



Syntheses and Metal-ion Binding Properties of Calix[4]arene Derivatives Containing Soft Donor Atoms: Highly Selective Extraction Reagents for Ag⁺

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Abstract

A series of calix[4]arene derivatives containing N or S atoms at the lower rim were synthesized by etherification of OH groups and their metal-ion extraction abilities were studied. The extraction selectivity for Ag⁺ over other ions with these novel receptors was outstanding. Among these ligands, calix[4]arene podand, which possessed two linear ligands, has shown better binding ability with Ag⁺ than calix[4]crowns.

Introduction

As interesting building blocks, calixarenes and their functionalized derivatives have been extensively studied in the last twenty years and shown novel recognition ability for metal ions, anions and organic molecules [1]. Many examples displayed that their high selectivity for the substrates was due to the accurate arrangement of the binding sites in space. Calixcrowns, a kind of calixarene derivatives bridged with polyether chains at the hydroxyl groups (lower rim), possessed the highest selectivity for the alkali metals among all the synthetic receptors owing to their preorganized structures [2]. Some calix[4]arene derivatives bearing amides, carboxylic acids or ketones (calixarene podands), have also notable recognition properties. For example, the high extraction separation ability of Ca²⁺ with calix[4]arene podands has been reported [3]. Except for alkali metal and alkaline earth metals, the studies on molecular recognition for transition metal ions with calixarenes were also reported extensively [1e, 4]. Especially, according to the hard-soft acid-base principle, by introducing “softer” N and S atoms into the calixarenes, we could obtain better ligands for the “softer” transition metal ions. For example, the calixarene derivatives containing thio-ethers or thioamides could efficiently extract Ag⁺, Pb²⁺ or Hg²⁺ [4, 5]. But among these reported calix[4]arene derivatives, the selectivity for these transition metals was not very satisfying. And most of them could extract a little amount of alkali and alkaline earth metal ions, which would disturb separation of the Ag⁺ from wastewater. In order to improve the extraction selectivity for Ag⁺, we synthesized several new calix[4]arene derivatives containing sulfur atoms and investigated their metal-ion binding properties.

Experimental section

Materials and methods

Melting points were uncorrected. NMR spectra were measured with a Varian Unity spectrometer (¹H, 200 MHz; ¹³C, 50.3 MHz) in deuterated chloroform with tetramethylsilane as an internal standard. Elemental analyses were performed by the Analytical Laboratory of the Institute. IR spectra were recorded with a Perkin-Elmer 782 spectrometer and a Bruker IMX20 spectrometer. Mass spectra were recorded on a KYKY-ZHT-5 instrument. All solvents were dried by 4 Å molecular sieve for more than a week. Flash column chromatography was performed with silica gel H60. *p*-*tert*-Butylcalix[4]arene (**1**) [6], 5,11,17,23-tetra-*tert*-butyl-25,27-bis-(2'-bromoethoxy)calix[4]arene (**3a**) [7] and compounds **5–7** [8] were prepared according to literature procedures.

