Potentiometric Selectivities of Dibenzo-16-crown-5 Compounds for Alkali and Alkaline Earth Metal Cations and Ammonium Ions

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Abstract. Potentiometric selectivities toward alkali and alkaline earth metal cations and ammonium ions are utilized to probe the complexation of these cationic species by dibenzo-16-crown-5 lariat ethers. Attachment of one or two pendant groups to the central carbon of the three-carbon bridge in dibenzo-16-crown-5 markedly alters the potentiometric responses of the ionophores when incorporated in solvent polymeric membrane electrodes. Results obtained for dibenzo-16-crown-5 compounds with coordinating side arms containing ether, carboxylic acid, ester, and amide groups provide insight into the role of the side arm in metal ion complexation by lariat ether compounds.

1. Introduction

A wide variety of macrocyclic polyether compounds (crown ethers) has been synthesized and evaluated in alkali and alkaline earth metal complexation, determination, and separation processes due to their superior binding ability for these metal ions [1–3]. Attachment of one or more potential metal ion coordination sites to a crown ether framework produces complexing agents known as lariat ethers [4–6]. Interaction of the side arm with the crown ether-complexed metal ion provides an opportunity for three-dimensional complexation.

Due to the synthetic accessibility of dibenzo-16-crown-5 compounds with pendant groups attached to the central carbon of the three-carbon bridge [7–12], the dibenzo-16-crown-5 ring system provides a convenient platform for investigating the influence of structural variation within lariat ethers upon their selectivity and efficiency in metal ion complexation processes. Also, the two limiting conforma-
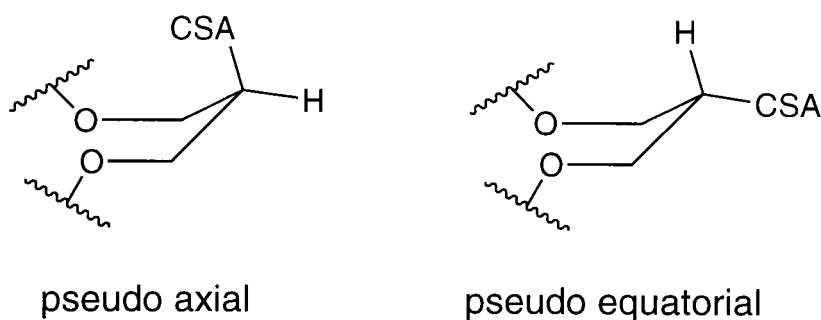

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Figure 1. Side-arm orientations in dibenzo-16-crown-5 compounds. (CSA = coordinating side arm.)

tions for the three-carbon bridge shown in Figure 1 allow a functional side arm to occupy either a pseudoaxial or pseudoequatorial position. In the former orientation, the functional side arm can interact with a metal ion which is complexed within the polyether cavity; whereas in the latter, it cannot.

To probe the influence of nonionizable side arms upon the complexation of alkali and alkaline earth metal cations and ammonium ions by lariat ethers, we have prepared solvent polymeric membrane electrodes containing dibenzo-16-crown-5 lariat ethers, incorporated the membranes into ion-selective electrode (ISE) assemblies, and measured their selectivities. The structural variation in the dibenzo-16-crown-5 lariat ethers includes a coordinating side arm, OCH_3, $OCH_2CH_2OCH_3$, OCH_2CO_2H, OCH_2CO_2R, or $OCH_2C(O)NR_2$, attached to the central carbon of the three-carbon bridge. Also present may be a *geminal*, non-coordinating normal alkyl, branched alkyl, fluoroalkyl, alkenyl, or alkynyl group. The results of these studies are now reviewed.

2. Experimental

The method for preparation of the solvent polymeric membrane and incorporating it into an ion-selective electrode assembly is illustrated in Figure 2. A solution of poly(vinyl chloride) (PVC), NPOE (*o*-nitrophenyl octyl ether, the membrane solvent), the lariat ether, and potassium tetrakis(*p*-chlorophenyl)borate (a membrane modifier with a lipophilic anion) in tetrahydrofuran (THF) was prepared. A few drops of this solution were dropped onto a polytetrafluoroethylene (PTFE) mesh attached to a PVC tube and allowed to evaporate for 15–20 minutes. Addition of the THF solution and evaporation were repeated eight or nine times. The resultant PVC tube with the coated PTFE membrane was fixed in an electrode body and the electrode was conditioned by soaking in 0.1 M sodium chloride solution for 12 hours before use. For each combination of ionophore and membrane solvent, two membrane electrodes were prepared.

Details of the potentiometric measurements have been published previously [13]. The potentiometric selectivities were determined by the fixed interference
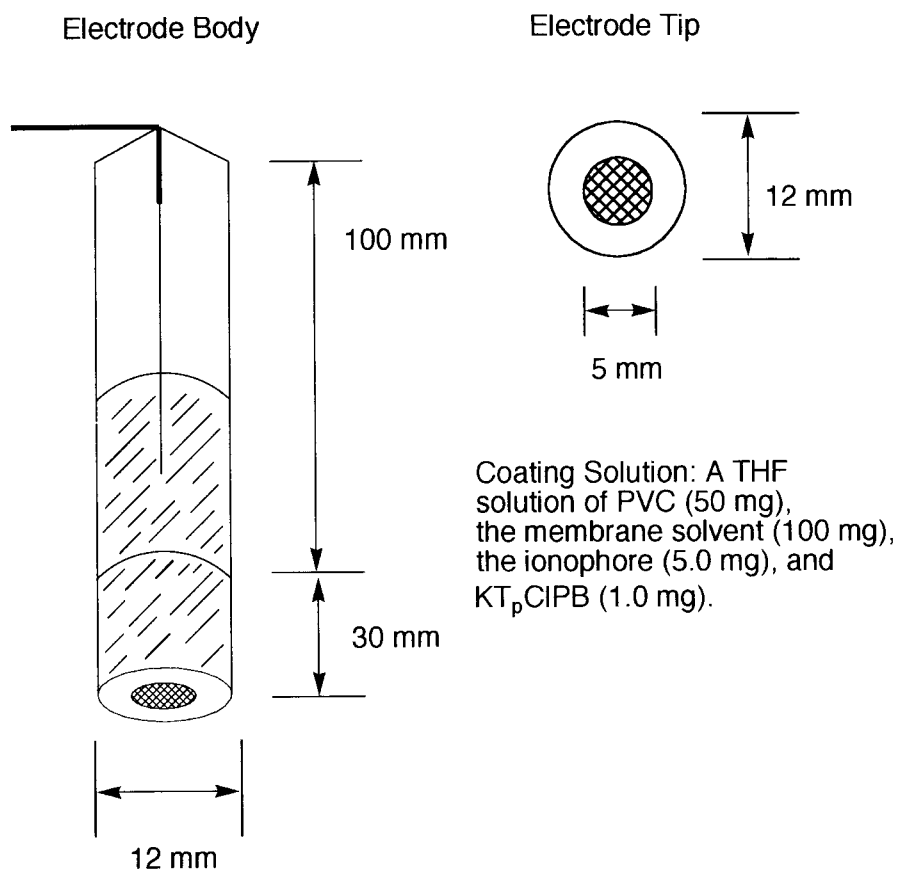
Figure 2. Apparatus for the preparation of solvent polymeric membrane electrodes.

