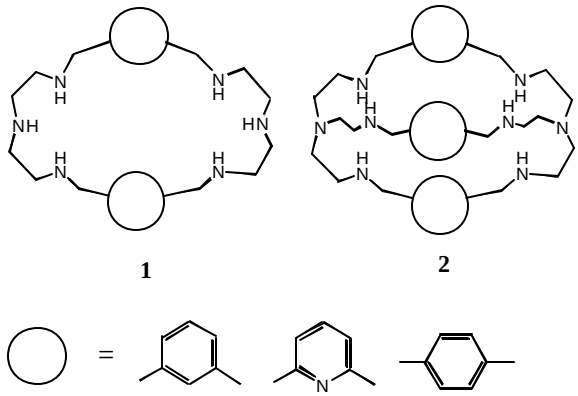
RESEARCH OBJECTIVE: The original funded project (1996) had as its major goal the design and synthesis of polyammonium macrocyclic receptors for oxoanions of environmental importance, particularly those found in high level waste tanks. Nitrate was a major ion of focus. The project evolved over the last six years to target important and timely problems of critical interest to the EMSP mission. Emphasis was shifted from polyammonium receptors to lipophilic amide-based receptors more amenable for both separations and sensing applications in the last renewal, and significant effort was directed toward selective recognition of sulfate because of its detrimental role in the vitrification process. The last three years have been focused on the basic chemical aspects of anion receptor design of functional pH independent systems, with the ultimate goal of targeting the selective binding of sulfate, as well as design of separations strategies for selective and efficient removal of targeted anions. Key findings during these years include: (1) among the first synthetic sulfate-selective anion-binding agents; (2) simple, structure-based methods for modifying the intrinsic anion selectivity of a given class of anion receptors; and (3) two new classes of macrocyclic ligands, mixed amide/quaternary amine, thioamide-based macrocycles and cryptands.

Research Progress and Implications: As of June 2003, this project is at the end of a 2.5 year funded renewal period. Areas probed during this past funding period include: I. Design, synthesis, and physical and structural characterization of receptors; II. Examination of the technique known as ITIES, Interface Between Two Immiscible Electrolyte Solutions, as an analytical probe for anion analysis; and II. Investigation of anion and dual ion pair extraction using lipophilic amide receptors for anion binding. Most of the information for area II (ITIES) has been reported in previous yearly reports, and this final year has focused on new and selective receptors for sulfate and separations experiments. Outcomes from two areas will be described below and references can be obtained from the numbered papers in the section on Information Access:

I. Design, synthesis, and physical and structural characterization of receptors. Due to space limitations, only highlights of work will be summarized, and more detailed information can be obtained from the references cited within this report.



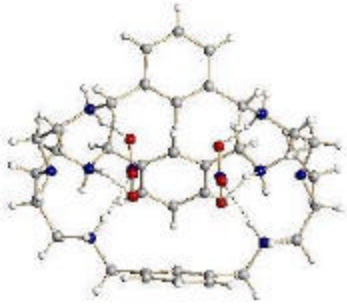
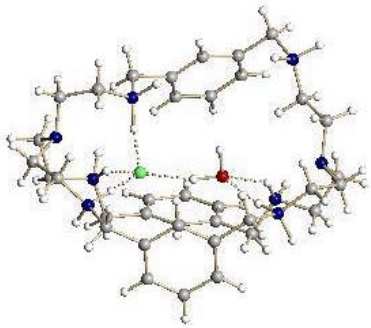


Figure 1. Polyammonium macrocycles **I**

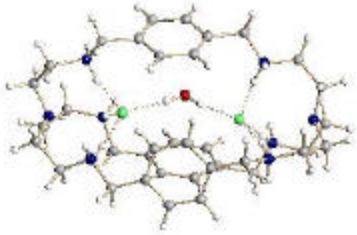
Polyammonium Receptors. The first target hosts investigated included monocyclic, **1**, and bicyclic, **2**, polyammonium systems. Many of these hosts are readily synthesized from Schiff base condensations followed by borohydride reductions, and available with various spacer aromatic or heterocyclic units (**Figure 1**).

The first major result in our project was the isolation and characterization of a ditopic nitrate complex with a polyammonium-based aza cryptand, **I**, with m-xylyl spacers.[*1,2] Subsequent studies indicated that dimensionality plays a major role on binding affinities in anion complexes.[12,13] While monocyclic systems may bind multiply valent anions with significant affinity, they do not have even measurable affinities in some cases for monoanions. A number of crystal structures for both cryptand and monocyclic systems also indicated inclusion complex formation for the former, but more generally a layered cation receptor/anion structure for the latter.[3-5,7,14,15]

A mixed fluoride/water encapsulated complex was also crystallographically characterized, **II**.[5,12] In addition to the solid state structure, ^{19}F NMR studies (**Figure 2**) allowed an examination of the solution structure with fluoride ion. The ^{19}F NMR clearly showed only one sharp signal at ~ –120 ppm at pH 10.5 (**A**) assigned as solvated fluoride. However, a new signal at –89 ppm arises as protonation of the macrocycle begins, eventually replacing the free fluoride signal (**E**, pH = 6.5). We attribute this signal to encapsulated fluoride.



II



III

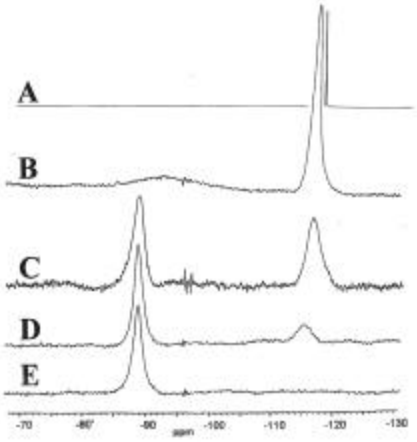


Figure 2. pH: **A**, 10.5; **B**, 9.0; **C**, 8.0; **D**, 7.0; **E**, 6.5.

By expanding the aza cryptand cavity using a *p*-xylyl spacer, we isolated a ditopic fluoride complex that resembles transition metal cascade complexes. In this structure, the two fluorides

[*] In views of crystal structures, only the central "complex" is shown, and additional anions which may be required to satisfy the charge requirements are omitted.

play the role of the metal ion and are bridged by a "cascading" water molecule (**III**).[14] It was revealing that just a minor adjustment in cavity size resulted in a significant structural difference. Furthermore, crystal structures of the chloride and bromide salts with the *p*-xylyl-spaced cryptand show structures similar to that of the fluoride with the *m*-xylyl spacer, i.e., a single halide and water inside the cavity

The structural characterization of an encapsulated chloride in a tiny octaazacryptand, previously assumed to be capable of incorporating only fluoride inside the cavity, was also surprisingly revealing.[7,15] NMR studies as a function of pH indicated chloride binding to be pH controlled, occurring only at pD 2.5 and lower. This is approximately when the sixth proton is added to the small cryptand. *This finding emphasizes the importance of careful examination of all contributing aspects of anion coordination including pH.*

These early studies, using polyammonium macrocycles as receptors for inorganic ions, led to expanded explorations of receptors more readily amenable to applications during this funding period.

