Electrochemical Switching of Lariat Ethers. Survey of Cation Binding by Neutral and Reduced Forms of One- and Two-Armed Carbon- and Nitrogen-Pivot Lariat Ethers

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Abstract: The electronic behavior of 14 electron-deficient aromatic systems has been determined by cyclic voltammetric techniques in both the absence and presence of Li^+, Na^+, and K^+. The substrates include carbon- and nitrogen-pivot lariat ethers, nitroaromatic podands, and simple nitroaromatic ethers as well as an azocryptand. The carbon-pivot lariats used in this study are ethers attached at the methyl group of 2-methyl-15-crown-5 or -18-crown-6 and have the following side arms: 2-nitrophenoxy, 4-nitrophenoxy, and 2,4-dinitrophenoxy. The nitrogen-pivot lariat ethers are 2- and 4-nitrobenzyl derivatives of aza-15-crown-5 or bis(2-nitrobenzyl)-4,13-diaza-18-crown-6. As model systems, 2- and 4-nitroanisole, 2- and 4-nitrotoluene, and (methoxyoctaethoxy)nitrobenzene were also examined. Finally, 3,3′-dimethylazobenzene and the [2.2]azocryptand derived therefrom were prepared. Generally, the electrochemistry of the macrocyclic nitroaromatics was as expected for the aromatic portion of the molecule irrespective of the macroring. When cations were added to the nitroaromatic lariat ethers in which the nitro groups were sterically accessible to a ring-bound cation, new, quasi-reversible couples were observed which are attributed to intramolecular ion pairing. When two side arms were present, only one of them interacted with a ring-bound Na^+. From the differences in potentials, it was found that binding of the cations was enhanced from 15- to 13 000 000-fold upon electrochemical reduction. With the exception of the azocryptand, binding enhancements were in the order $Li^+ > Na^+ > K^+$. In the azocryptand case, the nearly exact fit between the cryptand cavity and the K^+ makes the enhancement greater with this cation than with Na^+. As a result, both cation-binding enhancements and cation-binding selectivity are possible in these electrochemically switched systems.

The lariat ethers are compounds which contain a macrocyclic (crown) polyether ring to which is appended a donor-group-bearing side arm.[1] In the examples thus far surveyed, cation-binding enhancements relative to the parent crowns have been observed when the donor groups are appropriately situated on the side arm. These enhancements result from an appropriate steric disposition of the side arm with respect to the macroring, both in the solution phase[2] and in the solid state.[3]

When the side arm contains a residue which can be reduced to the corresponding anion radical, a new type of intramolecular cation complex can be formed. In such complexes, cooperative cation binding occurs involving both the neutral macroring donors and the radical anion. Examples of such complexes have been reported to result from lariat ethers having nitroaromatic residues when reduced electrochemically[4] or from quinonoid lariat ethers when reduced by an alkali metal.[5] Indeed, the reduced ligands thus far examined bind cations between 15- and 13 000 000-fold more strongly than the corresponding neutral cases.

In the 15-membered ring carbon and nitrogen-pivot lariat ethers, Na^+-binding enhancements were observed when the nitro donor groups were ortho, but not para, since the donor group in the latter is sterically too remote to interact with a ring-bound cation. Apparently as a result of greater molecular flexibility (or fewer conformational restrictions), the binding enhancements in the nitrogen-pivot molecules exceed those for the carbon-pivot molecules by substantial margins. We have observed similar cation effects on the electrochemistry of azocryptands.[6] Some interesting differences exist between the lariat ethers and the azocryptands, and the import of this is discussed below, along with a detailed account of our effort to date in this area.

Results and Discussion

The electrochemical behavior of nitrobenzene and substituted nitrobenzenes has been extensively investigated by using cyclic voltammetry[7] and electron spin resonance.[8] In the preliminary reports of this work, we showed that advantage could be taken of the nitroaromatic side arm to effect "switching" of the cation-binding process. The cyclic voltammetric behavior was shown to be quasi-reversible whether the nitro group was either ortho or para. The cyclic voltammogram of each compound is altered by the presence of alkali-metal cations, but these alterations are noticeable only when the nitro group is sterically disposed to interact with the ring-bound cation.

Ligand Syntheses. The lariat ethers prepared for this study are of either the carbon- (**1–4** and **17**) or nitrogen-pivot (**7**, **8**, **11**, and **12**) types. Compounds **1–4** and **17** were prepared by reaction of the anion (NaH, THF) formed from 2-(hydroxymethyl)-15-crown-5 (**1**, **3**, and **17**) or 2-(hydroxymethyl)-18-crown-6 (**2** and **4**) with 2-chloronitrobenzene for 4–18 h at either ambient or reflux temperature (eq 1) (see Experimental Section).[4] The hydroxy-

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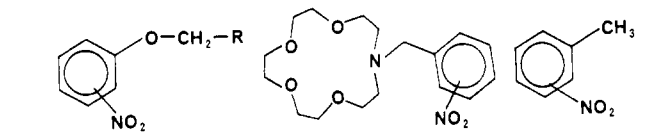
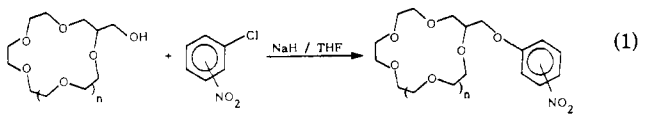


1. R = 15-crown-5; 2-nitro
2. R = 18-crown-6; 2-nitro
3. R = 15-crown-5; 4-nitro
4. R = 18-crown-6; 4-nitro
5. R = H, 2-nitro
6. R = H, 4-nitro
17. R = 15-crown-5, 2,4-dinitro

7. 2-nitro
8. 4-nitro

9. 2-nitro
10. 4-nitro



n = 1, 2

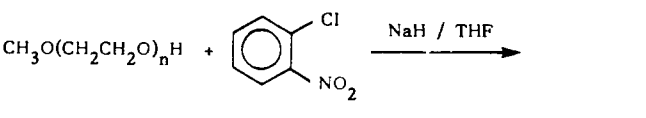
1: n = 1, ortho-NO_2
2: n = 2, ortho-NO_2
3: n = 1, para-NO_2
4: n = 2, para-NO_2

(1)

methyl crown ethers were, in turn, obtained by hydrogenolysis of the corresponding 2-benzyloxymethyl crowns as previously reported.[1]

Podands **13** and **14** were prepared as additional models for the lariat ethers by an analogous reaction (eq 2) in which the appropriate poly(ethylene glycol) monomethyl ether ether is substituted for the hydroxymethyl crown.[9]

The nitrogen-pivot lariat ethers were obtained by N-alkylation of the appropriate mono- or diazacrowns. *N*-Benzylaza-15-crown-5[10] was hydrogenolyzed to afford aza-15-crown-5, the precursor to compounds **7** and **8**. 4,10-Diaza-15-crown-5 and

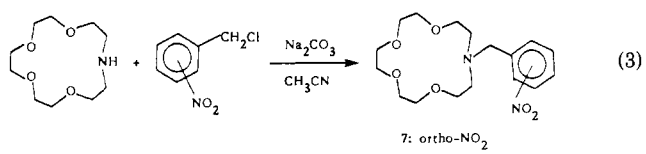


(2)

13: n = 8

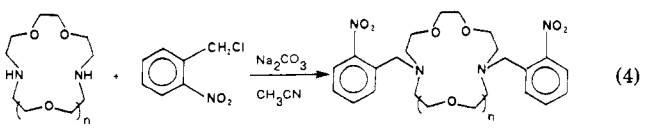
14: n = 12

4,13-diaza-18-crown-6, the precursors to compounds **11** and **12**, respectively, were obtained commercially. In each case, the azacrown was heated with the appropriate nitrobenzyl halide and Na_2CO_3 at reflux from 16 to 24 h in MeCN solution (eq 3 and 4). Yields of the N-pivot lariat ethers ranged from 22% to 90%



(3)

7: ortho-NO_2
8: para-NO_2



(4)

11: n = 1
12: n = 2

and varied with the difficulty of purification. Molecular distillation, which had proved to be a useful purification method for the C-pivot lariats was less effective with the N-pivot compounds. Indeed, compound **8** could be purified only by using a Chromatotron device.

