Synthesis of Calix[4]Crown-4 Oligomers Containing Hard and Soft Ion Binding Sites

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ABSTRACT: Three calix [4]crown-4 derivatives and their oligomers, *p*-tert-butylcalix [4]crown-4 oligomer **5**, *p*-tert-butylcalix [4]dioxacrown-4 oligomer **6**, *p*-tert-butylcalix [4]diazacrown-4 oligomer **7** that contain hard and soft ion binding sites, are synthesized to estimate selective extraction of cesium ions from the aqueous to the organic phase. The binding sites may complex alkali metal ions or transition metal ions selectively. Oligomers are fairly good extractants for transition metal ions in comparison with their monomers, which suggests that polyoxyethylene bridges are efficient for complexing metal ions, especially for transition metal ions. © 2007 Wiley Periodicals, Inc. J Appl Polym Sci 104: 3201–3205, 2007

Key words: calixarene; calixcrown; oligomer; ion-binding

INTRODUCTION

It is well known that polytoptic system may be constructed when two or more binding sites are combined together within the same architecture. Once recognition of each binding subunit has been identified, the ability of multiple recognition and mutual effects of binding subunit occupation provide entries to higher form of molecular behavior such as cooperativity, allostery, and regulation, as well as communication or metal transfer. Calixcrowns[1,2] comprise a family of calixarenes[3–5] in which the phenolic oxygens are linked intramolecularly via flexible poly-(oxyethylene) chains. As they possess preorganized structures and more rigid binding sites in comparison with calixarene and crown ethers, they exhibit superior recognition ability toward metal ions by the cooperative effects of calixarene and crown moieties. By changing calixarene size and the number of phenyl ring moiety, length of the polyether chains, a large variety of calixcrown with different physicochemical properties have been obtained.[6–11] To the best of our knowledge, only two cases are found about calixcrown-based polytoptic system. In 1997, Vicens et al. synthesized calyx[4]-triaza-oxa-benzo-crown-6 containing hard and soft ion binding sites.[12] Lately, Chen et al. reported a C_s-symmetrical *p*-tert-calix[6]-1,4-crown-4-2,6-dioxo-diaza-crown-4 with hard and soft ion binding sites.[13]

On the other hand, in comparison with the extensive and in-depth studies of monomeric calixcrown, more and more attentions are paid to polymeric calixcrown up to date. Zhong et al. first reported the syntheses and properties of calix[4]crown telomers.[14] Zhang et al. successfully prepared two linear polysiloxane with pendant hand-basket type calix[4]-crowns and investigated their gas chromatography behavior.[15] Ungaro et al. reported the utility of calix[4]crown bonded silica gel for the separation of Na^+ and Cs^+ in liquid chromatography.[16] Dozol et al. employed a solid membrane composed of calix[4]-biscrown-6 bonded to polysiloxane backbone to removal of cesium from model nuclear waster solution.[17] More recently, we first reported the calix[6]crown-containing organosilicon resins and their complexation toward metal ions.[18] However, no polytoptic system with different ion binding sites has been constructed based on polymeric calixcrown.

In the present work, we wish to report the syntheses of new three calix[4]crown-4 derivatives and their oligomers: *p*-tert-butylcalix[4]crown-4 oligomer **5**, *p*-tert-butylcalix[4]dioxacrown-4 oligomer **6**, and *p*-tert-butylcalix[4]diazacrown-4 oligomer **7** containing hard and soft ion binding sites, and also the extraction abilities toward different metal ions.

EXPERIMENTAL

Materials

Sodium hydride was purchased from Aldrich. Petroleum ether refers to the fraction with a boiling point in the range 60–90°C. All solvents were purified by standard procedures. All other chemicals were analytically pure and used without further purification.

Measurements

^{1}HNMR spectra were recorded on a Varian Mercury VX300 instrument. Tetramethylsilane was used as internal standard for NMR. Fast atom bombardment mass spectroscopy spectra, with m-nitrobenzyl alcohol as a matrix, were obtained from a Kratos MS80RF mass spectrometry service. IR spectra were recorded on a Perkin-Elmer 1605 FTIR spectrometer as KBr Pellets. UV–vis spectra were obtained on a Shimadzu 1601A UV–vis recording spectrophotometer. Elemental analyses were performed by the analytical laboratory of the department of chemistry.

