Sterically congested, geminal aryl-substituted, proton-ionizable *sym*-dibenzo-16-crown-5 lariat ethers: synthesis and alkali metal cation extraction

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Abstract

Three series of proton-ionizable *sym*-dibenzo-16-crown-5 ethers with sterically demanding 1-naphthyl, 2-naphthyl, and 9-phenanthryl geminal groups are synthesized and characterized. Variation of the proton-ionizable group includes oxyacetic acid and *N*-(X)sulfonyl oxyacetamide units with X = Me, Ph, C_6H_4-4-NO_2, and CF_3. For the latter series, variation of X provides 'tunable' acidity of the ligand. The metal ion-complexing properties of the proton-ionizable *sym*-(aryl)dibenzo-16-crown-5 compounds are probed by competitive solvent extraction of alkali metal cations from aqueous solutions into chloroform.

Keywords: Lariat ether, solvent extraction, alkali metal cations, crown ether

Introduction

Crown ethers, macrocyclic polyethers with a hydrophobic ring of ethylenic units surrounding a hydrophilic cavity of ether oxygen atoms, are exceptionally versatile and powerful in selectively binding a range of metal ion species.[1-2] Attachment of one or more side arms onto a crown ether ring produces a lariat ether.[3] This may enhance metal ion binding strength and selectivity over monocyclic crown ethers by providing donor sites in addition to those of the macroring resulting in three-dimensional complexation, thereby mimicking the dynamic complexation processes exhibited by natural macrocyclic ionophores.[3] However, such complexing agents may not be effective in practical extractions of metal ions due to the low distribution coefficients of common counteranions, such as chloride, nitrate, and sulfate between an aqueous phase and a contacting organic phase.[4] This problem can be overcome by attaching a proton-ionizable side arm to the crown ether ring so that the ligand provides not only a polyether binding site for metal ion

complexation, but also the requisite anion for formation of an electroneutral extraction complex. An ionizable group on the side arm eliminates the need to transfer one or more aqueous phase anions into the organic phase by operating in a cation-exchange mode with the metal ion. Following the extraction step, shaking of the separated organic phase with aqueous acid strips the extracted metal ions into a new aqueous phase and regenerates the neutral form of the extractant.[4-5]

During a metal ion separation process, the presence of lipophilic groups on the crown ether ring is important in reducing loss of the macrocyclic ligand from an organic phase into a contacting aqueous phase.[6] The dibenzo-16-crown-5 ring system provides a convenient scaffold for investigating the influence of structural variation within lariat ethers upon their selectivity and efficiency in metal ion complexation processes due to its synthetic accessibility with pendant groups attached to the central carbon of the three-carbon bridge.[7-8] In earlier studies, we found that the introduction of a lipophilic decyl group geminal to the functional side arm in *sym*-dibenzo-16-crown-5 oxyacetic acid (Figure 1) increased the Na^+ selectivity by preorganization of the binding site in which the alkyl group oriented the oxyacetic acid side arm over the polyether cavity.[9]

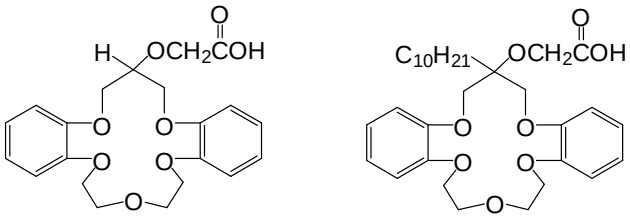
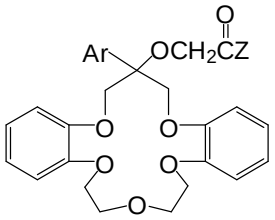


Figure 1. Structures of *sym*-dibenzo-16-crown-5-oxyacetic acid and *sym*-(decyl)dibenzo-16-crown-5-oxyacetic acid.

Various alkyl groups have been attached geminal to the proton-ionizable side arm in *sym*-dibenzo-16-crown-5 ethers to form effective and selective extractants for alkali metal cations.[5-6] In comparison, analogues with more sterically demanding geminal aryl groups have received very little attention. We now report the synthesis of three series of proton-ionizable *sym*-dibenzo-16-crown-5 ethers with geminal 1-naphthyl, 2-naphthyl, and 9-phenanthryl groups (Figure 2).



Ar = 1-naphthyl, 2-naphthyl, 9-phenanthryl

Z = OH, $NHSO_2Me$, $NHSO_2Ph$, $NHSO_2C_6H_4$-4-NO_2, $NHSO_2CF_3$

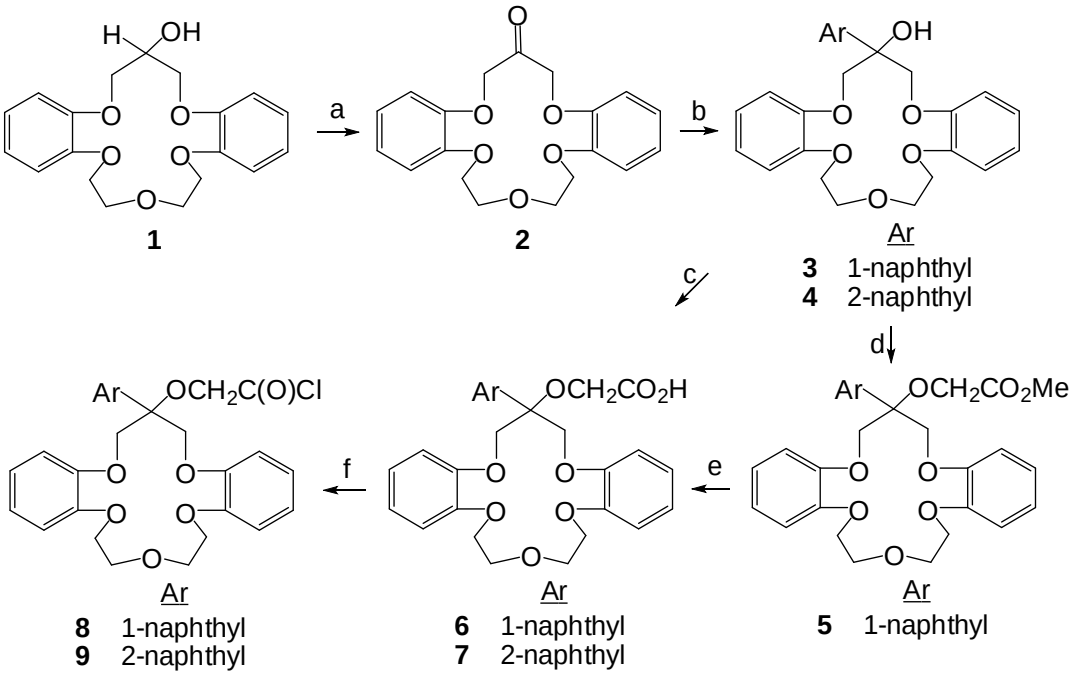
Figure 2. Structures of new proton-ionizable *sym*-(aryl)dibenzo-16-crown-5 ethers.

Variation of the proton-ionizable side arms include oxyacetic acid moieties and *N*-(X)sulfonyl oxyacetamide units with X = Me, Ph, C_6H_4-4-NO_2, and CF_3.[10] For the latter series, variation of the electron-withdrawing properties of X 'tunes' the acidity of the functional side arm. The influence of sterically hindered geminal aryl groups on metal ion complexation is evaluated in competitive solvent extraction of alkali metal cations from aqueous solutions into chloroform.

Results and Discussion

Synthetic routes

The synthetic routes to the new proton-ionizable *sym*-(1-naphthyl)- and *sym*-(2-naphthyl)dibenzo-16-crown-5 ethers are shown in Scheme 1.



	Ar	X
10	1-naphthyl	Me
11	1-naphthyl	Ph
12	1-naphthyl	C_6H_4-4-NO_2
13	1-naphthyl	CF_3
14	2-naphthyl	Me
15	2-naphthyl	Ph
16	2-naphthyl	C_6H_4-4-NO_2
17	2-naphthyl	CF_3

Scheme 1. Synthesis of proton-ionizable *sym*-(1-naphthyl)dibenzo-16-crown-5 ethers **6** and **10-13** and *sym*-(2-naphthyl)dibenzo-16-crown-5 ethers **7** and **14-17**. Reagents and conditions: (a) $(COCl)_2$, DMSO, Et_3N, CH_2Cl_2, -78°→0°C; b) i) ArBr, Mg, THF; ii) 5% NH_4Cl (aq); c) NaH,

$BrCH_2CO_2H$, THF, rt; d) NaH, $BrCH_2CO_2Me$, THF, rt; e) i) 10% aq. NaOH, THF, rt; ii) 6 N HCl (aq); f) $(COCl)_2$, C_6H_6, rt; g) NaH, NH_2SO_2X, THF, rt.

