Pergamon

Tetrahedron 56 (2000) 4651–4657

TETRAHEDRON

Lariat Ether Carboxylic Acids, *O*-Benzylhydroxamates and Hydroxamic Acids with Fluorinated Substituents: Synthesis, Metal Ion Complexation and Solubility in Supercritical Carbon Dioxide

Sadik Elshani,[a,b] Hongshan Du,[a] Kenneth E. Laintz,[a] Nicholas R. Natale,[a] Chien M. Wai,[a] Nazar S. A. Elkarim[b] and Richard A. Bartsch[b,*]

[a]*Department of Chemistry, University of Idaho, Moscow, ID 83844-2343, USA*
[b]*Department of Chemistry and Biochemistry, Texas Tech University, Lubbock, TX 79409-1061, USA*

Received 3 February 2000; revised 4 April 2000; accepted 4 May 2000

Abstract—A series of lariat ether carboxylic acids, *O*-benzylhydroxamates, and hydroxamic acids with fluorine-containing substituents is prepared. In general, the presence of fluorine-containing substituents is found to increase the solubility of the lariat ethers in supercritical carbon dioxide. Efficiencies of the fluorine-containing lariat ether carboxylic and hydroxamic acids are compared with those for non-fluorinated analogs in solvent extraction of lanthanide ions from aqueous solutions into chloroform. Responses of the fluorine-containing lariat ether *O*-benzylhydroxamates towards alkali metal cations in solvent polymeric membrane electrodes are compared with those analogous non-fluorinated compounds. © 2000 Elsevier Science Ltd. All rights reserved.

Introduction

Lariat ethers are based on crown ethers and have secondary coordination sites bound to the macrocycle by flexible side arms. Lariat ethers are designed to enhance the cation binding ability of crown ethers and also partly to mimic the dynamic complexation processes shown by naturally occurring macrocyclic ligands.[1]

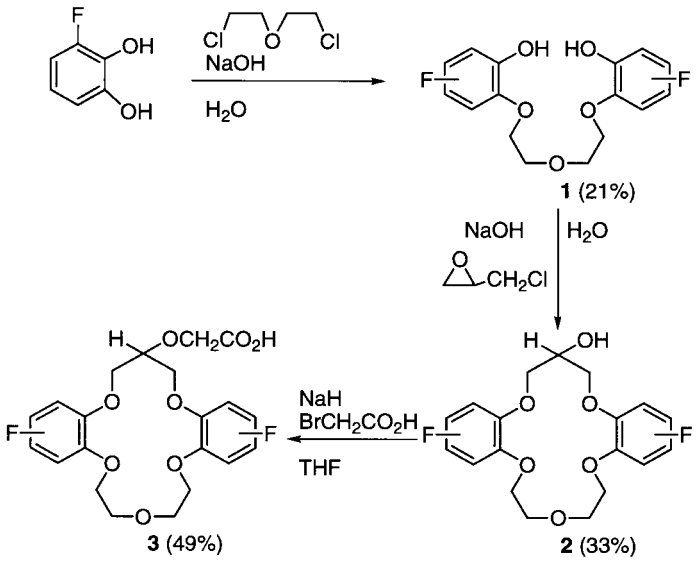
Recently there has been considerable interest in macrocyclic ligands that contain proton-ionizable functional groups.[2] When a proton-ionizable group is incorporated into the side arm of a lariat ether, the molecule is both a cation exchanger and a chelator.[3] Such an arrangement can provide an extraction system with greater selectivity and efficiency than one in which an lipophilic organic acid is simply mixed with a crown ether.[3] A very important advantage of these proton-ionizable lariat ethers is that the ionized group on the side arm provides the requisite counteranion for transport of a metal ion into an organic phase during separations by solvent extraction or transport across liquid membranes. Dibenzocrown ethers with pendant carboxylic acid[4–6] and hydroxamic acid groups in their side arms[6] have been shown to be efficient ligands for the solvent extraction of alkali metal, alkaline earth metal, and lanthanide ions.[7–20] The selectivity and pH range for extraction are influenced by the structure of the ligand.

Supercritical fluid extraction (SFE) of metal species from solids and liquids has been the subject of several recent studies.[21–28] This technique exhibits high efficiency when a fluorinated chelating agent, such as lithium bis(trifluoroethyl)dithiocarbamate or a fluorinated β-diketone, is used as an extractant in supercritical carbon dioxide. (This medium is particularly attractive since it is non-toxic, may be easily recycled, involves minimal waste generation, gives rapid separations and its solvation strength is tunable by density variation.) However, these chelating agents complex with a variety of metal and non-metal species and are non-selective.

In light of the observation that fluorinated substituents increase the solubility of metal chelates in supercritical carbon dioxide, we were intrigued by the possibility of introducing fluorine-containing substituents into proton-ionizable lariat ethers. We now report the synthesis of fluorine-containing lariat ether carboxylic acids, *O*-benzylhydroxamates, and hydroxamic acids and the effects of introducing such substituents on lanthanide ion extraction, alkali metal cation complexation and solubility in supercritical carbon dioxide. To the best of our knowledge, these are first lariat ether carboxylic acids, *O*-benzylhydroxamates, and hydroxamic acids with fluorine-containing substituents.