Amide/Thioamide-based Receptors. Drawbacks to ammonium-based receptors are water solubility (hampering their use as ion selective electrodes or in separations) and pH sensitivity. Thus neutral receptors fashioned after the polyammonium systems were targeted. Initial studies involved acyclic tripodal amide-based receptors, **3** (**Figure 3**).[7-9] These systems were found to show some unusual structures, including one with R = $(CH_2)_6CH_3$, which showed a lipid bilayer structure.[7] The tripods were used in both the ITIES[9] and separations[8] studies (*vide infra*).

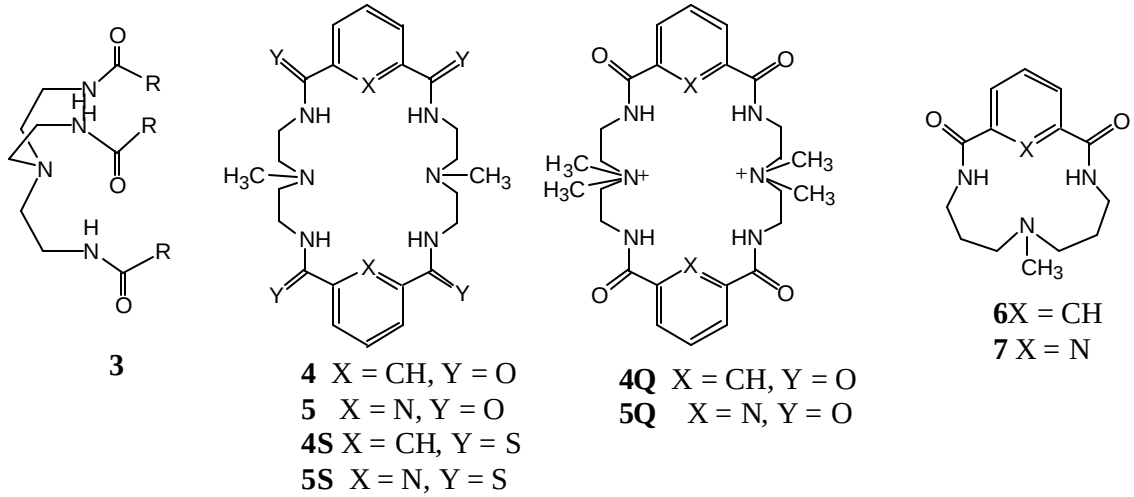
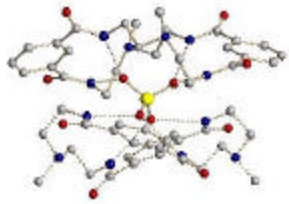


Figure 3. Tripodal and monocyclic amide- and thioamide-based anion receptors.

New mixed amine/amide macrocyclic-based receptors were also synthesized:[10,11,17,19] **4**[10] and **5**; their quaternized versions, **4Q** and **5Q**;[17] and thioamide analogs, **4S** and **5S** (**Figure 3**).[19] Smaller macrocycles, **6** and **7**, have been isolated from 1:1 condensation reactions. The inclusion of amines in these systems lends chemical versatility. To illustrate, **4** and **5** show high affinity for protonated anions such as HSO_4^- and $H_2PO_4^-$, over others. We attribute this finding to a complex interplay of the acid/base properties of both the anion and the macrocyclic amine. For example, crystals isolated from reacting HSO_4^- with **4** indicated SO_4^{2-} (not HSO_4^-) sandwiched between two molecules of **4**. We also observe even greater binding for almost all anions by changing the *m*-xylyl spacer to pyridine.



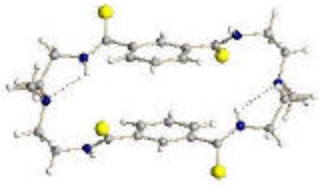
IV

In the sulfate sandwich structure with **4** each of the sulfate oxygen atoms is held by two hydrogen bonds from the amide hydrogens (**IV**). This multiple hydrogen bond network is probably responsible for the high affinity seen for this complex with sulfate (log K = 4.50 in $CDCl_3$).[10] The two macrocycles are rotated by 90° in order to accommodate the S_4 symmetry of the sulfate.

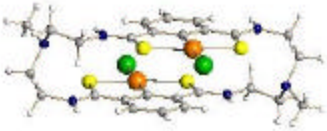
Thioamide macroycles **4S** and **5S**[19] have been recently synthesized and characterized in our group. *To our knowledge thioamide macrocycles have not been previously reported, and thus represent totally new additions to the macrocyclic arena.* Preliminary binding studies (**Table 1**) have been obtained as well as crystallographic data for the free base of **4S** (**V**). **4S** is exceedingly selective for $H_2PO_4^-$ and studies are currently underway to probe this finding.

Table 1. Association constants of **4** and **4S** with anions in DMSO-d_6 at 25 °C.

Anions	log K (M^{-1})	
	4	**5**
$H_2PO_4^-$	831	93,300
HSO_4^-	794	1,412
CN^-	---	800
Cl^-	25	107
Br^-	20	100
NO_3^-	<10	10



V



VI

A promising aspect of the new thioamide macrocycles is their potential for binding transition metal ions. A complex of palladium(II) with **4S** has been isolated and crystallographically characterized (**V**). The structure reveals a ditopic cyclometallated complex, with the palladium ions each coordinated to two thioamide sulfurs and a carbon of the *m*-xylyl spacer. The fourth coordination site is occupied by a chloride ion. These macrocycles could thus have potential as transition metal ligands in a variety of areas including, but not limited to, catalysis, biomedical applications and new materials.

Another degree of complementarity, quaternization, gave **4Q** and **5Q** (**Figure 3**).[17] The new positively charged receptors showed significantly enhanced binding for anions (in most cases one or more orders of magnitude greater) (**Figure 4**). (Some anions are not shown because of complications in determination of binding, or because binding has not been determined.) In both neutral and quaternized systems, we found that the pyridine analogs showed higher affinity than

their *m*-xylyl corollaries in most cases (HSO_4^- the exception). We now attribute this effect to a preorganization influence provided by the pyridine nitrogen.

