

SYNTHESIS OF THIACROWNOPHANES EXHIBITING HIGH Ag^+ SELECTIVITIES ON THE LIQUID-LIQUID EXTRACTION

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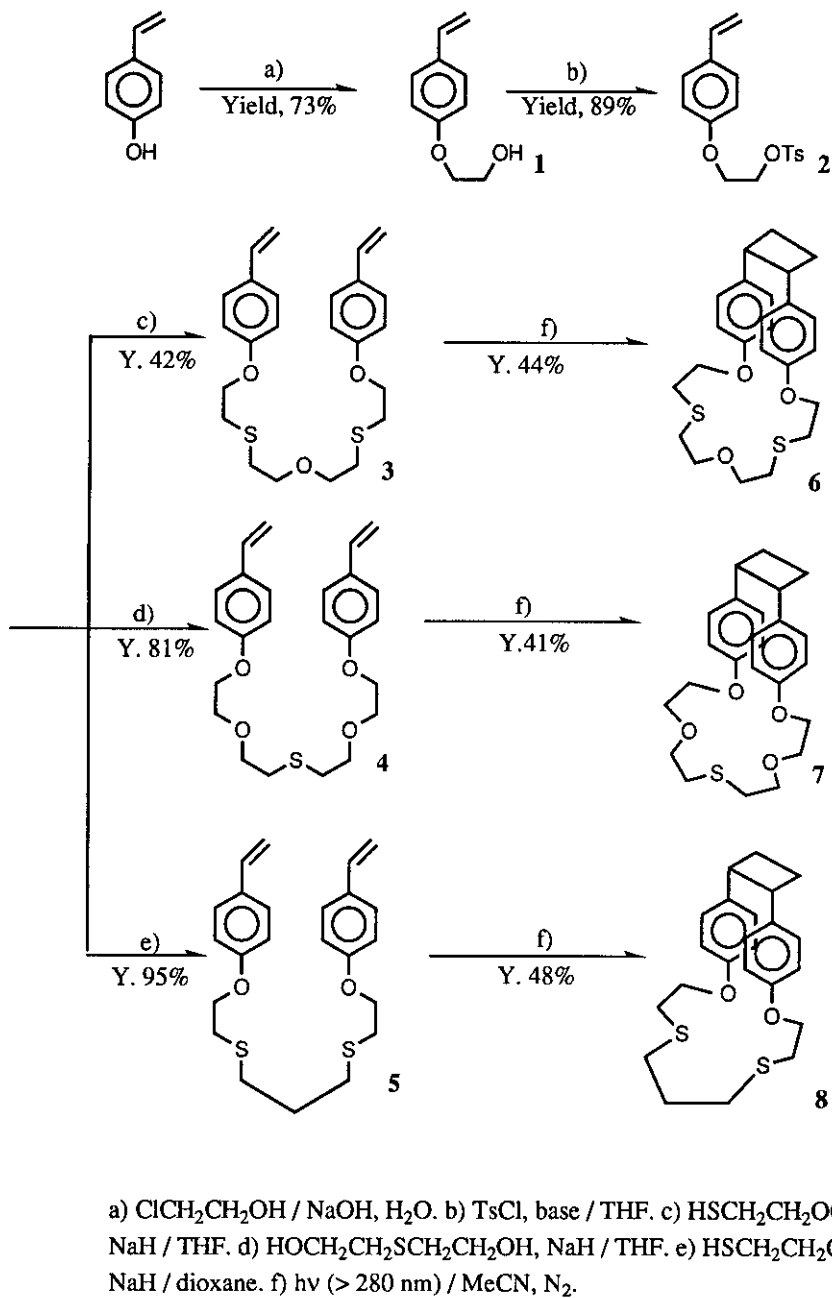
Abstract-Thiacrownophanes (6-8) were prepared by means of intramolecular [2 + 2] photocycloaddition. Thiacrownophane (6) with two sulfur and three oxygen atoms showed the most efficient extractability toward Ag^+ with high selectivity even if the extraction system did not contain any special lipophilic counter anion.