method [14]. Nerstian response (59 mV/decade) was observed for all of the ISEs. Duplicate potentiometric measurements were performed with each of the two membrane electrodes for each ionophore-membrane solvent combination. The standard deviation in the log K^{Pot} values was 0.05 or less.

3. Results and Discussion

From the examination of Corey-Pauling-Kortum (CPK) space-filling models, the cavity diameter of dibenzo-16-crown-5 is estimated to be 2.0-2.4 Å. The alkali metal cation diameters are: Li^+, 1.36 Å; Na^+, 1.96 Å; K^+, 2.66 Å; Rb^+, 2.98 Å; and Cs^+, 3.30 Å [15]. From the relationship between the metal ion and crown ether cavity diameters, it is anticipated that Li^+ and Na^+ will be accommodated within the crown ether cavity and form inclusion complexes. In contrast, the other alkali metal ions are too large to fit within the cavity and will produce complexes in which the metal ion sits on top of the polyether oxygens. Thus, "nesting" complexes
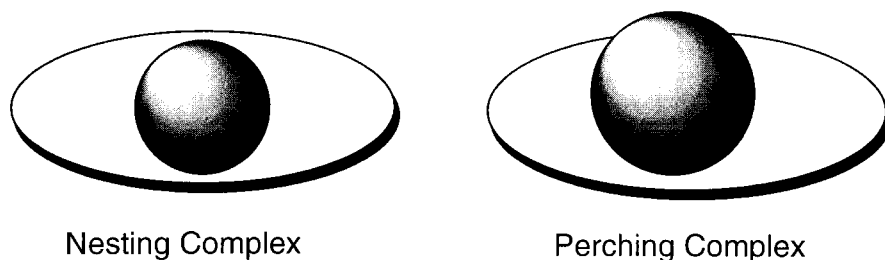
Figure 3. Nesting and perching complexes of metal ions with a crown ether.

Table I. Potentiometric selectivities of dibenzo-16-crown-5 compounds **1–12**[a]

With $R_1 = H$				With $R_1 = C_3H_7$		
Cmpd	$\log K^{Pot}_{Na,K}$	$\log K^{Pot}_{Na,Li}$	R_2	Cmpd	$\log K^{Pot}_{Na,K}$	$\log K^{Pot}_{Na,Li}$
1	+0.23	−2.59	H			
2	+0.68	−2.31	C_3H_7			
3	−0.15	−3.25	OCH_3	**8**	−0.34	−2.99
4	−0.46	−3.23	$OCH_2CH_2OCH_3$	**9**	−1.34	−3.49
6	−0.45	−3.87	$OCH_2CO_2C_2H_5$	**11**	−1.49	−3.73
5	−0.65	−3.46	OCH_2CO_2H	**10**	−1.74	−3.52
7	−0.79	−3.02	$OCH_2C(O)N(C_2H_5)_2$	**12**	−1.98	−2.84

[a]Data from References 13 and 18, except for compounds **1** and **3**.

[16] are expected for Li^+ and Na^+; whereas less stable "perching" complexes [16] would be formed by the larger alkali metal cations (Figure 3). Of the two nesting complexes, Na^+ would provide a better fit within the polyether cavity [17]. Therefore, selective complexation of Na^+ by dibenzo-16-crown-5 is anticipated.

3.1. SELECTIVITIES OF DIBENZO-16-CROWN-5 AND ITS LARIAT ETHER DERIVATIVES FOR LITHIUM, SODIUM, AND POTASSIUM IONS

3.1.1. *Na^+/K^+ Selectivity*

Ionophores **1–12** (Figure 4) were incorporated into solvent polymeric membranes with PVC as the polymer and NPOE as the membrane solvent. The Na^+/K^+ selectivities ($\log K^{Pot}_{Na,K}$) and Na^+/Li^+ selectivities ($\log K^{Pot}_{Na,Li}$) of solvent polymeric membrane electrodes which contain the dibenzo-16-crown-5 compounds **1–12** as ionophores are recorded in Table I. For the lariat ether carboxylic acids **5** and **10**, the aqueous sample solution was made acidic to ensure that the ionophores in their nonionized forms were interacting with the metal ions.