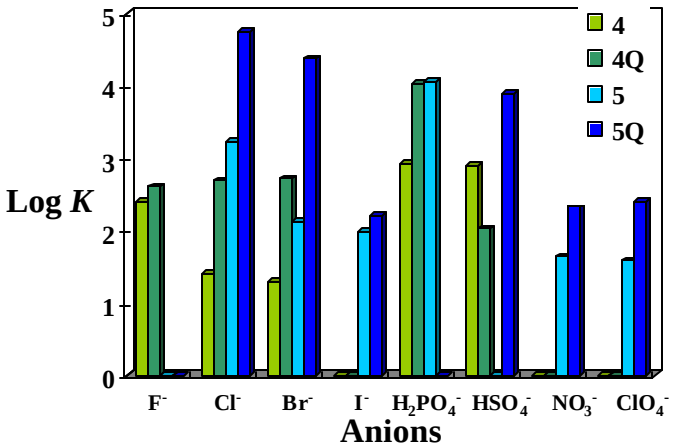
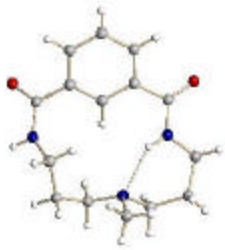
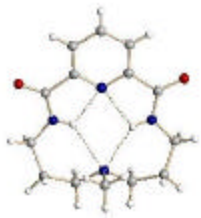


Figure 4 Bar graph illustrating binding (log K) differences between neutral and quaternized receptors.

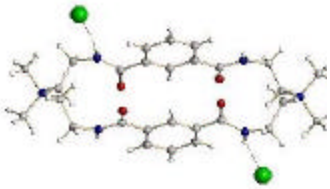
Crystal structures of the small macrocycles, **6** (**VII**), **7** (**VIII**) and **7S** (not shown) along with the structures of the quaternized receptors **4Q** (**X**) and **5Q** (**XI**)[17] support a preorganization concept for pyridine, compared with the "non-preorganized" *m*-xylyl spacers. The outcome of this preorganization, which could account for the increased affinities of the pyridine analogs, is the anion equivalent of the chelate effect. As in transition metal chemistry, the chelate effect in anion chemistry consists of multiple hydrogen bond interactions between the receptor (ligand) and the anion. In the structure of the chloride complex with **4Q** (**IX**), only a single hydrogen bond is observed from a given amide hydrogen to the halide. In the iodide complex of the pyridine-containing **5Q**, the shape of the macrocycle is altered by the presence of the pyridines, with amide hydrogens pointed in the direction of the pyridines as in the small macrocycles. This directionality results in ideally oriented (i.e., preorganized) hydrogens for hydrogen bonding in a chelate fashion with the iodide (**X**).



VII

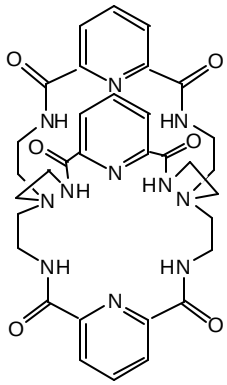


VIII

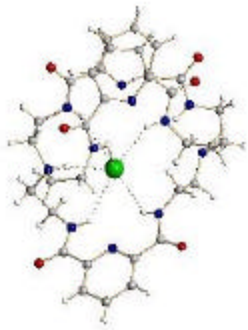


IX

X



8



XI

The preorganization influence of the pyridine spacer was used to facilitate synthesis of the amide-based cryptand, **8**.[18] *This is, to our knowledge, the first amide-based cryptand.* The crystal structure of what was presumed to be the free base of the macrocycle surprisingly showed a positively charged cryptand, with a protonated bridgehead amine (**XI**) and chloride in the cavity. Subsequent investigation revealed that **8** readily "sponges up" contaminating HCl in chlorinated solvents such as $CHCl_3$.

II. Analytical Applications. Interface Between Two Immiscible Electrolyte Solutions (ITIES). These studies were completed early in the program and are reported in reference 9 under **Information Access**, as well as in earlier yearly reports.

III. Extraction Studies In the past three years, efforts have focused on a systematic survey of sulfate extraction behavior in the context of the 11 approaches outlined in **Table 2**. The results confirmed generally that the use of anion receptors weakens, and in some cases even overcomes, Hofmeister bias and will be reported.[20]

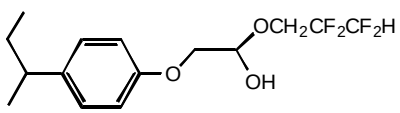
Table 2. Eleven approaches to liquid-liquid extraction.

Case	Name	Description
#1	No host	A polar solvent (e.g., 1-octanol) is used to solvate both cation and anion.
#2	Cation host	A cation host (e.g., crown ether) binds the cation. Anion remains primarily solvated.
#3	Anion host	An anion host binds the anion. Cation remains primarily solvated.
#4	Dual hosts	Cation host and anion host are used in synergistic combination.
#5	Ion-pair host	A single host binds both the cation and anion.
#6	Cation exchange	A lipophilic weak organic acid is employed to effect cation exchange. No hosts are used.
#7	Synergistic cation exchange	A cation host is used in synergistic combination with a lipophilic weak organic acid.
#8	Ditopic cation exchange	A weakly acidic functionality is incorporated into the cation host.
#9	Anion exchange	A salt of a lipophilic cation is employed to effect anion exchange. No hosts are used.
#10	Synergistic anion exchange	An anion host is used in synergistic combination with an anion exchanger.
#11	Ditopic anion exchange	An anion-exchange functionality is incorporated into the anion host

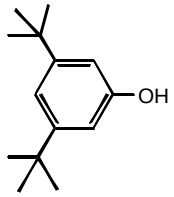
Experimental techniques employed radiometric counting methods for the determination of cation and anion distribution on equilibrating organic and aqueous phases at 25 °C. Tracers included gamma isotopes ^{22}Na and ^{137}Cs, as we have often used previously, and methods were worked out for employing $^{35}SO_4^{2-}$ tracer for a direct measurement of sulfate distribution. Following the cation is useful for surveys of many anions, as it gives an indirect measure of the co-anion distribution by

a single methodology, whereas following sulfate is needed for anion exchange. The sulfate distribution ratio D_{SO4} was measured by beta liquid scintillation counting.