TEXT

Thiacrown compounds have been prepared by various methods and used as binders of heavy and transition metals.¹⁻⁶ In general, many synthetic steps are required for the preparation of the compounds and the cyclization yields are often low.

Recently, we have succeeded in the preparation of crown compounds fused in cyclophane skeletons by means of intramolecular [2 + 2] photocycloaddition of styrene derivatives. The yields⁷⁻¹¹ were excellent, compared with those of Okahara's cyclization¹² which is one of the most efficient and convenient method for crown ether syntheses. These compounds were named "crownophanes."⁷ It was also found that the crownophanes showed high Li^+ -selectivities due to their unique phane structures.^{7,8} The potential complexing specificity led us to examine the cation-binding properties of thiacrownophanes, sulfide analogs of the crownophanes, toward some heavy and transition metals. In this paper, we would like to report the synthesis and properties of the noble crown compounds, *i.e.*, thiacrownophanes having sulfur atom(s) in the polyether moiety.

EXPERIMENTAL



Scheme 1 Preparation of thiacrownphanes

Apparatus. ^1H Nmr spectra were recorded on a Varian Gemini-200 FT nmr spectrometer. Uv spectra were measured with a Shimadzu 160A photometer. Hplc analysis was performed with a Shimadzu LC-6A pump, an LC-6A UV detector, and an RC-4A data processor. Metal cations were analyzed by a Hitachi 170-50 atomic absorption spectrophotometer.

Reagents. Dioxane and THF were purified by distillation over Na after prolonged reflux under a nitrogen atmosphere. Guaranteed reagent grade CH_2Cl_2 was distilled before use. Commercially available highest grade of AgNO_3 , $\text{Cu}(\text{NO}_3)_2$, $\text{Pb}(\text{NO}_3)_2$, $\text{Ni}(\text{NO}_3)_2$, $\text{Zn}(\text{NO}_3)_2$, $\text{Co}(\text{NO}_3)_2$, $\text{Mn}(\text{NO}_3)_2$, and $\text{Fe}(\text{NO}_3)_3$ were used without any further purification. All aqueous solutions were prepared with distilled, deionized water.

Preparation of 2-(*p*-vinylphenoxy)ethanol (1). A mixture of commercially available *p*-vinylphenol (4.33 g, 0.036 mol) and 2-chloroethanol (14.5 g, 0.180 mol) in 10% aqueous NaOH solution (73 ml) was stirred under a nitrogen atmosphere at room temperature. After 24 h, the mixture was neutralized with 6 M HCl and extracted with chloroform (3 x 100 ml). The chloroform extracts were combined, washed with 1% aqueous NaHCO_3 (2 x 100 ml), dried over anhydrous magnesium sulfate, then the solvent was evaporated, and the residue was recrystallized from hexane-ethanol to give **1** as white crystals (4.32 g, 73% yield). mp 65.0-65.9°C. ^1H Nmr (CDCl_3) δ =7.34 (2H, ABq, J =6.7 Hz), 6.88(2H, ABq, J =6.7 Hz), 6.67 (1H, dd, J =17.6 and 11.3 Hz), 5.62 (1H, dd, J =17.6 and 0.98 Hz), 5.13 (1H, dd, J =11.3 and 0.98 Hz), 4.10 (2H, m), 3.97 (3H, m).