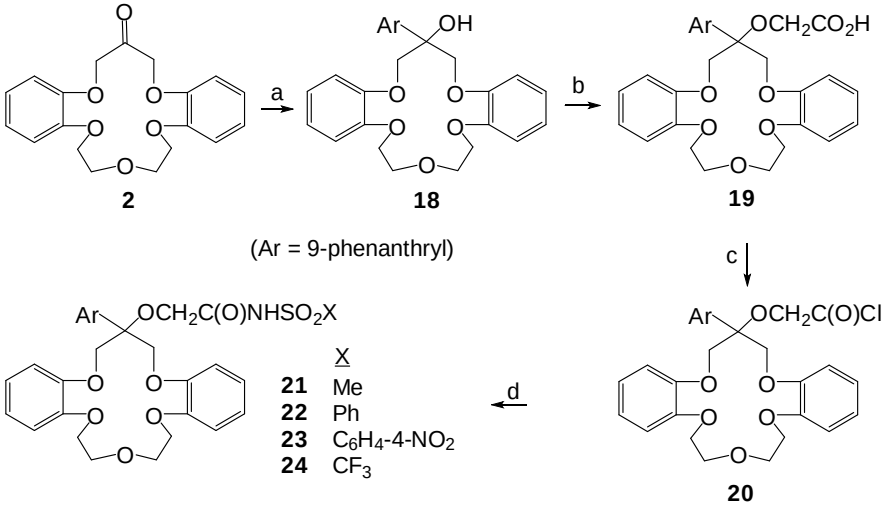
Preparation of *sym*-(keto)dibenzo-16-crown-5 (**2**) was accomplished in improved yield by the Swern oxidation of *sym*-(hydroxy)dibenzo-16-crown-5 (**1**). The lariat ether alcohols **3** and **4** were synthesized by the addition of 1-naphthyl- and 2-naphthylmagnesium bromides, respectively, to ketone **2**. The Grignard reagents were formed by addition of a solution of the aryl bromide in THF to dry magnesium turnings. The mixture was heated to initiate the reaction, then stirred at room temperature until a colored solution was observed. Tertiary alcohols **3** and **4** were obtained in 95 and 90% yields, respectively.

Deprotonation of alcohol **4** with NaH in THF followed by addition of dry bromoacetic acid gave *sym*-(2-naphthyl)dibenzo-16-crown-5-oxyacetic acid **7** in 82% yield. However, analogous reaction of alcohol **3** gave only a low yield of lariat ether carboxylic acid **6**. In an alternate route, a solution of methyl bromoacetate in THF was added to the deprotonated alcohol **3** in THF to produce methyl *sym*-(1-naphthyl)dibenzo-16-crown-5-oxyacetate (**5**) in 79% yield. Subsequent stirring of the ester with aqueous 10% NaOH and THF followed by protonation of the resultant lariat ether carboxylate gave **6** in 85% yield.

Synthesis of *N*-(X)sulfonyl *sym*-(aryl)dibenzo-16-crown-5-oxyacetamides **10**-**17** from the corresponding carboxylic acids **6** and **7** was accomplished by a two-step procedure. First, the carboxylic acid was reacted with oxalyl chloride in benzene to give the corresponding acid chloride. Formation of the acid chloride was verified by IR spectroscopy with the appearance of the strong carbonyl group absorption near 1810 cm^{-1} and the disappearance of the carbonyl group absorption around 1730 cm^{-1}.[11-12] The crude acid chloride was reacted with the corresponding sodium sulfonamide anions in THF to afford proton-ionizable *sym*-(aryl)dibenzo-16-crown-5 ethers **10**-**17** in 37-75% yields.

The synthetic route to the new proton-ionizable *sym*-(9-phenanthryl)dibenzo-16-crown-5 ethers is presented in Scheme 2. To initiate formation of the Grignard reagent from 9-phenanthryl bromide and Mg in THF, a crystal of iodine was needed. A solution of ketone **2** in THF was added to the Grignard reagent and the mixture was stirred overnight. After workup, lariat ether tertiary alcohol **18** was obtained in 82% yield. Attempted reaction of alcohol **18** with NaH and bromoacetic acid in THF was unsuccessful. In an alternative synthetic route, the alcohol precursor was deprotonated by NaH in THF and ethyl bromoacetate was added. After reaction and workup, the product was found to be the lariat ether carboxylate **19** instead of the anticipated ethyl ester. This was unusual since similar reactions reported in literature always gave esters.[13-14] Protonation of the lariat ether carboxylate gave the target lariat ether carboxylic acid **19** in 91% yield. As described earlier, the carboxylic acid **19** was converted into the corresponding acid chloride **20** by reaction with oxalyl chloride in benzene followed by reaction of the crude acid chloride with the appropriate sodium sulfonamide in THF to produce the proton-ionizable *sym*-(9-phenanthryl)dibenzo-16-crown-5 ethers **21**-**24** in 70-94% yields.

The new proton-ionizable *sym*-(aryl)dibenzo-16-crown-5 lariat ethers **6**, **7**, **10**-**17**, **19**, and **21**-**24** were characterized by IR spectrophotometry, ^{1}H and ^{13}C NMR spectroscopy, and combustion analysis.



Scheme 2. Synthesis of proton-ionizable *sym*-(9-phenanthryl)dibenzo-16-crown-5 ethers **19** and **21**-**24**. Reagents and conditions: a) i) 9-phenanthryl bromide, Mg, I_2 (cat), THF; ii) 5% NH_4Cl (aq); b) NaH, $BrCH_2CO_2Et$, THF, rt; c) $(COCl)_2$, C_6H_6, rt; d) NaH, NH_2SO_2X, THF, rt.

For each of the three series of compounds with *N*-(X)sulfonyl oxyacetamide functional side arms, the carbonyl group IR absorption increased in wavenumbers as the electron-withdrawing ability of X was enhanced in the order Me ≤ Ph < C_6H_4-4-NO_2 < CF_3 (Table 1).

Table 1. Carbonyl stretching absorptions in wavenumbers for *N*-(X)sulfonyl oxyacetamide lariat ethers **10**-**17** and **21**-**24**

	Geminal Group		
X	1-Naphthyl	2-Naphthyl	9-Phenanthryl
Me	1719	1723	1722
Ph	1726	1723	1723
C_6H_4-4-NO_2	1731	1729	1728
CF_3	1758	1754	1748

Also in the ^{1}H NMR spectra for *N*-(X)sulfonyl oxyacetamides **10**-**17** and **21**-**24**, the NH peaks for each of the three series shifted further downfield as the electron-withdrawing ability of X increased in the order Me < Ph < C_6H_4-4-NO_2 < CF_3 (Table 2).

Table 2. Chemical shifts in $CDCl_3$ for NH in ppm for *N*-(X)sulfonyl oxyacetamide lariat ethers **10**-**17** and **21**-**24**

	Geminal Group		
X	1-Naphthyl	2-Naphthyl	9-Phenanthryl
Me	9.52	9.57	9.58
Ph	9.67	9.72	9.72
C_6H_4-4-NO_2	9.81	9.80	9.85
CF_3	10.13	10.14	10.16

^{1}H NMR spectroscopy provides qualitative information about the flexibility of the crown ether ring.[5,9] Lariat ethers with a three-carbon bridge have two limiting conformations in solution, as illustrated in Figure 3. The two methylene protons in the three-carbon bridge are diastereotopic. The rate of conformational inversion can be estimated from the spin pattern of the geminal protons. An AB pattern results from rapid conformational inversion, which indicates a flexible ring structure. Interesting differences are observed in the ^{1}H NMR spectra of the *N*-(X)sulfonyl *sym*-(aryl)dibenzo-16-crown-5-oxyacetamides **10**-**17** and **21**-**24** in $CDCl_3$. AB patterns were found when the aryl group was 1-naphthyl and 9-phenanthryl; whereas AX patterns were noted when the aryl group was 2-naphthyl. By this measure, the crown ether rings in the proton-ionizable *sym*-(2-naphthyl)dibenzo-16-crown-5 lariat ethers **6** and **10**-**13** in solution are judged be more rigid. Of the lariat ether carboxylic acids, **7** with a 2-naphthyl group was insoluble in $CDCl_3$. In d_6-DMSO, an AB pattern was observed. In $CDCl_3$, **6** with a 1-naphthyl group exhibited an AB pattern and **19** with a 9-phenanthryl group showed an A_2 singlet for the geminal protons on the three-carbon bridge.

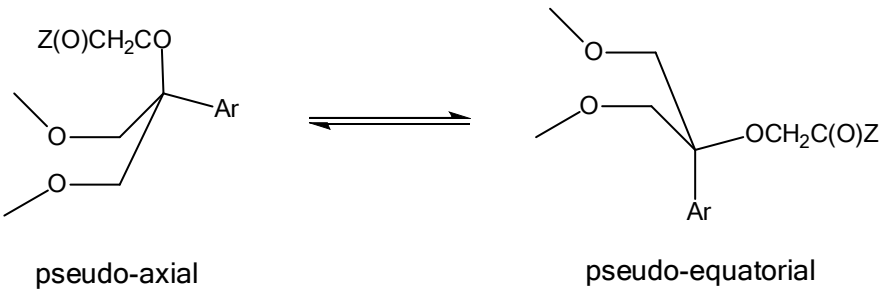


Figure 3. Limiting conformations of a geminally substituted lariat ether with a three-carbon bridge.

Competitive solvent extraction of alkali metal ions

The metal ion-complexing properties of proton-ionizable lariat ethers **6**, **7**, **10-17, 19,** and **21-24** were evaluated by competitive solvent extraction of alkali metal cations from aqueous solutions into chloroform. Aqueous solutions of Li^+, Na^+, K^+, Rb^+, and Cs^+ (10 mM in each) with varying pH were extracted with equal volumes of chloroform containing 1.0 mM proton-ionizable lariat ether. After separation of the chloroform layer, it was stripped with 0.1 M aqueous HCl. Alkali metal cation concentrations in the strippants were determined by ion chromatography.