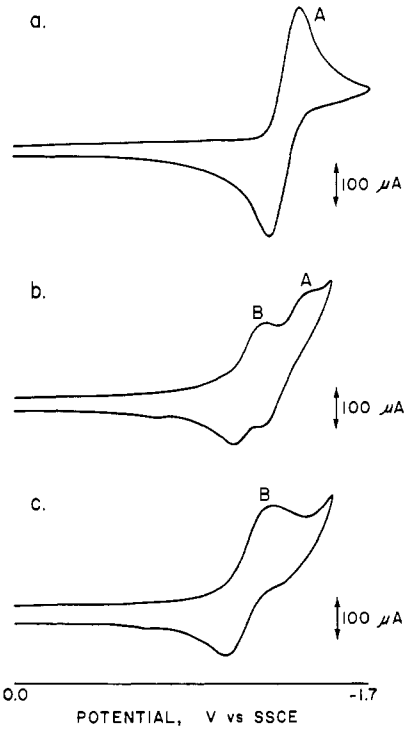


Figure 1. Cyclic voltammograms for 2-((2-nitrophenoxy)methyl)-15-crown-5, **1**, (a) in the absence of Na^+, (b) in the presence of 0.5 equiv of Na^+, and (c) in the presence of 1.0 equiv of Na^+.

Cyclic Voltammetry. 2-((Nitrophenoxy)methyl)-15-crown-5, **1**, shows a typical cyclic voltammogram at potentials similar to those observed for 2-nitroanisole, **5** (see Figure 1). When 0.5 equiv of Na^+ is added, a new redox couple appears, the current of which is enhanced in the presence of a full equivalent of Na^+ while the original couple vanishes.[4a] In contrast, no new redox couple is observed for the para isomer **3** even in the presence of a full equivalent of Na^+. Similar results have been observed for the corresponding nitrogen-pivot lariat ether compounds **7** and **8**.[4b]

We interpret these results as follows. When Na^+ is added to the crown-containing solution, it is bound by the macroring and also interacts with the side-arm nitro group. The electron-withdrawing ability of Na^+ makes the nitroaromatic residue more easily reduced, and the new redox couple is observed at a more positive potential. When a full equivalent of Na^+ is present, the new redox couple is enhanced and the first couple disappears. These results are observed only when the nitro group is appropriately placed to allow simultaneous interaction of the cation with both the macroring and the side arm.

The fact that a second redox couple is observed for ortho compounds **1** and **7** but not for their para isomers, **3** and **8**, clearly demonstrates that the ion-pairing phenomenon is intramolecular. In addition, when the macroring is absent as it is in 2-nitroanisole (**5**) and 2-nitrotoluene (**9**), the second redox couple is invariably irreversible. This precludes the application of any thermodynamic studies. It is, however, good evidence for the intramolecular nature of the interaction in the crown case but not when the ring is absent. An interesting observation is that while the two para compounds (**6** and **10** are indifferent to the presence of Na^+, 2-nitroanisole (**5**) interacts with it much more strongly than does 2-nitrotoluene (**9**). This is expected since methoxy is a strong donor group whereas methyl is not. The irreversibility of the new redox couple for **5** and **9** reflects the unfavorable enthalpy change involved in the dissociation of a contact ion pair. In the crown-containing compounds, this effect is compensated by the solvation enthalpy of the cation by the polyether macroring.

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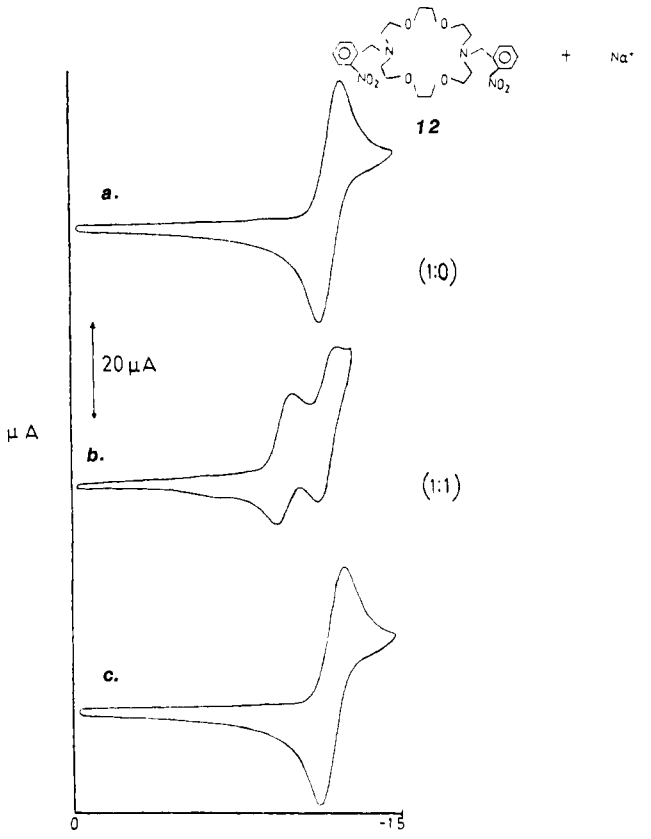


Figure 2. Cyclic voltammograms for two-armed lariat ether **12** (a) in the absence of Na^+, (b) in the presence of 1.0 equiv of Na^+, and (c) as in (b) except that 1.0 equiv of [2.2.1]cryptand has been added.

Table I. Homogeneous Stability Constants for Lariat Ethers

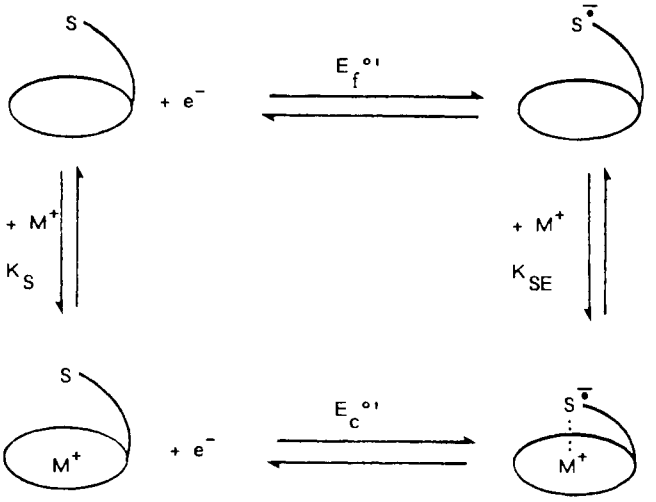
compd. no.	pivot atom	ring size	ortho or para	MeOH[a]	MeCN[b]	notes
1	C	15	ortho	2.83	2.50	*c*
2	C	18	ortho	3.82	3.35	*d*
3	C	15	para	2.72	nd	
4	C	18	para	3.67	nd	
7	N	15	ortho	2.40	nd	
8	N	15	para	2.30	nd	

[a] Homogeneous stability constants were determined by using ion-selective electrode (ISE) techniques are previously described (ref 11). [b] Values reported for acetonitrile were determined by NMR methods as described in the Experimental Section. [c] Note that this value differs from that estimated for the calculations in ref 4a. That value was based on measurements of binding made in anhydrous methanol by using ISE methods. [d] This value differs from the values obtained respectively in anhydrous methanol (log K_S = 3.45) and in 97.5% acetonitrile, by ISE methods (log K_S = 3.72).

