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Decalino-14-crown-4. New Type of Lithium Ion Selective Ionophore

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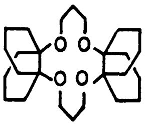
Synopsis. A new type of crown ether, decalino-14-crown-4, has been synthesized and found to be a highly selective and effective ionophore for lithium ion.

Recently, lithium has become increasingly important not only in the wide area of the synthetic and industrial chemistry but also in the field of the atomic fusion as a vital raw material for tritium.[1] From the viewpoint of supplying for its great demand, much attention has been paid even to the concentration of lithium from the sea water. But the extration of lithium ion from the aqueous phase has been very difficult because of the strong hydration of water molecules around the cation. Only a few reports have been so far presented on the extraction or transport of lithium ion. Bartsch et al. reported that 14-crown-4 derivative bearing carboxyphenyl group as an additional binding site exhibited good lithium/sodium ion selectivity in competitive extraction.[2] Takagi,[3] Sasaki,[4] Shono,[5] and their co-workers independently reported that crown ethers with phenolic group as an additional binding site showed the excellent lithium/sodium ion selectivity in extraction of alkali metal ions.

On the other hand, as an extension of a decalin wall strategy for the design of new host molecules with high guest-selectivity,[6] we have previously reported that the cylindrical crown ether, didecalino-14-crown-4[†] (**1**), with no additional binding site exhibits highly effective extractabilty for lithium ion due to the embedding effect of decalin wall, by which the coordinated lithium ion was buried deep in lipophilic cylinder and was protected from the hydration of water molecules.[7] Althogh the crown ether **1** was an excellent **extractant** for lithium ion, it is not expected to be a selective and effective **ionophore** for lithium ion, because of the low efficiency of decomplexation process suppressed by the embedding effect of the decalin walls.

We now design a new type of lithium ion selective ionophore, decalino-14-crown-4 (**2**), containing one decalin subunit. This molecule is expected to satisfy the indispensable conditions as a selective ionophore: i) the appropriate balance between complexation and decomplexation abilities with the cation and ii) high lipophilicity required for efficient recycle of ionophore. In this paper, we wish to report on the synthesis of **2** and the effect of incorporated decalin subunits on lithium ion transport.



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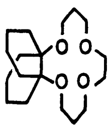

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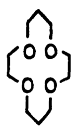

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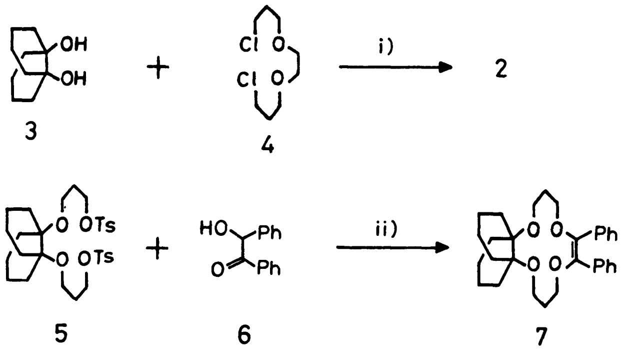
Results and Discussion

The target ionophore **2** was synthesized by the similar procedure described by Liotta et al.[8] Reaction of 4a,8a-decalindiol (**3**) with 1,10-dichloro-4,7-dioxadecane (**4**) in dimethyl sulfoxide (DMSO) with NaOH as a base at 110 °C gave **2** as crystals (mp 69—70 °C), as shown in Scheme 1. As a reference compound, stilbene-incorporated decalino-18-crown-6, 7,8-dipheyl-2,6,9,13-tetraoxatricyclo[12.4.4.$0^{1,14}$]docos-7-ene (**7**), was designed. In this molecule, the stilbene unit is expected to have high lipophilicity as well as the decalin subunit. But, there is a marked difference in influence on the structure of crown ether ring between two subunits. Namely, two vinyl oxygen atoms bonding to the stilbene subunit must be fixed on the same plane, in contrast with gauche conformation of two oxygen atoms bonding to the decalin subunit or flexible conformation of them bonding to the ethane subunit. Crown ether **7** was synthesized by the method similar to that described by Merz[9a] and Inoue et al.[9b] Namely, reaction of 4a,8a,-bis[3-(tosyloxy)propoxy]decalin (**5**) and benzoin with aqueous NaOH under phase-transfer conditions produced **7** in 22% yield as crystals (mp 154—155 °C).



i) NaOH, $LiClO_4$ ii) NaOH, Bu_4NBr

Scheme 1.