Preparation of 2-(*p*-vinylphenoxy)ethyl *p*-toluenesulfonate (2). After removal of the protecting mineral oil from NaH (60% in oil, 3.03 g, 0.076 mol) by washing with hexane, THF (50 ml), alcohol(1), and triethylamine (5.57 g, 0.055 mol) were added to it with stirring at room temperature. Then the mixture was stirred for 20 min. From the additional funnel, *p*-toluenesulfonyl chloride (15.82 g, 0.083 mol) dissolved in THF (100 ml) was added dropwise to the mixture in 15 min with stirring. The mixture was stirred for additional 2 h at room temperature and then at 55 °C for 1 h. After the mixture was cooled to room temperature, a small amount of water was carefully added to destroy excess of NaH. The solid material was filtered off. The filtrate was evaporated *in vacuo* and the residue was

purified by column chromatography (SiO₂, gradient elution by hexane and acetone) to afford **2** as a colorless crystals (7.14 g, 89% yield). mp 63.0~63.9 °C. ¹H Nmr (CDCl₃) δ=7.82 (2H, d, *J* = 8.4 Hz), 7.33 (2H, ABq, *J*=6.5 Hz), 7.29 (2H, d, *J*=8.4 Hz), 6.74 (2H, ABq, *J*=6.5 Hz), 6.64 (1H, dd, *J*=17.6 and 11.0 Hz), 5.61 (1H, dd, *J*=17.5 and 1.06 Hz), 5.14 (1H, dd, *J*=11.0 and 1.06 Hz), 4.37 (2H, m), 4.15 (2H, m), 2.45 (3H, s).

Preparation of α-(*p*-vinylphenyl)-ω-(*p*-vinylphenoxy)oligo(thia)ethers (3-5).

The typical procedure is described for the preparation of **3**. A dioxane solution (50 ml) of di(2-mercaptoethyl) ether (0.87 g, 0.063 mol) was added to a suspension of NaH (60 % in mineral oil, 3.03 g, 0.076 mol, washed with hexane) with stirring at room temperature. After stirred for 30 min, tosylate (**2**) (5.00 g, 0.0158 mol) dissolved in 100 ml of dioxane was added dropwise in it in 1 h and the mixture was refluxed for 10 h. It was cooled to room temperature, filtered, and concentrated. The crude amber oil was column chromatographed (SiO₂, benzene/acetone=20/1 to 1/1) to give **3** as a pale yellow solid (2.20 g, 81% yield). mp 46.1-47.0 °C.

3: ¹H Nmr (CDCl₃) δ=7.34 (4H, ABq, *J* = 8.8 Hz), 6.87 (4H, ABq, *J*=8.8 Hz), 6.65 (2H, dd, *J*=17.9 and 10.9 Hz), 5.61 (2H, dd, *J*=17.9 and 0.98 Hz), 5.13 (2H, dd, *J*=10.9 and 0.98 Hz), 4.14 (4H, t, *J*=6.8 Hz), 3.68 (4H, t, *J*=6.6 Hz), 2.95 (4H, t, *J*=6.8 Hz), 2.82 (4H, t, *J*=6.6 Hz).

4: ¹H Nmr (CDCl₃) δ=7.23 (4H, ABq, *J* = 8.8 Hz), 6.87 (4H, ABq, *J*=8.8 Hz), 6.65 (2H, dd, *J*=17.6 and 10.9 Hz), 5.60 (2H, dd, *J*=17.6 and 0.98 Hz), 5.12 (2H, dd, *J*=10.9 and 0.98 Hz), 4.11 (4H, m), 3.98 (4H, m), 3.84 (4H, m), 3.02 (4H, m).

5: ¹H Nmr (CDCl₃) δ=7.33 (4H, ABq, *J* = 8.7 Hz), 6.87 (4H, ABq, *J*=8.7 Hz), 6.65 (2H, dd, *J*=17.6 and 10.9 Hz), 5.61 (2H, dd, *J*=17.6 and 0.98 Hz), 5.13 (2H, dd, *J*=10.9 and 0.98 Hz), 4.14 (4H, t, *J*=6.8 Hz), 2.90 (4H, t, *J*=6.8 Hz), 2.75 (4H, t, *J*=7.1 Hz), 1.94 (2H, m).