Unequivocal evidence for ion-pairing interactions, causing the appearance of the new redox couples, derives from the following observations. When a solution of 2-nitroanisole (**5**) containing Na^+ is studied, two redox couples are observed (see above). Addition of 15-crown-5 (1 equiv) causes the second redox couple corresponding to oxidation–reduction of the Na^+ complex to disappear. Furthermore, when [2.2.1]cryptand is added to a solution containing reduced **12** and 1.0 equiv of Na^+, the two redox couples (see Figure 2) collapse to the single, original couple. These experiments rule out the possibility that the voltammetric response to cation addition was due to cation-catalyzed reactions and clearly demonstrates the ion-pairing nature of the effect. In sum, the ion-pairing phenomenon is completely reversible.

The relative positions of the peak potentials, as demonstrated below, indicate that the Na^+ complexes of reduced **1**, **2**, **7**, **11**, **12**, and **17** are much more stable than those with the neutral ligands (Table I). Since the electrochemical reduction of these ligands is chemically reversible, it is possible to switch these ligands between their neutral and anionic forms to control cation-binding ability on demand.

Scheme I



Cation Binding by Lariat Ether Radical Anions. The chemical processes occurring in a solution of a switchable ligand, such as **1** or **7**, and a metal ion are obviously dependent on the oxidation state of the ligand. Scheme I summarizes the chemical equilibria of interest.

K_S represents the binding constant for the neutral ligand, K_{SE} stands for the binding constant exhibited by the reduced ligand, and $E_f°'$ and $E_c°'$ represent the formal redox potentials for the free ligand and the complex, respectively. Since the four processes complete a cycle, it can be easily demonstrated that

$$\frac{K_{SE}}{K_S} = \exp\left[-\frac{F}{RT}(E_f°' - E_c°')\right] \quad (5)$$

Thus the binding constant enhancement for a given cation–ligand complex upon electrochemical reduction can be calculated from the formal potentials of the free ligand and that of the complex.

Table II summarizes the CV potentials measured for all the ligands under study, in the absence and presence of Li^+, Na^+, and K^+. Some complications arose in the K^+ studies because $KClO_4$ is sparingly soluble in nonaqueous solvents. Although $KClO_4$ solubility is usually greater when a macrocyclic ligand is present, the process is slow and care must be taken to ensure complete dissolution.

The redox couples for the free ligands behave as one-electron, quasi-reversible electron-transfer steps, with the exception of ligands **11** and **12**, for which the only peaks observed, down to −2.0 V vs. SSCE, correspond to the simultaneous reduction (oxidation on the reverse scan) of the two nitrobenzene side arms and thus indicate a two-electron redox couple.

Lithium perchlorate addition to a solution containing any of the macrocyclic ligands leads to the observation of a new redox couple at a more positive potential than that of the free compound. Interestingly, these new redox couples exhibit broad reduction peaks at a much more positive potential than the other peaks in the voltammogram. This fact, common to all ligands surveyed, indicates that (i) Li^+ ion pairs with the reduced side arms are remarkably strong and (ii) upon forced dissociation of the ion pair (due to reoxidation of the side arm), the solvation provided by the medium to Li^+ is not extensive. This is consistent with the known weakness of the interaction between Li^+ and 15- and 18-membered ring macrocycles. The marked irreversibility of the ion-pair redox couple precludes the determination of thermodynamic formal potentials in these cases. However, an estimate of the binding enhancements can be obtained from the difference between the two reduction peaks.

Sodium ion interacts with all the ligands, leading also to new redox couples for the ion-paired species. These new redox couples show electrochemical quasi-reversibility, as was the case with lariat

ethers **1** and **7**. The latter shows a larger distance between the formal potentials of the two couples as a result of its greater flexibility (**7** is a nitrogen-pivot compound) when compared to **1** (a carbon-pivot lariat). Thus, increased structural flexibility translates into a stronger interaction between the anion radical on the side arm and the ring-bound cation. There is also an effect due to the different numbers of oxygen atoms in the macroring (five for compound **1** and four for compound **7**), which reduces macroring binding strength in the case of the nitrogen-pivot lariats, permitting a stronger interaction with the side arm. That this is the case can be inferred from the results for compound **2**. Cyclic voltammograms for this compound in the presence of Na^+ reveal two electrochemical couples, with the second one appearing as a shoulder on the initial couple. The distance between the formal potentials of these two couples is small, indicating that a comparatively weak ion-pair species is formed after reduction of the side arm. This observation must be related to ring size, because there is no other structural difference between compounds **1** and **2**. It is well established that 18-membered ring polyether ligands form quite stable complexes with Na^+.[11] Therefore, the macroring–cation interaction is stronger in the complex with neutral **2** than it is with **1** (see Table I), resulting in a weaker ion pair with the reduced side arm, as indicated by the electrochemical results.

Similar arguments can be used to explain the absence of new voltammetric waves upon addition of $KClO_4$ to solutions containing ligands **1**, **2**, or **4**, respectively. Potassium forms even more stable complexes than Na^+ with 18- and 15-membered ring polyethers, which is translated into weak ion-pair species, undetectable within the energy resolution of the CV technique. Furthermore, K^+ has the smallest charge-to-size ratio among the three cations surveyed and, inherently, tends to form the weakest ion pairs. However, when only four, or less than four, oxygen atoms exist in the crown macroring (compounds **7**, **11**, and **12**), K^+ addition causes the appearance of new redox couples, and binding constant enhancements can be measured.

The binding constant enhancements, calculated by using eq 5, appear in Table II. For all the ligands studied, the enhancement values decrease from Li^+ to K^+. As noted above, this is also the order of decreasing charge-to-size ratio for these alkali-metal cations. This again is a confirmation of the ion-pairing nature of the interaction between the reduced nitroaromatic side arm and the ring-bound cation. The values obtained for ligands **1**, **2**, **7**, **11**, and **12** are readily explained with the arguments utilized to discuss the CV results, in terms of ring size and molecular flexibility. The enhancement values for ligand **17** are smaller than those of **1**. The only structural difference between these two compounds is the additional *p*-nitro group on the side arm of **17** (see Figure 3). Upon electrochemical reduction of the side arm, the added electron density is less localized on the *o*-nitro group because of the electron-withdrawing effect of the second nitro group in the para position. Thus, the ion pair formed is weaker in this case than it is for compound **1**, resulting in a smaller enhancement value.