When dibenzo-16-crown-5 (**1**) is incorporated into the solvent polymeric membrane, the observed positive $\log K^{Pot}_{Na,K}$ value (Table I) reveals a greater potentio-

$R_1 = H$ $\qquad$ R_2 $\qquad$ $R_3 = C_3H_7$

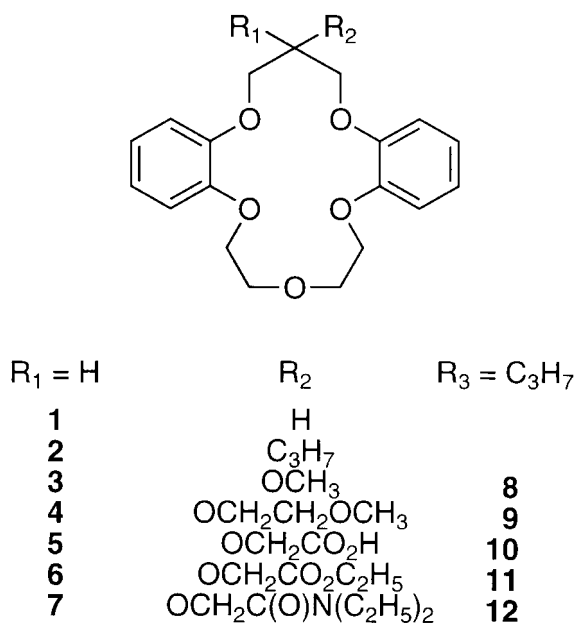|		
1	H	
2	C_3H_7	
3	OCH_3	**8**
4	$OCH_2CH_2OCH_3$	**9**
5	OCH_2CO_2H	**10**
6	$OCH_2CO_2C_2H_5$	**11**
7	$OCH_2C(O)N(C_2H_5)_2$	**12**

Figure 4. Structures for dibenzo-16-crown-5 compounds.

metric response of the ISE to K^+ than Na^+. This is attributed to a higher hydration energy of Na^+ [19]. A two-phase equilibrium (the aqueous and membrane phases) is involved in the ISE. Since appreciable dehydration of an aqueous-phase metal ion must take place during its transfer from the aqueous phase, both the hydration energy of the metal ion in the aqueous phase and the formation of metal ion-crown ether complexes in the membrane phase are important factors. A positive log $K^{Pot}_{Na,K}$ value is also noted for crown ether **2** in which a propyl group has been attached to the central carbon of the three-carbon bridge in dibenzo-16-crown-5.

Lariat ethers **3**–**7** are substituted dibenzo-16-crown-5 compounds with one or more oxygen atoms in the side arm. As shown in Figure 1, the side arm with potential ligation sites for metal ions can be located in either a pseudoaxial or pseudoequatorial position with respect to the polyether ring. For **3**, which has a methoxy group for the side arm, the ISE exhibits a slightly higher response to Na^+ than K^+. (When log $K_{Na,K}$ is negative, the potentiometric response to Na^+ is greater that to K^+.) It is proposed that this results from an increase of Na^+ binding by **3**, relative to **1** and **2**, due to interaction of the Na^+ which is complexed within the cyclic polyether cavity by the ether oxygen in the side arm. Incorporation of the methoxy group side arm more than offsets the cation hydration effect which caused **1** to exhibit a greater potentiometric response to K^+ than to Na^+. A gauche effect [20] of the oxygen atom in the methoxy group with the two proximate oxygen atoms in the side arm is anticipated to enhance the propensity for a pseudoaxial side arm orientation in **3** relative to **2**.

Incorporation of a second ether oxygen in the side arm of lariat ether **4** increases the Na^+/K^+ selectivity appreciably compared with **3** which has only a methoxy group in the side arm. Examination of CPK space-filling models indicates that with an axial conformation for the side arm in **4** both ether oxygens can coordinate with a cavity-bound metal ion.

Lariat ethers **5**–**7** are a series of dibenzo-16-crown-5 compounds with side arms of OCH_2CO_2H, $OCH_2CO_2C_2H_5$ and $OCH_2C(O)N(C_2H_5)_2$, respectively. CPK space-filling models reveal that in **5**–**7** the oxygen atom of the carbonyl group can be positioned directly over the crown ether cavity when the side arm is pseudoaxial. In ISEs, lariat ether ester **6** exhibit enhanced Na^+/K^+ compared with that for compound **3** which has a pendant methoxy group. The lariat ether carboxylic acid **5** and amide **7** show appreciably higher Na^+/K^+ selectivities than does lariat ether ester **6**. The Na^+/K^+ selectivity is observed to increase as the terminal group of the side arm is varied ester < carboxylic acid < amide, which parallels the oxygen basicity of the carboxylic acid derivatives [21]. Thus increased oxygen basicity in the side arm of the lariat ether is found to enhance the Na^+/K^+ selectivity of the ionophore.

In lariat ethers **8**–**12**, the central carbon of the three-carbon bridge of dibenzo-16-crown-5 bears a propyl group as well as an oxygen-containing side arm. Compared with lariat ethers **3**–**7**, which do not possess a geminal propyl group, the log $K_{Na,K}^{Pot}$ values for **8**–**12** are more negative by 0.2–1.2 units. Thus introduction of a geminal propyl group into the lariat ether substantially enhances the Na^+/K^+ selectivity. In the X-ray crystal structures of lariat ether carboxylic acid **4** and *sym*-(decyl)dibenzo-16-crown-5-oxyacetic acid (an analog of **8** with a decyl geminal group in place of propyl), the oxyacetic acid side arms are oriented pseudoequatorial and pseudoaxial, respectively [22]. Thus the presence of a geminal alkyl group positions the oxyacetic acid side arm in the latter in a conformation which requires minimal structural reorganization for metal ion complexation. Such preorganization of the binding site is known to enhance selectivity [16, 23]. Therefore, the increased Na^+/K^+ selectivity observed for lariat ethers **8**–**12** compared with **3**–**7** is attributed to preorganization of the binding site by the geminal propyl group.

The differences in log $K_{Na,K}^{Pot}$ values for analogous ionophores with and without a geminal propyl group are presented in Table II. When the side arm has a terminal carboxylic acid, ester, or amide group, the magnitude of Δ log $K_{Na/K}^{Pot}$ is much larger than when the side arm is OCH_3 and somewhat larger than when the side arm is $OCH_2CH_2OCH_3$. For the carboxylic acid derivatives, the difference becomes slightly larger in the order ester < carboxylic acid < amide, which is the same ordering as the Na^+/K^+ selectivity enhancements for ionophores **5**–**7** and **10**–**12**. Thus the influence of preorganization of the binding site appears to become more important for a side arm unit which interacts more strongly with a crown ether cavity-bound Na^+.