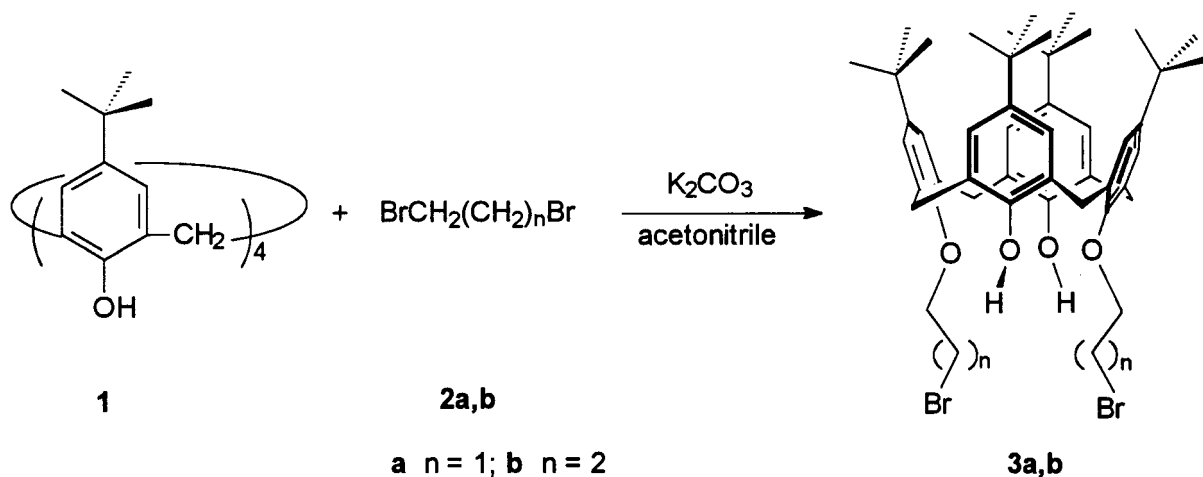
Preparation of metal picrates

Sodium and potassium picrates were prepared according to the literature procedure [9a]. Silver, magnesium and calcium picrates were prepared according to the literature procedure [9b]. Tl(I) picrate was prepared by reaction of thallos carbonate with picric acid according to the literature procedure [9c]. Pb(II) picrate was prepared according to the literature procedure [9d]. Fe(II), Co(II), Ni(II), Cu(II), Zn(II), Mn(II) picrates were prepared according to the literature procedures [9e].

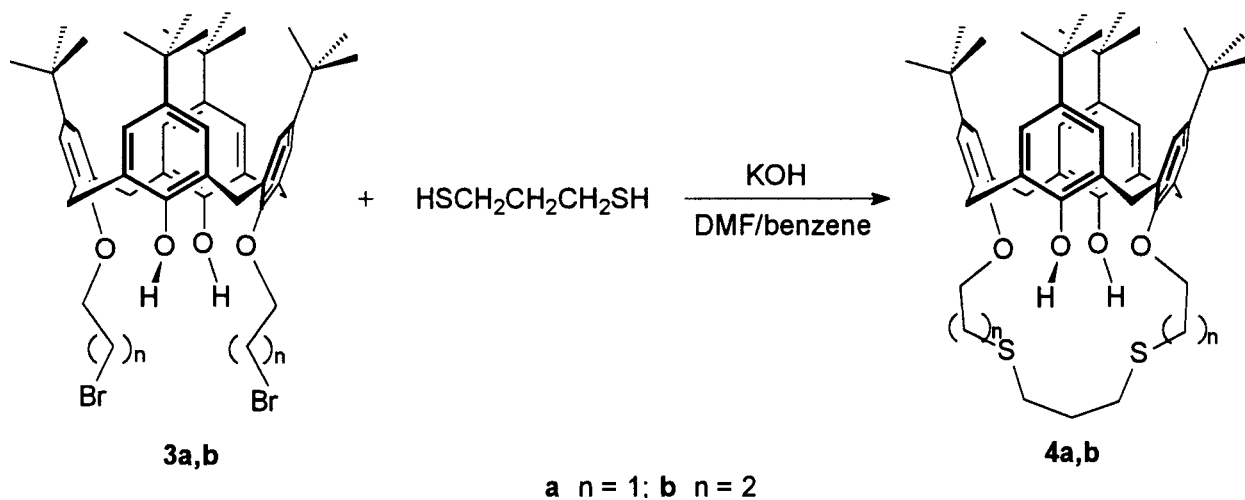
Hg(II) picrate was prepared similar as the literature procedure [9f]. A yellow precipitate was obtained by adding a saturated picric acid solution to mercury(II) nitrate solution, then was washed and dried over phosphorus pentoxide.

Cd(II) picrate was prepared similar as the literature procedure [9e]. CdCO₃ was dissolved in a hot aqueous solution of picric acid. This mixture was stirred at 60 ~ 70 °C for 1 h, then filtered to remove the unreacted CdCO₃. The

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Scheme 1.