Keywords: crown ethers; substituent effects; solvents and solvent effects; complexation.
* Corresponding author. Tel.: +1-806-742-3069; fax: +1-806-742-1289; e-mail: rabartsch@ttu.edu

0040–4020/00/$ - see front matter © 2000 Elsevier Science Ltd. All rights reserved.
PII: S0040-4020(00)00380-X



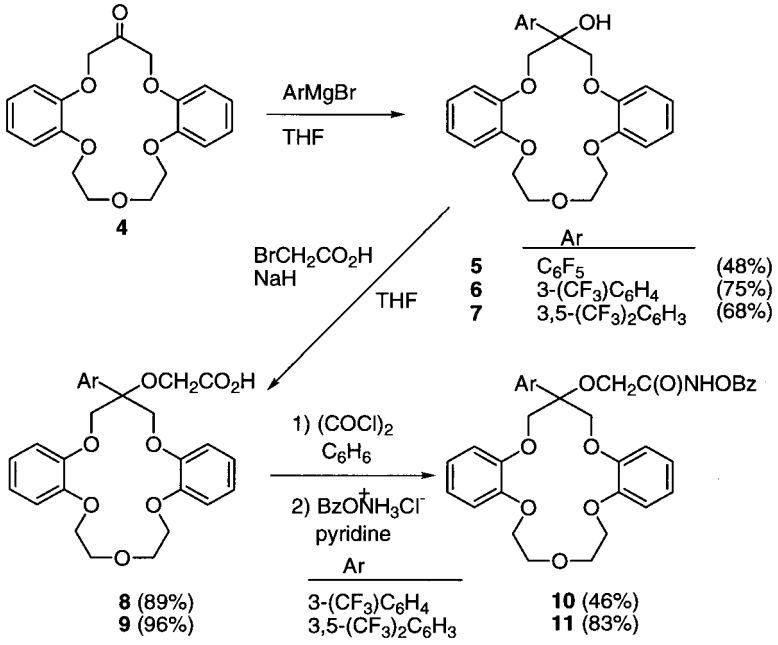
Scheme 1.

Results and Discussion

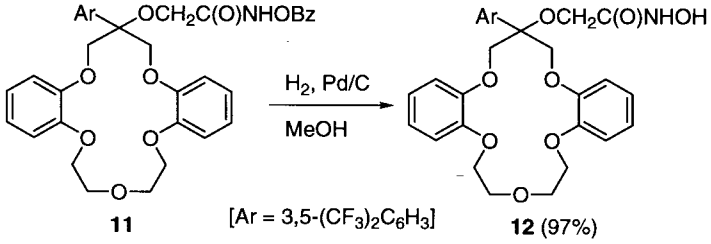
Synthesis of fluorine-containing lariat ethers

Two different strategies were employed. In the first, commercially available 3-fluorocatechol was used in the preparation of ring-fluorinated *sym*-dibenzo-16-crown-5-oxyacetic acid **3** (Scheme 1). Thus, 3-fluorocatechol was reacted with bis-(2-chloroethyl) ether and sodium hydroxide in water to produce the fluorine-containing bisphenol **1**. Ring closure by reaction of **1** with epichlorohydrin and sodium hydroxide in water gave lariat ether alcohol **2**, which was reacted with sodium hydride and bromoacetic acid in THF to produce the ring-fluorinated lariat ether carboxylic acid **3**. Lariat ether carboxylic acid **3** was isolated as a mixture of regioisomers which could not be separated by column chromatography.

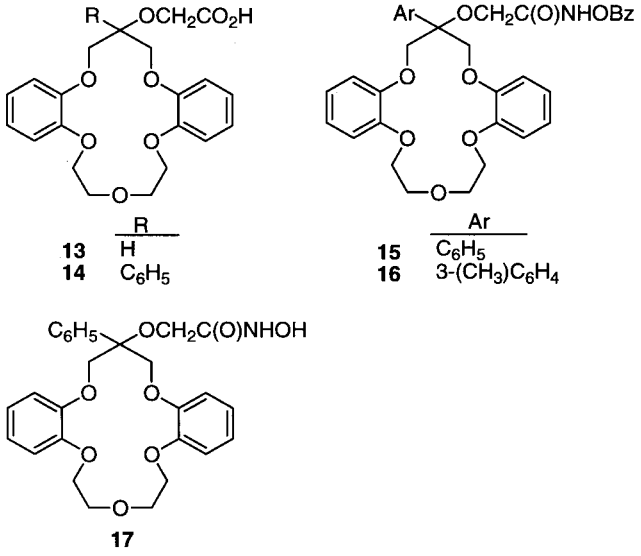
The second strategy involved reactions of fluorine-containing aryl Grignard reagents with *sym*-(keto)dibenzo-16-crown-5 (**4**)[5] to give lariat ether tertiary alcohols **5**–**7** (Scheme 2). Reactions of alcohols **6** and **7** with sodium hydride and bromoacetic acid in THF produced fluorine-containing lariat ether carboxylic acids **8** and **9**, respectively. An analogous reaction of *sym*-(hydroxy)(pentafluorophenyl)-dibenzo-16-crown-5 (**5**) gave a complicated product mixture from which none of the desired lariat ether carboxylic acid could be isolated. Presumably this resulted from nucleophilic attack on the pentafluorophenyl ring.