The effect of varying the length of the geminal alkyl group in *sym*-(alkyl)dibenzo-16-crown-5-oxyacetic acids is shown in Table III. The structural

Table II. Difference in log $K_{Na,M}^{Pot}$ for lariat ethers with and without a geminal propyl group[a]

R_2	$\Delta \log K_{Na,K}^{Pot}$	$\Delta \log K_{Na,Li}^{Pot}$
OCH_3	-0.19	$+0.09$
$OCH_2CH_2OCH_3$	-0.88	$+0.24$
$OCH_2CO_2C_2H_5$	-1.04	$+0.14$
OCH_2CO_2H	-1.09	-0.06
$OCH_2C(O)N(C_2H_5)_2$	-1.19	-0.18

[a] Data from References 13 and 18.

Table III. Effect of the geminal alkyl group on the Na^+/K^+ potentiometric selectivities for *sym*-(alkyl)dibenzo-16-crown-5-oxyacetic acids[a]

Alkyl group	$\log K_{Na,K}^{Pot}$	Alkyl group	$\log K_{Na,K}^{Pot}$
None	-0.65	C_8H_{17}	-1.73
CH_3	-1.19	$C_{10}H_{21}$	-1.76
C_2H_5	-1.59	$C_{12}H_{25}$	-1.79
C_3H_7	-1.74	$C_{14}H_{29}$	-1.78
C_4H_9	-1.73	$C_{16}H_{33}$	-1.77
C_6H_{13}	-1.73	$C_{18}H_{37}$	-1.77

[a] Data taken from References 13 and 25.

variation includes methyl, ethyl, propyl, butyl, hexyl, octyl, decyl, dodecyl, tetradecyl, hexadecyl, and octadecyl groups. As can be seen, attachment of even the smallest alkyl group (*i.e.*, methyl) at the geminal position induces a marked enhancement in the Na^+/K^+ selectivity. A smaller increase in selectivity occurs when methyl is replaced by an ethyl group. The change from an ethyl to a propyl group produces another small enhancement in Na^+/K^+ selectivity. Further elongation of the geminal alkyl group from three to sixteen carbon atoms does not alter the Na^+/K^+ selectivity. These data establish that even a small geminal alkyl group is sufficient to preorganize the binding site and enhance the Na^+/K^+ of the ionophores.

It has been reported that the attachment of a long alkyl group to disubstituted 16-crown-5 compounds produces a marked diminution in their Na^+ selectivities [24]. However, for the present lariat ether carboxylic acids, as well as analogous esters and amides [25], enhanced lipophilicity does not diminish the Na^+ selectivity.

Table IV. Effect of the geminal alkyl group on the Na^+/Li^+ potentiometric selectivities for *sym*-(alkyl)dibenzo-16-crown-5-oxyacetic acids[a]

Alkyl group	$\log K_{Na,Li}^{Pot}$	Alkyl group	$\log K_{Na,Li}^{Pot}$
None	−3.46	C_8H_{17}	−3.53
CH_3	−3.50	$C_{10}H_{21}$	−3.52
C_2H_5	−3.50	$C_{12}H_{25}$	−3.53
C_3H_7	−3.52	$C_{14}H_{29}$	−3.45
C_4H_9	−3.58	$C_{16}H_{33}$	−3.44
C_6H_{13}	−3.55	$C_{18}H_{37}$	−3.45

[a] Data taken from Reference 13 and 25.

3.1.2. Na^+/Li^+ Selectivity

When incorporated into solvent polymeric membrane electrodes in the ISE system, the parent crown ether, dibenzo-16-crown-5 (**1**), and its crown ether (**2**) and lariat ether derivatives (**3**–**12**) all exhibit high Na^+/Li^+ selectivities (Table I). Selective complexation of Na^+ over Li^+ is favored by both the crown ether ring size and the high hydration energy of Li^+ [19].

Lariat ethers **3**–**12** show substantially higher Na^+/Li^+ selectivities than do crown ethers **1** and **2**. For the lariat ether carboxylic acid derivatives **5**–**7** and **10**–**12**, the Na^+/Li^+ selectivity increases as the carbonyl group in the side arm unit is varied amide < carboxylic acid < ester. This is the opposite of the ordering for Na^+/K^+ selectivity. Also, little change is apparent when a propyl group is introduced geminal to the functional side arm (Table I) or for variation of the length of the geminal alkyl group in a series of lariat ether carboxylic acids (Table IV).

It is proposed that the observed difference in effects of structural variation within the dibenzo-16-crown-5 lariat ethers upon the Na^+/K^+ and Na^+/Li^+ selectivities arises from the types of metal ion-lariat ether complexes that are formed. Both Li^+ and Na^+ should form nesting complexes (Figure 3). Thus, structural changes which enhance binding of Na^+ (*e.g.*, preorganization of the binding site) may also promote complexation of Li^+ and produce little change in the Na^+/Li^+ selectivity. In contrast, for the competitive complexation of Na^+ and K^+, a nesting complex is expected for the former but the latter must form a perching complex. Therefore, a structural variation such as preorganization of the binding site, which increases Na^+ binding, would not necessarily facilitate K^+ complexation.

Table V. Potentiometric selectivities of dibenzo-16-crown-5 compounds **1**, **3**, **7**, and **12** for alkali metal, alkaline earth metal, and ammonium ions[a]

| Cmpd | $\log K^{\mathrm{Pot}}_{\mathrm{Na,M}}$ | | | | | | |
	Rb^+	Cs^+	Mg^{2+}	Ca^{2+}	Sr^{2+}	Ba^{2+}	NH_4^+
1	+0.06	−0.48	−3.36	−2.49	−2.22	−2.62	−0.94
3	−0.29	−0.88	−3.53	−2.88	−2.50	−2.59	−1.48
7	−1.42	−2.05	−3.76	−2.90	−2.31	−1.40	−2.11
12	−2.62	−3.07	−3.83	−3.55	−2.66	−2.76	−3.02

[a] Data from Reference 18.