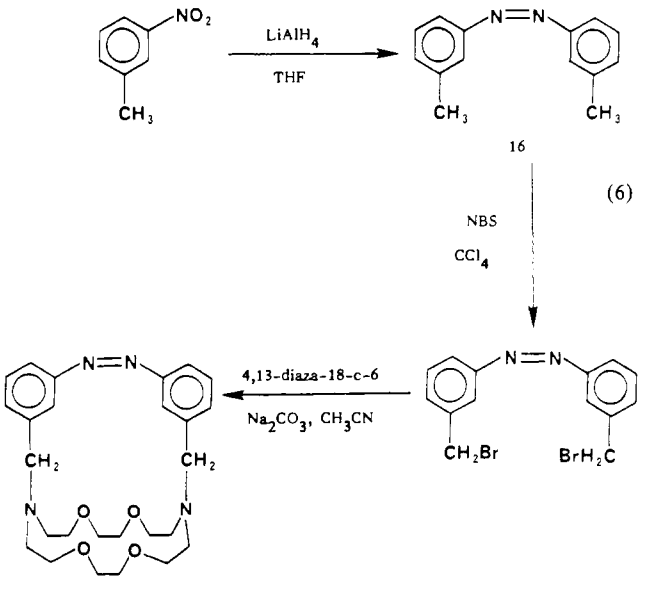
In order to assess the importance played by the macroring in these complexes, we prepared two podand analogues (**13** and **14**) of carbon-pivot lariat ethers **1** and **2** (see eq 2, above). Their electrochemical behavior was essentially similar to that of **5**, suggesting that the preorganized macroring is important for cation complex stability.[9]

The factors controlling the binding constant increase upon electrochemical reduction of the side arm can be summarized as follows: (i) *Reduced side arm–cation ion-pair formation* is responsible for the binding enhancement. It depends on the side-arm structure and on the cation's charge-to-size ratio. (ii) *Macroring–cation interaction* provides most of the binding energy to the neutral ligand complex. If it is too large, it can prevent the interaction of the alkali-metal ion with the reduced side arm. (iii) *Structural flexibility of the ligand* is mainly determined by the type of side arm–macroring covalent linkage. Flexibility should be as great as possible to favor the adoption of a wrapping, three-dimensional conformation by the reduced ligand around the cation.

The most striking binding enhancement is observed with Li^+. Although these are not thermodynamically rigorous measurements, this is expected since Li^+ is the most polarizing of the cations examined. We have measured the Li^+ cation-binding constant, K_S, for 2-((2-nitrophenoxy)methyl)-15-crown-5, **1**, in acetonitrile solution by NMR methods (see Experimental Section). The binding constant is $130 \pm 50\ M^{-1}$. This means that the stability constant for the complex $Li^+ \cdot \mathbf{1}^-$ is estimated to be 2.2×10^7. This value places the binding ability of this ligand within the range of many cryptands. We have also determined other binding constants in acetonitrile solution, but a full set of data is not currently in hand. However, the available values follow a similar pattern to that found for lariat ethers in anhydrous methanol, i.e., these ligands bind in the order K^+, Na^+, and Li^+, and the difference in binding strength in each case lies near a factor of 100. If we generalize and estimate the binding constants for the ligands as 10^2, 10^4, and 10^6 for Li^+, Na^+, and K^+, respectively, the enhancement multipliers place the binding strengths of the reduced ligands in approximately the same range. This means that while the binding strength may be increased to the level of cryptands, the solubility of the latter compounds appears not to be emulated. This "leveling effect" does not cancel the great potential of these molecules to function as molecular switches but in applications without selectivity requirements.

Cation Selectivity and Binding Enhancements in Azocryptands. The cation enhancement selectivity order for the radical anion forms of **1**, **7**, etc., is opposite the cation selectivity order observed for neutral monocyclic crowns and lariat ethers. The leveling effect referred to above precludes any cation selectivity and suggested that efforts to prepare an electrochemically switchable Na^+ or K^+ selective ligand were doomed to failure. Since cryptands often exhibit higher orders of selectivity than simple crowns or lariat ethers, we prepared 7,16-azobis(1,3-phenylenemethylene)-1,4,10,13-tetraoxa-7,16-diazaoctadecane, **15**, in the hope that this compound might exhibit K^+ selectivity in both the neutral and reduced forms.

The synthesis of **15** is shown in eq 6.[12] The cyclic voltammograms for **15** resembled those for 3,3′-azotoluene, **16**, alone or in the presence of Li^+ or Na^+ cations. The CV of **16** is



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indifferent to the presence of K^+ in solution. When K^+ is present in a solution containing **15**, a second, well-resolved redox couple

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Table II. Cation Dependence of Lariat Ether Electrochemistry

compd no.	cation	equiv added	E_p^{c1}	E_p^{a1}	$E^{\circ\prime 1}$	E_p^{c2}	E_p^{a2}	$E^{\circ\prime 2}$	ΔE°	enhancement	notes
1			−1.36	−1.21	−1.28						
	Li^+	0.5	−1.33	−1.24	−1.29	−1.05	small				
		1.0	−1.36	−1.23	−1.30	−1.05	−0.43		0.31	1.7×10^5	*a*
	Na^+	0.5	−1.38	−1.18	−1.28	−1.17	−1.04	−1.11	0.17	7.5×10^2	
		1.0				−1.22	−1.00	−1.11			
	K^+	0.5	−1.37	−1.20	−1.28						
2			−1.32	−1.24	−1.28						
	Na^+	0.5	−1.33	−1.23	−1.28	−1.25			0.07	15	*a*
	K^+	0.5	−1.33	−1.23	−1.28						
		1.0	−1.33	−1.20	−1.27						
3			−1.28	−1.15	−1.22						
	Na^+	0.5	−1.28	−0.99	−1.14						
4			−1.24	−1.08	−1.16						
	Li^+	0.5	−1.35	−1.04	−1.20	−0.94					
	Na^+	0.5	−1.25	−1.03	−1.14						
		1.0	−1.23	−0.96	−1.10						
	K^+	0.5	−1.23	−1.07	−1.15						
		1.0	−1.21	−1.08	−1.14						
5			−1.36	−1.22	−1.29						
	Na^+	0.5	−1.37	−1.21	−1.29	−1.20	−0.87		0.16	5.1×10^2	
	K^+ [b]	0.5	−1.36	−1.22	−1.29						
6			−1.29	−1.17	−1.23						
	Na^+	0.5	−1.33	−1.17	−1.25						
	K^+	0.5	−1.29	−1.17	−1.23						
7			−1.28	−1.05	−1.16						
	Li^+	0.5	−1.29	−1.05	−1.17	−0.90	−0.74	−0.82	0.35	8.2×10^5	
		1.0		−1.05		−0.90	−0.74	−0.82	0.38	2.6×10^6	*a*
	Na^+	0.5	−1.26	−1.05	−1.16	−0.98	−0.82	−0.90	0.26	2.5×10^4	
		1.0				−1.00	−0.80	−0.90	0.28	5.4×10^4	*a*
	K^+	0.5	−1.23	−1.03	−1.13	−1.01	−0.58		0.22	5.2×10^3	*a*
		1.0	−1.22	−1.01	−1.12	−1.02	−0.57		0.20	2.4×10^3	*a*
8			−1.18	−0.97	−1.08						
	Li^+	0.5	−1.15	−0.98	−1.06						
		1.0	−1.24	−0.98	−1.11						
	Na^+	0.5	−1.17	−0.95	−1.06						
		1.0	−1.15	−0.92	−1.04						
	K^+	0.5	−1.13	−1.00	−1.06						
		1.0	−1.13	−1.00	−1.06						
9			−1.28	−1.05	−1.16						
	Li^+	0.5	−1.31	−1.06	−1.18	−0.98					
	Na^+	0.5	−1.30	−1.05	−1.18						
		1.0	−1.30	−1.05	−1.18						
	K^+	0.5	−1.24	−1.08	−1.16						
		1.0	−1.25	−1.07	−1.16						
10			−1.24	−1.00	−1.12						
	Li^+	0.5	−1.29	−0.98	−1.14	−0.96					
	Na^+	0.5	−1.24	−1.00	−1.12						
		1.0	−1.25	−1.01	−1.13						
	K^+	0.5	−1.18	−1.02	−1.10						
		1.0	−1.19	−1.02	−1.10						
11			−1.26	−1.08	−1.17						
	Li^+	0.5	−1.26	−1.08	−1.17	−0.85	−0.73	−0.79	0.38	2.6×10^6	
		1.0	−1.34	−1.09	−1.22	−0.85	−0.71	−0.78	0.39	3.9×10^6	
	Na^+	0.5	−1.26	−1.06	−1.16	−0.98	−0.83	−0.91	0.25	1.7×10^4	
		1.0	−1.23	−1.07	−1.15	−0.98	−0.83	−0.91	0.24	1.1×10^4	
		2.0				−0.99	−0.82	−0.91			
	K^+	0.5	−1.25	−1.09	−1.17	−1.03	small		0.23	7.7×10^3	*a*
		1.0	−1.25	−1.08	−1.17	−1.03	−0.93	−0.98	0.19	1.6×10^3	
12			−1.23	−1.07	−1.15						
	Li^+	0.5	−1.26	−1.09	−1.18	−0.81			0.42	1.3×10^7	*a*
		1.0	−1.32	−1.10	−1.21	−0.84			0.39	3.7×10^6	*a*
	Na^+	0.5	−1.23	−1.05	−1.14	−0.96	−0.84	−0.90	0.25	1.7×10^4	
		1.0	−1.21	−1.04	−1.12	−0.96	−0.84	−0.90	0.25	1.7×10^4	
	K^+	0.5	−1.23	−1.06	−1.14	−0.98	−0.90	−0.94	0.21	3.5×10^3	
15			−1.45	−1.32	−1.38						
	Li^+	0.5	−1.46	−1.32	−1.39	−1.27			0.19	1.6×10^3	
		1.0	−1.48			−1.30			0.18	1.1×10^3	
	Na^+	0.5	−1.46	−1.32	−1.39						
		1.0	−1.42	−1.29	−1.36						
	K^+	0.5	−1.46	−1.32	−1.39	−1.28					
		1.0	−1.46	−1.32	−1.39	−1.29	−1.19	−1.24	0.15	3.4×10^2	
		2.0				−1.31	−1.16	−1.23	0.15	3.4×10^2	
				−1.06	−0.99	−1.02					
17	Li^+	0.5	−1.07	−0.99	−1.03	−0.91			0.15	3.4×10^2	*a*
	Na^+	0.5	−1.06	−0.99	−1.02	−0.96	−0.82	−0.89	0.13	1.6×10^2	
	K^+	0.5	−1.06	−0.99	−1.02						