Synthesis of p-tert-butylcalix[4]crown-4 2

A mixture of p-tert-butylcalix[4]arene **1** (6.5 g, 10 mmol), anhydrous Na_2CO_3 (5.3 g, 50 mmol), triethylene glycol ditosylates (4.6 g, 10 mmol) in 350 mL CH_3CN was refluxed for 24 h. After the suspension was cooled to room temperature and filtered, the filtrate was evaporated to dryness and the residue was treated with a solution of HCl (10% v/v) and extracted with ethyl acetate. After purification by column chromatography (CH_2Cl_2-petroleum ether = 1 : 3 v/v), 4.9 g white powder **2** was obtained in 64% yield. The analytical and characterization data of **2** were the same as the literature.[19]

Synthesis of p-tert-butylcalix[4]dioxacrown-4 3

A mixture of **1** (1.53 g, 2.36 mmol), anhydrous K_2CO_3 (0.75 g, 5.4 mmol), glycol bischloroacetate (0.54 g, 2.5 mmol), and KI (0.7 g, 4 mmol) in 200 mL CH_3CN was refluxed for 2.5 days. After the suspension was cooled to room temperature and filtered, the filtrate was evaporated to dryness and the residue was treated with a solution of HCl (10% v/v) and extracted with ethyl acetate. The residue was given to column chromatography (ethyl acetate-petroleum ether = 1 : 5 v/v) to afford 0.50 g of **3** as white powder in 27% yield. The analytical and characterization data of **3** was the same as the literature.[20]

Synthesis of p-tert-butylcalix[4]diazacrown-4 4

A mixture of **1** (1.53 g, 2.36 mmol), anhydrous K_2CO_3 (0.75 g, 5.4 mmol), N,N′-bis(chloroacetyl)ethylenediamine (0.53 g, 2.5 mmol), and KI (0.7 g, 4 mmol) in 200 mL of CH_3CN was refluxed for 24 h under N_2. After the suspension was cooled to room temperature and filtered, the filtrate was evaporated to dryness and the residue was treated with a solution of HCl (10% v/v) and extracted with ethyl acetate. After the solvent was removed under reduced pressure, the residue was recrystallized from chloroform/methanol to afford 0.75 g of **4** as white powder in 41% yield. The analytical and characterization data of **4** was the same as the literature.[21]

General procedure for synthesis of oligomers

A mixture of calix[4]crown (1 mmol) and triethylene glycol ditosylate (1.2 mmol) was dissolved in a minimum proportion of dry dioxane (15 mL). To this solution, 60% NaH (2 g, 50 mmol) was added slowly with continuous stirring at room temperature. The reaction mixture was stirred for 6–8 h at room temperature under N_2. Then the solvent was evaporated, it was first washed with hexane and then MeOH (Caution!). After that, a portion of water was added for precipitation (Caution!). The solid material was filtered, washed with water, and dried. Finally, purified by reprecipitation from the chloroform–methanol system and then concentrated to dryness, the following oligomers were thus afforded.

Oligomer 5 from 2 and triethylene glycol ditosylate

Oligomer **5** was obtained in 78% yield. $M_n = 4400$ Da IR (KBr): 3409 cm^{-1} (—OH, H_2O), 1183 cm^{-1} (C—O). ^{1}HNMR (CDCl$_3$, 300 MHz) δ0.85(s, 18H, Bu^t), 1.25 (s, 18H, Bu^t), 3.45 (b d, 4H, ArCH$_2$Ar), 4.15 (m, 8H, CH$_2$O), 4.26–4.50 (m, 20H, CH$_2$O and ArCH$_2$Ar), 7.10–7.45 (m, 8H, ArH). Anal. calcd for (C$_{56}$H$_{76}$O$_8$)$_5$: C 76.68, H 8.73; found C 76.35; H 9.02.