3.2. SELECTIVITIES OF DIBENZO-16-CROWN-5 AND ITS LARIAT ETHER DERIVATIVES FOR ALKALI METAL, ALKALINE EARTH METAL, AND AMMONIUM IONS

Although the initial investigations of the crown and lariat ethers **1**–**12** were focused upon the potentiometric responses of dibenzo-16-crown-5 compounds in solvent polymeric membranes to Li^+, Na^+, and K^+, the study was subsequently extended to examination of all of the alkali metal cation species, as well as alkaline earth metal and ammonium ions [18]. Potentiometric selectivity data for Na^+ versus Rb^+, Cs^+, Mg^{2+}, Ca^{2+}, Sr^{2+}, Ba^{2+}, and NH_4^+ for dibenzo-16-crown-5 (**1**), *sym*-(methoxy)dibenzo-16-crown-5 (**3**), N,N-di(ethyl) *sym*-dibenzo-16-crown-5-oxyacetamide (**7**), and N,N-di(ethyl) *sym*-(propyl)dibenzo-16-crown-5-oxyacetamide (**12**) are presented in Table V.

It is observed that both the Na^+/Rb^+ and Na^+/Cs^+ selectivities increase in the order **1** < **3** < **7** < **12**. Thus, the relative binding propensity for Na^+ relative to that of these two larger alkali metal cations increases by a factor of two when a methoxy group is incorporated into dibenzo-16-crown-5. Replacement of the methoxy group with a N,N-di(ethyl) oxyacetamide side arm in **7** further enhances the Na^+ selectivities by a factor of more than ten. Finally the presence of both a N,N-di(ethyl) oxyacetamide side arm and a geminal propyl group in **12** increases the Na^+ selectivities by more than a factor of ten compared with **7**. Thus preorganization of the binding site is shown to enhance the Na^+ selectivities in the dibenzo-16-crown-5 lariat ether series for Rb^+ and Cs^+, as well as for K^+.

The Na^+/NH_4^+ selectivities also are noted to increase in the order **1** < **3** < **7** < **12**. Since NH_4^+ is somewhat larger than K^+, it is also expected to form a perching-type complex. For NH_4^+, hydrogen bonding to the polyether oxygens of the crown ether ring may also be an important factor in its complexation.

Except for the Na^+/Ba^{2+} response of **7**, the potentiometric selectivities for Na^+ versus the alkaline earth metal cations are in the range of $\log K^{\mathrm{Pot}}_{\mathrm{Na,M}}$ of −2.2 to −3.8 and appear to be nearly independent of structural variation for the series of crown and lariat ether compounds **1**, **3**, **7**, and **12**.
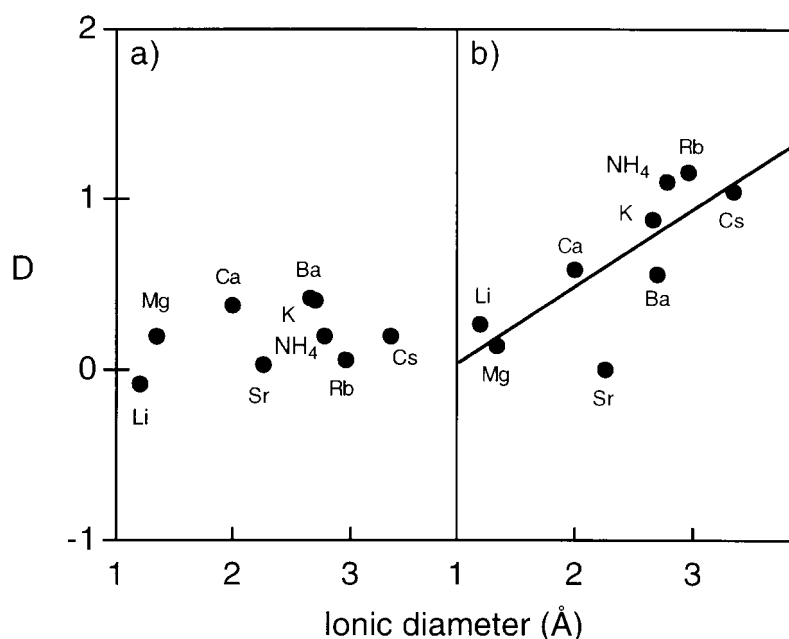
Figure 5. Difference in log $K^{\text{Pot}}_{\text{Na,M}}$ between lariat ethers with and without a geminal propyl group $[-D = (\log K^{\text{Pot}}_{\text{Na,M}}$ for the lariat ether with a geminal propyl group$) - (\log K^{\text{Pot}}_{\text{Na,M}}$ for the corresponding lariat ether with a geminal hydrogen atom$)]$ for dibenzo-16-crown-5 lariat ethers with (a) OCH_3 and (b) $OCH_2CH_2OCH_3$ side arms versus the diameter of the interference ion M.

To further probe the effect of preorganization on Na^+ selectivity for **3–12**, the difference in the log $K^{\text{Pot}}_{\text{N,M}}$ values between lariat ethers with and without the geminal propyl group $[-D = (\log K^{\text{Pot}}_{\text{Na,M}}$ for the lariat ether with a geminal propyl group$) - (\log K^{\text{Pot}}_{\text{Na,M}}$ for the corresponding lariat ether with a geminal hydrogen atom$)]$ is plotted against the diameter of the interference cations (M^+ and M^{2+}) [18]. These plots are shown for dibenzo-16-crown-5 lariat ethers with OCH_3 and $OCH_2CH_2OCH_3$ side arms in Figure 5 and for compounds with $OCH_2CO_2C_2H_5$ and $OCH_2C(O)N(C_2H_5)_2$ in Figure 6.

Only a slight variation is noted as the diameter of the interference ion is increased when the oxygen-containing side arm is methoxy (Figure 5a). Thus it appears that this side arm is too short to undergo better positioning when the geminal propyl group is introduced.