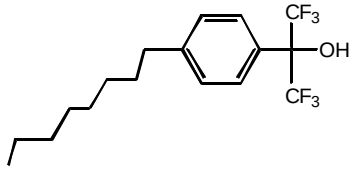
Several experiments were conducted in which sodium sulfate extraction into 1-octanol was measured (Case #1). 1-Octanol is reasonably good at solvating both cations and anions, as it is both a good electron-pair donor and hydrogen-bond donor. Even so, extraction still tends to be weak, as alcohols solvate ions more weakly than water, judging by tabulated values of the standard Gibbs energy of partitioning ($\Delta G_p°$). Using an aqueous phase consisting of 1 M NaOH, 0.1 mM Na_2SO_4, and tracer, a feeble D_{SO4} of 2×10^{-6} was obtained. As it is known that anion partitioning, particularly that of small anions, is influenced mostly by the hydrogen-bond donor ability of the solvent, it was postulated that addition of hydrogen-bond donors more acidic than 1-octanol to the 1-octanol solvent would enhance extraction. This modification may be thought of as a primitive Case #3 with a monofunctional anion receptor or perhaps just Case #1 with enhanced solvation. The simple monofunctional hydroxy compounds tested are given below:



9

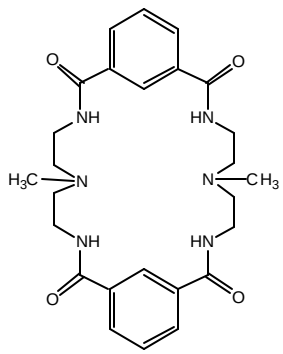


10

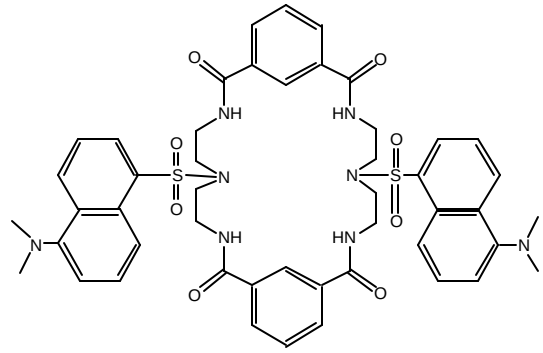


11

Compound **9** is the diluent modifier used in the CSSX process for $CsNO_3$ extraction by a calixcrown and is thought to function by solvation of the anion based on solvatochromic data.[69] On adding **9**, **10**, or **11** at 0.2 M to 1-octanol, D_{SO4} values were obtained as follows: 1.9×10^{-4}, 1.3×10^{-4}, and 3.4×10^{-4}, respectively. Although these are still very low distribution ratios, considerable extraction enhancement was observed. Sodium distribution was measured in parallel by gamma counting of ^{22}Na tracer. The hydroxy proton of **9** is not significantly exchangeable with sodium under the experimental conditions used, and thus, the enhancement of extraction is interpreted as being due to enhanced solvation of sulfate by hydrogen bonding. Similar behavior has been observed in nitrobenzene, where the enhancement itself is anti-Hofmeister, though too weak to reverse the net Hofmeister effect. On the other hand, the hydroxy protons of **10** and **11** are sufficiently acidic that an appreciable fraction of each compound is converted to its sodium salt, 70% in the case of **10** and 98% in the case of **11**. The enhanced sulfate extraction observed for these two compounds must therefore involve some other mechanism involving ionic interactions.



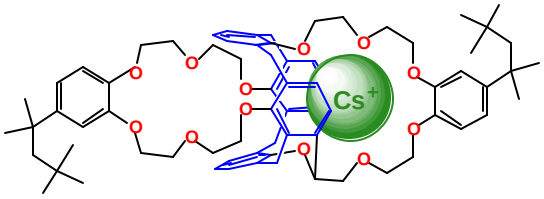
4



12

In accordance with expectations, Case #3 was confirmed to be weak. Addition of the anion receptor **4** (MMEAM), to 1-octanol weakly enhances sodium sulfate extraction from an aqueous solution containing 1 M NaOH, 0.1 mM Na_2SO_4, and tracer. On adding 10 mM **4** to 1-octanol, D_{SO4} increases from 2×10^{-6} to 3×10^{-5}. This is a feeble extraction, but the anion receptor does appear to have a noticeable effect. In other experiments, it was also demonstrated that **12** (DSMEAM) used alone (again Case #3, no cation receptor present) effects cesium salt extraction into nitrobenzene. Cesium salts are weakly extractable by nitrobenzene alone without any receptor at all, and it is therefore possible to detect the enhancement of the cesium salt extraction when an anion receptor is added. Receptor **12** at 3 mM in NB was used to extract cesium salts to which was added 1 mM NaOH and ^{137}Cs tracer. Distribution ratios of cesium salts of univalent anions were low but measurable; extraction of salts of divalent anions were too low for reliable determination. As an example, the distribution ratio for cesium nitrate was 0.0058 with **12** vs 0.0019 without. Evidence for Case #3 has been generally elusive in the literature, but limited data have been reported. Apparently, the anion receptor must be exceptionally strong to overcome the unfavorable cation partitioning. In other work we found that fluorinated calix[4] and calix[5]pyrroles have the requisite strength and can effect the moderate extraction of cesium salts into nitrobenzene without a cation receptor and with a decidedly non-Hofmeister order.

Dual-host extraction systems (Case #4) exhibited reasonably strong salt extraction with a synergistic effect being observed. Extraction experiments were conducted with **4** and **12** as anion receptors in synergistic combination with the cesium-selective calixcrown, calyx[4]arene-bis(*t*-octylbenzo)crown-6 (BOBCalixC6) in nitrobenzene (NB). In general, **4** was found to be somewhat weaker in enhancing cesium salt extraction than **12**, but the observed behavior was otherwise similar. In dual-host systems, the expected synergism is ideally ascribable to a new reaction in which the cation receptor B binds the cation M^+ and the anion receptor R binds the anion X^{q-}, resulting in extraction of the M*q*X salt in excess over that which would be extracted by B and R each acting independently. If the diluent is sufficiently polar that no ion-pairing occurs in the solvent phase, the new reaction may be expressed ideally in the following manner:



Calix[4]arene-bis(*tert*-octylbenzo-crown-6)
"BOBCalixC6"
(As complexed with Cs^+ ion)

$$qM^+ (aq) + X^{q-} (aq) + qbB (org) + rR (org) == qMB_b^+ (org) + R_rX^{q-} (org) \qquad (1)$$

The polar diluent NB was chosen so as to minimize any effect of ion-pairing interactions. The cation receptor BOBCalixC6 was chosen for convenience as a strong cesium extractant with simple well-characterized extraction reactions that for univalent anions conforms to:

$$Cs^+ (aq) + X^- (aq) + B (org) == CsB^+ (org) + X^- (org) \qquad (2)$$

In many cases, including the present case, the anion receptor has negligible ability to extract CsX salts by itself. When this is true, on addition of an anion receptor to the cation receptor BOBCalixC6, an enhancement of extraction may be interpreted in terms of anion binding according to the new reaction given in eq. 1. If the behavior is ideal, only 1:1 anion:receptor complexes form, and B and R do not form hydrogen-bonded aggregates B_bR_r, then one can in principle deduce the anion binding constant from the enhancement. Extraction surveys were performed with various concentrations of **4** or **12** added to 10 mM BOBCalixC6 in NB. The aqueous phases consisted of single 1:1 or 2:1 Cs_qX (q = 1 or 2) salts to which was added 1 mM NaOH and ^{137}Cs tracer. The cesium distribution ratio was determined radiometrically. Results for **12** are illustrated in **Figure 5**.