[a] Value calculated from reduction potentials only. [b] Potassium perchlorate, the source of potassium cation, is only marginally soluble in acetonitrile in the absence of a ligand. If ligand solvation is weak, too little cation will be present for accurate measurements.

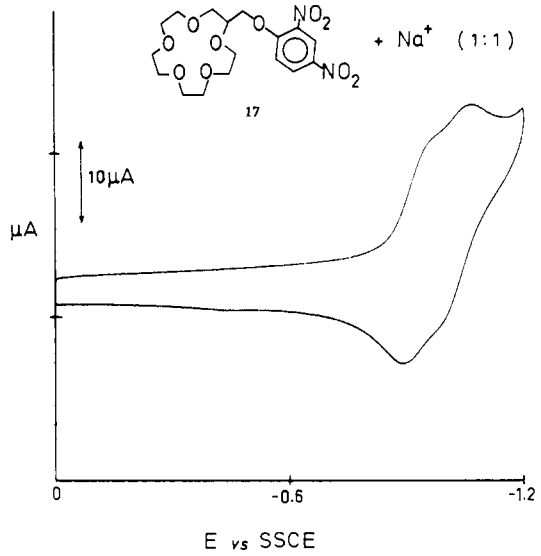

Figure 3. Cyclic voltammogram of **17** in the presence of an equimolar amount of Na^+.

is observed at a more positive potential. This was not the case with Na^+, where only a poorly resolved shoulder was observed in addition to the original couple. This clearly indicates that reducible cryptands can be electrochemically switched to afford enhanced cation binding while simultaneously exhibiting cation selectivity. This overcomes the selectivity limitation observed with lariat ethers and offers the prospect of devising potent and highly selective, electrochemically switched cation binders.

Summary

It is shown that reduction of electron-deficient aromatic species is dramatically affected by the presence of Li^+, Na^+, or K^+ cations when a donor present in the aromatic system can interact with the ring-bound cation. This ability to interact is determined by steric considerations, and, when observed, the binding enhancements range from 15- to 13 000 000-fold. The binding enhancements are due to intramolecular ion pairing and are generally in the order $Li^+ > Na^+ > K^+$. Nitroanisole, nitrotoluene, or nitroaromatic podands which lack the inherent cation-binding ability of the macrocycle do not exhibit such ion-pairing effects. For the rigid azocryptand system, K^+ was more strongly bound than Na^+ after reduction. We attribute this to a match in size between the cation and the cavity. Although not yet possible with the flexible lariat ethers, the azocryptands offer the possibility of selective cation binding in electrochemically switched systems.

Experimental Section

Reagents and Solvents. Acetonitrile (MCB, distilled in glass) was stored over Linde 4-Å molecular sieves and flask-to-flask distilled from CaH_2 in a vacuum line, immediately before using it. All solutions were prepared under an inert atmosphere of dry nitrogen gas. Tetrabutylammonium perchlorate (TBAP, from MCB) was twice recrystallized from ethyl acetate and stored in a desiccator. Alkali-metal perchlorate salts were recrystallized from deionized water and dried in a vacuum oven at 110 °C for 24 h.

CV Experiments. The electrochemical equipment used consisted of a Universal Programmer (Princeton Applied Research, Model 175), for the generation of potential functions, a potentiostat (P.A.R., Model 173) equipped with a current follower (P.A.R., Model 176), and a Hewlett-Packard XY recorder (Model 7045A). All electrochemical experiments were done in a simple three-compartment cell, with the different compartments separated by medium-porosity glass-fritted disks. A glassy carbon electrode (P.A.R.) was used as the working electrode, a platinum wire was used as the counter-electrode, and a homemade sodium-saturated calomel half-cell (SSCE) served as the reference.

Ordinarily, 25 mL of a 0.1 M tetrabutylammonium perchlorate solution in freshly distilled acetonitrile was prepared for each experiment. This solution was transferred into the cell, maintained under a dry nitrogen atmosphere, and electrochemically tested for purity and dryness from 0.0 to −2.0 V vs. SSCE. When a flat voltammogram was obtained, the nitrogen flow was increased, the working electrode was taken out of the cell, and enough electroactive compound to reach a concentration of 1 mM was added to the 10 mL of solution in this compartment. The working electrode was again placed in position, the nitrogen flow was reduced to its initial level, and the experiment was continued. All additions to the cell were performed by following a similar procedure.

All the cyclic voltammograms were obtained at 25 °C, under single sweep conditions. The scan rates utilized ranged from 50 to 500 mV/s. The built-in capability of IR compensation in the current-follower module was always used, since the conductive properties of the $TBAP/CH_3CN$ solutions make this advisable.

Before each experiment, the glassy carbon surface of the working electrode was polished with an aqueous suspension of alumina on a soft surface. Occasionally, it was necessary to repeat this polishing procedure during a voltammetric experiment to reactivate the surface of the electrode.

NMR Determination of Binding Constants. A mixture (70:30 v/v) of acetonitrile and acetonitrile-d_3 was prepared and purified as described above. This mixture was used as the solvent for the preparation of the NMR samples. A minimum of 11 samples with different [ligand]/[cation] ratios was prepared for each ligand studied. All samples were 0.14 M in the alkali-metal perchlorate salt, in order to keep approximately constant the medium's ionic strength. All solutions were prepared under an inert nitrogen atmosphere, degassed by at least three freeze-pump-thaw cycles, and sealed under vacuum in 5-mm-o.d. NMR tubes.