Extraction results for the three *sym*-(aryl)dibenzo-16-crown-5-oxyacetic acids **6**, **7**, and **19** with geminal 1-naphthyl, 2-naphthyl, and 9-phenanthryl groups, respectively, are presented in Figure 4. As is readily evident, all three ligands are highly selective extractants for Na^+. The extraction selectivity order is $Na^+ >> K^+ > Li^+$, Rb^+, Cs^+ with barely detectable or negligible levels of the last three alkali metal cations. The maximal Na^+/K^+ selectivities for **6**, **7**, and **19** exceeded 100, which is the precision of the alkali metal cation analysis. In comparison, a Na^+/K^+ ratio of 27 was reported for competitive alkali metal cation extraction by *sym*-(decyl)dibenzo-16-crown-5-oxyacetic acid.[6] Thus replacement of the geminal linear alkyl group in the lariat ether carboxylic acids with geminal 1-naphthyl, 2-naphthyl, and 9-phenanthryl units produces a marked enhancement in the selectivity for Na^+ extraction. Alkali metal cation loading is nearly quantitative for formation of 1:1 ionized lariat ether-metal ion extraction complexes. Such high extraction selectivity for Na^+ strongly suggests simultaneous metal ion complexation by the polyether oxygens and the oxyacetic acid side arm.[6,9]

A qualitative measure of acidity for proton-ionizable ligands is $pH_{0.5}$, the aqueous phase pH at which half of the maximal metal ion loading is reached.[15] For lariat ether carboxylic acids **6**, **7**, and **19**, the same $pH_{0.5}$ value of 7.0 was observed. Thus structural variation of the geminal aryl group from 1-naphthyl to 2-naphthyl to 9-phenanthryl in the *sym*-(aryl)dibenzo-16-crown-5-oxyacetic acid extractants did not influence the ligand acidity.

Extraction results for the *N*-(X)sulfonyl *sym*-(1-naphthyl)dibenzo-16-crown-5-oxyacetamides **10**-**13** with X = Me, Ph, C_6H_4-4-NO_2, and CF_3, respectively, are shown in Figure 5. Although the extraction selectivity order is once again $Na^+ >> K^+ > Li^+$, Rb^+, Cs^+, the maximum Na^+/K^+ selectivities in the range of 26-54 are well below the >100 value observed with the carboxylic acid analog **6**. The Na^+/K^+ ratios are similar to those of 47-49 reported earlier[10] for alkali metal cation extractions by *N*-(X)sulfonyl *sym*-(decyl)dibenzo-16-crown-5-oxyacetamides. The $pH_{0.5}$ values for **10**-**13** are 7.4, 7.4, 6.4, and 3.0, respectively. This ordering is consistent with enhanced acidity as the electron-withdrawing propensity of X is increased.

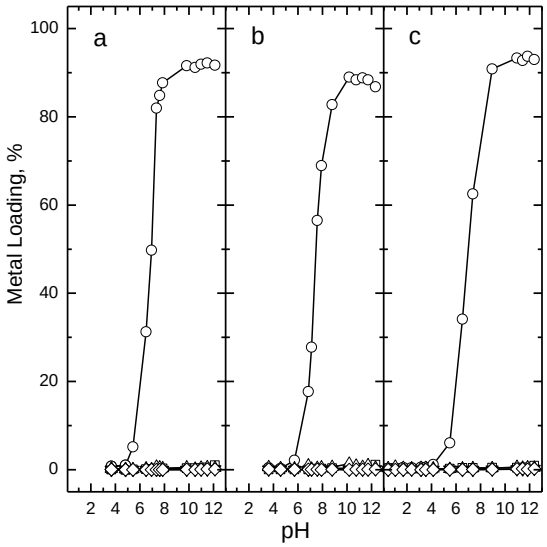


Figure 4. Percent metal loading *vs.* the equilibrium pH of the aqueous phase for competitive solvent extraction of alkali metal ions into chloroform by *sym*-(aryl)dibenzo-16-crown-5-oxyacetic acids a) **6** with aryl = 1-naphthyl, b) **7** with aryl = 2-naphthyl, and c) **19** with aryl = 9-phenanthryl. (□ = Li^+; ○ = Na^+; Δ = K^+; ▼ = Rb^+ , ◊ = Cs^+).

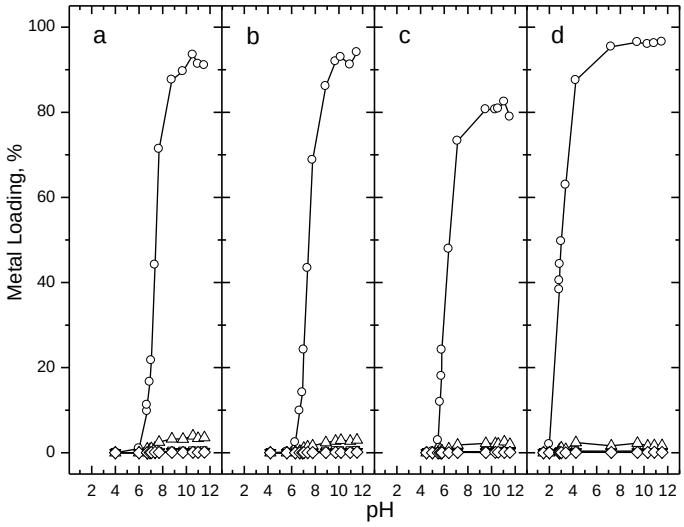


Figure 5. Percent metal loading *vs.* equilibrium pH of the aqueous phase for competitive solvent extraction of alkali metal ions into chloroform by *N*-(X)sulfonyl *sym*-(1-naphthyl)dibenzo-16-crown-5-oxyacetamides a) **10** with X = Me, b) **11** with X = Ph, c) **12** with X = C_6H_4-4-NO_2, and d) **13** with X = CF_3. (□ = Li^+ ; ○ = Na^+ ; Δ = K^+ ; ▼ = Rb^+ , ◊ = Cs^+).

Extraction results for the *N*-(X)sulfonyl *sym*-(2-naphthyl)dibenzo-16-crown-5-oxyacetamides **14**-**17** with X = Me, Ph, C_6H_4-4-NO_2, and CF_3, respectively, are shown in Figure 6. The extraction selectivity order is once again $Na^+ >> K^+ > Li^+$, Rb^+, Cs^+, but with maximum Na^+/K^+ selectivities of 17-35 which are far below the >100 value observed with the carboxylic acid analog **7**. It should be noted that for a given X group the maximum Na^+/K^+ selectivity for a member of the *N*-(X)sulfonyl *sym*-(2-naphthyl)dibenzo-16-crown-5-oxyacetamide series was consistently less than that found for the *N*-(X)sulfonyl *sym*-(1-naphthyl)dibenzo-16-crown-5-oxyacetamide series. The $pH_{0.5}$ values for **14**-**17** are 7.9, 8.0, 6.8, and 3.8, respectively, which is consistent with the electron-withdrawing power of X.

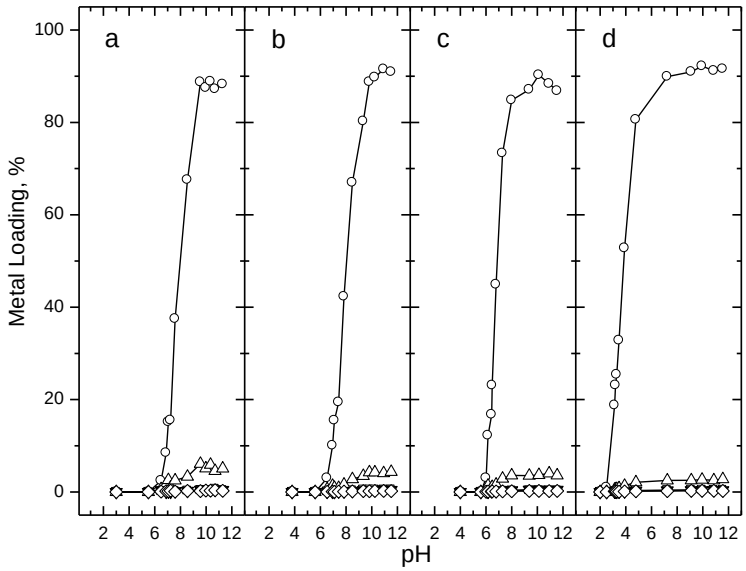


Figure 6. Percent metal loading *vs.* equilibrium pH of the aqueous phase for competitive solvent extraction of alkali metal ions into chloroform by *N*-(X)sulfonyl *sym*-(2-naphthyl)dibenzo-16-crown-5-oxyacetamides (a) **14** with X = Me, (b) **15** with X = Ph, (c) **16** with X = C_6H_4-4-NO_2, and (d) **17** with X = CF_3. (□ = Li^+; ○ = Na^+; Δ = K^+; ▼ = Rb^+ , ◊ = Cs^+).

Alkali metal cation extraction profiles for the *N*-(X)sulfonyl *sym*-(9-phenanthryl)-dibenzo-16-crown-5-oxyacetamides **21**-**24** with X = Me, Ph, C_6H_4-4-NO_2, and CF_3, respectively, are presented in Figure 7. The extraction selectivity order is $Na^+ >> K^+ > Li^+$, Rb^+, Cs^+. The Na^+ extraction selectivities more closely resemble those for *N*-(X)sulfonyl *sym*-(1-naphthyl)dibenzo-16-crown-5-oxyacetamide analogues than for the analogous *N*-(X)sulfonyl *sym*-(2-naphthyl)dibenzo-16-crown-5-oxyacetamide compounds. The $pH_{0.5}$ values for extractants **21**-**24** are 7.7, 7.5, 6.3, and 3.0, respectively, in agreement with the electron-withdrawing ability of X.

Magnitudes of the $pH_{0.5}$ values for a given X when the geminal group is 9-phenanthryl are more similar to those when the geminal group is 1-naphthyl than 2-naphthyl.