Scheme 2.

solution was concentrated till crystallization. The crystal of Cd(II) picrate was filtered and recrystallized from hot aqueous solution.

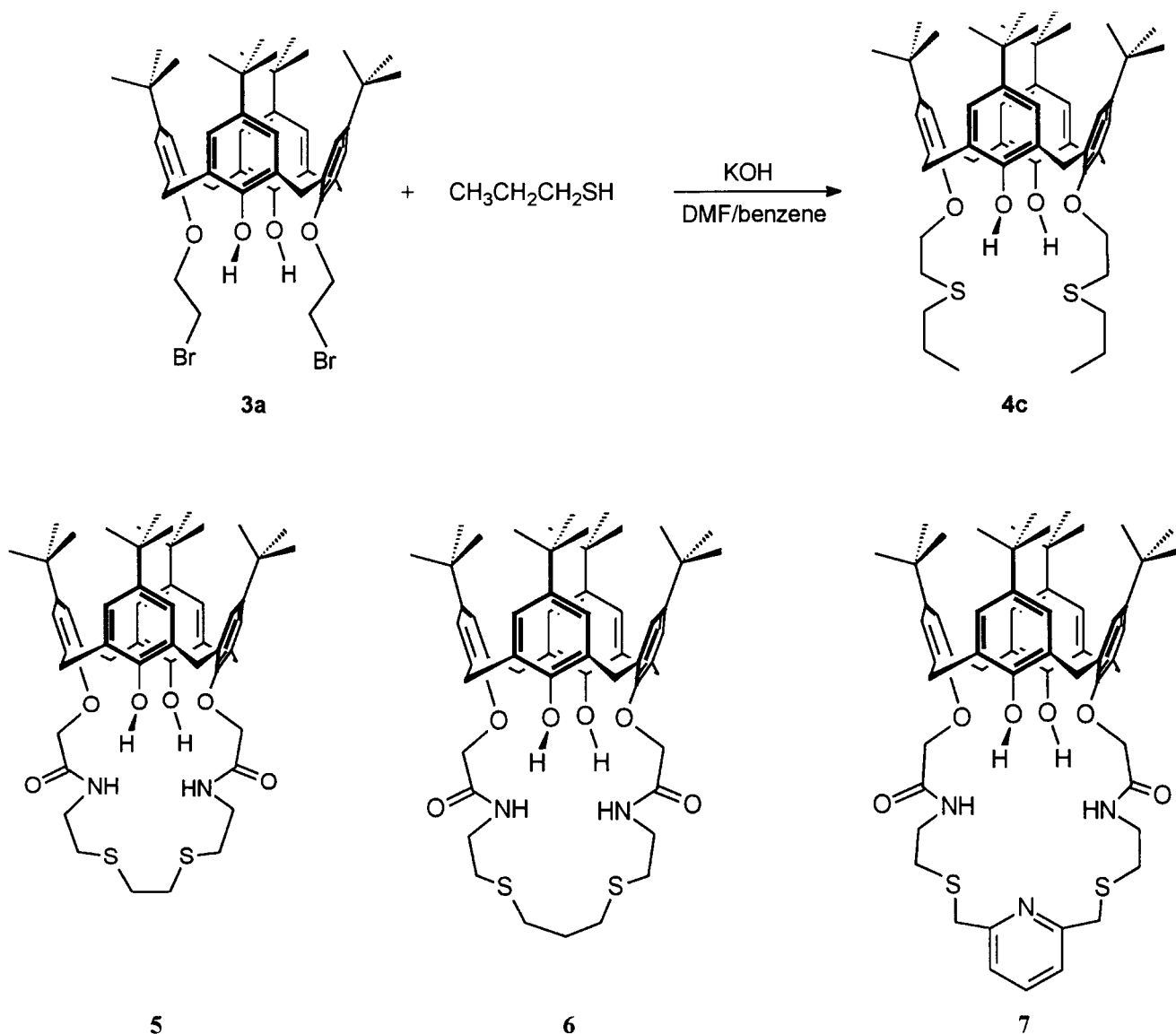
The amount of water in the hydrated metal picrates was determined by elemental analyses.

