

Extraction performance of calixarene derivatives as a novel host molecule for salt ions

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Novel extractant calixarenes have been developed for separating and concentrating salt ions. The extraction behavior of alkaline and alkaline earth ions was systematically investigated with the cyclic host compound calixarene. The calixarene derivatives showed high extractability for all the salt ions compared to that of a noncyclic monomer analog. The extraction behavior of alkaline and alkaline earth metals is closely related to the cavity size of the cyclic ligands; thus, the tetramer selectively extracted sodium and calcium ions, while the hexamer did so for cesium and barium ions. These results indicate that the cyclic structure is effective for the recognition of alkaline and alkaline earth ions. All of the salt ions were confirmed to be extracted with the cyclic ligands by forming a 1 : 1 complex, which was also supported by the results of computational modeling.

1. INTRODUCTION

In the field of clinical and food industries, there is a high demand for selective recognition of a target salt ion. Therefore, attempts are made to develop highly selective molecules that can recognize the target salt ion in an aqueous solution containing various salt ions. In a salt analysis, as the extractant has a crucial effect on separation and concentration efficiency, it is important to develop an efficient ligand for a target salt ion, and the selection of the ligand often decides the success of the analysis.

Apart from the large amount of work on extraction of transition metals, relatively few papers have reported on salt ions. Furthermore, in most of the work commercially available extractants have been employed as the host molecules for salt ions and

little attention has been paid to the development of novel host compounds.

In the present study, we have synthesized novel host compound calixarenes, which is a new cyclic ligand connecting some phenol rings. Using the newly synthesized ligands, separation and concentration of various salt ions were conducted. The extraction behavior is also sustained by computational modeling. The novel host compound calixarene has given promising results, which lines it up as a potential extractant for the high recognition of salt ions.

2. EXPERIMENT

In the present study, we investigated the extraction behavior of eight kinds of salt ions, alkaline metal

(Li, Na, K, Cs), and alkaline earth metal ions (Mg, Ca, Sr, Ba) using two different cyclic compound calixarenes (o-carboxylate derivatives of p-tert-octylcalix[n]arene ($n=4,6$)) along with the monomer analog ($n=1$).

2.1. Reagents

Figure 1 shows the structures and abbreviations of the extractants designed in the present study. The novel extractants ${}^t\text{Oct}[1]$, ${}^t\text{Oct}[4]\text{CH}_2\text{COOH}$, and ${}^t\text{Oct}[6]\text{CH}_2\text{COOH}$ were synthesized according to a procedure described in a previous paper [1].

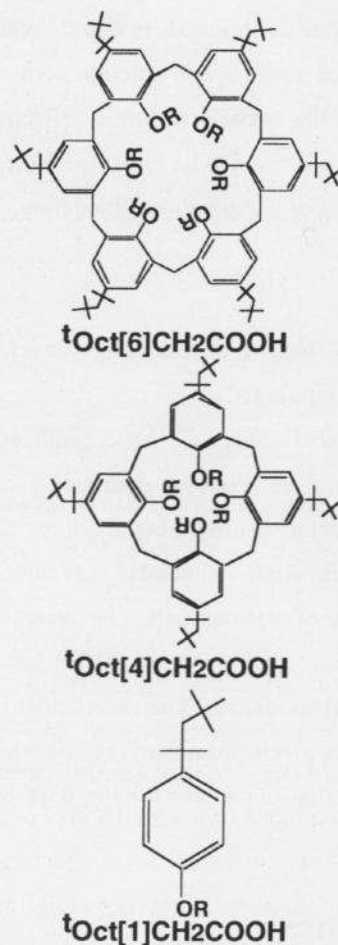


Figure 1. Structures and abbreviations of novel extractants developed in this study.