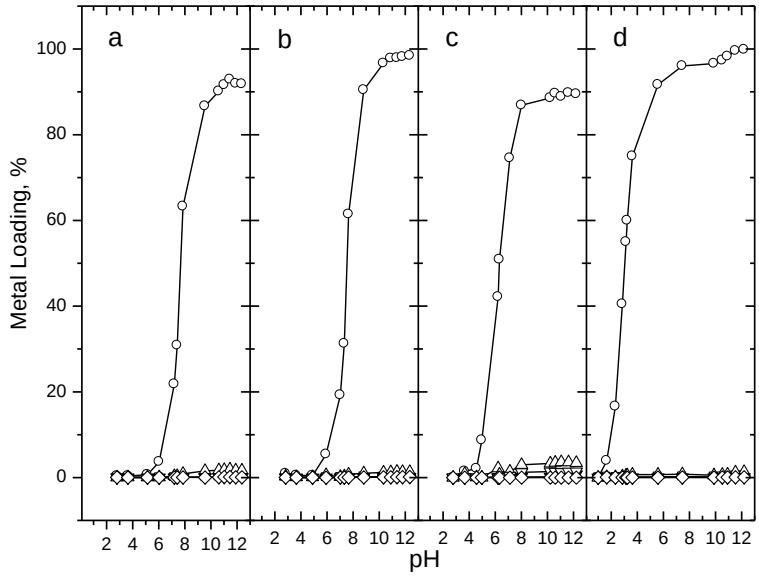


Figure 7. Percent metal loading *vs.* equilibrium pH of the aqueous phase for competitive solvent extraction of alkali metal ions into chloroform by *N*-(X)sulfonyl *sym*-(2-naphthyl)dibenzo-16-crown-5-oxyacetamides (a) **21** with X = Me, (b) **22** with X = Ph, (c) **23** with X = C_6H_4-4-NO_2, and d) **24** with X = CF_3. (□ = Li^+; ○ = Na^+; Δ = K^+; ▼ = Rb^+, ◊ = Cs^+).

Conclusions

Three series of proton-ionizable *sym*-(aryl)dibenzo-16-crown-5 ligands with systematic structural variations in the geminal aryl group and the functional side arm have been synthesized. The aryl group identity was varied to include 1-naphthyl, 2-naphthyl, and 9-phenanthryl. Functional side arms employed were oxyacetic acid and *N*-(X)sulfonyl oxyacetamide with changes of X from Me and Ph to C_6H_4-4-NO_2 to CF_3 to 'tune' the acidity of the proton-ionizable side arm.

The metal cation complexing abilities of the 15 new proton-ionizable lariat ethers were assessed by competitive solvent extractions of five alkali metal cation species from aqueous solution into chloroform. All 15 compounds exhibited high Na^+ extraction selectivity consistent with three-dimensional complexation of the metal ion by the polyether oxygens and the ionized side arm. For the three *sym*-(aryl)dibenzo-16-crown-5-oxyacetic acids, the extraction selectivity order was $Na^+ >> K^+ > Li^+$, Rb^+, Cs^+ with Na^+/K^+ selectivity ratios exceeding 100, the upper limit for the

ion chromatographic analytical method. This is an appreciably greater Na^+ extraction selectivity that that reported for *sym*-(decyl)dibenzo-16-crown-5-oxyacetic acid.

Within each of the three series of *sym*-(aryl)dibenzo-16-crown-5 compounds having *N*-(X)sulfonyl oxyacetamide side arms and a common aryl group, the extractant acidity, as assessed by $pH_{0.5}$ (the pH of half metal ion loading) increased as X was varied in the order of Me, Ph < C_6H_4-4-NO_2 < CF_3 consistent with the electron-withdrawing ability of X. Although extraction selectivity orders of Na^+ >> K^+ > Li^+, Rb^+, Cs^+ were again observed, the Na^+/K^+ ratios were appreciably lower that those found for their lariat ether carboxylic acid analogues. This lower Na^+ selectivity may result from a larger size of the ionized group which makes three-dimensional complexation of the metal cation more difficult.

Experimental Section

General. Reagents were obtained from commercial suppliers and used directly, unless otherwise noted. THF was dried over sodium wire with benzophenone ketyl as an indicator. Magnesium turnings were dried in an oven overnight before use. Et_3N and DMSO were stored over 4Å molecular sieves. The *sym*-(hydroxyl)dibenzo-16-crown-5 was prepared by a reported method.[16] Infrared spectral analyses were performed with a Perkin-Elmer 1600 FT-IR spectrophotometer as deposits from CH_2Cl_2 solutions on a NaCl plate. The absorptions are given in wavenumbers (cm^{-1}). NMR spectra were measured in $CDCl_3$ with a Varian Unity Inova FT-500 spectrometer (499.7 MHz for ^1H, 125.7 MHz for ^{13}C) at 296 K. Chemical shifts (δ) are expressed in ppm downfield from TMS and coupling constants (*J*) values are given in Hz. Melting points were determined with a Mel-Temp melting point apparatus. Elemental analysis was performed by Desert Analytics Laboratory (now Columbia Analytical Services) of Tucson, Arizona.

***sym*-(Keto)dibenzo-16-crown-5 (2) (improved synthesis).** Oxalyl chloride (3.92 mL, 45 mmol) and CH_2Cl_2 (65 mL) were added to a 3-necked flask in a hood. A nitrogen purge was started and the flask was placed in a Dry Ice-acetone bath. DMSO (4.25 mL, 60 mmol) was added with a syringe pump at a rate of 1 mL/min. After 10 min, a solution of lariat ether alcohol **1** (5.19 g, 15 mmol) in CH_2Cl_2 (20 mL) was added dropwise. The solution was stirred for 30 min and then Et_3N (20.91 mL, 150 mmol) was added dropwise. After 30 min, the Dry Ice-acetone bath was replaced with an ice-water bath and stirring was continued for 15 min. The solution was diluted with CH_2Cl_2 (25 mL) and then H_2O (25 mL) was added to quench the reaction. After separation, the aqueous layer was extracted with CH_2Cl_2 (25 mL). The organic layers were combined and washed with 5% aq HCl (3×125 mL), H_2O (125 mL), 1.05% diluted commercial bleach (125 mL), commercial bleach (5.25%, 125 mL), satd aq Na_2SO_3 (2×125 mL), and H_2O (2×125 mL). The organic layer was dried over $MgSO_4$ and evaporated *in vacuo* to give a pale yellow solid, which was chromatographed on silica gel with CH_2Cl_2-EtOAc(3:2) as eluent and then

recrystallized from THF-hexanes (3:1) to give 3.92 g (76%) of white needles with mp 141-143 °C (lit[8] mp 138-139 °C).

General procedure for the synthesis of *sym*-(aryl)(hydroxy)dibenzo-16-crown-5 compounds 3 and 4

Oven-dried magnesium turnings (1.06 g, 43.6 mmol) in THF (20 mL) were added to a 3-necked flask under nitrogen. A solution of the appropriate aryl bromide in THF (20 mL) was added dropwise *via* an addition funnel over a 0.5-h period. The reaction was initiated by heating followed by stirring for 2 h at room temperature. Once the Grignard reagent had formed (indicated by a gray/green solution and the disappearance of Mg), a solution of lariat ether ketone **2** (5.00 g, 14.5 mmol) in THF (50 mL) was added dropwise over a 30-min period. The mixture was stirred overnight and the reaction was quenched by addition of 5% aq NH_4Cl (75 mL). The THF was evaporated in *vacuo* and the residue was extracted with CH_2C1_2 (2×75 mL). The combined CH_2C1_2 layers were dried over $MgSO_4$ and evaporated in *vacuo* to give a white solid. The residue was purified by column chromatography or recrystallization.

***sym*-(Hydroxy)(1-naphthyl)dibenzo-16-crown-5 (3)** was chromatographed on silica gel with EtOAc-hexanes (1:3) as eluent to give 6.50 g (95%) of white solid with mp 110 °C. ν_{max} (film)/cm^{-1}: 3542 (O-H), 1257, 1060 (C-O). δ_H 3.92-4.04 (m, 4H), 4.09 (s, 1H), 4.13-4.27 (m, 4H), 4.68 (d, *J* 10, 2H), 4.87 (d, *J* 10, 2H), 6.77-6.84 (m, 4H), 6.84-6.86 (m, 1H), 6.86-6.88 (m, 1H), 6.88-6.95 (m, 2H), 7.40-7.54 (m, 3H), 7.76-7.90 (m, 2H), 8.07 (d, *J* 5, 1H), 8.85 (d, *J* 10, 1H). δ_C 68.0, 69.8, 75.1, 78.3, 114.2, 118.2, 121.5, 122.9, 124.7, 125.0, 125.5, 126.6, 126.8, 129.2, 129.5, 131.9, 134.9, 135.6, 148.6, 150.2. Found: C, 73.82; H, 6.05%. $C_{29}H_{28}O_6$ requires C, 73.71; H, 5.97%.

***sym*-(Hydroxy)(2-naphthyl)dibenzo-16-crown-5 (4)** was chromatographed on silica gel with EtOAc-hexanes (1:3) as eluent to give 5.86 g (90%) of white solid with mp 135-136 °C. ν_{max} (film)/cm^{-1}: 3508 (O-H), 1257, 1053 (C-O). δ_H 3.92 (s, 1H), 3.96-4.07 (m, 4H), 4.11-4.29 (m, 4H), 4.53 (dd, *J* 10, 30, 4H), 6.74-6.83 (m, 4H), 6.83-6.89 (m, 2H), 6.89-6.95 (m, 2H), 7.39-7.52 (m, 2H), 7.80-7.94 (m, 4H), 8.28 (s, 1H). δ_C 67.9, 69.8, 76.0, 76.4, 114.0, 118.3, 121.5, 123.0, 124.3, 124.5, 125.8, 127.5, 127.6, 128.3, 132.8, 133.3, 138.9, 148.7, 150.2. Found: C, 73.82; H, 6.00%. $C_{29}H_{28}O_6$ requires C, 73.71; H, 5.97%.