Prior to the transport experiment of alkali metal ions, solvent extraction was carried out in water/dichloromethane system[7] in order to know the complexation ability of the ionophore **2** toward some alkali metal ions. The results are listed in Table 1. The data in Table 1 clearly show that ionophore **2** has both excellent extractability for lithium ion (81%) and prominent Li^+/Na^+ selectivity (Li^+/Na^+=16), as

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[†] Ortho-fused cyclic compound is tentatively named "decalino" for decahydronaphtho[4a, 8a].

compared with **1** ($Li^+/Na^+=5$) and the reference compounds, **7** ($Li^+/Na^+=4$) and 14-crown-4 (**8**) ($Li^+/Na^+=11$). In addition, ionophore **2** could hardly extract K^+, Rb^+, and Cs^+. The selectivity order of **2** is $Li^+ \gg Na^+ > K^+ \simeq Rb^+ \simeq Cs^+$, indicating that ionophore **2** would be an efficient and selective ionophore for lithium ion. These high extractability of **1** and **2** is ascribed to the embedding effect of decalin wall by which the coordinated lithium ion is buried deep in the lipophilic atmosphere and is protected from hydration by excluding water molecules out of its coordination sphere. The difference of Li^+ and Na^+ extractability by using **1** and **2** is explained as follows: In the case of **1** having two decalin subunits, the embedding effect is expected to be very strong. Accordingly, ionophore **1** extracts Na^+ which is somewhat larger than the cavity size of **1**, not to mention Li^+ being suitable for its cavity. In the case of **2** having one decalin subunit, the embedding effect is not so strong as compared with in the case of **1**. Therefore, ionophore **2** extracts only Li^+ effectively being suitable for its cavity, while does not Na^+ being somewhat larger than its cavity.

Next, the competitive alkali metal ion transport was executed at 25 °C in a double glass cell where two aqueous phases were separated by the chloroform membrane containing the ionophore. Figure 1a illustrates the plots for competitive transport of Li^+ by using **2**, **7**, or **8** and in which those for other alkali metal ions are omitted from a graph for clarification.[10] As expected, the target ionophore **2** turned out to be an effective ionophore for Li^+ as compared with the reference compounds **7** and **8** (Fig. 1a). The rate of Li^+ transport by using **2** is about ten-fold faster than those by using **7** and **8**. Figure 1b illustrates the results of competitive transport of alkali metal ions by using **2**. The ionophore **2** did not transport K^+, Rb^+, and Cs^+ at all. The most outstanding in Fig. 1b is the high Li^+/Na^+ selectivity of **2**. Significantly, the Li^+/Na^+ selectivity, although not very accurate because of the slow transport of Na^+, was determined to be 20 (calculated from the ratio of the average flux during 24 h). As a result, a new type of ionophore **2** having one decalin subunit without additional binding site is proved to be a highly lithium ion selective and effective ionophore.

Further studies on the separation of isotopes ($^6Li^+$ and $^7Li^+$) by the decalino-14-crown-4 derivatives are now in progress.

Table 1. Extraction of Alkali Metal Picrates in Water/Dichloromethane System by Ionophores, **2**, **7**, and **8**

Ionophore	Extractability/%				
	Li^+	Na^+	K^+	Rb^+	Cs^+
1	ca. 100	20			
2	81	5	1	1	ca. 0
7	13	3	3	3	3
8	11	1	ca. 0	ca. 0	ca. 0

[ionophore]=7.0×10^{-4} M, [picric acid]=7.0×10^{-5} M, and [alkali metal hydroxide]=0.1 M at 25.0±0.1 °C.