Natural abundance ^{23}Na NMR spectra were recorded at a frequency of 23.71 MHz in a JEOL FX-90-Q spectrometer. Half-height line widths were measured and reduced to unit viscosity by using measured bulk viscosities determined with an Ostwald viscometer. Lithium cation binding constants were determined by measurement of ^7Li chemical shifts at an observation frequency of 34.81 MHz. This was required because the small nuclear quadrupole moment of ^7Li causes the line widths to be insensitive to complexation. All ^7Li chemical shifts are relative to a 0.14 M $LiClO_4$ acetonitrile solution. Either Li^+ or Na^+ binding constants were determined by using the iteration method described by Laszlo and co-workers.[12]

Electrochemical Procedure: Reduction of 2-((2-Nitrophenoxy)-methyl)-15-crown-5. A 2.0 mM solution of 2-((2-nitrophenoxy)-methyl)-15-crown-5, **1**, was prepared by mixing 18.6 mg (0.05 mmol) of the lariat ether, 341.0 mg (1.0 mmol) of Bu_4NClO_4, and 25 mL of MeCN. A 12-mL aliquot was added to a standard three-compartment cell equipped with a magnetic stirrer and an inlet for dry N_2. After 0.25 h of N_2-purging and stirring, a cyclic voltammogram was recorded of the unstirred solution. The potential scan was initiated at 0 V and switched at −1.6 V. A scan rate of 200 mV/s and a current setting of 100 μA/V were used. A quasi-reversible, one-electron redox couple at −1.28 V was observed. Anhydrous $NaClO_4$ (0.5 equiv) was added to the electrochemical cell and the solution stirred until the salt dissolved. The voltammogram was recorded and a new (quasi-reversible) redox couple appeared at −1.11 V with the original couple remaining at −1.28 V. When a full equiv of Na^+ was added, the redox couple at −1.28 V disappeared, and only the couple at −1.11 V with an enhanced current was observed.

Determination of Homogeneous Stability Constants by Ion-Selective Electrode Techniques. Homogeneous equilibrium stability constants (K_S) for complexation of alkali- and alkaline-earth-metal cation by the ligands reported herein were determined in anhydrous methanol solution by using ion-selective electrode (ISE) methods as previously reported.[11] ISE methods proved unsuccessful for anhydrous acetonitrile solutions because of poor electrode response. Values for K_S in MeCN were therefore determined by NMR analysis as described above.

Syntheses. Melting points were determined on a Thomas Hoover capillary apparatus and are uncorrected. Infrared spectra were recorded on a Perkin-Elmer Model 281 spectrophotometer on neat samples unless specified and are calibrated against the 1601-cm^{-1} band of polystyrene. Routine ^1H NMR spectra were recorded on a Varian EM 360 spectrometer as ca. 15 wt% solutions in $CDCl_3$ unless otherwise specified. Chemical shifts are reported in parts per million (δ) downfield from internal Me_4Si. Gas chromatographic analyses were conducted on a Varian Model 920 analytical gas chromatograph equipped with a thermal conductivity detector and a 5 ft × 0.25 in. 1.5% OV-101 column on 100/120 mesh Chromosorb G. Helium was used as the carrier gas, and the flow rate was ca. 60 mL/min. Combustion analyses were determined in house at the University of Maryland.

All reagents were the best grade commercially available and were used without further purification unless otherwise specified. THF was distilled from $LiAlH_4$ under a dry N_2 atmosphere immediately prior to use.

Acetonitrile was purified for the electrochemical experiments as described above.

2-((2-Nitrophenoxy)methyl)-15-crown-5, 1. 2-((2-Nitrophenoxy)-methyl)-15-crown-5, **1**, was prepared by treating the anion (NaH, THF) of 2-(hydroxymethyl)-15-crown-5 with 1 equiv of 1-chloro-2-nitrobenzene (25 °C, 4 h). Lariat ether **1** was a pale yellow oil isolated (55%) by chromatography over alumina. ^{1}H NMR ($CDCl_3$) δ 3.9 (m, 21 H), 6.9–8.1 (m, 4 H). Anal. Calcd for $C_{17}H_{25}NO_8$: C, 54.98; H, 6.78; N, 3.77. Found: C, 54.62; H, 6.91, N, 3.78.

2-((2-Nitrophenoxy)methyl)-18-crown-6, 2. Sodium hydride (0.36 g, 15 mmol) was washed with hexane (3 × 25 mL) to remove the oil, and THF (20 mL) was added. A solution of 2-(hydroxymethyl)-18-crown-6 (2.0 g, 6.79 mmol) in THF (15 mL) was added dropwise during 3 min. After the solution was stirred for 15 min, 1-fluoro-2-nitrobenzene (0.96 g, 6.8 mmol) in THF (10 mL) was added in a stream. The resulting mixture was stirred at room temperature for 1 h and then at reflux overnight. The reaction mixture was cooled and filtered and the solvent was evaporated in vacuo. The residue was column chromatographed (Al_2O_3, 0–10% 2-propanol/hexane). The product **2** crystallized in the eluent and was recrystallized from 2% 2-propanol in hexane (1 g/15 mL solvent) to give pale yellow crystals (0.8 g, 28%): mp 66–67 °C; ^{1}H NMR δ 6.8–8.0 (m, 4 H), 3.7 (m, 25 H). IR (Nujol) 3000, 2900, 1425, 1100 cm^{-1}. Anal. Calcd for $C_{19}H_{29}NO_9$: C, 54.93; H, 7.03; N, 3.37. Found: C, 55.07; H, 7.22; N, 3.23. ^{13}C NMR δ 152.46, 144.31, 133.75, 125.27, 120.22, 114.82, 78.30, 77.39, 77.04, 75.76, 71.08, 70.71, 70.34, 70.20.

2-((4-Nitrophenoxy)methyl)-15-crown-5, 3. 2-((4-Nitrophenoxy)-methyl)-15-crown-5, **3**, was prepared in analogy to **1** and isolated (bp 175 °C/0.1 mm) as a yellow oil in 74% yield: ^{1}H NMR 3.7 (m, 21 H), 7.0-8.2 (dd, 4 H); Anal. (isomer of **1**) Found: *C, 54.99; H, 6.95; N, 3.90.*

2-((4-Nitrophenoxy)methyl)-18-crown-6, 4. 2-((4-Nitrophenoxy)-methyl)-18-crown-6, **4**, was prepared in analogy to **2** and isolated after column chromatography as a yellow oil (1.6 g, 59%): ^{1}H NMR 3.7 (m, 25 H), 6.8–8.4 (d, 4 H); Anal. (isomer of **2**) Found: C, 55.02; H, 7.16; N, 3.31.

2-Nitroanisole, **5**, and 4-nitroanisole, **6**, were purchased from Eastman Organic Chemicals and used as obtained.

Preparation of N-Pivot Lariat Ethers by N-Alkylation of Azacrowns. Aza-15-crown-5 and aza-18-crown-6 were obtained by hydrogenolysis (H_2, 10% Pd–C, absolute EtOH) of the corresponding *N*-benzylaza-15-crown-5 or *N*-benzylaza-18-crown-6 as previously described.[10] The parent monoazacrowns were treated with various alkylating agents in the presence of Na_2CO_3 in either THF or CH_3CN solvent as specified below.