On the other hand, linear relationships between the D values and the ionic diameters are evident for the lariat ethers with $OCH_2CH_2OCH_3$ side arms in Figure 5b and $OCH_2CO_2C_2H_5$ and $OCH_2C(O)N(C_2H_5)_2$ in Figures 6a and 6b, respectively. Thus as the size of the interference cation increases, the difference in Na^+ selectivity between lariat ethers with and without the geminal propyl group becomes larger. These correlations include data points for monovalent alkali metal and ammonium
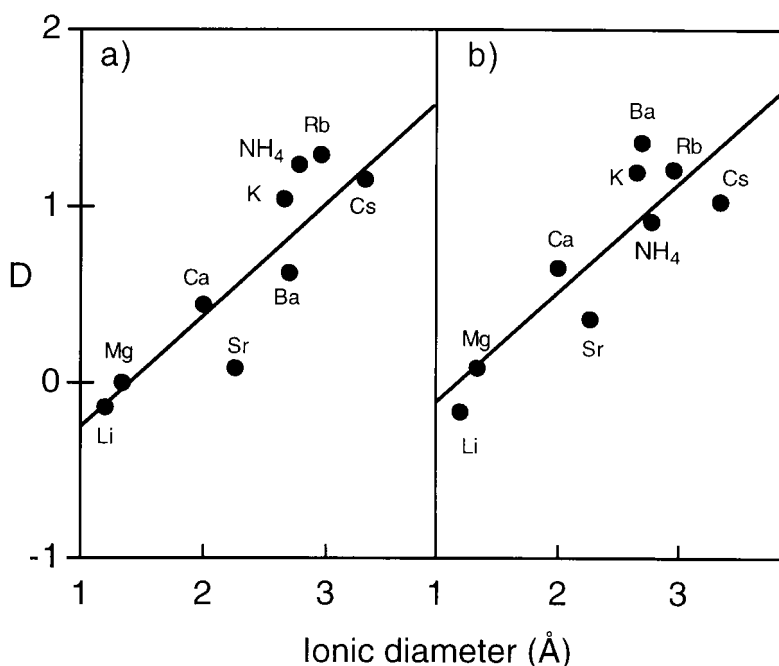
Figure 6. Difference in log $K^{Pot}_{Na,M}$ between lariat ethers with and without a geminal propyl group [$-D = $ (log $K^{Pot}_{Na,M}$ for the lariat ether with a geminal propyl group) $-$ (log $K^{Pot}_{Na,M}$ for the corresponding lariat ether with a geminal hydrogen atom)] for dibenzo-16-crown-5 lariat ethers with (a) $OCH_2CO_2C_2H_5$ and (b) $OCH_2C(O)N(C_2H_5)_2$ side arms versus the diameter of the interference ion M.

ions, as well as divalent alkaline earth metal ions. Thus, the D value is found to depend upon the size of the interference ion, but not its charge. It appears that a preorganized lariat ether structure disfavors formation of the perching complexes [16] that are anticipated for cations larger than Na^+ by a steric effect. As the size of the interference cation is increased, conformational preorganization of the side arm becomes increasingly detrimental to the stability of a perching complex for the interference cation.

The slopes of the correlation lines in Figures 6a and 6b are noticeably greater than that for the correlation line in Figure 5b. Thus the slopes are greater when the side arm of the lariat ether terminates with an ester or amide function compared with a terminal ether group, even though an ether oxygen is more basic than a carbonyl oxygen [21]. For the ester and amide groups, the carbonyl group is sp^2 hybridized. Therefore, the carbon atom α to the carbonyl group, the carbonyl carbon, the carbonyl oxygen, and the second oxygen atom of the ester (or the nitrogen atom of the amide) must be coplanar. Thus considerable rigidity is introduced into the side arm by the presence of a terminal carbonyl function. For the present series of lariat ether esters and amides, this helps position the carbonyl oxygen over the
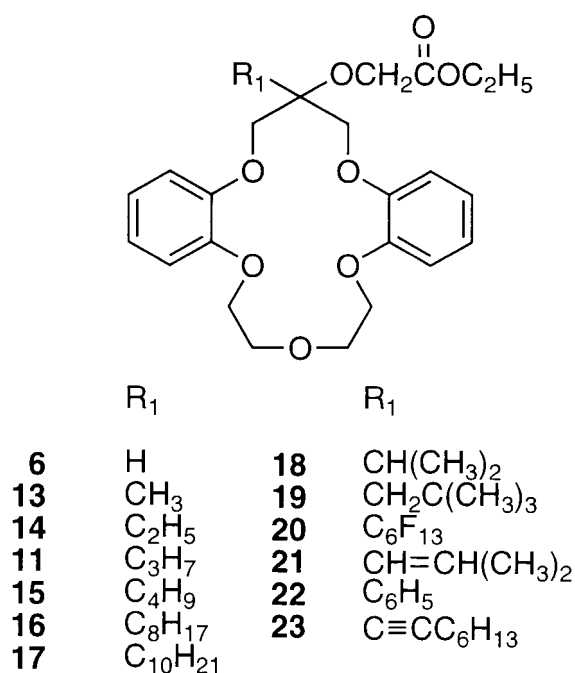
Figure 7. Structures of dibenzo-16-crown-5 esters.

crown ether cavity and preorganizes the binding site. On the other hand, a lower level of preorganization is provided by the more flexible $OCH_2CH_2OCH_3$ side arm. It is proposed that the greater preorganization of the binding sites in the lariat ether esters and amides enhances their sensitivity to the size of the interference ion in a perching complex. This increases the slope of the correlation lines shown in Figures 5 and 6 for the lariat ethers with ester and amide-containing side arms.

3.3. SODIUM ION-SELECTIVE ELECTRODES BASED ON DIBENZO-16-CROWN-5 COMPOUNDS WITH PENDENT ESTER GROUPS

In the investigations described above, only geminal linear alkyl groups were utilized to orient the coordinating side arms in the lariat ethers and preorganize the binding sites. The effect of additional structural variation within the geminal group was investigated with the series of dibenzo-16-crown-5 compounds **6**, **11**, and **13**–**23**, which have $OCH_2CO_2C_2H_5$ side arms (Figure 7). Potentiometric Na^+/K^+ and Na^+/Li^+ selectivities for this series of lariat ether esters are presented in Table VI.