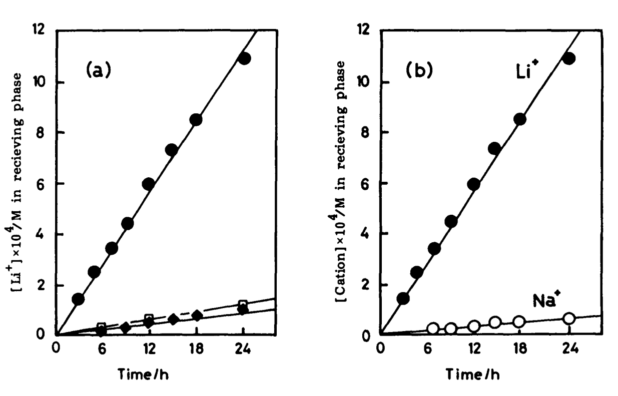

Fig. 1. Competitive transport of alkali metal ions through chloroform membrane containing ionophores.
(a): Plots for transport of Li^+ by using —●— **2**, —◆— **7**, or —□— **8**. Plots for Na^+, K^+, Rb^+, and Cs^+ were omitted from the graph for clarification.
(b): Plots for competitive transport of alkali metal ions by using **2**. K^+, Rb^+, and Cs^+ were not transported under these conditions.

Experimental

All melting points were uncorrected. IR spectra were recorded on a Hitachi 260-10 spectrometer. Mass spectra were recorded on a Hitachi RMU-6E spectrometer at 70 eV ionization energy. ^1H NMR spectra were measured on a JEOL JNM-PS 100 spectrometer in $CDCl_3$ solution using Me_4Si as an internal standard. ^{13}C NMR spectrum was measured on a JEOL JNM-FX-60 spectrometer in $CDCl_3$ solution. Electronic spectra were taken with a Hitachi 356 spectrophotometer. Flame photometric analyses were performed on a Nippon Jarrell Ash AA-8500 Mark II spectrophotometer.

Materials. Benzoin and dimethyl sulfoxide (DMSO) were purchased from Wako Pure Chemical Industries.

Synthesis. 1,10-Dichloro-4,7-dioxadecane (**4**) was prepared from 4,7-dioxadecane-1,10-diol[5] by chlorination as an oil: IR (neat) 1120 cm^{-1}; MS *m/z* (rel intensity) 214 (M^+), 151 (4), 122 (24), 108 (72), 41 (100); ^1H NMR (CCl_4) $\delta=1.95$ (q, $J=6$ Hz, 4H), 3.4—3.7 (m, 12H). Found: C, 44.62; H, 7.55; Cl, 32.75%. Calcd for $C_8H_{16}Cl_2O_4$: C, 44.67; H, 7.50; Cl, 32.96%. 4a,8a-Bis[3-(tosyloxy)propoxy]decalin (**5**) was prepared from 4a,8a-bis(3-hydroxypropoxy)decalin by usual method and was used without further purification. 4a,8a-Bis(3-hydroxypropoxy)decalin was prepared from 4a,8a-decalindiol (**3**) by reaction with allyl bromide followed by hydroboration-oxidation: IR (neat) 3400, 1080 cm^{-1}; MS *m/z* (rel intensity) 286 (M^+), 211 (8), 136 (100); ^1H NMR (CCl_4) $\delta=1.0$—2.1 (m, 20H), 3.3—4.2 (m, 10H). Found: C, 65.93; H, 10.55%. Calcd for $C_{16}H_{30}O_4\cdot0.3\,(H_2O)$; C, 65.86; H, 10.56%.