Scheme 2.



Scheme 3.



Scheme 4.

Treatment of fluorine-containing lariat ether carboxylic acids **8** and **9** with oxalyl chloride in benzene gave the corresponding lariat ether acid chlorides which were reacted with *O*-benzylhydroxylamine hydrochloride and pyridine in acetonitrile to form lariat ether *O*-benzylhydroxamates **10** and **11**, respectively (Scheme 2). For **11**, catalytic hydrogenolysis of the *O*-benzyl group gave fluorine-containing lariat ether hydroxamic acid **12** (Scheme 3).

Non-fluorinated lariat ether carboxylic acids **13**[4] and **14**,[6] *O*-benzylhydroxamates **15**[6] and **16** and hydroxamic acid **17**[6] were prepared by reported or analogous methods for comparison purposes (Scheme 4).

Structures of the new lariat ether compounds were consistent with their IR and NMR spectra and verified by combustion analysis.

Solubilities of lariat ether carboxylic acids in supercritical carbon dioxide

No solubility data for lariat ether carboxylic acids in supercritical carbon dioxide have appeared in the literature. The critical temperature (T_c) and pressure (P_c) of carbon dioxide are 32°C and 73 atm, respectively.[29] The solubilities of ring-fluorinated lariat ether carboxylic acid **3** and the non-fluorinated analog **13** and lariat ether carboxylic acid **9** with a geminal, fluorine-containing substituent in supercritical carbon dioxide at 50°C in the pressure range of 100–300 atm are given in Table 1.

At pressures of less than 200 atm, **3** exhibits greater solubility in supercritical carbon dioxide than does the non-fluorinated analog **13**. The solubility difference appears to depend on the pressure with the greatest difference occurring at 117 atm. Under this condition, the solubility of **3** is 3.8 times higher than that for non-fluorinated **13**. At 200 and 300 atm, there is no difference in the solubilities of **3** and **13**. The solubility of **9** in supercritical carbon dioxide is slightly higher than that of **3**, probably because lariat ether carboxylic acid **9** contains six fluorine atoms instead of two. However, even for lariat ether carboxylic acid **9**, the solubility in supercritical carbon dioxide is too low for practical use as a metal ion extractant.

Solvent extraction of lanthanide ions by lariat ether carboxylic and hydroxamic acids

The availability of fluorine-containing lariat ether carboxylic acids **3**, **8** and **9** and hydroxamic acid **12** encouraged the investigation of their behavior as lanthanide ion extractants.[16,17] Distribution coefficients for extraction of La(III) and Lu(III) from aqueous solutions into chloroform and the La/Lu selectivities for lariat ether carboxylic acids **3**, **8** and **9** and the desfluoro analogs **13** and **14** are given in Table 2. The lariat ether carboxylic acid **3** with a fluorine attached to each benzene ring appears to appreciably increase the lanthanide extraction efficiency relative to

Table 1. Solubilities of lariat ether carboxylic acids in supercritical carbon dioxide at 50°C as a function of pressure. The estimated error is ±20% of the stated value

Lariat ether	Pressure (atm)				
	100	117	150	200	300
3	7.9×10^{-6} M	8.4×10^{-5} M	9.9×10^{-5} M	1.2×10^{-4} M	2.1×10^{-4} M
13	7.6×10^{-6} M	2.2×10^{-5} M	7.6×10^{-5} M	1.2×10^{-4} M	2.1×10^{-4} M
9	3.0×10^{-5} M	9.0×10^{-5} M	1.3×10^{-4} M	1.6×10^{-4} M	2.1×10^{-4} M

Table 2. Distribution coefficients for the solvent extraction of lanthanum(III) and lutetium(III) from aqueous solutions at pH 6.5±0.2 into chloroform by fluorine-containing lariat crown ether carboxylic acids **3**, **8** and **9** and hydroxamic acid **12**. The estimated error is ±10% of the stated value. Values for non-fluorinated lariat ether carboxylic acids **13** and **14** and hydroxamic acid **17** are shown for comparison

Lariat ether	$^{D}Lu^{3+}$	$^{D}La^{3+}$	Ratio (Lu^{3+}/La^{3+})
3	39	13.3	2.9
13	19.6	3.0	6.5
8	4.82	0.25	19.2
9	2.99	0.22	13.6
14	7.96	0.35	23.1
12	75.9	1.27	59.8
17	147	0.25	588

non-fluorinated analog **13**, even though the La/Lu selectivity is decreased. For fluorine-containing lariat ether carboxylic acids **8** and **9** and the non-fluorinated analog **14**, the lanthanide extraction efficiency and the La/Lu selectivity decrease as the geminal substituent is varied C_6H_5>3-$(CF_3)C_6H_4$>3,5-$(CF_3)_2C_6H_3$.