Preparation of thiacrownophanes (6-8). Into a 1000-ml flask with a magnetic stirring and N₂ inlet was placed 2.0 mmol of α-(*p*-vinylphenyl)-ω-(*p*-vinylphenoxy)oligo(thia)ethers (**3-5**) dissolved in acetonitrile (800 ml), and nitrogen gas was bubbled in it for 20 min. The solution was irradiated by a 400-W high-pressure mercury lamp through a Pyrex filter. The progress of the reaction was followed by hplc. After the disappearance of

the olefin (*ca.* 2 h), the reaction mixture was evaporated. The crude reaction product was purified by column chromatography (SiO₂, benzene/acetone=20/1 to 1/1) to afford **6-8** (**6**, 44%; **7**, 41%; **8**, 48%) as white solids. **6**: mp 62.0~63.0 °C; ¹H Nmr (CDCl₃) δ=6.78 (4H, ABq, *J* = 8.7 Hz), 6.64 (4H, ABq, *J* = 8.7 Hz), 4.07 (4H, m), 3.91 (2H, m), 3.59 (4H, m), 2.83 (4H, m), 2.73 (4H, m), 2.39 (4H, m). Anal. Calcd for C₂₄H₃₀O₃S₂: C, 66.94; H, 7.02; S, 14.89, Found: C, 66.61; H, 7.25; S, 14.60.

7: mp 55.5-56.5 °C; ¹H Nmr (CDCl₃) δ=6.78 (4H, ABq, *J* = 6.6 Hz), 6.66 (4H, ABq, *J* = 6.6 Hz), 4.08 (4H, m), 3.94 (2H, m), 3.70 (8H, m), 2.75 (4H, m), 2.41 (4H, m). Anal. Calcd for C₂₄H₃₀O₄S₁: C, 69.54; H, 7.29; S, 7.73, Found: C, 66.93; H, 7.54; S, 7.50.

8: mp 97.0-98.0 °C; ¹H Nmr (CDCl₃) δ 6.76 (4H, ABq, *J* = 6.6 Hz), 6.62 (4H, ABq, *J* = 6.6 Hz), 4.11 (4H, t, *J*=6.4 Hz), 3.93 (2H, m), 2.76 (4H, t, *J*=6.4 Hz), 2.62 (4H, t, *J*=7.2 Hz), 2.41 (4H, m), 1.77 (2H, m). Anal. Calcd for C₂₃H₂₈O₂S₂: C, 68.96; H, 7.05; S, 16.01, Found: C, 68.66; H, 7.31; S, 15.77.

Solvent extraction of heavy metal picrates. A CH₂Cl₂ solution of thiacycrownophane (1 x 10⁻⁴ mol dm⁻³, 5.0 ml) and an aqueous metal nitrate solution with picric acid ([metal nitrate]=0.1 M, [picric acid]=1 x 10⁻⁴ M, 5.0 ml), were shaken in a 20-ml test tube with a ground-glass stopper at room temperature (18-20 °C) for 2 h. After two liquid phases were separated, the remaining picrate anion in the aqueous phase was spectrophotometrically (uv) determined to evaluate the picrate extracted into the organic phase. At the same time an aliquot (2 ml) of organic phase was evaporated under reduced pressure, and then 0.1 M HNO₃ solution (2 ml) was added to the residue, and finally the extracted metal cation was analyzed by atomic absorption spectroscopy.

Solvent extraction of heavy metal nitrates. A CH₂Cl₂ solution of thiacycrownophane (1 x 10⁻⁴ M, 5.0 ml) and an aqueous metal nitrate solution (0.1 M, 5.0 ml), whose pH value was adjusted as high as possible not to precipitate the hydroxides, were shaken in a 20-ml test tube with a ground-glass stopper at ambient temperature (18-20 °C) for 2 h. Two liquid phases were separated. Then the extracted cation into the organic phase was measured by the same manner as described above.