Synthesis

5,11,17,23-Tetra-*tert*-butyl-25,27-bis-(3'-bromopropoxy) calix[4]arene (3b): A mixture of 5 g (7.72 mmol) of 5,11,17,23-tetra-*tert*-butylcalix[4]arene (**1**), 1.5 g (10.87 mmol) of anhydrous K_2CO_3 , and 8 mL of 1,3-dibromopropane (**2b**) was refluxed in 120 mL of anhydrous CH_3CN for 17 h. Then the solvent was removed under reduced pressure, and the residue was recrystallized from $CHCl_3/CH_3OH$ to give the corresponding product **3b** as white powder. Yield: 44.1%. M.p.: >300 °C. IR (KBr) ν/cm^{-1} 3409, 1599, 1486. 1H -NMR ($CDCl_3$) δ 7.72 (s, 2H, ArOH), 7.05 (s, 4H, ArH), 6.88 (s, 4H, ArH), 4.26 (d, $J_{AB} = 13.0$ Hz, 4H, $ArCH_2Ar$), 4.10 (t, $J = 5.3$ Hz, 4H, OCH_2), 4.02 (t, $J = 6.6$ Hz, 4H, $BrCH_2$), 3.34 (d, $J_{AB} = 13.0$ Hz, 4H, $ArCH_2Ar$), 2.51 (quin, $J = 6.0$ Hz, 4H, $CH_2CH_2CH_2$), 1.25 (s, 18H, $C(CH_3)_3$), 1.02 (s, 18H, $C(CH_3)_3$). ^{13}C -NMR ($CDCl_3$) δ 150.59, 149.15, 147.25, 141.67, 132.77,

127.52, 125.68, 125.17, 73.33, 34.03, 33.81, 33.49, 31.86, 31.67, 31.03, 30.34. MS-FAB (positive) m/z : 889 $[(M+H)^+]$. Elemental analysis for $C_{50}H_{66}Br_2O_4$. Calcd: C, 67.41; H, 7.47. Found: C, 67.38; H, 7.49.

5,11,17,23-Tetra-*tert*-butyl-25,27-dihydroxy-26,28-(3',7'-dithianonane)dioxycalix[4]arene (4a): After a mixture of 0.6 mmol of 1,3-propanethiol and 1.2 mmol of KOH was refluxed in 50 mL of benzene and 25 mL of DMF for 10 min under a nitrogen atmosphere, 0.5 mmol of **3a** was added and continued to reflux for 4 h. Then the solvent was removed under reduced pressure, and the residue was recrystallized from $CHCl_3/CH_3OH$ to afford **4a** (0.35 g, yield: 87.5 %) as white crystals. M.p.: 263–264 °C. IR (KBr) ν/cm^{-1} 3390, 1590, 1480, 1455. 1H -NMR ($CDCl_3$) δ 7.10 (s, 4H, ArH), 6.71 (s, 2H, ArOH), 6.70 (s, 4H, ArH), 4.33 (d, $J_{AB} = 13.0$ Hz, 4H, $ArCH_2Ar$), 4.18 (t, $J = 5.0$ Hz, 4H, OCH_2), 3.33 (d, $J_{AB} = 13.0$ Hz, 4H, $ArCH_2Ar$), 3.20 (t, $J = 7.2$ Hz, 4H, $SCH_2CH_2CH_2S$), 3.08 (t, $J = 5.0$ Hz, 4H, OCH_2CH_2S), 2.15 (quin, $J = 6.8$ Hz, 2H, $SCH_2CH_2CH_2S$), 1.32 (s, 18H, $C(CH_3)_3$), 0.90 (s, 18H, $C(CH_3)_3$). ^{13}C -NMR ($CDCl_3$) δ 150.68, 149.88, 146.90, 141.49, 132.05, 127.80, 125.43, 124.97, 77.21, 33.84, 32.91, 31.95, 31.73, 31.41, 31.20, 30.92, 30.15. MS-FAB (negative) m/z : 807 (M^+-1).