Although the cyclic ligand, ${}^t\text{Oct}[4]\text{CH}_2\text{COOH}$, possesses four structural isomers, in this study the cone compound in which the four carboxyl groups are immobilized in the lower side of the calixarene platform was isolated and employed[2]. As the upper side, we introduced tertiary octyl groups to enhance the solubility of the extractants in an organic solvent. As the functional part, carboxyl groups were introduced in the lower rim where salt ions interact with the extractant. Analytical-grade toluene was employed as an organic diluent in the liquid-liquid extraction operation.

2.2. Extraction of salt ions in liquid-liquid extraction

An aqueous solution was prepared by dissolving a group of chloride salts into 100mM nitric acid and glycine solution. The pH of the aqueous solution was controlled by mixing both solutions. An organic solution was prepared by weighting an extractant into toluene. The experimental procedure for the extraction equilibrium was the same as that described in a previous paper [3]. Since we confirmed that it takes about two hours to reach the extraction equilibrium, the samples were left in a thermostated water bath for at least five hours. The concentrations of metals were determined by Atomic Absorption Spectroscopy (SHIMADZU AA-6700).

3. RESULTS AND DISCUSSION

3.1 Extraction behavior of salt ions

Figure 2 shows the effect of cyclic ligands on the extraction behavior of alkaline metal ions. It has been found that the degree of metal extraction increases along with an increase in the pH. Alkaline metal ions were not extracted by the monomer

analog, ${}^t\text{Oct}[1]\text{CH}_2\text{COOH}$, even though a 4-fold concentration compared to that of the cyclic ligand was added to the organic phase. The calixarene derivatives showed a high extractability for the alkaline ions compared with the monomer analog, due to a chelating effect of the multi-functional groups. This result indicates that a cyclic ligand is effective for the extraction of alkaline metal ions.

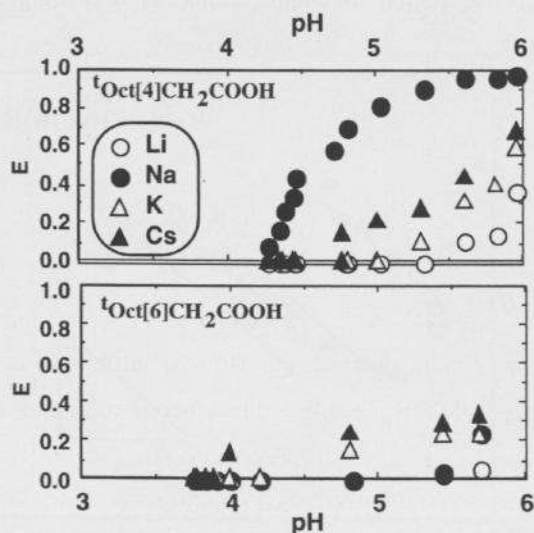


Figure 2. Effect of ring size on the extraction behavior of alkaline metal ions (metal concentration, 0.05 mM; extractant concentration, 5 mM).

In the case of ${}^t\text{Oct}[4]\text{CH}_2\text{COOH}$, sodium ions were selectively extracted, because the size of sodium ion fits into the ring size of the calix[4]arene [4] (see Fig. 2). On the other hand, in the case of ${}^t\text{Oct}[6]\text{CH}_2\text{COOH}$, the degree of extraction was relatively low for the alkaline metal ions due to the larger ring size of the hexamer calix[6]arene and the low binding constants of the carboxyl group to alkaline salt ions. The extracted ratio in the hexamer increased in the order $\text{Li} < \text{Na} < \text{K} < \text{Cs}$, which agrees with that of the ionic radius. As a result, the extraction behavior of alkaline metal ions with a

cyclic ligand was explained by the ionic size-recognition mechanism.

The effect of extractants on the extraction behavior of alkaline earth metal ions is shown in Figure 3. Alkaline earth metal ions as well as alkaline metal ions were not extracted by the monomer analog under the present pH conditions. The metal ions were effectively extracted by the calixarenes in the pH range less than 6; furthermore, the pH range in which alkaline-earth metal ions are extracted was found to be low compared to the case of alkaline metal extraction.