Compared with the lariat ether esters **11** and **14**–**17**, which have linear geminal alkyl groups, the log $K_{Na,K}^{Pot}$ values for **18** and **19**, which have branched alkyl groups (isopropyl and neopentyl, respectively), are more negative by 0.14–0.37. Thus the change from a linear to a branched geminal alkyl group enhances the Na^+/K^+ selectivity. On the other hand, the Na^+/Li^+ selectivities of lariat ether esters **11** and

Table VI. Effect of R_1 group variation on the potentiometric Na^+/K^+ and Na^+/Li^+ selectivities of ethyl *sym*-(R_1)dibenzo-16-crown-5-oxyacetates **6**, **11**, and **13–23**[a]

Cmpd	R_1	$\log K_{Na,K}^{Pot}$	$\log K_{Na,Li}^{Pot}$
6	H	−0.45	−3.87
13	CH_3	−1.36	−3.74
14	C_2H_5	−1.49	−3.73
11	C_3H_7	−1.49	−3.73
15	C_4H_9	−1.54	−3.78
16	C_8H_{17}	−1.55	−3.75
17	$C_{10}H_{21}$	−1.59	−3.75
18	$CH(CH_3)_2$	−1.73	−3.67
19	$CH_2C(CH_3)_3$	−1.70	−3.68
20	C_6F_{13}	−1.26	nm[b]
21	C_6H_5	−1.39	−3.83
22	$CH=C(CH_3)_2$	−1.25	−3.85
23	$C\equiv CC_6H_{13}$	−0.94	−3.90

[a] Data from References 13 and 26.
[b] nm = not measured.

14–17 with linear geminal alkyl groups are noted to be somewhat superior to those of lariat ether esters **18** and **19**.

To probe the influence of geminal substitutents on the Na^+ selectivity, the $\log K_{Na,K}^{Pot}$ values for lariat ether esters **6**, **11**, **13–16**, **18**, and **19** were plotted against σ_α, the polarizability constant which provides a quantitative measure of substituent polarizability or bulkiness [27]. The geminal substituent variation includes hydrogen, methyl, ethyl, propyl, butyl, octyl, isopropyl, and neopentyl groups, respectively. A linear relationship is evident (Figure 8a). It should be noted that linear relationships were not obtained with other substituent constants, such as Taft σ^* substituent constants [28] and Taft E_s steric constants [29].

Since σ_α values may reflect either the polarizability or bulkiness of a substituent [27], $\log K_{Na,K}^{Pot}$ values were determined for the same set of lariat ether esters in solvent polymeric membranes for which the membrane solvent was changed from NPOE (dielectric constant, $\epsilon = 24$) to dibenzyl ether ($\epsilon = 4$). The Na^+/K^+ selectivity was noted to decrease for each lariat ether ester when dibenzyl ether was the membrane solvent. However, the slope of the plot was very nearly the same as that observed for the correlation shown in Figure 8a. Since the polarity of the membrane solvent would be expected to influence the substituent, it appears that the σ_α values reflect the bulkiness of the substituent in this case rather than its polarizability.
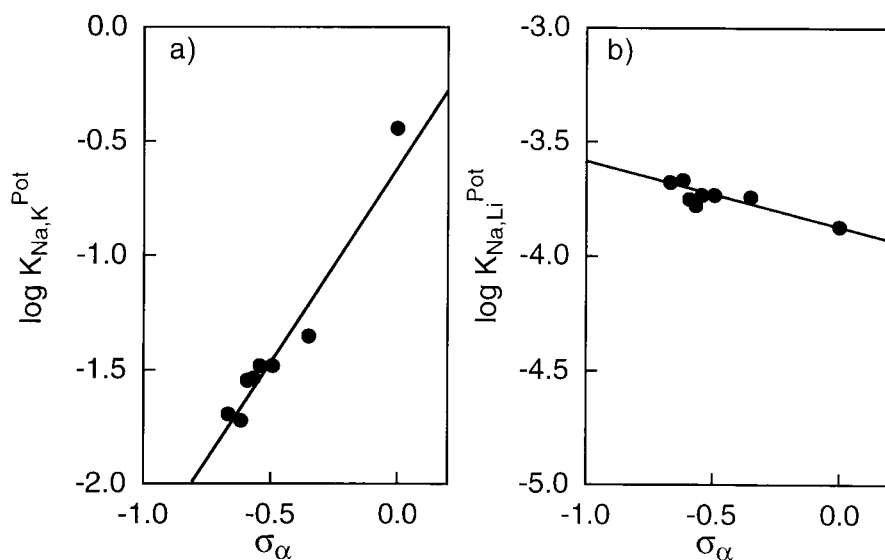
Figure 8. Plot of log $K^{Pot}_{Na,M}$ with (a) M = K and (b) M = Li versus σ_α for lariat ether esters.

A plot of log $K^{Pot}_{Na,Li}$ versus σ_α (Figure 8b) shows a linear relationship with a small negative slope. Thus the presence of branched geminal alkyl groups (isopropyl and neopentyl) appears to modestly diminish the Na^+/Li^+ selectivity compared with that for linear alkyl groups. The opposing effects of geminal group branching upon the Na^+/K^+ and Na^+/Li^+ selectivities may be rationalized by consideration of the types of metal-ion complexes which are formed (*vide supra*).

The lariat ether esters **21–23** have unsaturated geminal substituents (2-methyl-1-propenyl, phenyl, and 1-octynyl, respectively) attached to the central carbon of the three-carbon bridge of the dibenzo-16-crown-5 ring. The Na^+/K^+ selectivity is observed to decrease as the geminal substituent is varied: branched alkyl (**18** and **19**)> linear alkyl (**11, 14–17**) > methyl (**13**) > phenyl (**22**) >alkenyl (**21**) > alkynyl (**23**) and hydrogen (**6**). Comparison of the σ_α values for the unsaturated geminal groups with their Na^+/K^+ selectivities revealed that the points for the unsaturated geminal groups were divergent from the correlation line defined by the saturated alkyl groups. Thus when the hybridization of the first atom of the geminal hydrocarbon group is changed from sp^3 to sp^2 or sp, the Na^+/K^+ selectivity no longer correlates with σ_α, the polarizability constant. A possible explanation of the lower Na^+/K^+ selectivities observed for lariat ether esters with unsaturated geminal hydrocarbon substituents involves the electron-withdrawing nature of such groups. Electron withdrawal by the geminal substituent could decrease the electron density on the ether oxygen of the side arm and thereby diminish the overall binding ability of the ionophore. In agreement, the Na^+/K^+ selectivity for lariat ether ester **20** which has a saturated, but strongly electron-withdrawing,

geminal perfluorohexyl group is appreciably lower than that observed for linear alkyl groups.