Scheme 3.

Elemental analysis for C₅₁H₆₈O₄S₂. Calcd: C, 75.70; H, 8.47. Found: C, 75.04; H, 8.12.

5,11,17,23-Tetra-*tert*-butyl-25,27-dihydroxy-26,28-(4',8'-dithiaundecane)dioxycalix[4]arene (**4b**): As the procedure described above for **4a**, a mixture of 0.6 mmol of 1,3-propanethiol and 1.2 mmol of KOH was used and refluxed with 0.5 mmol of **3b** for 8 h. Then the solvent was removed under reduced pressure, and the residue was purified by chromatography using petroleum ether (60–90 °C)/ethyl acetate (100:1 v/v) as eluent to afford **4b** (0.14 g, yield: 33%) as white crystals. M.p.: 276–278 °C. IR (KBr) ν/cm^{-1} 3453, 1600, 1485. ¹H-NMR (CDCl₃) δ 7.12 (s, 2H, ArOH), 7.08 (s, 4H, ArH), 6.73 (s, 4H, ArH), 4.26 (d, $J_{\text{AB}} = 13.0$ Hz, 4H, ArCH₂Ar), 4.01 (t, $J = 5.2$ Hz, 4H, OCH₂), 3.31 (d, $J_{\text{AB}} = 13.0$ Hz, 4H, ArCH₂Ar), 3.07 (t, $J = 6$ Hz, 4H, OCH₂CH₂CH₂S), 2.73 (t, $J = 5.8$ Hz, 4H, SCH₂CH₂CH₂S), 2.20–2.27 (m, 4H, OCH₂CH₂CH₂S), 2.08 (quin, $J = 5.8$ Hz, 2H, SCH₂CH₂CH₂S), 1.31 (s, 18H, C(CH₃)₃), 0.90 (s, 18H, C(CH₃)₃). ¹³C-NMR (CDCl₃) δ 150.59, 149.58, 146.83, 141.40, 132.19, 127.69, 125.34,

124.97, 75.47, 33.84, 33.80, 31.70, 31.35, 31.20, 30.92, 30.67, 29.94, 28.59. MS-FAB (positive) m/z : 837 [(M+H)⁺]. Elemental analysis for C₅₃H₇₂O₄S₂ · ½CHCl₃. Calcd: C, 71.64; H, 8.15. Found: C, 72.06; H, 8.16.

5,11,17,23-Tetra-*tert*-butyl-25,27-di-(2'-propylthioethoxy)calix[4]arene (**4c**): As the procedure described above for **4a**, 3 mmol of propanethiol and 3 mmol of KOH were refluxed with 0.5 mmol of calix[4]arene (**3a**) to afford **4c** as white crystals (0.28 g, yield: 65%). M.p.: 159–161 °C. IR (KBr) ν/cm^{-1} 3370, 1599, 1485. ¹H-NMR (CDCl₃) δ 7.06 (s, 4H, ArH), 6.77 (s, 4H, ArH), 4.31 (d, $J_{\text{AB}} = 13.2$ Hz, 4H, ArCH₂Ar), 4.12 (t, $J = 7.3$ Hz, 4H, OCH), 3.32 (d, $J_{\text{AB}} = 13.2$ Hz, 4H, ArCH₂Ar), 3.09 (t, $J = 7.3$ Hz, 4H, OCH₂CH₂S), 2.64 (t, $J = 7.2$ Hz, 4H, SCH₂CH₂CH₃), 1.58–1.76 (m, 4H, CH₂CH₃), 1.29 (s, 18H, C(CH₃)₃), 1.02 (t, $J = 7.4$ Hz, 6H, CH₂CH₃), 0.94 (s, 18H, C(CH₃)₃). ¹³C-NMR (CDCl₃) δ 150.43, 149.66, 146.88, 141.52, 132.37, 127.85, 125.49, 125.06, 75.60, 34.71, 33.88, 33.81, 31.67, 30.98, 23.12. MS-FAB (positive) m/z : 853 [(M+H)⁺]. Ele-