Compared with lariat ether carboxylic acid **9**, the analogous lariat ether hydroxamic acid **12** exhibits a 25-fold increase in Lu(III) extraction, but only a six-fold increase in La(III) extraction. Thus, the lariat ether hydroxamic acid **12** exhibits a much higher Lu/La selectivity than does the analogous carboxylic acid. When the geminal 3,5-di(trifluoromethyl)phenyl group in lariat ether hydroxamic acid **12** is replaced by a phenyl group in **17**, the extraction efficiency for Lu(III) increases by approximately two-fold, but the extraction of La(III) drops by a factor of five. For all of the proton-ionizable lariat ethers examined in this study, the Lu/La selectivity is greatest for the nonfluorinated lariat ether hydroxamic acid **17**.

Potentiometric selectivities of lariat ether *O*-benzylhydroxamates for alkali metal cations in solvent polymeric membrane electrodes

Metal-ion selectivities of non-ionizable macrocyclic ligands are frequently determined with polymeric membrane electrodes.[30] (Due to their ion-exchange behavior, proton-ionizable macrocyclic ligands are not suitable.) To probe the influence of introducing one and two trifluoromethyl groups into the geminal aryl group of *O*-benzyl *sym*-(aryl)dibenzo-16-crown-5-oxyacetylhydroxamates, plasticized poly(vinyl chloride) membranes containing lariat ethers **10**, **11**, **15** and **16** were prepared and incorporated into ion-selective electrode assemblies and their potentiometric selectivities were measured (Table 3). The geminal aryl group is systematically varied from phenyl to 3-methylphenyl to 3-(trifluoromethyl)phenyl to 3,5-di(trifluoromethyl)phenyl in ligands **15**, **16**, **10** and **11**, respectively.

Table 3. Potentiometric selectivities, $-\log K^{Pot}_{Na,M}$, of *O*-benzyl sym-(aryl)-dibenzo-16-crown-5-oxyacetyl-hydroxamates. The standard deviation of the log K^{Pot} values from the average obtained from duplicate determinations with two membranes was less than 0.05

Lariat ether	Aryl group	$-\log K^{Pot}_{Na,M}$ for M^+			
		Li^+	K^+	Rb^+	Cs^+
15	C_6H_5	3.42	1.60	2.04	2.34
16	3-$(CH_3)C_6H_4$	3.55	1.56	2.10	2.36
10	3-$(CF_3)C_6H_4$	3.40	1.52	1.77	1.79
11	3,5-$(CF_3)C_5H_3$	3.39	1.44	1.56	1.19

For all four ion-selective electrodes, the greatest potentiometric response is for Na^+ which provides the best fit for a dibenzo-16-crown-5 cavity.[31,32] The Na^+/Li^+ selectivities are very high and remain approximately the same when one or two trifluoromethyl groups are introduced into the geminal aryl group. On the other hand, the Na^+/K^+ selectivity is much lower and exhibits a perceptible decrease as the number of trifluoromethyl groups is enhanced. A diminution of Na^+ selectivity with the introduction of trifluoromethyl groups is clearly evident when the competing alkali metal cations are Rb^+ and Cs^+. Although Na^+ fits within the crown ether cavity to form a nesting complex,[33] K^+, Rb^+ and Cs^+ are too large and form perching complexes.[33] Apparently the addition of trifluoromethyl groups to the geminal aryl group lessens the disfavoring for formation of a perching complex versus a nesting complex with an alkali metal cation.

Experimental

Materials and methods

The 3-fluorocatechol was obtained from Aldrich and used without purification. Other fluorinated compounds were purchased from PCR. Tetrahydrofuran was distilled from benzophenone ketyl. *sym*-(Keto)dibenzo-16-crown-5[5] and non-fluorinated lariat ethers **13**–**15** and **17** were prepared by reported methods.[4,6] NMR spectra were obtained with a Bruker AF200 spectrometer (200 MHz for ^1H and 188.31 MHz for ^{19}F). Combustion analyses were performed by Desert Analytics Laboratory, Tucson, AZ.

Synthesis of bis-2-[3(4)-fluoro-2-hydroxyphenoxy]ethyl ether (1). To a solution of 3-fluorocatechol (20.0 g, 156 mmol) in 200 mL of water under nitrogen, NaOH (2.14 g, 53.64 mmol) was added and the reaction mixture was warmed to reflux. Bis(2-chloroethyl) ether (2.78 mL, 26.2 mmol) was added slowly over a 3 h period and refluxing was continued for 48 h. Upon cooling to room temperature, a dark oil separated which solidified on standing. This solid was recrystallized from benzene–petroleum ether to give 1.80 g (21%) of **1** as a white solid with mp 67–68°C: IR (KBr) 3406 (OH) cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.77–4.25 (m, 8H), 6.61–6.94 (m, 6H), 7.55 (s, 2H); ^{19}F NMR ($CDCl_3$) δ −131.5 (m, 1F), −136.0 (m, 1F). Anal. calcd for $C_{16}H_{16}F_2O_5$: C: 58.89; H, 4.94. Found: C, 58.79; H, 4.94.