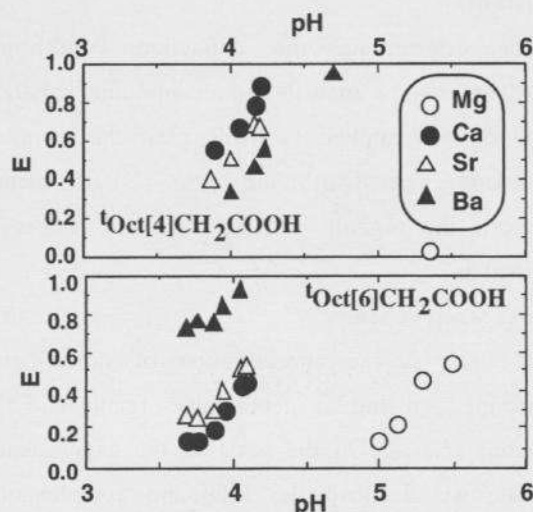


Figure 3. Effect of ring size on the extraction behavior of alkaline-earth metal ions (metal conc., 0.05 mM; extractant conc., 5 mM).

The shift in the metal-extraction pH to a lower region compared to that of alkaline metals is due to the higher affinity of alkaline-earth metals to the carboxyl group than that of alkaline metals. In the case of the tetramer, calcium ions were most preferentially extracted among the metal ions because the ionic size of calcium is similar to that of sodium and approximately agrees with the ring size of the calix[4]arene. On the other hand, in the

hexamer, barium ions having the largest ionic radius among the alkaline earth metals were selectively extracted due to the larger ring size of the calix[6]arene. In the extraction of alkaline earth metal ions, it was found that the extractability of metal ions increased with the degree of affinity of metal ions to the functional group, and that the separation ability among their metal ions was closely related to the ionic size effect brought about by the cyclic structure.

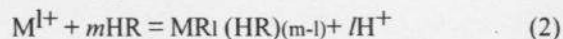
3.2. Determination of the extraction equilibrium constants

For determining the extraction equilibrium constants, a slope analysis and a continuous variation method were applied to make clear the complex formation. The distribution ratio (D) of metals between the organic and the aqueous phases is defined as

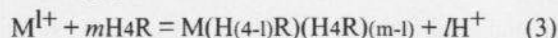
$$D = C_{M,org} / C_{M,aq} \quad (1)$$

where C_M is the concentration of metal ions; subscripts org and aq denote the organic and the aqueous phases. On the basis of the experimental results, we deduced the following complexation reactions for each metal-extraction system:

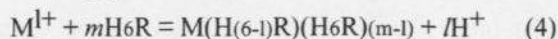
For ${}^t\text{Oct}[1]\text{CH}_2\text{COOH}$



For ${}^t\text{Oct}[4]\text{CH}_2\text{COOH}$



For ${}^t\text{Oct}[6]\text{CH}_2\text{COOH}$



The extraction equilibrium constants in the above equations with a calix[n]arene, $K_{ex,n}$ are expressed by the following equation:

$$K_{ex,n} = ([M]_{org}[H]^n) / ([M]_{aq}[HnR]^m) \quad (5)$$

Eq. (5) can be converted to Eq. (6) by combining with Eq. (1):

$$\log D = m \log [HnR] - / \log [H] + \log K_{ex,n} \quad (6)$$

The experimental data are summarized by logarithmic plots between the distribution ratio and the concentration of chemical species according to Eq.(6).