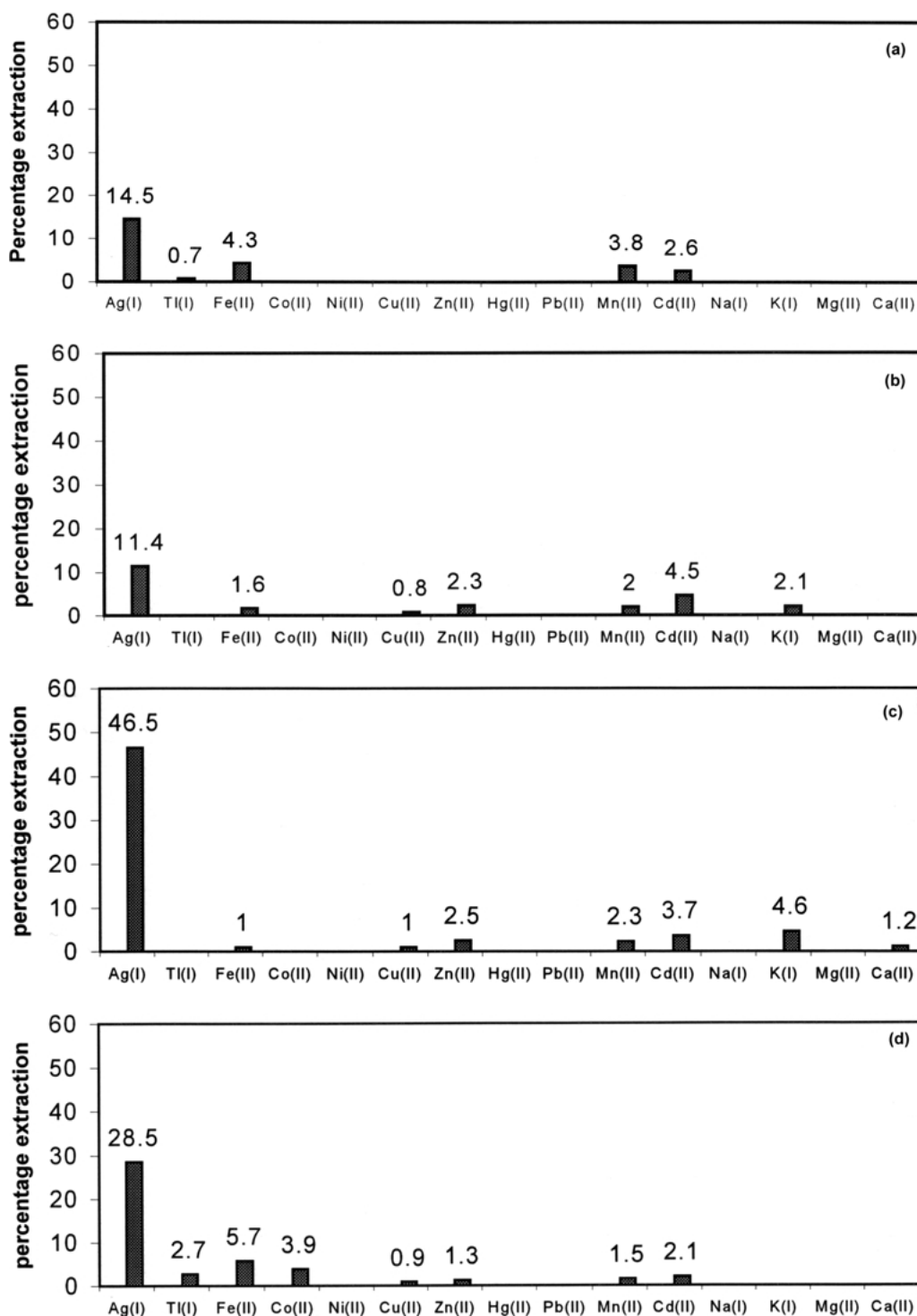


Figure 1. Extraction of metal picrates with compounds (a) **4a**, (b) **4b**, (c) **4c**, (d) **5**, (e) **6** and (f) **7**; $C_{Mpic} = 2.5 \times 10^{-4} \text{ mol dm}^{-3}$; $C_{calix} = 2.5 \times 10^{-4} \text{ mol dm}^{-3}$; pH = 7.0.