***sym*-(Hydroxy)-3(6),3′ (6′)-difluorodibenzo-16-crown-5 (2).** A mixture of bisphenol **1** (1.68 g, 5.15 mmol), NaOH (0.41 g, 10.3 mmol) and water (120 mL) was stirred under nitrogen at 90°C until a solution was obtained. The solution was cooled to 50°C and epichlorohydrin (0.48 g, 5.15 mmol) was added over a 3-h period. The reaction mixture was stirred for an additional 5 h and then cooled to room temperature. The aqueous solution was decanted from the oily residue, which was dissolved in CH_2Cl_2. The resultant solution was washed with water, dried over $MgSO_4$ and evaporated in vacuo. The residue was

recrystallized from petroleum ether to give 0.65 g (33%) of **2** as a white solid with mp 78–80°C: IR (KBr) 3441(OH), 1256, 1124 (C–O) cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.46 (s, 1H), 3.76–4.47 (m, 13H), 6.65–7.16 (m, 6H); ^{19}F NMR ($CDCl_3$) δ −130.9 (m, 1F), −131.8 (m, 1F). Anal. calcd for $C_{19}H_{20}F_2O_6$: C, 59.68; H, 5.27. Found: C, 59.91; H, 5.48.

General method for the preparation of lariat ether alcohols 5–7

A three-necked flask was charged with 0.144 g (6.0 mmol) of magnesium turnings and flame-dried under an atmosphere of dry nitrogen. THF (20 mL) and a crystal of iodine were added. A small portion of the substituted bromobenzene was added to initiate the reaction. The reaction mixture was cooled with an ice bath to control the reaction once it commenced. After the initial reaction subsided, the remainder of the substituted bromobenzene was added slowly. After completion of the addition, the reaction mixture was stirred for 1 h and a solution of 1.03 g (3.0 mmol) of sym-(keto)dibenzo-16-crown-5 in 10 mL of THF was added dropwise. Stirring at room temperature was continued overnight and then 20 mL of 5% aqueous NH_4Cl solution was added. The mixture was stirred for 10 h and the THF was evaporated in vacuo. The residue was extracted with CH_2Cl_2 and the CH_2Cl_2 layer was washed with water, dried over $MgSO_4$ and evaporated in vacuo. The residue was chromatographed on silica gel with CH_2Cl_2 and then Et_2O as eluents to afford the product.

sym-(Hydroxy)(pentafluorophenyl)dibenzo-16-crown-5 (5). It was obtained in 48% yield as a white solid with mp 128–129°C: IR (KBr) 3339 (OH), 1258, 1123 (C–O) cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.91–4.26 (m, 8H), 4.52 (d, J=9.6 Hz, 2H), 4.62 (d, J=9.6 Hz, 2H), 6.79–7.00 (m, 8H); ^{19}F NMR ($CDCl_3$) δ −138 (s, 2F), −155 (s, 1F), −162 (s, 2F). Anal. calcd for $C_{25}H_{21}F_5O_6$: C, 58.60; H, 4.13. Found: C, 58.20; H, 4.32.

sym-(Hydroxy)[3-(trifluoromethyl)phenyl]dibenzo-16-crown-5 (6). It was obtained in 75% yield as a white solid with mp 54–56°C: IR (KBr) 3444 (OH), 1258, 1122 (C–O) cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.45 (s, 1H), 3.83–4.20 (m, 8H), 4.36 (d, J=9.5 Hz, 2H), 4.50 (d, J=9.52 Hz, 2H), 6.78–6.96 (m, 8H), 7.45–7.57 (m, 2H), 7.96–8.07 (m, 2H); ^{19}F NMR ($CDCl_3$) δ −62.4 (s). Anal. calcd for $C_{26}H_{25}F_3O_6$: C, 63.67; H, 5.14. Found: C, 64.07; H, 5.15.

sym-(Hydroxy)[3,5-bis(trifluoromethyl)phenyl]dibenzo-16-crown-5 (7). It was obtained in 68% yield as a white solid with mp 56–58°C: IR (KBr) 3441 (OH), 1259, 1135 (C–O) cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.82–4.20 (m, 8H), 4.29 (d, J=9.57 Hz, 2H), 4.64 (d, J=9.55 Hz, 2H), 6.79–6.98 (m, 8H), 7.80 (s, 1H), 8.32 (s, 2H); ^{19}F NMR ($CDCl_3$) δ −62.5 (s). Anal. calcd for $C_{27}H_{24}F_6O_6$: C, 58.07; H, 4.33. Found: C, 57.89; H, 4.59.