Titration of crownphane (6) with silver perchlorate. A acetonitrile- d_3 solution of 6 (5.0×10^{-2} M) was prepared. Of this, 500 μ l was placed in an nmr tube, and the solvent level was marked. A second solution was made in acetonitrile- d_3 with $AgClO_4$ concentration of 2.5×10^{-1} M. An initial spectrum was recorded, then 50 μ l of the lithium ion solution was added to the nmr tube and the solvent level was reduced by evaporation to the mark. The spectrum was then recorded again. This procedure was repeated until the separation in chemical shift of the aromatic carbon resonances remained constant for successive spectra.

Results and Discussion

Synthesis of thiacyclopentane (6-8). A number of thiacyclopentane compounds reported^{16,17} were synthesized by using nucleophilicity of terminal thiolate(s) in a molecule except Okahara's cyclization.¹⁸ Our cyclization making a cyclobutane linkage in the lipophilic part is quite unique in the synthetic field of crown compounds. Although there were three steps to prepare them, thiacyclopentane precursors (3-6) were readily obtained because of the simple procedure and easy purification. The intramolecular [2 + 2] photocycloaddition afforded thiacyclopentanes (6-8) in moderate yields without any problematic byproducts. All thiacyclopentanes were of cis-configuration which was proved by the specific methine proton signals at δ 3.91-3.93.

Extraction of heavy metal cations by thiacyclopentanes. The complete recovery of silver cation from the waste stream in the photographic industries is required from the resource saving and environmental preservation points of view.¹³ Many articles on thiacyclopentane compounds have been disclosed and discussed their structural effects on the affinity toward heavy metal cations, especially Ag^+ .¹⁻⁶ Accordingly we were prompted to prepare some thiacyclopentanes and to examine the Ag^+ extraction with specificity due to their characteristic structures.

First, the thiacyclopentanes were used as extractants for liquid-liquid system under the conditions shown in Table 1. Extracted picrate anion was easily determined by uv spectro-

scopy. Extraction data are summarized in Table 1. This analysis sometimes suggests more metal extractions than the real one, because of the unavoidable extraction of picric acid itself. This problem was experienced in the system including an acidic aqueous phase.¹⁴

Table 1 Extraction of metal picrates with ligands^{a)}

Ligand	Percent extraction ^{b)}							
	Ag ⁺	Cu ²⁺	Pb ²⁺	Ni ²⁺	Zn ²⁺	Co ²⁺	Mn ²⁺	Metal-free
6	63(4.0)	5(3.7)	3(3.7)	8(3.2)	3(4.0)	6(3.6)	5(3.9)	4(3.9)
7	38(5.2)	4(3.7)	3(3.7)	8(3.2)	2(4.0)	5(3.6)	4(3.9)	4(3.9)
8	45(4.8)	4(3.7)	3(3.7)	8(3.2)	3(4.0)	4(3.6)	5(3.9)	3(3.9)
none	3(5.1)	3(3.7)	2(3.7)	7(3.2)	1(4.0)	4(3.6)	3(3.9)	3(4.0)

a) Extraction conditions: Aq. phase, [metal nitrate] = 1×10^{-1} M and [picric acid] = 1×10^{-4} M, 5 ml; org. phase, CH₂Cl₂, [ligand] = 1×10^{-4} M, 5 ml. b) Calculated values of picrate anions on the basis of [picric acid], which were analyzed by uv spectrophotometer. Values in parentheses are equilibrium pH of aqueous phase.