***sym*-(Hydroxy)(9-phenanthryl)dibenzo-16-crown-5 (18).** Dry magnesium turnings (1.64 g, 67.5 mmol) were placed in an oven-dried, 3-necked flask equipped with a dropping funnel and a condenser under nitrogen. THF (10 mL) and a crystal of iodine were added to the flask. A solution of 9-bromophenanthrene (15.42 g, 60 mmol) in THF (70 mL) was added over a 30-min period. The mixture was heated to initiate the reaction and then the mixture was stirred at room temperature. The reaction was completed when the color of the mixture turned yellow-brown (about 3 h). A solution of **2** (5.16 g, 15 mmol) in THF (100 mL) was added over a 2-h period. The mixture was stirred overnight. After cooling to 0 °C, 5% aq NH_4Cl (30 mL) was added to the flask dropwise. After stirring for 10 h, the white solid was filtered. For the filtrate, the THF was

evaporated *in vacuo* and the aqueous solution was extracted with CH_2Cl_2 (2 × 50 mL). The combined organic layers were dried over $MgSO_4$ and evaporated *in vacuo.* The filtered solid and the additional solid recovered from the filtrate were combined and recrystallized from hexanes-THF (2:1) to obtain 6.40 g (82%) of white solid with mp 97-98 °C. ν_{max} (film)/cm^{-1} 3528 (br O-H), 1264, 1123, 1043 (C-O). δ_H 4.07-4.01 (m, 4H, OCH_2), 4.12 (s, 1H), 4.23 (t, *J* 4, 4H), 4.80 (d, *J* 10, 2H), 4.97 (d, *J* 10, 2H,), 6.94-6.79 (m, 8H), 7.67-7.56 (m, 4H), 7.94 (dd, *J* 8, 1, 1H), 8.35 (s, 1H), 8.67 (d, *J* 8, 1H), 8.77 (dd, *J* 8, 2, 1H), 9.00 (d, *J* 8, 1H). δ_C 68.1, 69.9, 75.1, 78.2, 114.3, 118.3, 121.6, 122.3, 123.0, 123.3, 125.8, 126.1, 126.6, 126.9, 127.3, 128.3, 129.2, 130.5, 130.6, 131.2, 131.6, 133.6, 148.7, 150.2. Found: C, 76.12; H, 5.93%. $C_{33}H_{30}O_6$ requires C, 75.84; H, 5.79%.

Methyl *sym*-(1-naphthyl)dibenzo-16-crown-5-oxyacetate (5). NaH (0.39 g, 16.9 mmol) and THF (20 mL) were added to a 3-necked flask. The mixture was stirred under nitrogen for 30 min and a solution of lariat ether alcohol **3** (2.00 g, 4.33 mmol) dissolved in THF (20 mL) was added dropwise over a 1-h period. After stirring for 1 h, a solution of methyl bromoacetate (0.80 g, 8.46 mmol) in THF (50 mL) was added dropwise over a 3-4-h period. The reaction mixture was stirred for an additional 10 h and then quenched by cooling to 0 °C and adding water (20 mL). The THF was evaporated in *vacuo* and water (10 mL) was added to the mixture. After extraction with CH_2C1_2 (3 × 25 mL), the combined organic layers were dried over $MgSO_4$ and evaporated in *vacuo.* The residue was purified by chromatography on silica gel with hexanes-Et_2O (1:1) then EtOAc as eluents to give 1.93 g (79%) of white solid with mp 67-68 °C. ν_{max} (film)/cm^{-1}: 1754 (C=O), 1249, 1060 (C-O). δ_H 3.60-3.77 (m, 3H), 3.86-4.10 (m, 4H), 4.10-4.28 (m, 4H), 4.55 (s, 1H), 4.63-4.77 (m, 3H), 5.01 (d, *J* 25, 2H), 6.61-7.07 (m, 8H), 7.41-7.57 (m, 3H), 7.82-8.03 (m, 2H), 8.52 (d, *J* 20, 1H), 8.95 (d, *J* 20, 1H). δ_C 51.6, 64.5, 67.6, 69.9, 74.5, 84.4, 113.4, 113.5, 117.6, 121.3, 122.8, 124.6, 125.1, 125.7, 126.3, 129.3, 129.7, 130.5, 131.8, 134.7, 148.1, 150.2, 171.7. Found: C, 70.88; H, 5.93%. $C_{32}H_{32}O_8$ requires C, 70.66; H, 5.96%.

***sym*-(1-Naphthyl)dibenzo-16-crown-5-oxyacetic acid (6).** A mixture of **5** (1.15 g, 2.11 mmol), THF (10 mL) and 10% aq NaOH (5 mL) was stirred overnight at room temperature. The THF was evaporated *in vacuo* and the aqueous residue was acidified with 6 N HCl to pH 1. Additional 6 N HCl (20 mL) and CH_2C1_2 (20 mL) were added and the mixture was stirred overnight. The mixture was extracted with CH_2C1_2 (3 × 20 mL**)**. The combined organic layers were dried over $MgSO_4$ and evaporated *in vacuo.* The residue was recrystallized from hexanes to give 1.03 g (85%) of white solid with mp 98-99 °C. ν_{max} (film)/cm^{-1}: 1731 (C=O), 1255, 1058 (C-O). δ_H 3.75-3.99 (m, 2H), 3.99-4.14 (m, 2H), 4.14-4.28 (m, 4H), 4.68 (s, 2H), 4.89 (dd, *J* 30, 10, 4H), 6.75-6.83 (m, 4H), 6.83-6.91 (m, 2H), 6.91-7.01 (m, 2H), 7.42-7.54 (m, 2H), 7.54-7.62 (m, 1H), 7.91 (d, *J* 10, 2H) 8.02 (d, *J* 5, 1H), 8.64-8.80 (m, 1H). δ_C 113.0, 117.4, 121.1, 123.1, 124.7, 125.4, 125.5, 126.6, 128.4, 129.5, 130.6, 131.6, 132.0, 134.8, 147.6, 150.2, 172.8. Found: C, 68.53; H, 5.58%. $C_{31}H_{30}O_8$ requires C, 68.21; H, 5.57%.

General procedure for the synthesis of *N*-(X)sulfonyl *sym*-(1-naphthyl)dibenzo-16-crown-5-oxyacetamides 10-13

Benzene (50 mL), **6** (1.20 g, 2.26 mmol) and oxalyl chloride (1.20 mL, 13.56 mmol) were combined in a 1-necked flask and stirred at room temperature for 1.5 h. The benzene was evaporated *in vacuo* and an IR spectrum of the residue was taken. Disappearance of the C=O peak at 1731 cm^{-1} and appearance of a C=O peak at 1824 cm^{-1} verified formation of acid chloride **8**. The sulfonamide salt was prepared under nitrogen by adding NaH (0.54 g, 22.6 mmol) and THF (20 mL) to a 3-necked flask. A solution of the appropriate sulfonamide (2.71 mmol) in THF (20 mL**)** was added over a 10-min period. The mixture was stirred at room temperature for 1.5 h followed by the dropwise addition of a solution of the acid chloride **8** in THF (20 mL). The reaction mixture was stirred overnight (3 h when X = C_6H_4-4-NO_2) at room temperature and cooled to 0 ºC. Water (15 mL) was added dropwise to destroy the excess NaH. The THF was evaporated *in vacuo* and then 40 mL of distilled water was added to the residue. The mixture was extracted with CH_2C1_2 (100 mL then 50 mL). The combined organic extracts were washed with 10% aq K_2CO_3 (2×50 mL). The combined aq layers were extracted with CH_2C1_2 (2×50 mL). The combined organic layers were dried over $MgSO_4$ and evaporated in *vacuo* to give a solid that was purified by chromatography and recrystallization.

***N*-Methanesulfonyl *sym*-(1-naphthyl)dibenzo-16-crown-5-oxyacetamide (10)** was chromatographed on alumina with EtOAc-hexanes (1:1) as eluent. Recrystallization from the same solvent gave 0.82 g (75%) of white solid with mp 100 ºC. ν_{max} (film)/cm^{-1}: 3342 (N-H), 1723 (C=O), 1257, 1061 (C-O), 1343, 1158 (SO_2). δ_H 3.09 (s, 3H), 3.85-3.99 (m, 2H), 4.02-4.15 (m, 2H), 4.15-4.28 (m, 4H), 4.80 (s, 2H), 4.91 (dd, *J* 10, 30, 4H), 6.74-7.84 (m, 4H), 6.84-6.91 (m, 2H), 6.91-6.99 (m, 2H), 7.45-7.59 (m, 3H), 7.86-7.94 (m, 3H), 8.71 (d, *J* 10, 1H), 9.52 (s, 1H). δ_C: 41.1, 65.9, 67.1, 69.3, 72.1, 84.5, 112.7, 117.6, 121.1, 123.3, 124.8, 125.6, 126.6, 127.2, 129.6, 130.3, 131.6, 132.4, 147.4, 150.2, 170.8. Found: C, 63.38; H, 5.21; N, 2.55. $C_{32}H_{33}NO_9S$ requires C, 63.25; H, 5.47; N, 2.30%.