General method for the synthesis of lariat ether carboxylic acids 3, 8 and 9

A 100 mL three-necked flask was charged with NaH (0.34 g, 14 mmol) and THF (20 mL) under nitrogen and a solution of the appropriate lariat ether alcohol (2.0 mmol) dissolved in THF (15 mL) was added over a 30-min period. Stirring was continued for 1 h and a solution of bromoacetic acid (0.56 g, 4.0 mmol) in THF (15 mL) was added over a 3-h period. After stirring for an additional 15 h, water was added cautiously to destroy the excess NaH. The THF was evaporated in vacuo from the mixture and the aqueous mixture was extracted with Et_2O (to remove the unreacted lariat ether alcohol), acidified with 6 N HCl and extracted with CH_2Cl_2. The combined organic layers were washed with water, dried over Na_2SO_4 and evaporated in vacuo.

sym-3(6),3′(6′)Difluorodibenzo-16-crown-5-oxyacetic acid (3). It was obtained in 49% yield as a white solid after trituration with Et_2O, mp 129–131°C: IR (KBr) 3437 (COOH), 1732 (C═O), 1255, 1124 (C–O) cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.85–4.51 (m, 15H), 6.67–6.99 (m, 6H); ^{19}F NMR ($CDCl_3$) δ −129.9 (m, 1F), −131.3 (m, 1F). Anal. calcd for $C_{21}H_{22}F_2O_8$: C, 57.27; H, 5.03; F, 8.62. Found: C, 57.24; H, 4.96; F, 8.32.

sym-[3-(Trifluoromethyl)phenyl]dibenzo-16-crown-5-oxyacetic acid (8). It was obtained in 89% yield as a white solid with mp 126–128°C: IR (KBr) 3410 (COOH), 1724 (C═O), 1256, 1124 (C–O) cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.73–4.18 (m, 8H), 4.36 (d, J=10.6, 2H), 4.74 (d, J=10.6 Hz, 2H), 4.90 (s, 2H), 6.68–6.98 (m, 8H), 7.58–7.63 (m, 2H), 7.87–7.94 (m, 2H); ^{19}F NMR ($CDCl_3$) δ −62.5 (s). Anal. calcd for $C_{28}H_{27}F_3O_8$: C, 61.30; H, 4.93; F, 10.39. Found: C, 61.04; H, 5.17; F, 10.25.

sym-[3,5-Di(trifluoromethyl)phenyl]dibenzo-16-crown-5-oxyacetic acid (9) It was obtained in 96% yield after purification by chromatography on silica gel with CH_2Cl_2–MeOH (9:1) as eluent as a white solid with mp 128–130°C: IR (KBr) 3421 (COOH), 1735 (C═O), 1257, 1132 (C–O) cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.70–4.17 (m, 8H), 4.45 (d, J=10.68 Hz, 2H), 4.71 (d, J=10.68 Hz, 2H), 4.89 (s, 2H), 6.70–6.99 (m, 8H), 7.89 (s, 1H), 8.19 (s, 2H); ^{19}F NMR ($CDCl_3$) δ −63.7 (s). Anal. calcd for $C_{29}H_{26}F_6O_8$: C, 56.49; H, 4.25; F, 18.49. Found: C, 56.14; H, 4.36; F, 18.13.

General procedure for the synthesis of *O*-benzyl sym-(aryl)dibenzo-16-crown-5-oxyacetylhydroxamates 10 and 11

To a solution of the appropriate lariat ether carboxylic acid (3.0 mmol) in benzene (20 mL) at 0°C was added dropwise oxalyl chloride (1.05 mL, 12.0 mmol). The mixture was stirred at room temperature for 1 h and then heated at 70°C for 1 h. The mixture was cooled to room temperature and evaporated in vacuo to provide a residue of the lariat ether acid chloride which was used directly in the next step. The residue was dissolved in MeCN and added dropwise to a solution mixture of *O*-benzylhydroxylamine hydrochloride (0.48 g, 3.0 mmol) and pyridine (0.48 g, 6.0 mmol) in MeCN at 0°C under nitrogen. The mixture was stirred for 24 h. The solvent was evaporated in vacuo and the residue was dissolved in EtOAc. The solution was washed with 0.6 N HCl, water and 0.6 M aqueous sodium bicarbonate, dried over Na_2SO_4 and evaporated in vacuo.

***O*-benzyl sym-[3-(trifluoromethyl)phenyl]dibenzo-16-crown-5-oxyacetylhydroxamate (10).** It was realized in

46% yield as a white solid with mp 63–65°C after purification by column chromatography on silica gel with CH_2Cl_2 then CH_2Cl_2–EtOAc (9:1) as eluents followed by recrystallization from EtOAc–hexanes: IR (deposit from CH_2Cl_2 solution on a NaCl plate) 3281 (NH), 1686 (C═O), 1257, 1124 (C–O) cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.86–3.91 (m, 2H), 4.01–4.17 (m, 6H), 4.31 (d, 2H, J=10.6 Hz), 4.68 (d, 2H, J=10.6 Hz), 4.83 (s, 2H), 4.91 (s, 2H), 6.68–6.99 (m, 8H), 7.22–7.32 (m, 5H), 7.35–7.73 (m, 3H), 7.86 (s, 1H), 9.43 (s, 1H). Anal. calcd for $C_{35}H_{34}F_3NO_8$: C, 64.31; H, 5.24; N, 2,14. Found; C, 64.32; H, 5.26; N, 2.01.