Oligomer 6 from 3 and triethylene glycol ditosylate

Oligomer **6** was obtained in 76% yield. $M_n = 5400$ Da IR (KBr): 3415 cm^{-1} (—OH, H_2O), 1733 cm^{-1} (C=O), 1178 cm^{-1} (C—O). ^{1}HNMR(CDCl$_3$, 300 MHz) δ0.90(s, 18H, Bu^t), 1.28 (bs, 18H, Bu^t), 3.35(b d, 4H, ArCH$_2$Ar), 4.12 (bs, 4H, COCH$_2$O), 4.25–4.65 (m, 20H, ArCH$_2$Ar and CH$_2$O), 7.0–7.40 (m, 8H, ArH). Anal. calcd for (C$_{56}$H$_{72}$O$_{10}$)$_6$: C 74.31, H 8.02; found C 74.65, H 7.77.

Oligomer 7 from 4 and triethylene glycol distosylate

Oligomer **7** was obtained in 65% yield. $M_n = 4500$ Da IR (KBr): 3460 cm^{-1} (—OH, H_2O), 1644 cm^{-1} (C=O), 1210 cm^{-1} (C—O). ^{1}HNMR(CDCl$_3$, 300 MHz)δ1.10 (s, 18H, Bu^t), 1.30 (s, 18H, Bu^t), 3.45 (d, 4H, ArCH$_2$Ar), 3.75 (bs, 4H, CH$_2$—N), 4.25–4.53

TABLE I
The Molecular Weight and Polydispersity of Oligomers

	M_n (Da)	Polydispersity[a]
5	4400	1.24
6	5400	1.12
7	4500	1.08

[a] GPC in THF vs. polystyrene at 25°C.

(m, 16H, —CH$_2$O and ArCH$_2$Ar), 4.60(s, 4H, —COCH$_2$), 7.1–7.3 (m, 8H, Ar—H), 8.54(bs, 2H, NH) Anal. Calcd for (C$_{56}$H$_{74}$N$_2$O$_8$)$_5$: C 74.47, H 8.26; found C 74.19, H 8.59.

Solvent extraction

Picrate extraction experiments were performed following Ho's procedure.[22] A 5 mL volume of a 5 × 10^{-3}M aqueous picrate solution and 5 mL 5 × 10^{-3}M solution of calixarene in CHCl$_3$ were vigorously agitated in a stoppered glass tube with a mechanical shaker for 5 min then magnetically stirred in a thermostated waterbath at 25°C for 2 h, and finally left standing for an additional 30 min. The concentration of picrate ion remaining in the aqueous phase was then determined by UV spectra from the resulting absorbance at 380 nm.[22] Blank experiments showed that no picrate extraction occurred in the absence of calixarene.

RESULTS AND DISCUSSION

The syntheses of calix[4]crown 2–4 were based on the previous procedures.[19–21] Reacting p-tert-butylcalix[4]-arene with bifunctional group agents in the presence of carbonate salts as base in acetontrile were obtained compounds 2–4 in yield of 64, 27, and 41%, respectively. Thus, calix[4]crown 2–4 were reacted sequentially with NaH and triethylene glycol ditosylate in a minimum amount of dioxane to give the corresponding oligomers 5–7. After purification by reprecipitation from a CHCl$_3$/MeOH system, they were obtained in
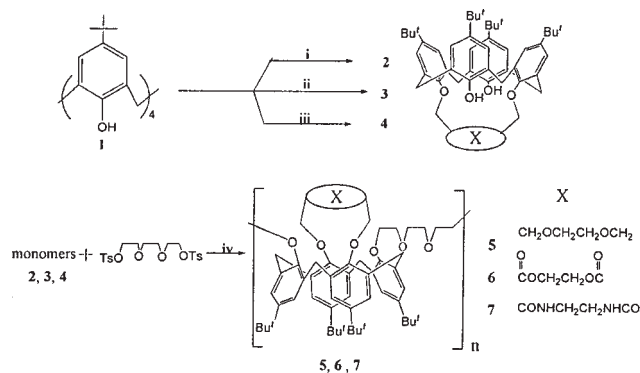
Scheme 1 (i) Na$_2$CO$_3$, TsO(CH$_2$CH$_2$O)$_2$CH$_2$CH$_2$OsT; (ii) K$_2$CO$_3$/KI,(ClCH$_2$CO$_2$CH$_2$)$_2$/benzene; (iii) K$_2$CO$_3$/KI, (ClCH$_2$CONHCH$_2$)$_2$/CH$_3$CN; (iv) NaH/dioxane.

yield of 78, 76, and 65%, respectively, M_n = 4400 Da for **5**; M_n = 5400 Da for **6**; M_n = 4500 Da for **7**. As could be seen in Table I, The polydispersities of three oligomers were low. Thus they were obtained on chain length around 5–6 calixcrown units. Synthetic routes are shown in Schemes 1.

