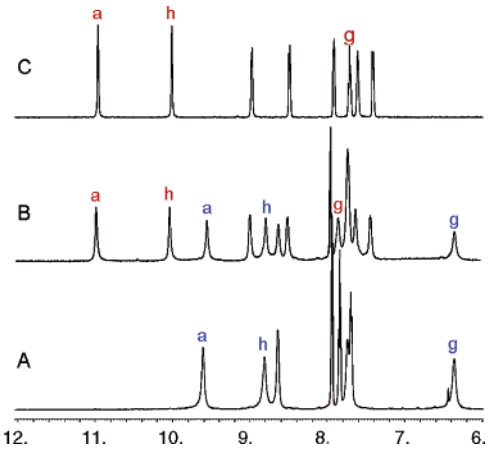


***Figure 2.*** $^1$H NMR spectra (DMSO-$d_6$) of the receptor **1**$[BF_4]_2$ ($5.0 \times 10^{-3}$ M) with added $SO_4^{2-}$ anion: (A) 0.0 equiv, (B) 0.5 equiv, (C) 1.0 equiv. NH and CH resonances undergoing the largest downfield shifts are shown with the established naming scheme; receptor: blue, $SO_4^{2-}$ complex: red.

hydrogen bonds to separate chloride anions. The chloride anions are situated above the Pt(II) center at 4.06 and 4.21 Å and slightly offset from an ideal axial positioning. The urea groups are oriented so that all NH···$Cl^-$ hydrogen bonds are essentially linear. A significant C−$H_a$···$Cl^-$ interaction also occurs in the solid state (see Figure 1). Interestingly, the resonance for this proton shifts considerably more than any other CH resonance during titration, consistent with this interaction contributing to binding in solution; 1.44 ($Cl^-$), 1.44 ($Br^-$), 0.75 ($I^-$) ppm downfield versus ~0.06 ppm upfield for all other CH protons regardless of anion. The second observation from Table 1 is that the oxo-anions sulfate and dihydrogen phosphate are bound very tightly even in the highly competitive solvent DMSO. For $H_2PO_4^-$ addition of substoichiometric amounts of anion results in fast exchange and broad spectra up to one equivalent, at which point a sharpened spectrum is observed. In contrast, the interaction with $SO_4^{2-}$ is slow on the NMR time sale regardless of the amount of anion present.[9] In both cases, large shifts are observed for resonances of both NH and $H_a$; Figure 2 shows NMR spectra of mixtures of receptor and sulfate anion that illustrate how the populations of receptor and adduct change upon addition of the anion.

An X-ray crystal structure of the complex $[Pt(L)_4][SO_4]$ shows that the metal−organic receptor adopts a cone conformation with all eight NH groups oriented toward a single anion. The mismatch of the four-fold symmetry of the receptor and the three-fold symmetry of the anion results in an asymmetric binding with the anion closest to the green urea group in Figure 3. The S-atom is 4.41 Å above the Pt center with the O-atom bonded to the blue urea group (see Figure 3) directly above the Pt center and involved in the closest Pt···O interaction at 3.72 Å (a top view of Figure 3 can be found in the SI). Nonetheless, a full complement of eight NH···O interactions from the four urea functional groups to three of the four sulfate oxygen atoms anchors the anion inside the cavity of the receptor (made possible by the adoption of the cone conformation of the flexible receptor).

This favorable arrangement surrounds the anion, shielding it from interactions with the surrounding solvent and along with the strong electrostatic component presumably accounts for the high stability

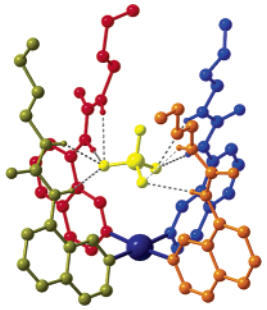

***Figure 3.*** Ball-and-stick representation of the receptor sulfate complex. Same color scheme as Figure 1.

of the complex and slow complexation−decomplexation kinetics relative to the NMR time scale.[10]

Taking further inspiration from the chemistry of the calix[4]-arenes, it may be possible to pre-organize the receptor for a cone conformation using a number of different strategies. Methods to control the conformational flexibility of this class of receptor are currently being explored in our laboratories and may allow tuning for selectivity to a variety of specific anions. The results of these studies will be reported in due course.

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**Supporting Information Available:** Synthetic procedures, NMR spectroscopic data, mass spectral data, X-ray crystallographic details (CIF file) and results of NMR titration experiments. This material is available free of charge via the Internet at http://pubs.acs.org.

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(8) $[PtL_4][Cl_2]$: Colorless crystal, monoclinic, $P2_1/n$, $a = 20.029(5)$ Å, $b = 21.508(5)$ Å, $c = 21.244(5)$ Å, $\beta = 100.491(6)°$, $V = 8999(4)$ Å$^3$, $T = 173.5(1)$ K, $Z = 6$, R1 = 0.0655 ($I > 2\sigma(I)$), w$R2 = 0.1784$ (all data). $[PtL_4][SO_4]$: Colorless crystal, monoclinic, $P2_1/n$, $a = 20.700(3)$ Å, $b = 11.4505(16)$ Å, $c = 27.823(4)$ Å, $\beta = 96.944(3)°$, $V = 6546.2(16)$ Å$^3$, $T = 173.5(1)$ K, $Z = 4$, R1 = 0.0750 ($I > 2\sigma(I)$), wR2 = 0.1646 (all data).
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