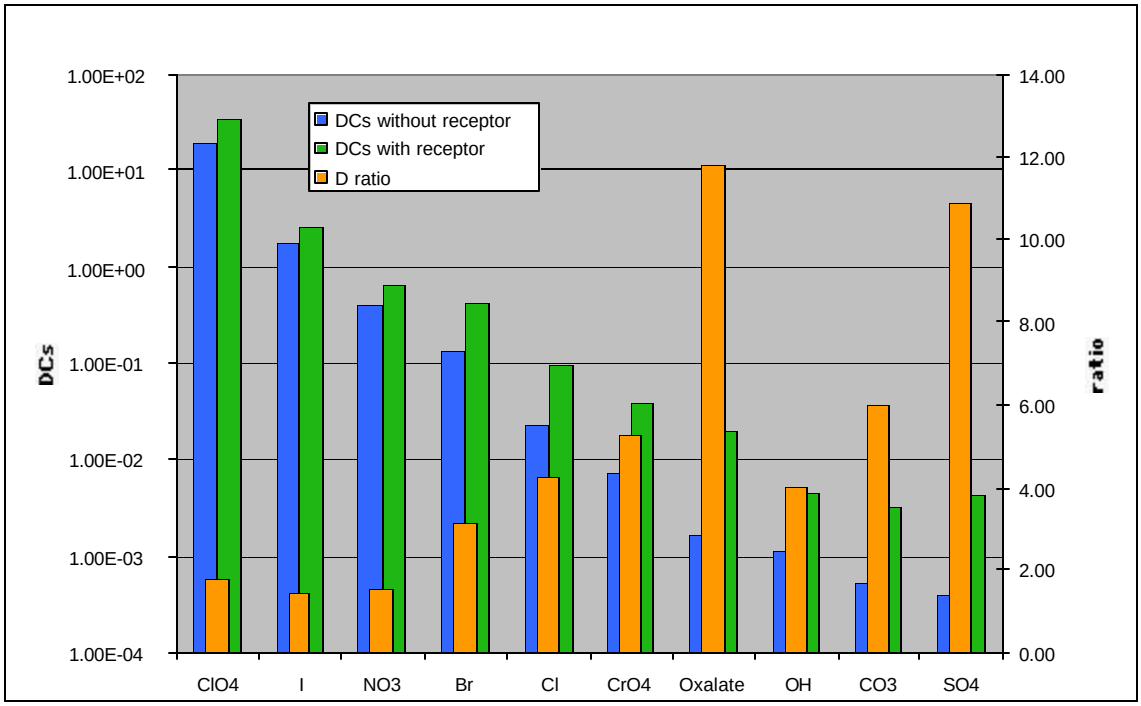


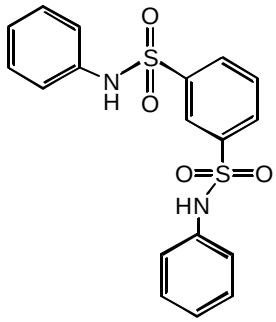
Figure 5. Synergistic extraction of cesium salts into nitrobenzene by dual hosts **13** and BOBCalixC6. The cesium distribution ratio is shown on the left Y-axis, and the enhancement ratio D_{Cs}(**13** + BOBCalixC6)/ D_{Cs}(BOBCalixC6 alone) is shown on the right Y-axis.

In general, it was found that **12** enhances Cs_qX extraction by BOBCalixC6, and the enhancement increases with increasing anion hydration, decreasing anion radius for a given charge, increasing charge, and increasing anion-receptor concentration. Among the univalent anions, the enhancement is strictly anti-Hofmeister. That is, anion binding increases as the anions become smaller or more hydrated. This effect is typical, as the smaller the anion is, the stronger is the hydrogen bond with a given hydrogen-bond donor. Among all the anions, enhancement of sulfate extraction was one of the strongest (11-fold for **12**, 4-fold for **4**). At 3 mM, **12** exhibited a higher

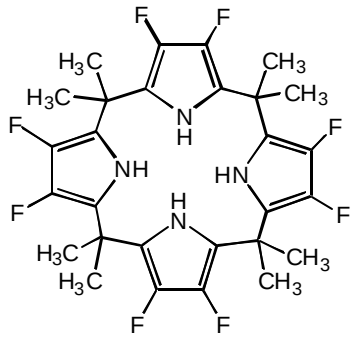
enhancement (16-fold), which was the highest seen for any of the anions at that receptor concentration. It is not clear whether the selectivity for sulfate is due to special complementarity (e.g., sandwich formation) or simply to the higher charge density on sulfate. We should keep in mind that we have been discussing enhancement, whereas the small anions are difficult to extract in absolute terms, owing to their large hydration energies. Note the low salt distribution ratios D_{Cs} for small anions and the decreasing trend with increasing size from left to right in **Figure 5**. The anti-Hofmeister *enhancement* that we observe is therefore not of sufficient magnitude to offset the dominant Hofmeister effect of eq. 2. The net extraction observed thus follows Hofmeister behavior. Relevant to the problem of sulfate removal from nitrate waste, cesium nitrate is overall two orders of magnitude more strongly extracted than cesium sulfate in the dual-host system with **12**.

On the basis of our systematized 11 approaches to extraction (**Table 2**), it was considered advantageous to experiment with the anion-exchange systems represented by Cases #9–#11. In such systems, an aqueous cation is not co-transported with the anion, and thus all considerations of cation transport and binding are removed. Rather, anion exchange gives a direct measure of competitive extraction of one anion for the other. Case #9 is the baseline case, and for that we chose the classical extractant methyltri-*n*-octyl(decyl)ammonium nitrate. This extractant has major industrial uses and is marketed under the name Aliquat 336 in the chloride form; it is a mixture of random substitution of normal octyl and decyl groups. Prior to use, it was converted to the nitrate form by contacting organic solutions with aqueous sodium nitrate. The choice of solvent is the main parameter controlling the selectivity, though the structure of the quaternary ammonium group is also important. On addition of an anion host, the resulting increase (synergism) or decrease (antagonism) in the distribution ratio of one of the anions, reflects the direct competitive preference of the host for the two anions presented to it. It may be noted that this synergism of anion exchange using an anion receptor in bulk liquid-liquid extraction is fairly novel, though it has been in common use in membrane electrodes.