Table 2 Extraction of metal cations with ligands in the presence of picric acid^{a)}

Ligand	Percent extraction ^{b)}							
	Ag ⁺	Cu ²⁺	Pb ²⁺	Ni ²⁺	Zn ²⁺	Co ²⁺	Mn ²⁺	Fe ³⁺
6	36(4.0)	0(3.7)	0(3.7)	0(3.2)	0(4.0)	0(3.6)	0(3.9)	1(1.9)
7	20(5.2)	0(3.7)	0(3.7)	2(3.2)	0(4.0)	0(3.6)	0(3.9)	0(1.9)
8	13(4.8)	0(3.7)	0(3.7)	0(3.2)	1(4.0)	0(3.6)	1(3.9)	0(1.9)
none	0(5.1)	0(3.7)	0(3.7)	0(3.2)	0(4.0)	0(3.6)	0(3.9)	0(1.9)

a) Extraction conditions: Aq. phase, [metal nitrate] = 1×10^{-4} M and [picric acid] = 1×10^{-4} M, 5 ml; org. phase, CH₂Cl₂, [ligand] = 1×10^{-4} M, 5 ml. b) Calculated values of metal cations on the basis of [ligand], which were analyzed by atomic absorption spectrophotometer. Values in parentheses are equilibrium pH of aqueous phase.

Hence, the cation extracted into organic phase itself was analyzed by atomic absorption spectroscopy. The data are summarized in Table 2.

Next, we examined the extraction experiments without picric acid, not only to avoid its coextraction, but also to mimic the industrial waste stream conditions. Both prototypical

crownophane (**9**) and simple dithiacrown ether (**10**) were also used as reference extractants. Data are listed in Table 3.

Table 3 Extraction of metal nitrates with ligands

Ligand	Percent extraction							
	Ag ⁺	Cu ²⁺	Pb ²⁺	Ni ²⁺	Zn ²⁺	Co ²⁺	Mn ²⁺	Fe ³⁺
6	43(4.4)	0(4.1)	6(4.8)	2(6.9)	0(5.3)	0(7.0)	0(6.1)	0(1.7)
7	16(4.2)	0(4.2)	0(4.9)	8(6.9)	2(5.2)	0(7.0)	0(6.3)	0(1.7)
8	13(4.3)	0(4.3)	0(4.8)	2(6.8)	0(5.3)	0(7.0)	0(6.2)	0(1.7)
9	2(4.1)	0(4.3)	8(5.0)	0(6.9)	0(5.5)	0(7.0)	0(5.9)	0(1.7)
10	15(5.0)	0(4.3)	0(5.0)	0(7.0)	0(5.7)	0(7.0)	0(6.2)	0(1.9)

Extraction conditions: Aq. phase, [metal nitrate] = 1×10^{-1} M, 5 ml; org. phase, CH₂Cl₂, [ligand] = 1×10^{-4} M, 5 ml.
Values in parentheses are equilibrium pH of aqueous phase.

From the comparison of data in Tables 2 and 3, especially those of Ag⁺, it is clear that lipophilic picrate anion plays an important role to extract the cation. It may act as a useful counter anion working cooperatively with the thiacycrownophane. On the other hand, the percent Ag⁺ extraction of thiacycrownophane (**6**) is significantly high even without picric acid, suggesting that the phane can be used practically to extract silver nitrate. All thiacycrownophanes and conventional compound (**10**) except for non-sulfur-containing **9** showed some Ag⁺-affinity, and the extraction behavior significantly depends on their structures. The order of Ag⁺ extractability of the crownophanes is **9** < **8** ≤ **7** < **6**, indicating that the number of sulfur atoms in the phanes is important for the Ag⁺ extraction. As a result of the smaller cavity size than **6** to fit Ag⁺, ligand (**8**) showed a relatively low extractability. Ligand (**6**) exhibited higher Ag⁺-extractability than **10** because the former has a phane moiety as a lipophilic part and the latter does not have any special hydrophobic part. It is believed that the lipophilicity plays an important role in this case.

The phane moiety, however, not only plays a significant role to control the hydrophilic-lipophilic balance (HLB)¹⁵ but also forces a polyether shape to fit the cation (the phane having cis-butane moiety). Actually, thiacycrownophane (**10**), in which two sulfur atoms are placed closely to each other when their ligating hetero atoms are oriented to the cation,

seemed not to fit well the cation because of shortened distance between its two sulfur atoms, but **6** does, according to the frame-work examination.