***N*-(2-Nitrobenzyl)aza-15-crown-5, 7.** Aza-15-crown-5 (2.0 g, 0.009 mol), Na_2CO_3 (1.9 g, 0.018 mol), CH_3CN (30 mL), and 2-nitrobenzyl chloride (1.6 g, 0.009 mol) were stirred at reflux for 24 h, cooled, and filtered, and the solvent was evaporated in vacuo. The residue was taken up in $CHCl_3$ (20 mL), cooled, and filtered, and the solvent was evaporated. The residual oil was chromatographed over alumina (2% 2-propanol/hexanes) and distilled (Kugelrohr, 155 °C/0.05 torr) to provide lariat ether **7** (1.1 g, 35%) as a yellow oil: ^{1}H NMR δ 2.75 (t, 4 H), 3.60 (m, 16 H), 3.95 (s, 2 H), 7.50 (m, 4 H); ^{13}C NMR δ 54.99, 57.32, 69.79, 70.17, 70.55, 70.99, 123.79, 127.32, 131.05, 132.19, 135.39; IR 2860, 1530, 1450, 1355, 1300, 1125, 935, 740 cm^{-1}. Anal. Calcd for $C_{17}H_{26}N_2O_6$: C, 57.61; H, 7.39; N, 7.90. Found: C, 57.81; H, 7.58; N, 8.09.

***N*-(4-Nitrobenzyl)aza-15-crown-5, 8.** Aza-15-crown-5 (2.0 g, 0.009 mol), Na_2CO_3 (1.9 g, 0.018 mol), CH_3CN (50 mL), and 4-nitrobenzyl bromide (1.95 g, 0.009 mol) were stirred at reflux for 24 h, cooled, and filtered, and the solvent was evaporated in vacuo. The residue was taken up in $CHCl_3$ (20 mL), cooled, and filtered, and the solvent was evaporated. The residual oil was chromatographed over alumina (2% 2-propanol/hexanes), followed by chromatography over a column of silica gel (18:1 v/v $CHCl_3$/MeOH). The lariat ether was further purified by Chromatotron chromatography (0.75 g of **8**/10 mL $CHCl_3$ applied to a 4-mm silica gel rotating plate, eluted with $CHCl_3$, 5-mL fractions) to provide pure **8** (0.7 g, 22%), which solidified to a glass upon standing for 500 h: ^{1}H NMR δ 2.75 (t, 4 H), 3.65 (m, 18 H), 7.85 (dd, 4 H); ^{13}C NMR δ 54.82, 59.83, 69.79, 70.20, 70.50, 70.99, 123.09, 129.07, 146.96, 148.01; IR (nujol) 2900, 1600, 1520, 1350, 1310, 1260, 1125, 860, 750 cm^{-1}. Anal. Calcd for $C_{17}H_{26}N_2O_6$: C, 57.61; H, 7.39; N, 7.90. Found: C, 57.38; H, 7.58; N, 7.80.

2-Nitrotoluene (**9**) and 4-nitrotoluene (**10**) were purchased from Eastman Organic Chemicals, and the former was used as obtained. Compound **10** was recrystallized from 90% EtOH and dried in vacuo prior to use.

***N,N'*-Bis(2-nitrobenzyl)-4,13-diaza-18-crown-6, 12.** A stirred solution containing 1.0 g (3.8 mmol) of 1,10-diaza-18-crown-6, 1.3 g (7.8 mmol) of 2-nitrobenzyl chloride, 2.0 g (19.0 mmol) of Na_2CO_3, and 20 mL of CH_3CN was heated at reflux for 16 h. The reaction was cooled and concentrated and the oily residue added to 20 mL of $CHCl_3$. The organic phase was washed with 20 mL of distilled water, dried over anhydrous $MgSO_4$, and concentrated in vacuo. Upon standing at 0 °C, the oily residue crystallized. After two recrystallizations (EtOH followed by 5% hexanes/EtOH), 1.8 g (90%) of a yellow solid (mp 78–79 °C) was obtained: ^{1}H NMR δ 2.80 (t, 8 H, NCH_2), 3.60 (t and s, 16 H, OCH_2), 4.00 (s, 4 H, benzyl), 7.33–7.92 (m, 8 H, aromatic); IR (KBr) 2860, 1520, 1360, 1350, 1140, 1130, 730 cm^{-1}; Anal. Calcd for $C_{26}H_{36}N_4O_8$: C, 58.62; H, 6.83; N, 10.52%. Found: C, 58.59; H, 7.02; N, 10.66%.

2-(Methoxyoctaethoxy)nitrobenzene, 13. To a N_2-purged, stirring suspension of hexane-washed NaH (4.8 g, 50% in oil, 100 mmol) in THF (100 mL) was added (dropwise, 5 h) a solution of poly(ethylene glycol) monomethyl ether (average molecular weight = 350, 20.0 g, 57 mmol) in THF (50 mL). After stirring 1 h, a solution of freshly recrystallized 2-chloronitrobenzene (13.0 g, 80 mmol) in THF (50 mL) was added dropwise, and stirring continued overnight. The mixture was filtered (celite) and evaporated in vacuo. The residual dark oil was chromatographed (alumina, 0–10% 2-propanol in hexane) to afford **13** (18.0 g, 68%) as a red oil. Osmometric molecular weight determination (494 ± 15 daltons) showed that an average of 7.8 ethyleneoxy units were present in the side chain. A previous, independent molecular weight determination[2b] conducted on the starting ether gave a molecular weight of 400 daltons, suggesting eight ethyleneoxy units. The analysis below is calculated for eight ethyleneoxy units. Anal. Calcd. for $C_{23}H_{39}NO_{11}$: C, 54.65%; H, 7.72%; N, 2.77%. Found: C, 54.45%; H, 7.66%; N, 3.23%. The nitrogen value in this analysis is high (+0.46%) as suggested by the molecular weight data: ^{1}H NMR (best fit of the integral is for seven ethyleneoxy units) δ 3.35 (s, 3 H), 3.35 (s, 3 H), 3.5–4.4 (m, 28 H), 6.8–8.0 (m, 4 H); IR (neat, strong bands) 2900, 1600, 1525, 1350, 1280, 1120 cm^{-1}.

2-(Methoxydodecaethoxy)nitrobenzene, 14. The preparation of **14** was identical with that for **13** except that it was conducted on a 9 mmol scale (5.0 g of PEG-MME, average molecular weight = 550): yield: 3.7 g, 61% of a red oil; Osmometric molecular weight, 704, calculated 681; The IR and NMR spectra were essentially identical with those of **13**. Anal. Calcd for $C_{31}H_{55}NO_{15}$: C, 54.63%; H, 8.08%; N, 2.06%. Found: C, 54.36%; H, 8.30%; N, 2.40%.

Preparation of Azocryptand 15. A. 3,3'-Azotoluene, 16. To a vigorously stirred solution containing 61.8 g (0.45 mol) of 3-nitrotoluene in anhydrous benzene (500 mL) was cautiously added a solution containing 41.5 g (1.09 mol) of $LiAlH_4$ in anhydrous Et_2O (250 mL). The reaction mixture was stirred for an additional 40 h. Water (100 mL) was cautiously added, and the inorganic salts were removed by filtration. The filtrate was washed (5% Na_2CO_3 followed by H_2O), dried (Na_2CO_3), and concentrated in vacuo to yield, after alumina chromatography (7% CH_2Cl_2–hexanes) and recrystallization from MeOH, 23.6 g (50%) of an orange solid (mp 49–50 °C).

3,3'-Bis(bromomethyl)azobenzene. A solution containing 29.0 g (0.163 mol) of *N*-bromosuccinimide, 17.0 g (0.081 mol) of 3,3'-azotoluene, and 400 mL of CCl_4 was heated at reflux for 20 h while being exposed to the light emitted from a 150-W unfrosted light bulb. The reaction mixture was cooled, filtered, and concentrated in vacuo to yield, after two recrystallizations from MeCN, 11.62 g (39%) of an orange solid (mp 141–142 °C): ^{1}H NMR δ 4.57 (s, 4 H, benzyl), 7.45–7.93 (c, 8 H, aromatic); IR (KBr) 2980, 1480, 1445, 1210, 910, 810, 695, 660 cm^{-1}. Anal. Calcd for $C_{14}H_{12}N_2Br_2$: C, 45.68; H, 3.29; N, 7.61%. Found: C, 45.53; H, 3.22; N, 7.81%.