Our investigations of anion receptors in synergistic anion exchange have produced exciting results. The tests have so far been limited to surveys of anion receptors and different solvents to quickly identify key parameters and most interesting behavior. An experiment was devised to directly measure sulfate selectivity vs. nitrate, the key parameter for waste applications. One can envision the quaternary ammonium cation providing exchangeable nitrate anions in the solvent phase. In a given solvent matrix, the exchange will give a characteristic value of D_{SO4} measured by tracer techniques, reflecting whether a given receptor exhibits a greater affinity for sulfate vs. nitrate. Accordingly, values of D_{SO4} were measured for 10 mM Aliquat 336 in a series of diluents. The aqueous phase contained 10 mM $NaNO_3$ plus 0.1 mM Na_2SO_4 and $^{35}SO_4^{2-}$ tracer. The sodium sulfate concentration was made small for convenience so that the extractants would not be significantly loaded with sulfate and so that the nitrate distribution ratio remains effectively constant. In these systems, $D_{SO4} > 1$ indicates sulfate selectivity, as gauged by the selectivity factor α, defined as the ratio D_{SO4} / D_{NO3}. The value D_{NO3} is approximately unity for these conditions, since $[NO_3^-]$org = ~10 mM and $[NO_3^-]$aq = ~10 mM. All values of D_{SO4} were less than 1 with no receptor added, which indicates nitrate selectivity, in accord with the higher hydration of sulfate. It was found that exchange with no anion receptor is most favorable (better stated as least unfavorable) for sulfate (highest D_{SO4}) with 1-octanol as the diluent in comparison with toluene, dodecane, and 1,2-dichloroethane. This is not surprising, as the hydrogen bonding provided by 1-octanol will favor the more charge-dense anion, sulfate.



14



15

Selected survey results for different receptors and different diluents are given in **Table 3**. In addition to compounds **9-13**, a 1,3-benzene disulfonamide **14** and the octafluorinated calix[4]pyrrole **15** have been examined. It was intended to examine the two disparate diluents 1-octanol and toluene most extensively, with more limited extension to other diluent systems. Solubility limitations were encountered for **4** and **13** in toluene. Enhancement of anion exchange is taken quantitatively as the ratio of D_{SO4} in the system with receptor vs the system without the receptor. In no case was extraction by the anion receptor alone sufficient to be taken into account.

One may see at once a striking effect of both diluent and receptor type. In 1-octanol, enhancements tend to be weak, which is interpreted in terms of the ability of this diluent to act as both a hydrogen-bond donor and acceptor. Hence, the diluent competes with the receptor for anion binding and with the anion for receiving hydrogen bonds from the receptor. In this medium, **4** somewhat outperforms **14**, and **13** exhibits no activity. Addition of hydroxy hydrogen-bond donors at elevated concentration produces a positive effect. Selected tests were performed at 0.1 M quaternary ammonium salt in 1-octanol (not tabulated), where it was noted, for example, that addition of 10 mM of **4** approximately halved the value of D_{SO4} from 3.6×10^{-1} to 1.9×10^{-1}. This apparent dependence of the enhancement on the exchanger concentration strongly suggests an effect of aggregation.

Quaternary ammonium salts are notorious for aggregating in organic solvents due to their high dipole moments. Hence, the exchanger is presumably at a higher state of aggregation when it is at 100 mM vs. 10 mM. **12** apparently interacts more strongly with nitrate at the higher aggregation state. Unfortunately, it was not possible to examine the effect of **4** in toluene, as it was not soluble in the presence of the quaternary ammonium nitrate salt. For fluorinated calix[4]pyrrole **14**, the ordering of diluents with increasing enhancement of anion exchange was 1-octanol < 0.5 M tributylphosphate (TBP) in dodecane < 1,2-dichloroethane < toluene < 2:1 hexane:chloroform. It makes sense that in the TBP system, the good hydrogen-bond accepting ability of the phosphoryl oxygen ties up the anion receptor, giving weak enhancement. Enhancements for **14** in toluene and 2:1 hexane:chloroform were quite striking, exceeding three orders of magnitude for the latter. In these two systems, the diluents are not polar nor are they capable of engaging in significant hydrogen bonding. Enhancement tended to correlate inversely with the sulfate distribution ratio without receptor, as anion binding and hence enhancement will be favored in the absence of competing strong solvation effects, which are otherwise favorable for sulfate relative to nitrate.

Table 3. Survey of anion receptors as synergists for anion exchange for various diluents.[a]

Receptor	[Receptor] mM	Diluent	D_{SO4}	Enhancement factor
None	0	1-octanol	4.4×10^{-3}	
9	200	"	9.7×10^{-3}	2.2
10	200	"	1.0×10^{-2}	2.3
11	200	"	1.1×10^{-2}	2.5
12	10	"	7.3×10^{-3}	1.7
13	10	"	4.4×10^{-3}	1.0
14	10	"	6.4×10^{-3}	1.5
None	0	Toluene	3.9×10^{-4}	
10	200	"	3.6×10^{-3}	9.2
14	3	"	2.1×10^{-3}	5.4
15	3	"	2.4×10^{-2}	62
15	10	"	1.9×10^{-1}	490
		"		
None	0	1,2-Dichloroethane	1.6×10^{-4}	
15	10	"	7.8×10^{-4}	4.9
None	0	2:1 Hexane/$CHCl_3$	1.7×10^{-4}	
15	10	"	2.0×10^{-1}	1200
None	0	0.5 M TBP, dodecane	2.3×10^{-3}	
15	10	"	5.5×10^{-3}	2.4

[a] All systems run at 10 mM Aliquat 336 in the indicated diluent. The aqueous phase contained 10 mM $NaNO_3$ plus 0.1 mM Na_2SO_4 and $^{35}SO_4^{2-}$ tracer. Contacting at 1:1 phase ratio at 25 °C.