***N*-Benzenesulfonyl *sym*-(1-naphthyl)dibenzo-16-crown-5-oxyacetamide (11)** was chromatographed on alumina with EtOAc-hexanes (1:1) as eluent followed by recrystallization from the same solvent to give 0.65 g (65%) of white solid with mp 100 ºC. ν_{max} (film)/cm^{-1}: 3332 (N-H), 1723 (C=O), 1257, 1060 (C-O); 1353, 1160 (SO_2). δ_H 3.78-3.87 (m, 2H), 3.91-4.00 (m, 2H), 4.00-4.08 (m, 2H), 4.09-4.21 (m, 2H), 4.71 (s, 2H), 4.65-4.75 (dd, *J* 20, 11, 4H), 6.70-7.75 (m, 2H), 6.75-6.85 (m, 4H), 6.88-6.99 (m, 2H), 7.27-7.36 (m, 2H), 7.43-7.59 (m, 4H), 7.80-7.95 (m, 5H) 8.64 (t, *J* 3, 1H), 9.67 (s, 1H). δ_C 65.7, 67.0, 69.4, 71.6, 76.4, 84.2, 112.5, 117.4, 120.9, 123.2, 124.7, 125.5, 125.7, 126.9, 128.3, 128.5, 129.5, 130.2, 131.5, 132.7, 133.4, 134.9, 138.8, 147.3, 150.2, 169.5. Found: C, 66.15; H, 5.18; N, 2.28%. $C_{37}H_{35}NO_9S$ requires C, 66.35; H, 5.27; N, 2.09%.

***N*-(4-Nitrobenzene)sulfonyl *sym*-(1-naphthyl)dibenzo-16-crown-5-oxyacetamide (12**) was chromatographed on alumina with EtOAc-hexanes (1:1) as eluent. Recrystallization from the same solvent gave 0.64 g (55%) of yellow solid with mp 125-126 ºC. ν_{max} (film)/cm^{-1}: 3474 (N-H), 1729 (C=O), 1254, 1062 (C-O), 1348, 1127 (SO_2). δ_H 3.71-3.93 (m, 2H), 3.94-4.09 (m, 2H),

4.09-4.21 (m, 2H), 4.76 (s, 2H), 4.83 (dd, *J* 10, 30, 4H), 6.66-6.76 (m, 2H), 6.76-7.85 (m, 4H), 6.92-7.01 (m, 2H) 7.43-7.52 (m, 2H), 7.55 (t, *J* 15, 1H), 7.80 (d, *J* 5, 1H), 7.87-7.94 (m, 2H), 7.94-7.99 (m, 2H), 7.99-8.05 (m, 2H), 8.55-8.73 (m, 1H), 9.81 (s, 1H). δ_C 65.6, 67.0, 69.3, 71.4, 84.4, 112.4, 117.5, 121.0, 123.4, 123.6, 124.7, 125.6, 125.8, 126.5, 129.6, 130.4, 131.5, 132.6, 135.0, 144.1, 147.2, 150.1, 150.3, 168.9. Found: C, 56.64; H, 4.48; N, 3.57%. $C_{37}H_{34}N_2O_{11}S•1.1CH_2Cl_2$ requires C, 58.84; H, 4.56; N, 3.70%.

***N*-Trifluoromethanesulfonyl *sym*-(1-naphthyl)dibenzo-16-crown-5-oxyacetamide (13)** was chromatographed on alumina with EtOAc-hexanes (1:1) as eluent. Recrystallization from the same solvent gave 0.95 g (69%) of white solid with mp 125-126 ºC. ν_{max} (film)/cm^{-1}: 3296 (N-H), 1754 (C=O), 1256, 1061 (C-O), 1343, 1136 (SO_2). δ_H 3.82-3.95 (m, 2H), 3.95-4.10 (m, 2H), 4.10-4.28 (m, 4H), 4.83 (d, *J* 10, 2H), 4.95 (d, *J* 10, 2H), 5.03 (s, 2H), 6.71-6.84 (m, 4H), 6.84-6.91 (m, 2H), 6.91-7.03 (m, 2H), 7.45-7.55 (m, 2H), 7.59 (t, *J* 15, 3H), 7.84 (d, *J* 5, 1H), 7.90-7.98 (m, 2H), 8.55-8.69 (m, 1H), 10.12 (s, 1H). δ_C 66.2, 67.0, 69.3, 71.5, 84.4, 112.5, 117.4, 117.8, 120.3, 121.0, 123.5, 124.8, 125.6, 126.6, 129.6, 130.4, 132.4, 135.0, 147.1, 150.1, 169.0. Found: C, 57.96; H, 4.71; N, 1.96%. $C_{32}H_{30}F_3NO_9S$ requires: C, 58.09; H, 4.57; N, 2.12%.

sym*-(2-Naphthy1)dibenzo-16-crown-5-oxyacetic acid (7).** NaH (0.53 g, 21.2 mmol) and THF (20 mL) were added to a 3-necked flask. The mixture was stirred under nitrogen for 30 min and then a solution of alcohol **4** (1.05 g, 2.12 mmol) in THF (20 mL) was added dropwise during a 1-h period. The mixture was stirred for an additional 1 h and a solution of bromoacetic acid (0.45 g, 3.18 mmol) in THF (50 mL) was added dropwise over a 3-4-h period. The mixture was stirred for an additional 10 h and cooled to 0 ºC with an ice-water bath. Water (10 mL) was added and the THF was evaporated *in vacuo.** Additional water (25 mL) was added and the mixture was acidified with 6 N HCl to give a white solid, which was dried with a benzene azeotrope. The resulting solid was recrystallized from hexanes to give 2.10 g (92%) of a white solid with mp 228-229 ºC. ν_{max} (film)/cm^{-1} (KBr): 1734 (C=O), 1255, 1025 (C-O). δ_H ($(CD_3)_2SO$): 3.83-4.00 (m, 4H), 4.04-4.21 (m, 4H), 4.48 (d, *J* 10, 4H), 4.60 (d, *J* 10, 2H), 6.71-6.87 (m, 4H), 6.86-7.02 (m, 4H), 7.46-7.59 (m, 2H), 7.88-8.01 (m, 4H), 8.27 (s, 1H), 12.60 (s, 1H). δ_C ($(CD_3)_2SO$): 39.0, 39.2, 39.3, 39.5, 39.7, 39.8, 39.9, 40.0, 40.1, 63.0, 67.0, 68.9, 73.4, 81.2, 112.7, 117.3, 120.7, 122.8, 125.6, 126.0, 126.1, 127.2, 127.4, 128.0, 132.3, 132.6, 137.2, 147.2, 149.8, 172.0. Found: C, 68.35; H, 5.44%. $C_{31}H_{30}O_8$ requires C, 68.24; H, 5.63%.

General procedure for the synthesis of *N*-(X)sulfonyl *sym*-(2-naphthyl)dibenzo-16-crown-5-oxyacetamides 14-17

Benzene (50 mL), carboxylic acid **7** (0.74 g, 1.39 mmol), oxalyl chloride (0.74 mL, 8.46 mmol), and DMF (1 drop) were added to a 1-necked flask. The solution was stirred under reflux for 1.5 h and evaporated *in vacuo*. The residue was analyzed by IR spectroscopy. A carbonyl peak at 1824 cm^{-1} indicated completion of the reaction. The sulfonamide salt was prepared by adding NaH (0.17 g, 7.05 mmol) and THF (20 mL) to a 3-necked flask under nitrogen. A solution of the appropriate sulfonamide (1.69 mmol) in THF (20 mL) was added dropwise *via* an addition funnel. The mixture was stirred for 1.5 h at room temperature. A solution of acid chloride **9** in

THF (20 mL) was added dropwise and the mixture was stirred overnight (3 h when X = C_6H_4-4-NO_2). After cooling to 0 °C, water (15 mL) was added dropwise to destroy the excess NaH. The THF was evaporated *in vacuo* and water (40 mL) was added to the residue. The mixture was extracted with CH_2C1_2 (100 mL then 50 mL). The combined organic extracts were washed with 10 % aq K_2CO_3 (2×50 mL). The aqueous washes were back extracted with CH_2C1_2 (2×50 mL). The organic extracts and back extracts were combined, dried over $MgSO_4$, and evaporated *in vacuo.* The residue was dissolved in CH_2C1_2 and the sulfonyl salt precipitated. The product was acidified with 3 N HCl to pH 1. The organic layer was separated, washed with distilled water (2×50 mL), dried over $MgSO_4$, and evaporated *in vacuo.*

***N*-Methanesulfonyl *sym*-(2-naphthyl)dibenzo-16-crown-5-oxyacetamide (14)** was recrystallized from EtOAc-hexanes to give 0.36 g (42%) of white solid with mp 111-112 °C. ν_{max} (film)/cm^{-1}: 3420 (N-H), 1719 (C=O), 1256, 1061 (C-O), 1343, 1127 (SO_2). δ_H 3.09 (s, 3H), 3.89-3.93 (m, 4H), 4.06-4.1l (m, 4H), 4.15-4.25 (m, 7H), 4.39 (d, *J* 10, 2H), 4.92 (d, *J* 10H), 5.05 (s, 2H), 6.71-6.73 (m, 3H), 6.79-6.87 (m, 3H), 6.84-6.87 (m, 4H), 6.94-6.96 (m, 4H), 7.54-7.56 (m, 3H), 7.70-7.72 (m, 2H), 7.89-7.97 (m, 5H), 8.14 (s, 1H), 9.56 (s, 1H). δ_C 41.1, 66.1, 66.9, 69.4, 73.0, 82.4, 112.3, 117.4, 121.0, 123.4, 123.7, 125.8, 126.4, 126.5, 127.6, 128.4, 132.9, 133.2, 136.2, 147.2, 150.2, 171.6. Found: C, 63.19; H, 5.59; N, 2.69%. $C_{32}H_{33}NO_9S$ requires C, 63.26; H, 5.47; N, 2.30%.