***O*-benzyl sym-[3,5-di(trifluoromethyl)phenyl]dibenzo-16-crown-5-oxyacetylhydroxamate (11).** It was obtained in 83% yield as a white solid with mp 59–61°C: IR (KBr) 3290 (NH), 1689 (C═O), 1258, 1135 (C–O) cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.84–4.15 (m, 8H), 4.37 (d, J=10.7 Hz, 2H), 4.62 (d, J=10.7 Hz, 2H), 4.80 (s, 2H), 4.89 (s, 2H), 6.67–6.98 (m, 8H), 7.17–7.29 (m, 5H), 7.87 (s, 1H), 8.07 (s, 2H), 9.40 (s, 1H); ^{19}F NMR ($CDCl_3$) δ −62.8 (s). Anal. calcd for $C_{36}H_{33}F_6NO_8$: C, 59.92; H, 4.61, N, 1.94. Found: C, 59.96; H, 4.56; N, 2.01.

Preparation of sym-[3,5-di(trifluoromethyl)phenyl]dibenzo-16-crown-5-oxy-acetylhydroxamic acid (12). The *O*-benzyl hydroxamate ester **11** (1.54 g, 2.14 mmol) was dissolved in MeOH (120 mL) and 0.2 g of 10% Pd on charcoal was added. The mixture was stirred under one atmosphere of hydrogen at room temperature for 3 h and filtered. The filtrate was evaporated in vacuo to give a 97% yield of **12** as a white solid with mp 85–7°C: IR (KBr) 3387 (NHOH), 1678 (C═O), 1259, 1136 (C–O) cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.82–4.19 (m, 8H) ppm, 4.41 (d, J=10.79 Hz, 2H), 4.74 (d, J=10.8 Hz, 2H), 4.77 (s, 2H), 6.69–6.99 (m, 8H), 7.90 (s, 1H), 8.10 (s, 2H), 9.66 (s, 1H); ^{19}F NMR ($CDCl_3$) δ: −62.8 (s). Anal. calcd for $C_{29}H_{30}F_6NO_8$: C, 55.15; H, 4.30; N, 2.21. Found: C, 55.10; H, 4.25; N, 2.09.

Solubilities of lariat ether carboxylic acids in supercritical carbon dioxide

The solubility determinations were made according to the previously published procedure.[21] Briefly, the lariat ether carboxylic acid was dissolved in SFC grade carbon dioxide (Scott Specialty Gases) in a high pressure, stainless steel optical cell. Dissolution was achieved using a magnetic stir bar driven by a stirring motor and was monitored with a Varian Cary 2200 UV-Vis spectrophotometer equipped with a DS-15 Data Station. Molar absorptivities in supercritical carbon dioxide were calculated using the B-band of benzene at about 260 nm. Once the molar absorptivities had been calculated, the solubilities of the lariat ether carboxylic acids were determined by saturation of the view cell and use of Beer's Law to calculate the concentration of the macrocycle dissolved in the carbon dioxide. The temperature of the dissolution cell was maintained at 50°C.

Solvent extraction of lanthanide ions

The extraction studies were conducted as described previously.[16,17] A 3.0×10^{-3} M chloroform solution (10 mL) of the lariat ether was shaken vigorously with a 1.0×10^{-4} M aqueous solution (10 mL) of the lanthanide nitrate containing a rare-earth radioisotope as a tracer with a Burrell Model 75 mechanical shaker for 30 min at room temperature. After the separation of the phases, 5.0 mL portions of each phase were removed and subjected to γ counting.[34]

Potentiometric responses of solvent polymeric membrane electrodes to alkali metal cations

Membranes containing poly(vinyl choride), *o*-nitrophenyl octyl ether (the membrane solvent), potassium tetrakis(*p*-chlorophenyl)borate and the lariat ether were prepared by the reported method.[31,32] Potentiometric measurements were performed as before and selectivity coefficients (K^{Pot}) were determined by the fixed interference method.[35]

Acknowledgements

The research conducted at the University of Idaho was supported by the National Science Foundation's EPSCoR Program, Grant #R11-8902065. The research performed at Texas Tech University was supported by the Division of Chemical Sciences of the Office of Basic Energy Sciences of the US Department of Energy, Grant DE-FG03-94ER14416.