Decalino-14-crown-4 (2). A mixture of 4.5 g (0.11 mol) of NaOH and 12 g (0.11 mol) of $LiClO_4$ in 80 ml of DMSO was brought to 100 °C slowly and stirred for 20 min. After being cooled to room temperature, 8.2 g (48 mmol) of diol **3** was added. To this mixture was added dropwise a solution of 5.1 g (24 mmol) of dichloride **4** in 5 ml of DMSO over 2 h. The mixture was stirred at 110 °C for 24 h and then another 5.2 g (24 mmol) of **4** in 5 ml of DMSO was added dropwise over 2 h. The mixture was stirred for 12 h at 110 °C and cooled to room temperature. To this mixture was added 400 ml of water and the resulting solution was extracted with dichloromethane. The organic phase was dried over $MgSO_4$ and the solvent was evaporated in vacuo. The residure was chromatographed on silica gel (ether/light petroleum=5/95) to afford 100 mg (1%) of **2**: mp 69—70 °C (recrystallized from light petroleum); IR (KBr) 1120 cm^{-1}; MS *m/z* (rel intensity) 312 (M$^+$), 178 (6), 136 (100); ^{1}H NMR δ=1.0—1.9 (m, 20H), 3.0—4.0 (m, 12H, s at 3.69); ^{13}C NMR δ=20.7 (t, 2C), 23.4 (t, 2C), 30.4 (t, 2C), 31.3 (t, 4C), 56.7 (t, 2C), 67.6 (t, 2C), 71.3 (t, 2C), 78.0 (s, 2C). Found: C, 69.01; H, 10.35%. Calcd for $C_{18}H_{32}O_4$: C, 69.20; H, 10.32%.

7,8-Diphenyl-2,6,9,13-tetraoxatricyclo[12.4.4.0^{1,14}]docos-7-ene (7). A mixture of 10.9 g (18 mmol) of ditosylate **5** and 3.9 g (18 mmol) of benzoin in 130 ml of benzene was stirred mechanically for 1 h at 40 °C. After being cooled, 98 mg (0.47 mmol) of tetrabutylammonium bromide was added. To this mixture was added 20 ml of 50% NaOH. After continuous stirring for 40 h at 70 °C, the mixture was cooled to room temperature, washed with 100 ml of water and the organic phase was separated. The aqueous phase was extracted with dichloromethane and the combined organic phase was dried over $MgSO_4$. The solvent was removed by evaporation and the residue was chromatographed on silica gel (ether/light petroleum=3/97) to give 1.89 g (22%) of **7**: mp 154—155 °C (recrystallized from light petroleum); IR (KBr) 3050, 1590, 1100 cm^{-1}; MS *m/z* (rel intensity) 462 (M$^+$), 252 (65), 147 (100); ^{1}H NMR δ=1.2—2.1 (m, 20H), 3.4—4.2 (m, 8H), 7.0—7.4 (m, 10H). Found: C, 77.84; H, 8.33%. Calcd for $C_{30}H_{38}O_4$:, C, 77.89; H, 8.28%.

Extraction. Extraction of alkali metal picrates by crown ethers into dichloromethane was preformed by the method described previously.[7]

Transport. Competitive transport of alkali metal ions through chloroform membrane containing ionophore was performed at 25.0±0.1°C using a double glass cell (diameters: inner 2.6 cm and outer 5.0 cm) where two aqueous phases were separated by chloroform membrane containing ionophore. Membrane: ionophore (1.5×10^{-4} M; 1 M=1 mol dm^{-3}) in 60.0 ml of chloroform; source phase: LiOH, NaOH, KOH, RbOH, and CsOH (each 1.0×10^{-2} M) and picric acid (6.0×10^{-3} M) in 15.0 ml of deionized water; recieving phase: 20.0 ml of deionized water. Metal ion concentrations were determined by flame photometry.

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10) Na$^+$, K$^+$, Rb$^+$, and Cs$^+$ concentration in recieving phase by using **2**, **7**, and **8** are as follows: **2**: Na$^+$, 0.55×10^{-4} M/24 h; K$^+$, Rb$^+$, and Cs$^+$ were not transported after 24h under there conditions. **7** and **8**: Na$^+$, K$^+$, Rb$^+$, and Cs$^+$ were not detected after 24 h under these conditions.