***N*-Benzenesulfonyl *sym*-(2-naphthyl)dibenzo-16-crown-5-oxyacetamide (15)** was recrystallized from EtOAc-hexanes to give 0.46 g (53%) of white solid with mp 99-100 °C. ν_{max} (film)/cm^{-1}: 3335 (N-H), 1731 (C=O), 1246, 1060 (C-O), 1350, 1125 (SO_2). δ_H 3.63-3.78 (m, 2H), 3.78-3.97 (m, 4H), 3.99-4.15 (m, 2H), 4.30 (d, *J* 15, 2H), 4.85 (d, *J* 10, 2H), 4.95 (s, 2H), 6.61-6.73 (m, 2H), 6.73-6.84 (m, 4H), 6.91-7.03 (m, 2H), 7.25-7.36 (m, 2H), 7.43-7.52 (m, 1H), 7.52-7.60 (m, 2H), 7.71 (dd, *J* 10, 10, 1H), 7.77-7.87 (m, 2H), 7.87-8.03 (m, 3H), 8.14 (s, 1H), 9.72 (s, 1H). δ_C: 66.2, 66.8, 69.3, 72.5, 82.1, 112.1, 117.3, 120.9, 123.3, 123.6, 126.4, 127.5, 128.4, 132.9, 133.9, 136.5, 138.9, 147.0, 150.1, 170.1. Found: C, 66.26; H, 5.24; N, 2.18%. $C_{37}H_{35}NO_9S$ requires C, 66.35; H, 5.27; N, 2.09%.

***N*-(4-Nitrobenzene)sulfonyl *sym*-(2-naphthyl)dibenzo-16-crown-5-oxyacetamide (16)** was chromatographed on alumina with MeOH-CH_2C1_2 (1:10) as eluent. Recrystallization of the product from EtOAc-hexanes gave 0.37 g (37%) of yellow solid with mp 104-105 °C. ν_{max} (film)/cm^{-1}: 3335 (N-H), 1731 (C=O), 1246, 1044 (C-O), 1350, 1127 (SO_2). δ_H 3.73-3.84 (m, 2H), 3.85-3.96 (m, 4H), 4.06-4.13 (m, 2H), 4.27 (d, *J* 10, 2H), 4.78 (d, *J* 10, 2H), 5.00 (s, 2H), 6.62-6.71 (m, 2H), 6.71-6.76 (m, 2H), 6.76-6.84 (m, 2H), 6.92-7.02 (m, 2H), 7.52-7.61 (m, 2H), 7.66-7.71 (dd, *J* 10, 10, 1H), 7.88-7.99 (m, 7H), 8.14 (s, 1H), 9.80 (s, 1H). δ_C 66.1, 66.8, 69.2, 72.4, 82.3, 112.0, 117.4, 121.0, 123.4, 123.5, 125.5, 126.6, 127.6, 128.4, 128.5, 129.5, 133.0, 133.2, 136.4, 144.1, 150.0, 150.2, 170.4. Found: C, 62.11; H, 4.71; N, 4.21%. $C_{37}H_{34}N_2O_{11}S$ requires C, 62.18; H, 4.79; N, 3.92%.

***N*-Trifluoromethanesulfonyl *sym*-(2-naphthyl)dibenzo-16-crown-5-oxyacetamide (15)** was recrystallized from EtOAc-hexanes to give 0.60 g (65%) of white solid with mp 78-79 °C. ν_{max} (film)/cm^{-1}: 3420 (N-H), 1758 (C=O), 1256, 1065 (C-O), 1385, 1136 (SO_2). δ_H 3.77-3.92 (m,

2H), 3.93-4.05 (m, 2H), 4.10-4.18 (m, 2H), 4.18-4.26 (m, 2H), 4.25-4.36 (m, 2H), 4.90-5.01 (m, 2H), 5.23 (s, 2H), 6.65-6.74 (m, 2H), 6.76-6.82 (m, 2H), 6.82-6.91 (m, 2H), 6.92-7.02 (m, 2H), 7.51-7.60 (m, 2H), 7.69 (dd, *J* 10, 10, 1H), 7.87-7.96 (m, 2H), 8.16 (d, *J* 5, 1H), 8.16 (s, 1H), 10.14 (s, 1H). δ_C: 66.7, 66.8, 69.7, 72.5, 82.3, 112.1, 117.2, 121.0, 123.3, 123.6, 125.6, 126.6, 127.6, 128.4, 128.5, 133.0, 133.2, 136.2, 146.7, 150.1, 169.5. Found: C, 58.11; H, 4.76; N, 2.24%. $C_{32}H_{30}F_3NO_9S$ requires C, 58.09; H, 4.57; N, 2.12%.

***sym*-(9-Phenanthryl)dibenzo-16-crown-5-oxyacetic acid (19).** NaH (1.20 g, 50 mmol) and THF (30 mL) were added to a 1-necked flask. After the mixture was stirred for 30 min under nitrogen, a solution of lariat ether alcohol **18** (5.23 g, 10 mmol) in THF (80 mL) was added over a 1-h period. The mixture was stirred for 1 h and ethyl bromoacetate (3.34 g, 20 mmol) in THF (70 mL) was added over a 2-h period. The mixture was stirred overnight and quenched with H_2O (20 mL) at 0 °C. After the THF was evaporated *in vacuo*, H_2O (10 mL) was added to the residue. The solid was filtered. The filtrate was extracted with CH_2Cl_2 (2 × 50 mL). After separation, the filtered solid was dissolved in the combined organic CH_2Cl_2 layers. The resultant CH_2Cl_2 solution was dried over $MgSO_4$ and evaporated *in vacuo*. After chromatography on silica gel with CH_2Cl_2-MeOH (4:1) as eluent, the product was dissolved in CH_2Cl_2 and the resulting solution was shaken with 1 N HCl to obtain 5.30 g (91%) of white solid with a melting point of 101-102 °C. ν_{max} (film)/ cm^{-1} 3373 (br CO_2H), 1726 (C=O), 1264, 1126, 1051 (C-O). δ_H 3.94-3.91 (m, 2H), 4.11-4.07 (m, 2H), 4.24-4.15 (m, 4H), 4.68 (s, 2H), 5.00 (s, 4H), 6.98-6.78 (m, 8H), 7.74-7.59 (m, 4H), 7.98 (dd, *J* 8, 1, 1H), 8.31 (s, 1H), 8.70 (d, *J* 8, 1H), 8.82-8.80 (m, 2H), 10.08 (br s, 1H). δ_C 64.2 , 67.5, 69.5, 73.0, 84.7, 113.1, 117.5, 121.2, 122.5, 123.2, 123.6, 126.3, 126.3, 127.0, 127.0, 127.7, 129.2, 130.0, 130.1, 130.8, 130.8, 131.6, 147.6, 150.3, 172.0. Found: C, 72.10; H, 5.37%. $C_{35}H_{32}O_8$ requires C, 72.40; H, 5.56%.

General procedure for the synthesis of *N*-(X)sulfonyl *sym*-(9-phenanthryl)dibenzo-16-crown-5-oxyacetamides 21-24

Carboxylic acid **19 (**1.74 g, 3.00 mmol), oxalyl chloride (1.58 mL, 18 mmol), and benzene (80 mL) were combined in a 1-necked flask. The mixture was stirred for 1.5 h. The solvent was evaporated *in vacuo* and an infrared spectrum of the residue was taken. Disappearance of the peak at 1726 cm^{-1} and appearance of the peak at ~1810 cm^{-1} verified formation of the acid chloride **20**. The sulfonamide salt was prepared by adding NaH (0.72 g, 30 mmol) and THF (30 mL) to a 3-necked flask under nitrogen. The appropriate sulfonamide (3.6 mmol) in THF (30 mL) was added to the flask over a 10-min period. (Benzenesulfonamide was dried with a benzene azotrope before use.) The mixture was stirred for 1.5 h and then a solution of the acid chloride **20** in THF (60 mL) was added dropwise. The mixture was stirred overnight. After cooling to 0 °C, H_2O (20 mL) was added to quench the reaction and stirring was continued for 30 min. THF was evaporated *in vacuo* and the resultant solid was filtered. The filtrate was extracted with $CHCl_3$ (2×75 mL). After separation, the filtered solid was dissolved in combined $CHCl_3$ extracts and the resulting solution was washed with 10% aq K_2CO_3 (2×75 mL), dried over $MgSO_4$, and evaporated *in vacuo*. After purification by chromatography on silica gel or recrystallization, the

product was dissolved in CH_2Cl_2. The solution was shaken with 6 N HCl. The organic layer was dried over $MgSO_4$ and evaporated *in vacuo* to give the solid product.

***N*-Methanesulfonyl *sym*-(9-phenanthryl)dibenzo-16-crown-5-oxyacetamide (21).** Chromatography on silica gel with CH_2Cl_2-MeOH (19:1) as eluent gave 1.50 g (94%) of white solid with mp 103-104 ºC. ν_{max} (film)/ cm^{-1} 3344 (N-H), 1722 (C=O), 1256, 1124, 1047 (C-O), 1349, 1145 (SO_2). δ_H 3.10 (s, 3H), 3.98-3.94 (m, 2H), 4.13-4.09 (m, 2H), 4.27-4.18 (m, 4H), 4.77 (s, 2H), 5.00 (d, *J* 11, 2H), 5.03 (d, *J* 11, 2H), 6.88-6.81 (m, 6H), 6.98-6.94 (m, 2H), 7.74-7.62 (m, 4H), 7.95 (dd, *J* 8, 1, 1H), 8.17 (s, 1H), 8.71 (d, *J* 8, 1H), 8.81 (d, *J* 8, 2H), 9.58 (s, 1H). δ_C 41.1, 65.9, 67.2, 69.3, 72.2, 84.6, 112.9, 117.8, 121.1, 122.5, 123.3, 123.7, 126.4, 127.0, 127.7, 129.2, 129.3, 130.1, 130.3, 130.7, 130.8, 131.7, 147.5, 150.2, 170.7. Found: C, 63.41; H, 5.12; N, 2.04%. $C_{36}H_{35}NO_9S•0.4CH_2Cl_2$ requires C, 63.17; H, 5.22; N, 2.02%.