All compounds were characterized by a combination of IR, ^{1}HNMR, and elemental analysis. The conformational characterization of calixarenes was conveniently estimated by the slitting pattern of the ArCH$_2$Ar methylene protons in the ^{1}HNMR spectroscopy. All monomers 2–4 adapted a cone conformation.[19–21] From ^{1}HNMR data, it was deduced that the p-tert-butylcalix[4]arene units in the oligomers **5**, **6**, and **7** all existed in a cone conformation, which was clearly indicated by the typical AB system for the two anisotropic hydrogen atoms.

In this study our aim was to synthesize conformationally stable forms of the oligomers of calix[4]-crown containing different ion binding sites. Solvent extraction experiments were performed to see the effectiveness of the oligomers with different ion binding sites toward different metal ions and meantime to compare their complexing abilities with their corresponding monomers. The results of two-phase extraction measurements are summarized in Table II.

TABLE II
Percentage Extraction of Picrate Salts in CHCl$_3$ at 25°C

Host	Li$^+$	Na$^+$	K$^+$	Cs$^+$	Cu^{2+}	Co^{2+}	Ni^{2+}	Hg^{2+}	Cs$^+$/Na$^+$
2	<1.0	1.4	<1.0	<1.0	<1.0	<1.0	<1.0	6.2	–
3	<1.0	3.2	4.6	5.6	7.2	6.8	3.5	14.0	1.75
4	1.4	2.9	2.5	7.8	14.2	14.9	16.3	20.5	2.44
5	<1.0	2.3	3.5	3.7	<1.0	<1.0	3.4	14.3	1.61
6	1.3	2.5	7.3	9.9	14.0	11.0	19.8	25.0	3.96
7	2.5	4.4	7.5	49.7	19.6	18.6	26.8	33.9	11.30
8[a]	9.6	6.8	5.6	2.1					
PEG-400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	2.3	
Ion radii (Å)	0.68	0.97	1.33	1.67	0.72	0.72	0.69	0.80	

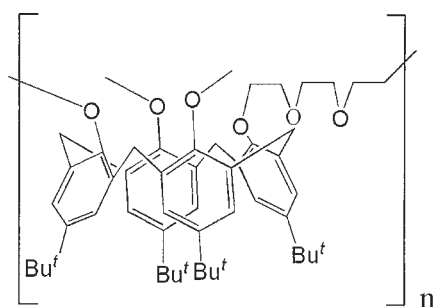[a] These data are quoted from Ref. 23.

Figure 1 Oligomer 8: *p*-tert-butylcalix[4]-1,3-dimethoxy oligomers.

Data obtained with monomers were included for comparison purposed. The blank experiment with plain oxyethylene oligomer, PEG-400, was made to estimate the influence of calixcrown on the percent of extraction. As shown in Figure 1, *p*-tert-butylca-lix[4]-1,3-dimethoxy oligomer **8** reported by Yilmaz and coworkers[23] was used as reference compound to determine the influence of the crown moiety on the percent of extraction. These data were obtained by using a chloroform solution of these compounds to extract metal picrates from the aqueous phase. The equilibrium concentration of picrates in the aqueous phase was determined spectrophotometrically.