mental analysis for $C_{54}H_{76}O_4S_2 \cdot CH_3OH$. *Calcd.*: C, 74.61; H, 9.11. *Found.*: C, 74.61; H 8.74.

Metal-ion extraction experiment

Ion binding properties were investigated by liquid-liquid extraction experiments at $10 \pm 2 \text{ }^\circ\text{C}$. A $2.5 \times 10^{-4} \text{ mol dm}^{-3}$ of aqueous picrate solution (2 mL) and a $2.5 \times 10^{-4} \text{ mol dm}^{-3}$ of solution of calixarenes in CH_2Cl_2

(2 mL) were magnetically stirred in a flask. The extraction equilibrium was reached after vigorous stirring for 2 h. After the two phases were allowed to settle for 1 h, the absorbance, A , of the aqueous phase was measured at 355 nm. A blank experiment without calixarenes was run under the same conditions, which yielded an absorbance A_1 of the aqueous phase. The absorbance of $2.5 \times 10^{-4} \text{ mol dm}^{-3}$ of aqueous picrate solution A_0 was also measured. The percentage cation extracted was calculated as the ratio $100 \times (A_1$

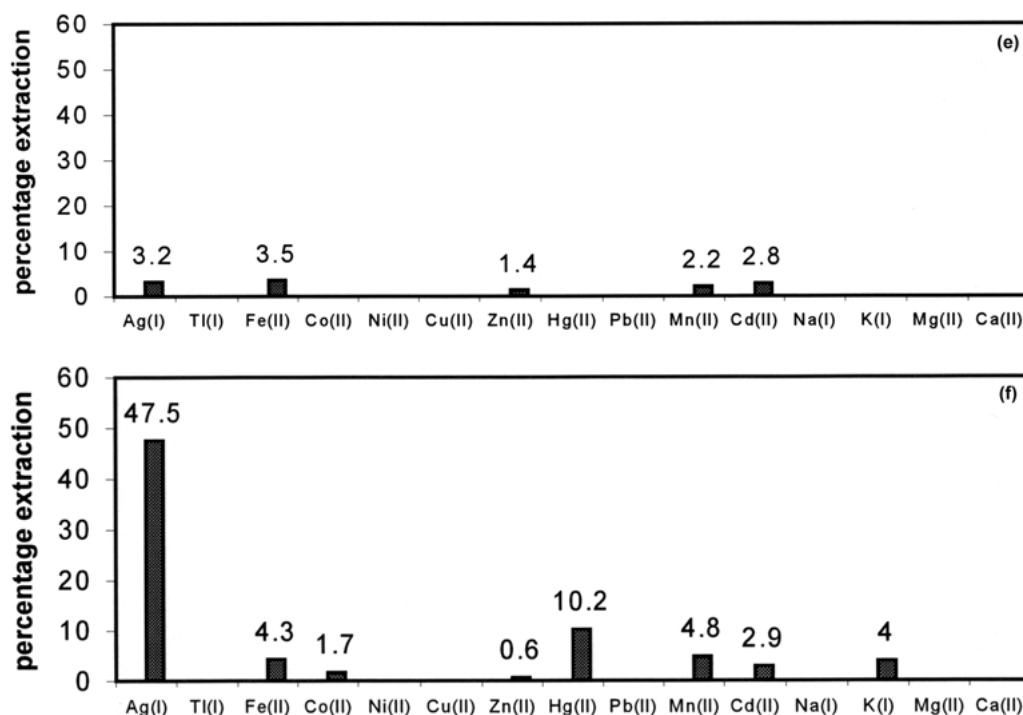


Figure 1. Continued.