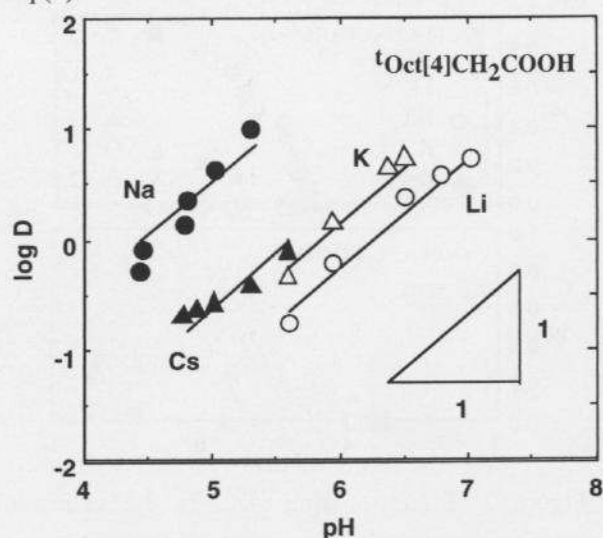


Figure 4. Relationship between the logarithmic distribution ratio of alkaline metal ions and the pH.

The extraction equilibrium relationship and the extraction equilibrium constant are determined from the slope and the intercept of the plots, respectively. Figure 4 shows the relationship between the logarithmic distribution ratio of the alkaline metal ions and the pH. Linear plots with a slope of one were obtained for all of the metals. Since alkaline metal ions are monovalent, the dissociation of a proton from the extractant is required to form a neutral complex. This result suggests that the extractant and the sodium ion forms a 1 : 1 complex.

We also confirmed that the sodium ion sits in the cavity of the calix[4]arene by computational modeling. Calculation for obtaining the lowest energy structure was carried out by a MM method with Compaq Digital Personal Workstation 300i⁺ [4,5]. The molecular mechanics (MM) calculation for the metal complex was performed by molecular modeling software HyperChem Release 5.1 (Hypercube, Inc., Canada). The lowest energy structure for the sodium-calix[4]arene complex calculated is shown in Fig. 5.

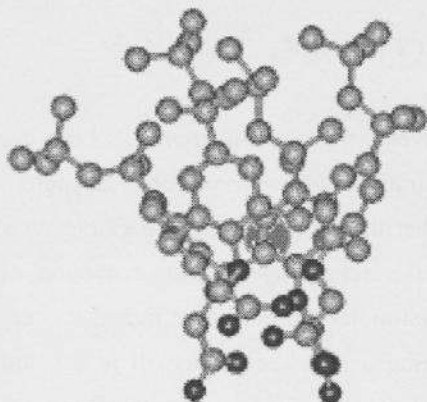
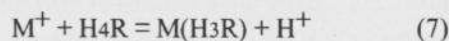


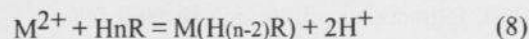
Figure 5. The lowest energy structure for sodium-calix[4]arene complex calculated by MM method.

This result indicates that complex formation between the calixarene tetramer and an alkaline metal ion proceeds according to the following extraction equilibrium equation:



Extraction behavior of alkaline earth metals was also investigated in detail. The pH dependence of the distribution ratio of alkaline earth ions was confirmed to be two for all of the extractants used in the present study. A slope of three was obtained for

the extractant ^tOct[1]. This result means that three monomer analogs are required for the extraction of alkaline earth metal ions. On the basis of the result of job's method, it was found that the concentration of strontium in the organic solution showed a maximum value when the ratio of strontium concentration to the total concentration was about 0.5. We found that the complex formation between alkaline earth metals and the calixarenes proceeds by the following equation:



The extraction equilibrium constants for the alkaline metal ions with the calix[4]arene are summarized on the basis of a slope analysis in Table 1.

Table 1. Extraction equilibrium constants for alkaline metals with ^tOct[4]CH₂COOH.