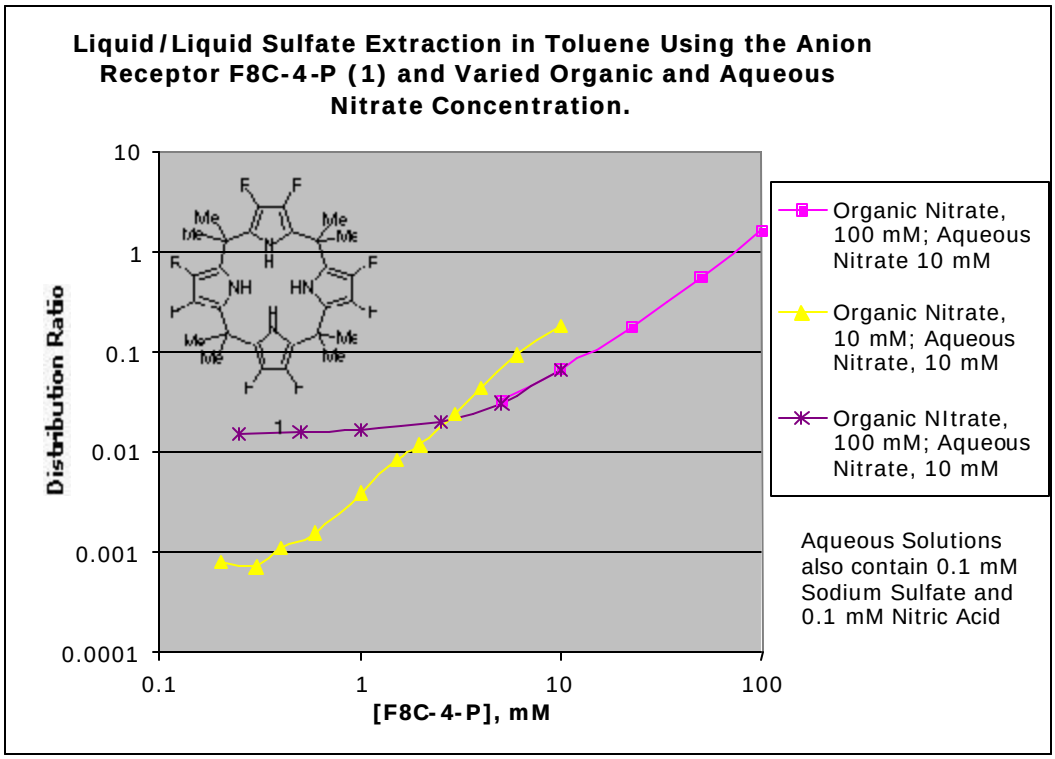


Figure 6. Enhancement of anion exchange as a function of the concentration of **7** in toluene. The aqueous phase contained 10 mM $NaNO_3$ plus 0.1 mM Na_2SO_4 and $^{35}SO_4^{2-}$ tracer.

In view of the striking enhancements obtained with the fluorinated calix[4]pyrrole **14**, most recent efforts have focused on obtaining a greater understanding of this system. Data obtained for 10 and 100 mM quaternary ammonium salt in toluene are shown in **Figure 6**. It may be seen that the distribution ratio for sulfate may be made to exceed unity. Above that value, sulfate is more than 50% extracted from the nitrate-rich aqueous phase, a useful benchmark pointing to possible applications. These data are now being subjected to equilibrium analysis with the program SXLSQI, forerunner to the expanded program SXFIT.

Planned Activities.

Most of the effort in the remaining months of funding are focused on examining the most highly selective receptors for sulfate in the Moyer laboratory, and examining the physical properties of the new classes of macrocycles, namely the thioamides and mixed amide/quaternized amine systems. The isolation of these new classes of macrocycles promises considerable new chemistry, and for the thioamides, especially a new realm of coordination chemistry with metal ions. These new receptors all look very promising for binding sulfate.

Information Access.

Publication Type: **Journal articles.**

1. S. Mason, T. Clifford, L. Seib, K. Kuczera, and K. Bowman-James, Unusual Encapsulation of Two Nitrates in a Single Bicyclic Cage, *J. Am. Chem. Soc.* **1998**, *120*, 8899-8900.

2. C&E News concentrate. September 7, 1998, page 30, "Two nitrates in a cage."

3. J. Wiórkiewicz-Kuczera, K. Kuczera, C. Bazzicalupi, A. Bencini, B. Valtancoli, A. Bianchi, and K. Bowman-James, Solid State to Solution: Crystal Structure and Molecular Dynamics Simulations of a Polyammonium Nitrate Host, *New J. Chem.* **1999**, *23*, 1007-1013.

4. O. A. Gerasimchuk, S. Mason, J. M. Llinares, M. Song, N. W. Alcock, and K. Bowman-James, Binding of Phosphate in a Simple Hexaaza Polyammonium Macrocycle, *Inorg. Chem.* **2000**, *39*, 1371-1375.

5. T. Clifford, S. Mason, J. M. Llinares, and K. Bowman-James, Snapshots of Fluoride Binding in an Azacryptand, *J. Am. Chem. Soc.*, 2000, *122*, 1814-1815

6. A. Danby, L. Seib, N. W. Alcock, and K. Bowman-James, Novel Structural Determination of a Bilayer Network Formed by a Tripodal Lipophilic Amide in the Presence of Anions, *Chem. Commun.* **2000**, 973-974.

7. M. A. Hossain, J. M. Llinares, C. Miller, and K. Bowman-James, Further Insight to Selectivity Issues in Halide Binding in the Tiny Octaaza Cryptand, *Chem. Commun.* **2000**, 2269-2270.

8. K. Kavallieratos, A. Danby, G. J. Van Berkel, M. A. Kelly, R. A. Sachleben, B. A. Moyer, K. Bowman-James, *Tris*(2-Aminoethyl)amine (tren) Triamide Derivatives Enhance $CsNO_3$ Extraction in 1,2-Dichloroethane via a Dual-Host Strategy, *Anal. Chem.* **2000**, *72*, 5258-5264.

9. Q. Qian, G. S. Wilson, K. Bowman-James, and H. H. Girault, MicroITIES Detection of NO_3^- by Facilitated Ion Transfer, *Anal. Chem.* **2001**, *73*, 497-503.

10. M. A. Hossain, J. M. Llinares, D. Powell, and K. Bowman-James, Multiple Hydrogen Bond Stabilization of a Sandwich Complex of Sulfate between Two Macrocyclic Tetraamides, *Inorg. Chem.* **2001**, *40*, 2936-2937.

11. *C&E News* concentrate. July 2, 2001, page 23, "Sulfate ion sandwich."

12. J. A. Aguilar, T. Clifford, A. Danby, J. M. Llinares, S. Mason, E. García-España, and K. Bowman-James, Fluoride Ion Receptors: A Comparison of a Polyammonium Monocycle versus its Bicyclic Corollary, *J. Supramolec. Chem.*, **2001**, *13*, 405-417.

13. T. Clifford, A. Danby, J. M. Llinares, S. Mason, N. W. Alcock, D. Powell, J. A. Aguilar, E. García-España, and K. Bowman-James, Anion Binding with Two Polyammonium Macrocycles of Different Dimensionality, *Inorg. Chem.*, **2001**, *40*, 4710-4720.

14. M. A. Hossain, J. M. Llinares, S. Mason, P. Morehouse, D. Powell, and K. Bowman-James, Parallels in Cation and Anion Coordination: A New Class of Cascade Complexes, *Angew. Chem., Int. Ed. Engl.* **2002**, *41*, 2335-2338.

15. M. A. Hossain, J. M. Llinares, N. W. Alcock, D. Powell, and K. Bowman-James, Structural and Anion Binding Effects of the Tiny Octaaza Cryptand, *J. Supramolec. Chem.* **2003**, in press.

16. M. A. Hossain, D. R. Powell, K. Bowman-James, A Potassium Crown Ether Complex with Dichloroaurate(I), *Acta Cryst. Section E, Structure Reports Online* **2003**, *E59*, m57-m58.