Azocryptand 15. To a vigorously stirred solution containing 1.06 g (10.0 mol) of Na_2CO_3 in 150 mL of refluxing MeCN was added, over a period of 24 h, 0.528 g (2.00 mmol) of 4,13-diaza-18-crown-6 in 40 mL of MeCN and 0.743 g (2 mmol) of 3,3'-bis(bromomethyl)azobenzene in 40 mL of MeCN/dioxane (1:1). The reaction mixture was heated for an additional 14 h, cooled, filtered, and concentrated in vacuo. The residue, after alumina chromatography (20% EtOAc–hexanes) and recrystallization (hexanes), yielded 290 mg (31%) of an orange solid (mp 131–132 °C) which was identified as the desired crown ether: ^{1}H NMR δ 2.73 (t, 8 H, NCH_2), 3.27–4.19 (c, 20 H, CH_2O and benzyl), 7.13–7.73 (c, 6 H, aromatic), 8.65 (s, 2 H, aromatic); IR (KBr) 2940, 2880, 2820, 1480, 1445, 1130, 800, 700 cm^{-1}; Anal. Calcd for $C_{26}H_{36}N_4O_4$: C, 66.63; H, 7.76; N, 11.95%. Found: C, 66.55; H, 8.00; N, 11.82%.

2-((2,4-Dinitrophenoxy)methyl)-15-crown-5, 17. A slurry of NaH (0.48 g, 20 mmol) in THF (30 mL) was treated with a THF (20 mL) solution of 2-(hydroxymethyl)-15-crown-5 (5.00 g, 20 mmole) and stirred until H_2 evolution ceased. A solution of 1-chloro-2,4-dinitrobenzene (4.05 g, 40 mmol) in THF (10 mL) was added in a stream. The mixture was stirred overnight at ambient temperature and then filtered; the solvent was evaporated and the residue chromatographed (alumina, 0–10% *i*-PrOH/hexane) to afford **4**, as a viscous pale yellow oil: 2.41 g (29%); NMR 3.56–4.43 (m, 21 H, singlet at 3.67), 7.40 (d, 1 H, J = 10 Hz), 8.53 (dd, 1 H, J = 10, 2 Hz), 8.87 (d, 1 H, J = 2 Hz); IR (neat) 1605,

1525, 1345, 1125 (br), 830 cm^{-1}. Anal. Calcd for $C_{17}H_{24}N_2O_{10}$: C, 49.04; H, 5.81; N, 6.73. Found: C, 49.22; H, 5.94; N, 6.69.

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Registry No. 1, 87453-20-1; **2**, 94978-62-8; **3**, 87453-21-2; **4**, 94978-63-9; **5**, 91-23-6; **6**, 100-17-4; **7**, 88548-59-8; **8**, 88548-60-1; **9**, 88-72-2; **10**, 99-99-0; **11**, 94978-64-0; **12**, 94978-65-1; **13**, 92670-57-0; **14**, 94978-66-2; **15**, 93824-65-8; **16**, 588-04-5; **17**, 94978-67-3; Li^+, 17341-24-1; Na^+, 17341-25-2; K^+, 24203-36-9; 3,3′-bis(bromomethyl)azobenzene, 93824-64-7; 2-(hydroxymethyl)-15-crown-5, 75507-25-4; 2-(hydroxymethyl)-18-crown-6, 70069-04-4; 4,13-diaza-18-crown-6, 23978-55-4; 1-chloro-2-nitrobenzene, 88-73-3; 1-fluoro-2-nitrobenzene, 1493-27-2; aza-15-crown-5, 66943-05-3; 2-nitrobenzyl chloride, 612-23-7; 4-nitrobenzyl bromide, 100-11-8; 1,10-diaza-18-crown-6, 23978-55-4; poly(ethylene glycol) monomethyl ether, 9004-74-4; 3-nitrotoluene, 99-08-1; 1-chloro-2,4-dinitrobenzene, 97-00-7.

Ab Initio Structures of Phosphorus Acids and Esters. 1. Phosphinic, Phosphonic, and Phosphoric Acids†

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Abstract: The molecular structures of all stable conformations of phosphinic, phosphonic, and phosphoric acid have been computed by employing complete geometry optimization in a variety of basis sets. Phosphinic acid, the species with the fewest torsional degrees of freedom, was examined in detail to determine the origin of forces giving rise to its preferred conformation. These forces are due almost entirely to electrostatic effects such as dipole–dipole interactions, with stereoelectronic ("anomeric") and steric effects each being at most 12% as large. Bond lengths and angles generally agree with the limited prior theoretical and experimental values. In each acid one or more additional higher energy stable conformations are found in the STO basis set, but these usually do not appear when larger basis sets are employed. All three acids exhibit a minimum-energy conformation in which the acidic hydrogens are oriented toward the phosphoryl oxygen and a distance from it, typically 2.7–2.8 Å, which is nearly the same in each case. The conformations of all three acids may be described solely on the basis of dipole–dipole interactions plus relatively small internal hydrogen bonding and steric effects. In contrast to earlier studies little conformational evidence of "anomeric" effects is found in any of these compounds.

The oxyacids of phosphorus have long been the subject of theoretical study, due in large measure to the role played by the phosphates in biological systems. The most important single property of these compounds is their detailed molecular structure. Yet determining these structures has often proven elusive due to the absence of experimental data on isolated molecules and the computational difficulties encountered in comprehensive theoretical treatments. As an example of the latter, all previously reported computations on this class of compounds have employed a relatively small basis set (either minimal STO-3G or a larger basis lacking polarization functions) and have not determined the complete minimal-energy structure. Yet it is now generally recognized that polarization functions on phosphorus are essential in determining correct bond lengths and angles involving that element,[1] and it is probable that inaccuracies in structural parameters are reflected in inaccurate energies of the various conformations.

For these reasons we considered it essential to reexamine some of these systems using larger basis sets (such as 4-31G*) with complete geometry optimization at each step. The recent development of analytical-gradient optimization techniques has provided an extremely important tool for investigations of this type.[2] As will be shown below, complete geometrical optimization can lead to qualitatively different conclusions concerning molecular structure than are obtained by even quite careful partial optimizations.

As a first set of compounds for study, we have considered the three simplest tetracoordinate acids of phosphorus: phosphinic, phosphonic, and phosphoric (H_3PO_2, H_3PO_3, and H_3PO_4). These may be considered formally to be derived from the hypothetical phosphine oxide molecule, H_3PO, by replacement of one, two, or three hydrogens by hydroxyl groups.

These compounds have been the subject of some previous theoretical studies. The conformation of phosphinic acid has been computed in an STO-3G basis by Hayes et al.[3] These authors studied the conformation and partially optimized the geometry of phosphoric acid in STO-3G and 4-31G basis sets but without polarization functions. Recently, Emsley et al.[4] computed the energy of phosphonic acid in a 4-31G basis, optimizing the structure of the P–O–H linkage only. Somewhat earlier Lehn and Wipff[5] computed the energies and Mulliken populations of phosphoric acid in a split-valence basis with and without d functions on phosphorus at three preselected conformations but did not compute any structural parameters.

Computational Details

All calculations reported here were carried out with the GAUSSIAN 80 program[6] and the analytical-gradient procedure for optimizing molecular structures that it contains. Each of the three title compounds was studied

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