– A)/A₀. All data were obtained from two independent experiments.

Results and discussion

In order to synthesize calix[4](thia)crowns, we first prepared the calixarenes derivatives **3a,b** by the reaction of *p*-*tert*-butylcalix[4]arene (**1**) with **2** in the presence of K₂CO₃ (Scheme 1). Calix[4](thia)crowns **4a,b** could be achieved by the reaction of 25,27-dibromoethanoxy-calix[4]arene (**3a**) or 25,27-dibromopropanoxy-calix[4]arene (**3b**) with 1,3-dipropanedithiol (Scheme 2).

Under similar conditions, we could also obtain the calix[4]arene podand **4c** (Scheme 3). All the structures of these compounds have been determined by NMR, IR, MS and elemental analysis. In their ¹H-NMR spectra, they all showed a pair of doublets at about δ 4.30 and 3.30 corresponding to the methylene protons between the phenol moieties, which indicated that these compounds adopted the cone conformation in CDCl₃.

The other three calixcrowns **5–7** containing both N and S atoms at the lower rim have also been synthesized by us [8]. By the method of ¹H-NMR titration, the complex of **4a** and Ag⁺ in a solution of CDCl₃ has been investigated [10].

In order to investigate the complexation ability of these compounds towards different metal ions and compare the recognition selectivity, their extraction behavior towards Na⁺, K⁺, Mg²⁺, Ca²⁺, Ag⁺, Tl⁺, Fe²⁺, Co²⁺, Ni²⁺, Cu²⁺, Zn²⁺, Pb²⁺, Hg²⁺, Mn²⁺ and Cd²⁺ was carried out. The results of extraction experiments are summarized in Figure 1.

Figure 1 shows that most of these macrocycles showed the highest extraction ability for Ag⁺ among all metal ions

except **6**, and that the extraction percentage for most of metal ions, even for Ag⁺, was not high (<50%) with all the calix[4]arene derivatives. However, the extraction selectivity of Ag⁺/Pb²⁺, Ag⁺/Hg²⁺ was higher than reported [4, 5]. Most of calixarene derivatives bearing thio-ethers or thio-amides could efficiently extract Ag⁺, Pb²⁺, Cu²⁺, Au³⁺ or Hg²⁺ with selectivity over alkali, alkaline earth and other metal ions. Although they have shown selectivity for extracting Ag⁺ among transition metal ions, a considerable amount of Pb²⁺, Cu²⁺ could also be extracted. Moreover, the extraction yield for the alkali and alkaline earth metal ions was very low with our synthesized calix[4]arene derivatives possessing two free OH groups. So, the extraction selectivity for transition metals over alkali and alkaline earth metal ions could be efficiently improved. We could use this regularity to design ligands for selectively extracting poisonous or noble metals.

The extraction selectivity of **4a** and **4b** was similar, and the extraction percentage of **4c** to Ag⁺ was higher than **4a** and **4b**. It may be because the structure of **4c** is somewhat flexible and metal ions can approach to its sulfur atoms more easily than **4a** and **4b**. Thus they can interact with Ag⁺ strongly. Compared with **5** and **7**, the extraction percentage of **6** for Ag⁺ was negligible. It is clear that the volume of the cavity at lower rim is very important for the extraction selectivity. The size of the thiacycrown cavity of **5** was more suitable for binding Ag⁺ ion than that of **6**. Compared with **5** and **6**, there was one more ligand, N atom, in the compound **7**. However, it showed the largest extraction percentage for Ag⁺. Compound **7** also was the only ligand which possessed obvious extraction ability for Hg²⁺ among these macrocycles.

From the above experimental results, we could conclude that compounds **4a**, **4b**, **4c**, **5** and **7** were all excellent extractors for Ag^+ .

Acknowledgement

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