***N*-Benzenesulfonyl *sym*-(9-phenanthryl)dibenzo-16-crown-5-oxyacetamide (22).** Chromatography on silica gel with CH_2Cl_2-MeOH (19:1) as eluent gave 1.77 g (81%) of white solid with mp 113-114 ºC. ν_{max} (film)/ cm^{-1} 3310 (N-H), 1723 (C=O), 1256, 1125, 1048 (C-O), 1344, 1138 (SO_2). δ_H 3.88-3.74 (m, 2H), 4.07-3.98 (m, 4H), 4.20-4.16 (m, 2H), 4.69 (s, 2H), 4.94 (d, *J* 11, 2H), 4.97 (d, *J* 11, 2H), 6.97-6.76 (m, 8H), 7.33-7.30 (m, 2H), 7.52-7.49 (m, 1H), 7.60-7.57 (m, 1H), 7.68-7.64 (m, 2H), 7.74-7.70 (m, 1H), 7.85 (dd, *J* 8, 1, 2H), 7.95 (dd, *J* 8, 1, 1H), 8.14 (s, 1H), 8.70 (d, *J* 8, 1H), 8.74 (d, *J* 8, 1H), 8.80 (d, *J* 8, 1H), 9.72 (s, 1H). δ_C 65.7, 67.1, 69.4, 71.6, 84.2, 112.6, 117.6, 121.0, 122.5, 123.2, 123.6, 126.3, 126.5, 126.9, 127.0, 127.7, 128.3, 128.6, 128.9, 129.2, 130.0, 130.6, 130.7, 130.8, 131.7, 133.4, 138.8, 147.4, 150.2, 169.5. Found: C, 68.04; H, 5.08; N, 1.97%. $C_{41}H_{37}NO_9S$ requires C, 68.41; H, 5.18; N, 1.94%.

***N*-(4-Nitrobenzene)sulfonyl *sym*-(9-phenanthryl)dibenzo-16-crown-5-oxyacetamide (23).** Chromatography on silica gel with CH_2Cl_2-MeOH (19:1) as eluent gave 1.79 g (78%) of yellow solid with mp 127-128 ºC. ν_{max} (film)/ cm^{-1} 3329 (N-H), 1728 (C=O), 1532, 1312 (NO_2), 1256, 1124, 1052 (C-O), 1350, 1160 (SO_2). δ_H 3.91-3.89 (m, 2H), 4.09-4.01 (m, 4H), 4.20-4.16 (m, 2H), 4.73 (s, 2H), 4.91 (d, *J* 11, 2H), 4.95 (d, *J* 11, 2H), 6.82-6.75 (m, 6H), 6.99-6.96 (m, 2H), 7.63-7.59 (m, 1H), 7.70-7.64 (m, 2H), 7.75-7.72 (m, 1H), 7.97-7.93 (m, 3H), 8.07-8.01 (m, 3H), 8.75-8.70 (m, 2H), 8.81 (d, *J* 8, 1H), 9.85 (s, 1H). δ_C 65.7, 67.1, 69.2, 71.4, 84.4, 112.6, 117.7, 121.1, 122.5, 123.5, 123.6, 123.7, 124.0, 126.4, 126.5, 126.8, 127.1, 127.8, 128.7, 129.2, 129.6, 129.8, 130.0, 130.5, 130.6, 130.8, 131.8, 144.1, 147.2, 150.1, 150.3, 169.9. Found: C, 63.95; H, 4.92; N, 3.64%. $C_{41}H_{36}N_2O_{11}S$ requires C, 64.39; H, 4.74; N, 3.66%.

***N*-Trifluoromethanesulfonyl *sym*-(9-phenanthryl)dibenzo-16-crown-5-oxyacetamide (24)**. Recrystallization from EtOAc-hexanes (1:1) gave 1.50 g (70%) of white solid with mp 108-109 ºC. ν_{max} (film)/ cm^{-1} 3304 (N-H), 1748 (C=O), 1252, 1135, 1047 (C-O), 1388, 1204 (SO_2). δ_H 3.94-3.91 (m, 2H), 4.07-4.03 (m, 2H), 4.26-4.18 (m, 4H), 4.95 (d, *J* 11, 2H), 5.01 (s, 2H), 5.04 (d, *J* 11, 2H), 6.82-6.81 (m, 4H), 6.88-6.87 (m, 2H), 7.00-6.96 (m, 2H), 7.64-7.61 (m, 1H), 7.71-7.66 (m, 2H), 7.76-7.72 (m, 1H), 7.98 (d, *J* 8, 1H), 8.17 (s, 1H), 8.72 (d, *J* 8, 2H), 8.82 (d, *J* 8, 1H), 10.16 (s, 1H). δ_C 66.3, 67.1, 69.3, 71.6, 84.5, 112.6, 117.6, 117.8, 121.1, 122.5, 123.6, 123.8, 126.4, 126.4, 126.9, 127.1, 127.8, 128.8, 129.2, 129.9, 130.7, 130.8, 131.8, 147.1, 150.2, 169.0.

Found: C, 59.41; H, 4.28; N, 1.98%. $C_{36}H_{35}NO_9SF_3$•0.8 H_2O requires C, 59.55; H, 4.66; N, 1.93%.

Extraction procedure

An aqueous solution of the alkali metal chlorides with hydroxides for pH adjustment (when X = CF_3, 0.10 M HCl was utilized for pH adjustment) (2.0 mL, 10.0 mM in each alkali metal ion species) and 2.0 mL of 1.0 mM ligand in chloroform in a capped, polypropylene, 15-mL centrifuge tube was vortexed with a Glas-Col Multi-Pulse Vortexer for 10 min at room temperature. The tube was centrifuged for 10 min for phase separation with a Becton-Dickinson Clay Adams Brand® centrifuge. A 1.5-mL portion of the organic phase was removed and added to 3.0 mL of 0.10 M HCl in a new, 15-mL, polypropylene centrifuge tube. The tube was vortexed for 10 min and centrifuged for 10 min. The alkali metal cation concentrations in the aqueous phase from stripping were determined with a Dionex DX-120 ion chromatograph with a CS12A column. The pH of the aqueous phase from the initial extraction step was determined with a Fisher Accumet AR25 pH meter with a Corning 476157 combination pH electrode.

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References

1. Bradshaw, J. S.; Izatt, R. M.; Bordunov, A. V.; Zhu, C. Y.; Hathaway, J. K. In *Comprehensive Supramolecular Chemistry*; Gokel, G. W., Ed.; Pergamon: New York, 1996, p 35.
2. Gokel, G. W.; Leevy, W. M.; Weber, M. E. *Chem. Rev.* **2004**, *104*, 2723.
3. Gokel, G. W.; Schall, O. F. In *Comprehensive Supramolecular Chemistry*; Gokel, G. W., Ed.; Pergamon: New York, 1996, p 97.
4. Strzelbicki, J.; Bartsch, R. A. *Anal. Chem.* **1981**, *53*, 1894.
5. Bartsch, R. A.; Ivy, S. N.; Lu, J. P.; Huber, V. J.; Talanov, V. S.; Walkowiak, W.; Park, C.; Amiri-Eliasi, B. *Pure Appl. Chem.* **1998**, *70*, 2393.
6. Walkowiak, W.; Charewicz, W. A.; Kang, S. I.; Yang, I. W.; Pugia, M. J.; Bartsch, R. A. *Anal. Chem.* **1990**, *62*, 2018.
7. Bartsch, R. A.; Lu, J. P.; Ohki, A. *J. Incl. Phenom. Macro. Chem.* **1998**, *32*, 133.
8. Bartsch, R. A.; Liu, Y.; Kang, S. I.; Son, B.; Heo, G. S.; Hipes, P. G.; Bills, L. J. *J. Org. Chem.* **1983**, *48*, 4864.

9. Bartsch, R. A.; Dalley, N. K.; Talanov, V. S.; Purkiss, D. W.; Vogel, H. F. *Tetrahedron* **2005**, *61*, 8351.
10. Huber, V. J.; Ivy, S. N.; Lu, J. P.; Bartsch, R. A. *Chem. Commun.* **1997**, 1499.
11. Tu, C.; Surowiec, K.; Gega, J.; Purkiss, D. W.; Bartsch, R. A. *Tetrahedron* **2008**, *64*, 1187.
12. Tu, C. Q.; Surowiec, K.; Bartsch, R. A. *Tetrahedron* **2007**, *63*, 4184.
13. Bartsch, R. A.; Bitalac, L. P.; Cowey, C. L.; Elshani, S.; Goo, M. J.; Huber, V. J.; Ivy, S. N.; Jang, Y. C.; Johnson, R. J.; Kim, J. S.; Luboch, E.; McDonough, J. A.; Pugia, M. J.; Son, B.; Zhao, Q. *J. Heterocycl. Chem.* **2000**, *37*, 1337.
14. Bartsch, R. A.; Cowey, C. L.; Elshani, S.; Goo, M. J.; Huber, V. J.; Ivy, S. N.; Johnson, R. J.; Kim, J. S.; Luboch, E.; McDonough, J. A.; Pugia, M. J.; Son, B.; Zhao, Q. *J. Heterocycl. Chem.* **2001**, *38*, 311.
15. Talanova, G. G.; Hwang, H. S.; Talanov, V. S.; Bartsch, R. A. *Chem. Commun.* **1998**, 419.
16. Heo, G. S.; Bartsch, R. A.; Schlobohm, L. L.; Lee, J. G. *J. Org. Chem.* **1981**, *46*, 3574.