References

1. For reviews on lariat ethers, their cation complexation properties and applications, see: (a) Gokel, G. W.; Trafton, J. E. In *Cation Binding by Macrocycles*; Inoue, Y., Gokel, G. W., Eds.; Marcel Dekker: New York, 1990; pp 253–310. (b) Gokel, G. W. *Chem. Soc. Rev.* **1992**, 39. (c) Gokel, G. W.; Schall, O. F. In *Comprehensive Supramolecular Chemistry*; Gokel, G. W., Ed.; Pergamon: New York, 1996; Vol. 1, pp 97–152.
2. (a) McDaniel, C. W.; Bradshaw, J. S.; Izatt, R. M. *Heterocycles* **1990**, *30*, 665. (b) Bradshaw, J. S. *J. Incl. Phenom. Mol. Recognit. Chem.* **1997**, *29*, 221.
3. McDowell, W. J. *Sep. Sci. Technol.* **1988**, *23*, 1251.
4. Bartsch, R. A.; Heo, G. S.; Kang, S. I.; Liu, Y.; Strzelbicki, J. *J. Org. Chem.* **1982**, *47*, 457.
5. 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.
6. Elshani, S.; Noriyuki, R.; Wai, C. M.; Natale, N. R.; Bartsch, R. A. *J. Heterocycl. Chem.* **1998**, *35*, 875.
7. Strzelbicki, J.; Bartsch, R. A. *Anal. Chem.* **1981**, *53*, 1894.
8. Strzelbicki, J.; Bartsch, R. A. *Anal. Chem.* **1981**, *53*, 2247.
9. Strzelbicki, J.; Bartsch, R. A. *Anal. Chem.* **1981**, *53*, 2251.
10. Pugia, M. J.; Ndip, G.; Lee, H. K.; Yang, I.-W.; Bartsch, R. A. *Anal. Chem.* **1986**, *58*, 2723.
11. Walkowiak, W.; Charewicz, W. A.; Kang, S. I.; Yang, I.-W.; Pugia, M. J.; Bartsch, R. A. *Anal. Chem.* **1990**, *62*, 2018.
12. Hayashita, T.; Goo, M. J.; Lee, J. C.; Kim, J. S.; Krzykawski, J.; Bartsch, R. A. *Anal. Chem.* **1990**, *62*, 2283.
13. Hayashita, T.; Lee, J. H.; Chen, S.; Bartsch, R. A. *Anal. Chem.* **1991**, *63*, 1844.
14. Hayashita, T.; Lee, J. H.; Lee, J. C.; Krzykawski, J.; Bartsch, R. A. *Talanta* **1992**, *39*, 857.
15. Hayashita, T.; Lee, J. H.; Hankins, M. G.; Lee, J. C.; Kim, J. S.; Knobeloch, J. M.; Bartsch, R. A. *Anal. Chem.* **1992**, *64*, 815.

16. Tang, J.; Wai, C. M. *Anal. Chem.* **1986**, *58*, 3233.
17. Tang, J.; Wai, C. M. *Analyst* **1989**, *114*, 451.
18. Tang, J.; Wai, C. M. *J. Membr. Sci.* **1988**, *35*, 339.
19. Tang, J.; Wai, C. M. *J. Radioanal. Nucl. Chem. Lett.* **1988**, *128*, 61.
20. Wood, D. J.; Elshani, S.; Du, H. S.; Natale, N. R.; Wai, C. M. *Anal. Chem.* **1993**, *65*, 1350.
21. Laintz, K. E.; Wai, C. M.; Yonker, C. R.; Smith, R. D. *J. Supercrit. Fluids* **1991**, *4*, 194.
22. Laintz, K. E.; Yu, J. J.; Wai, C. M. *Anal. Chem.* **1992**, *64*, 311.
23. Laintz, K. E.; Wai, C. M.; Yonker, C. R.; Smith, R. D. *Anal. Chem.* **1992**, *64*, 2875.
24. Wai, C. M.; Lin, Y.; Brauer, R. D.; Wang, S.; Beckert, W. F. *Talanta* **1993**, *40*, 1325.
25. Liu, Y.; Lopez-Avila, V.; Alcaraz, M.; Beckert, W. F. *J. High Resolut. Chromatogr.* **1993**, *16*, 106.
26. Lin, Y.; Brauer, R. D.; Laintz, K. E.; Wai, C. M. *Anal. Chem.* **1993**, *65*, 2549.
27. Lin, Y.; Wai, C. M.; Jean, F. M.; Brauer, R. D. *Environ. Sci. Technol.* **1994**, *28*, 1190.
28. Lin, Y.; Smart, N. G.; Wai, C. M. *Environ. Sci. Technol.* **1995**, *29*, 2706.
29. Stahl, E.; Schliz, W.; Schülz, E.; Willing, E. *Angew. Chem. Int. Ed. Engl.* **1978**, *17*, 731.
30. Kimura, K.; Shono, T. In *Cation Binding by Macrocycles*; Inoue, Y., Gokel, G., Eds.; Marcel Dekker: New York, 1990; pp 429–464.
31. Ohki, A.; Lu, J.-P.; Bartsch, R. A. *Anal. Chem.* **1994**, *66*, 651.
32. Bartsch, R. A.; Lu, J.-P.; Ohki, A. *J. Inclusion Phenom. Mol. Recognit. Chem.* **1998**, *32*, 133.
33. Cram, D. J.; Trueblood, K. N. In *Host Guest Complex Chemistry*; Vögtle, F., Weber, E., Eds.; Springer: New York, 1985; pp 125–128.
34. Mok, W. M.; Shah, N. K.; Wai, C. M. *Anal. Chem.* **1986**, *58*, 110.
35. Recommendations for nomenclature of ion-selective electrodes, *Pure Appl. Chem.* **1976**, *48*, 127.