Although other synthetic ionophores exhibit higher Na^+/K^+ selectivities than do the lariat ether esters utilized in this study, solvent polymeric membrane electrodes prepared with compounds **6** and **19**–**21** exhibit very high Na^+/Li^+ selectivities (log $K^{Pot}_{Na,Li}$ = −3.8 to −3.9) which surpass those reported for other ionophoric compounds [26, 30, 31].

3.4. SODIUM ION-SELECTIVE ELECTRODES BASED ON DIBENZO-16-CROWN-5 COMPOUNDS WITH PENDANT AMIDE GROUPS

As noted earlier from the data in Table I, dibenzo-16-crown-5 compounds with $OCH_2C(O)N(C_2H_5)_2$ side arms exhibit higher Na^+/K^+ selectivities than do analogous ethyl esters and carboxylic acids. Therefore the influence of structural variation upon Na^+ selectivity was investigated further for lariat ether amides [32–34]. Although potentiometric selectivities for Na^+ versus the other alkali metal cations, the alkaline earth metal cations, and ammonium ion were determined in some cases, the Na^+/K^+ selectivity was of special interest for probing conformational effects in the lariat ether compounds.

For N, N-di(R_2) *sym*-(propyl)dibenzo-16-crown-5-oxyacetamides with R_2 = ethyl, propyl, butyl, pentyl, hexyl, octyl, decyl, and dodecyl, the Na^+/K^+ selectivities are observed to be slightly higher for pentyl than for the other linear alkyl groups [32]. A lariat ether amide analogue with only one pentyl group on the amide nitrogen gave lower Na^+/K^+ selectivity than did N, N-di(pentyl) *sym*-(propyl)dibenzo-16-crown-5-oxyacetamide (**25**) (Figure 9) [13].

For a series of N, N-di(pentyl) *sym*-(R_1)dibenzo-16-crown-5-oxyacetamides, the influence of varying the R_1 group was examined [13]. The Na^+/K^+ selectivity increases by a factor of ten when R_1 is changed from hydrogen in **24** to a methyl group. An additional, albiet much smaller, enhancement in Na^+/K^+ selectivity is noted when the methyl group is replaced with ethyl. Further lengthening of the chain to include three, four, six, eight, ten, twelve, fourteen, sixteen and eighteen carbon atoms in the alkyl group did not produce a significant change in the Na^+/K^+ selelctivity. In addition to their potentiometric selectivities in ISEs, compounds with R_1 = propyl, octyl, and dodecyl groups were examined in ion-selective field effect transistors (ISFETs) [33]. The Na^+ selectivities relative to other alkali and alkaline earth metal cations for the ISFETs were almost equivalent to those for the ISEs. The Na^+/K^+ selectivities approach the best values reported for ISFETs which employ other neutral-carrier type ionophores [35].

As was described earlier for the lariat ether esters, replacement of the linear propyl group with a branched isopropyl group geminal to the amide-containing side arm produces a small increase in the Na^+/K^+ selectivity [34].

Since the potentiometric responses are measured by the competitive, fixed interference technique, it is not possible to determine if an enhancement in the Na^+/K^+
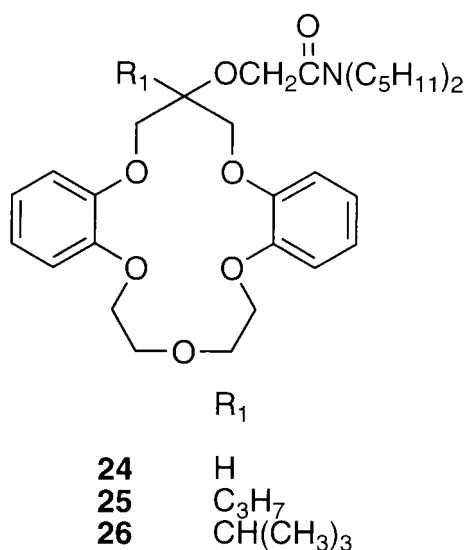
Figure 9. Structures of dibenzo-16-crown-5 amides.

selectivity results from increased binding of Na^+ or diminished complexation of K^+ or a combination of both. Insight into the causitive factors for increased Na^+/K^+ selectivity when a geminal hydrogen in **24** is replaced with a propyl group in **25** and then with an isopropyl group in **26** was gained from studies of solvent extraction of sodium and potassium picrates into 1,2-dichloroethane [34]. Ratios of the extraction constants for Na^+ and K^+ (log K_{ex}^{Na}/K_{ex}^K) were found to be similar in magnitude and show the same trends for structural variation within the ionophores as do the potentiometric selectivities between Na^+ and K^+ (log $K_{Na,K}^{Pot}$) in the polymeric membrane electrodes. From the picrate extraction results, it is deduced that the enhancement in potentiometric selectivity for Na^+ over K^+ when the R_1 group is changed from hydrogen to propyl is due to increased binding of Na^+ and diminished complexation of K^+. On the other hand, the enhanced potentiometric response for Na^+ over K^+ when a linear alkyl R_1 group is replaced by a branched alkyl group appears to arise only from decreased complexation of K^+.

The Na^+/K^+ selectivities observed for the lariat ether amides, as well as the carboxylic acids and esters, in these investigations are much lower than the remarkably high log $K_{Na,K}^{Pot}$ values of 5.0–5.3 which have been reported recently for calix[4]arene-based, sodium-selective electrodes [36].

4. Conclusions

The influence of attaching neutral side arms to the central carbon of the three-carbon bridge in dibenzo-16-crown-5 has been probed by incorporation of the ionophores in ISE systems. The potentiometric responses of dibenzo-16-crown-5 lariat ethers toward alkali metal, alkaline earth metal, and ammonium ions may

be rationalized in terms of the crown ether ring size and the oxygen basicity, conformational positioning and rigidity of the side arm. The Na^+/K^+ selectivity is increased by enhanced basicity of the oxygen atoms in the side arm and by preorganization of the binding site through attachment of an alkyl group to the same ring carbon which bears the oxygen-containing side arm. With the same structural variation in the ionophores, Na^+/Li^+ selectivity responds quite differently. Such variance is attributed to formation of nesting complexes of Na^+ and Li^+ within the cyclic polyether cavity, but formation of a perching complex for K^+.

Acknowledgements

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