17. M. A. Hossain, S. O. Kang, D. Powell, and K. Bowman-James, Anion Receptors: A New Class of Mixed Amide/Quaternized Amine Macrocycles and the Chelate Effect, *Inorg. Chem.* **2003**, *42*, 1397-1399.

18. S. O. Kang, J. M. Llinares, D. Powell, and K. Bowman-James, Polyamide Cryptands: Outstanding Ligands for Anions, submitted for publication.

19. M. A. Hossain, J. M. Llinares, D. Powell, and K. Bowman-James, Elite new Polythioamide Macrocycles and cryptands, submitted for publication.

20. C. Fowler, L. H. Delmau, A. Ruas, B. A. Moyer, A. M. Hossain, K. Bowman-James, J. L. Sessler, J. A. Shriver, and M. Marquez, M. "Selective Separation of Sulfate from Nitrate by Liquid-Liquid Anion Exchange Enhanced by Anion Receptors," to be submitted for publication.

Publication Type: Papers

K. Bowman-James, Supramolecular Chemistry of Anions, American Chemical Society, Boston. August, 1998.

S. Mason, Nitrate Recognition by Aza Cryptands, 216th National Meeting of the American Chemical Society, Boston, MA, August, 1998.

K. Bowman-James, G. Wilson, and K. Kuczera. DOE Environmental Management Sciences Workshop. Chicago, IL, July 27-30, 1998: Anion Recognition and Binding.

K. Kavallieratos, R. A. Sachleben, J. C. Bryan, B. A. Moyer, A. M. Danby, and K. Bowman-James, New Anion Receptors and their Role in Solvent Extraction. 217th National Meeting of the American Chemical Society, Anaheim, CA March, 1999.

K. Bowman-James, G. Wilson, and B. Moyer. DOE Environmental Management Sciences Workshop. Atlanta, GA, April 25-27, 2000: The Supramolecular Chemistry of Anion Recognition for Anions of Environmental Relevance.

K. Bowman-James, Invited Plenary Lecture: Supramolecular Chemistry of Anions and Macrocycles XXIV International Symposium on Macrocyclic Chemistry, Bellaterra (Barcelona) July 18-23, 1999.

K. Bowman-James, Invited Symposium Lecture: XXV International Symposium on Macrocyclic Chemistry, St. Andrews, Scotland, July 2-7, 2000. Symposium Lecture: Explorations in Anion Coordination Chemistry.

K. Bowman-James, Supramolecular Chemistry of Anions of Environmental Significance, Department of Energy, Tanks Focus Area Workshop, Salt Lake City, Utah, March 12-15, 2001.

K. Bowman-James, invited lecture, Inorganic Gordon Conference, July 15-19, 2001: Explorations in Anion Coordination Chemistry.

K. Bowman-James, invited lecture. American Chemical Society, Chicago, August 26-30, 2001. Symposium on Fundamentals and Applications of Anion Separations: Explorations in Anion Binding Concepts.

K. Bowman-James, invited lecture. Pittcon 2002, New Orleans, March 17-22, 2002. Symposium on Next Generation Environmental Sensors: Supramolecular Chemistry of Selective Anion Recognition for Anions of Environmental Relevance.

K. Bowman-James, Coordination Chemistry of Anions, Midwest Symposium on X-ray Crystallography, Lawrence, Kansas, August 2002.

XXVII Symposium on Macrocyclic Chemistry, Park City, Utah, June 23-27, 2002:

1) K. Bowman-James, J. M. Llinares, M. A. Hossain, S.-O. Kang
Corollaries between Transition Metal and Anion Coordination Chemistry.

2) M. A. Hossain, J. M. Llinares, D. Powell, and K. Bowman-James
A New Class of Mixed Amide/Quaternized Amine Macrocyclic Anion Receptors.

3) S.-O. Kang, K. C. Nam, and KI. Bowman-James
Synthetic Receptors for the Binding of Anions.

4) J. Kut, M. A. Hossain, J. M. Llinares, and K. Bowman-James
New Synthesis of N-Functionalized Macrocycles.

5) J. M. Llinares, K. Bowman-James, M. A. Hossain, S. Mason, P. Morehouse, and D. Powell. Detecting Anionic Cascade Complexes Inside a Cryptand Cavity.

American Chemical Society, Midwest Meeting, Lawrence, KS. Oct. 23-25, 2002.

1) K. Bowman-James, P. Morehouse, M. A. Hossain, J. M. Llinares. A Tosylated Azacryptand as an Anion Receptor. Mixed Amide-quaternized Amine Receptors for Anions. K. Bowman-James, S. O. Kang, M. A. Hossain,

2) K. Bowman-James, J. M. Llinares, M. A. Hossain. Detecting Anionic Cascade Complexes inside a Cryptand Cavity.

3) K. Bowman-James, J. Kut, M. A. Hossain, J. M. Llinares. New Synthesis of N-Functionalized Macrocycles.

4) K. Bowman-James, M. A. Hossain, J. M. Llinares. Binding and Selectivity of Halides in a Tiny Octaazacryptand.

Publication Type: Books and Chapters:

Supramolecular Chemistry of Anions, A. Bianchi, K. Bowman-James, E. García-Espana, Eds. Wiley-VCH: New York, 1997, 461 pp.

J. Wiórkiewicz-Kuczera and K. Bowman-James, Anion Binding Receptors: Theoretical Studies, in *Supramolecular Chemistry of Anions*, A. Bianchi, K. Bowman-James, E. García-España, Eds.; Wiley-VCH, New York, 1997, pp. 335-354.

Invited review. J. M. Llinares, D. Powell, K. Bowman-James, Quaternary Ammonium Based Anion Receptors, *Coord. Chem. Rev.* **2003**, *240*, 57-75.

Invited review. J. M. Llinares and K. Bowman-James, Protonate Aza-macrocycles for Anion Complexation, *Encyclopedia of Supramolecular Chemistry*, **2003**, in press.

K. Kavallieratos, J. C. Bryan, R. A. Sachleben, G. J. Van Berkel, O. D. Espetia, M. A. Kelly, A. Danby, K. Bowman-James, B. A. Moyer, Dual Host Combinations: Using Tripodal Amides to Enhance Cesium Nitrate Extraction by Crown Ethers, in Fundamentals and Applications of Anion Separations; B. A. Moyer and R. Singh, Eds.; ACS Symposium Series, Kluwer Academic/Plenum: New York, In press.

Publication Type: News Media

Lawrence Journal World, Sunday, December 8, 2002. On the Hill Commentary, Roger Martin: Kansas professor working to remove sulfate from waste.

Lawrence, Kansas Public Radio, News commentary, Friday, December 6, 2002. Commentary, Roger Martin, Kansas professor working to remove sulfate from waste.