Observed from the data given in Table II, in comparison with plain oxyethylene oligomer PEG400, all calixarene oligomers showed a higher affinity toward metal cations. This could be attributed to the calixcrown moieties introduced into oligomers framework. In comparison with *p*-tert-butylcalix[4]-1,3-dimethoxy oligomer **8**, all the synthetic calixarene oligomers showed a higher affinity toward metal cation and an ion binding selectivity toward different metal cations. This could be attributed to the different calixcrown binding moieties introduced. It was known that calixcrowns comprised a family of calixarenes in which the phenolic oxygens were linked intramolecularly via flexible poly(oxyethylene) chains. As they possessed preorganized structures and more rigid binding sites in comparison with calixarenes and crown ethers, they exhibited superior recognition ability toward alkali metal ions and other ions by the cooperative effects of calixarene and crown moieties. For instance, on the introduction of ester and amide groups into calixcrown moiety, the transferring characteristic of oligomers **6** and **7** were increased to some extent for transition metal cations. This could be attributed to the C=O, or NHC=O group containing π bonds, which was preferable to complex the more polarizable transition metal ions that was known soft metal cation due to cation–π interactions. The phenomenon might also reflect the ''Principle of hard and soft acids and bases'' introduced by Ho.[22]

Observation showed that the extraction ratio of Ni^{2+}(0.69Å) and Hg^{2+} (0.80 Å)with oligomer **5** increased as compared with its parent monomer **2**. In the case of oligomer **6** with ester groups, it showed better affinity for transition metal ions, especially for Ni^{2+} in comparison with its monomer **3**. It was also interestingly noted that the higher extractability by calixarene derivatives did also mean the higher cation selectivity. As shown in Figure 2, oligomer **7** exhibited the highest extractability, also afforded the best selectivity for Cs^+. Among the alkali metal ions used, the large the ion radii, the higher the extractive percentage, especially for oligomer **7**. Thus, it could be concluded that the alkali metal ion was included into the cavity composed of the polyoxyethylene spacer, and some cooperativity of the polyoxyethylene bridge and the diamide bridge occurred, i.e., the diamide segment strengthened the extraction ability and selectivity of the hard ion binding site toward cesium ion. And meanwhile oligomer **7** showed a high affinity toward transition metal ions in comparison with its monomer **4**. The increased affinity of oligomers could be attributed to the ethylene glycol bridges of the oligomers, which played an important role in extraction procedure.
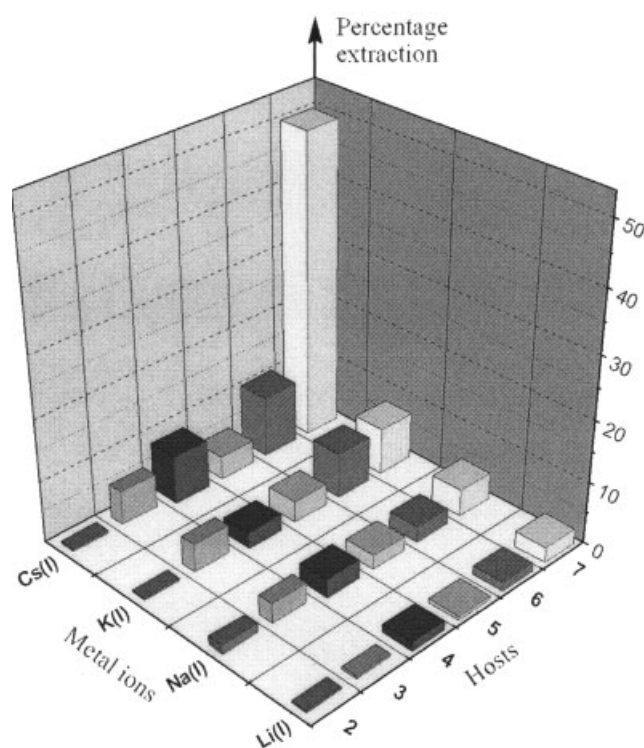

Figure 2 Extraction capacity of calix[4]crowns and their oligomers toward alkali metal ions.

SUMMARY

p-tert-butylcalix[4]diazacrown-4 oligomers, which contains hard and soft ion binding sites, are synthesized to estimate selective extraction of Cs^+ ions from the aqueous to the organic phase. The binding sites may complex alkali metal ions or transition metal ions selectively. Oligomers are fairly good extractants for transition metal ions in comparison with their monomers, which suggests that polyoxyethylene bridges are efficient for complexing metal ions, especially for transition metal ions. Further research on the application of calix[4]crown-4 oligomers is still underway.

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