Alkaline metals	K _{ex}
Li ⁺	3.0 × 10 ⁻³
Na ⁺	1.6 × 10 ⁻¹
K ⁺	8.2 × 10 ⁻³
Cs ⁺	1.4 × 10 ⁻²

The K_{ex} value of the sodium ion was the highest among the metal ions used. Since there is little affinity between alkaline metal ions and the carboxyl group, the order of extractability with the calix[4]arene for the alkaline metal ions does not relate to the degree of the binding constants to the carboxyl group. The calix[4]arene has a ring with a radius of one angstrom, and the ionic radius of the sodium ion is 0.99 Å. The ionic radius of the lithium ion (0.59 Å) is smaller, and that of the potassium

(1.37 Å) or cesium ions (1.67 Å) is larger than that of the sodium ion. Therefore, the cyclic structure of the tetramer was effective for the selective extraction of sodium ions.

The results of the extraction of alkaline-earth metal ions with cyclic ligands are summarized in Table 2. The ionic radius of the calcium ion is 1.00 Å, which is very close to that of the sodium ion. Therefore, the calix[4]arene shows a high selectivity for the calcium ion among alkaline-earth metal ions.

Table 2. Extraction equilibrium constants for alkaline earth metals with calixarene compounds.

Ligands	Metals	K_{ex} / mM
$t\text{Oct[4]CH}_2\text{COOH}$	Mg^{2+}	3.0×10^{-9}
	Ca^{2+}	1.2×10^{-4}
	Sr^{2+}	5.1×10^{-5}
	Ba^{2+}	2.8×10^{-5}
$t\text{Oct[6]CH}_2\text{COOH}$	Mg^{2+}	2.7×10^{-8}
	Ca^{2+}	7.8×10^{-6}
	Sr^{2+}	1.3×10^{-5}
	Ba^{2+}	1.1×10^{-4}

On the other hand, the calix[6]arene, which has a larger ring size of 1.4 Å in radius, extracted the barium ion selectively, which ionic radius (1.35 Å) is the largest among the alkaline-earth metal ions used. Furthermore, the extraction equilibrium constant of alkaline-earth metal ions with the calix[6]arene obeys the following order: $\text{Mg}^{2+} < \text{Ca}^{2+} < \text{Sr}^{2+} < \text{Ba}^{2+}$. This order agrees with that of the ionic radius. The extraction behavior of alkaline-earth metal ions with the cyclic ligands was also reflected by the cyclic structure.

The extractability of the calixarenes towards salt ions was significantly high compared to the monomer analog due to the inclusion effect by the cyclic ligands. The cyclic ligands were effective because the extraction behavior proceeded on the basis of the ionic size-recognition mechanism. Therefore, the tetramer calix[4]arene selectively extracted sodium and calcium ions which size suits the cavity size. Since the hexamer calix[6]arene has a larger ring size compared to that of all metal ions used in the present study, cesium and barium ions were preferentially extracted.

4. CONCLUSIONS

A novel extractant calixarene has been developed for separating and concentrating salt ions. It was found that the cavity size of the extractant strongly affects the selectivity of salt extraction, and the functional moiety in the cyclic ligand is a key factor in ensuring a high recognition. It is concluded that cyclic ligands are useful and show high selectivity when the cavity size fits the ionic size of a target ion.

REFERENCES

1. K. Ohto, M. Yano, K. Inoue, T. Yamamoto, M. Goto, F. Nakashio, S. Shinkai and T. Nagasaki, *Anal. Sci.*, 11, (1995) 893.
2. K. Ohto, K. Inoue, M. Goto, F. Nakashio, S. Shinkai, *Solv. Extr. Ion Exch.*, 14 (1996) 459.
3. T. Kakoi, T. Ohshima, F. Kubota, M. Goto, and F. Nakashio, *J. Membr. Sci.* 143 (1998) 125.
4. K. Araki, K. Uezu, M. Goto, and S. Furusaki, *Anal. Sci.*, 15 (1999) 651.
5. M. Goto, K. Uezu, F. Nakashio, K. Yoshizuka, K. Inoue, *Sep. Sci. & Technol.*, 34 (1999) 2125.