In order to clarify the complexing behavior of **6** with Ag^+ , ^{13}C -nmr titration method was performed using AgClO_4 in acetonitrile- d_3 . Ag^+ -Induced changes of an aromatic ring carbon were observed as shown in Figure 1. This result clearly indicates that **6** forms a 1 : 1 complex with Ag^+ .

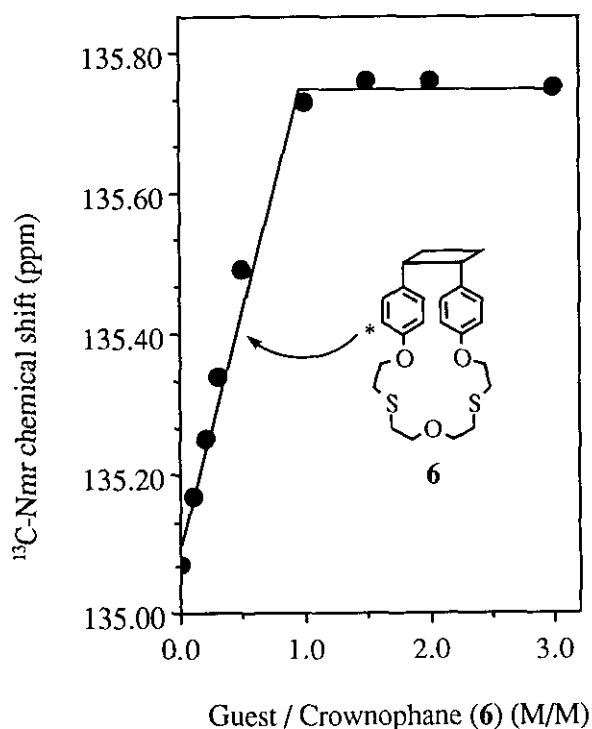


Figure 1 Ag^+ -induced change of an aromatic carbon of crownphane (**6**).

Competitive extraction between Ag^+ and Pb^{2+} was carried out by using ligand (**6**). The data are shown in Table 4.

While a small amount of Pb^{2+} was extracted by the ligand on the single extraction as shown in Table 3, only Ag^+ was efficiently extracted on this competitive experiment. This result can be explained as follows: Soft Ag^+ with coordination number of 2 is favorably

incorporate into **6**, since it has two soft sulfur atoms in its ring. Furthermore, lipophilicity of the resulting Ag^+ -complex carrying one equivalent NO_3^- is higher than that of Pb^{2+} -complex having two equivalent NO_3^- which is a relatively hydrophilic anion. Namely, the more strongly bound and higher lipophilic complex is formed, the more easily it is transferred into the organic phase from the aqueous phase.

Table 4 Competitive Extraction of Ag^+ and Pb^{2+} with thiacrownophane (**6**)^{a)}

Ligand	Percent Extraction	
	Ag^+	Pb^{2+}
6	43	0

a) Extraction conditions: Aq. phase, [metal nitrate] = 1×10^{-1} M, 5ml ; Org. phase, CH_2Cl_2 , [**6**] = 1×10^{-4} M, 5ml.

While a small amount of Pb^{2+} was extracted by the ligand on the single extraction as shown in Table 3, only Ag^+ was efficiently extracted on this competitive experiment. This result can be explained as follows: Soft Ag^+ with coordination number of 2 is favorably incorporate into **6**, since it has two soft sulfur atoms in its ring. Furthermore, lipophilicity of the resulting Ag^+ -complex carrying one equivalent NO_3^- is higher than that of Pb^{2+} -complex having two equivalent NO_3^- which is a relatively hydrophilic anion. Namely, the more strongly bound and higher lipophilic complex is formed, the more easily it is transferred into the organic phase from the aqueous phase.

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