Analysis of Ion Association Reaction between Crown Ether Complexes of Alkali Metal Ions and Hydrophobic Anions by Capillary Zone Electrophoresis

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Reaction equilibria in liquid–liquid distributions of alkali metals as crown ether complexes were clarified. The reactions and their equilibria of interest are the complex formation, the ion association of the complexes with the pairing anions in an aqueous solution, and the distribution of the formed ion associates to the organic phase. A capillary-electrophoretic method was proposed for the analysis of the equilibria in an aqueous solution. By using this method, complex formation and ion association in an aqueous solution were studied by electrophoretic mobility measurement, which was done in reactant systems consisted of alkali metal ion, dibenzo-18-crown-6, and picrate or perchlorate ion by capillary zone electrophoresis. Complex formation constants obtained agreed with the reported values obtained by the solubility measurement, and the ion association equilibria between the metal complexes and pairing anions were for the first time analyzed in this study. The reactivity of complex formation in the aqueous solution was in the order of $K^+ > Na^+ > Rb^+ > Cs^+ > Li^+$, and the ion associability with picrate ion was in the order of $Na^+ > K^+$. By using the ion association constants and the extraction constants, distribution coefficients of the ion associates between an aqueous and a benzene phase were calculated.

Since the finding of good reactivity of crown ether compounds with alkali metal ions,[1] host–guest chemistry has become one of the most active research fields, and more recently it has led to supramolecular chemistry.[2,3] To examine the reactivity of such compounds, various methods using calorimetry, conductometry, potentiometry with ion selective electrodes, NMR, solubility measurement, and spectrophotometry were proposed and examined.[4] However, some of the crown ether compounds are very hydrophobic and only slightly soluble in water; therefore, the complex formation of such compounds with metal ions in aqueous solution is difficult to study. For example, the solubility of 2,3-11,12-dibenzo-1,4,7,10,13,16-hexaoxacyclooctade-2,11-cene (dibenzo-18-crown-6 or DB18C6, L) in water is 1.3×10^{-5} $\mathrm{mol\,dm^{-3}}$, and the reaction analysis is limited to spectrophotometry. Shchori et al.[5] measured the complex formation constants for DB18C6 with metal ions using the solubility measurement by UV spectrophotometry. The method, however, can be easily interfered with by coexisting impurities, and is very time-consuming and troublesome.

Capillary zone electrophoresis (CZE) is a useful technique for the separation of ionic molecules in aqueous solutions, as well as a simple and accurate method for measuring the electrophoretic mobility of ions. Furthermore, the CZE method has an unique advantage, that the electrophoretic mobility of analytes at relatively low concentrations can be measured simply and accurately by a spectrophotometric detector, and also can be measured simultaneously or even in the presence of other impurities.

Recently, we proposed a method for the analysis of hydrophobic ion–ion interactions in aqueous solutions by using the CZE method, and succeeded in the analysis of weak interaction.[6—9] Concerning the reactivity of polyether compounds including a crown ether, Okada analyzed the reactivity in methanol by a CZE method.[10] However, that in any aqueous solution could not be analyzed because of the low solubility and weak reactivity of crown ethers.

In this study, we succeeded in the analysis of ion association between crown ether complexes and hydrophobic anions in an aqueous solution by the electrophoretic measurements in CZE. The complex formation reaction between alkali metal ions and a hydrophobic crown ether, DB18C6, in an aqueous solution was analyzed and compared with those previously reported.[5]

Experimental

Apparatus. An Applied Biosystems Model 270A-HT Capillary Electrophoresis System, with a UV detector, was used. A fused silica capillary purchased from GL Sciences was attached to the system; the capillary was 72 cm in total length, 50 cm in effective length to the UV detector, and had a 50 μm inner diameter. A Hitachi D-2500 Chromato-Integrator was used for recording electropherograms.

Reagents. Migrating buffer solutions containing H_3PO_4–Li_3PO_4, NaH_2PO_4–Na_2HPO_4, KH_2PO_4–K_2HPO_4, H_3PO_4–RbOH, and H_3PO_4–CsOH were prepared by dissolving each component in water. The accurate concentration of an alkali metal ion in each phosphate buffer was measured by a Capillary Ion Analysis method,[11] using ethylpyridinium (received as bromide salt, Tokyo Kasei) as an indirect photometric reagent. Alkali metal chlorides (MCl), sodium perchlorate, potassium perchlorate, sodium picrate, and picric acid were purchased from Wako and dissolved in water. All the reagents were used without further purification. Dibenzo-18-crown-6 was synthesized according to the literature[1)] from catechol and bis(2-chloroethyl) ether and was recrystallized from benzene;[12)] it was dissolved in ethanol and used after accurately diluting with water. The water used was de-ionized and distilled.

CZE Measurements for the Study of Complex Formation between Alkali Metal Ions and Dibenzo-18-crown-6. Migrating solutions, which contain the phosphate buffer (pH 7.1±0.2; total phosphate concentration: 5×10^{-3} mol dm^{-3}) and variable amounts of corresponding MCl in the concentration ranges up to 4.0×10^{-2} mol dm^{-3}, were used to fill both a cathodic and an anodic reservoir; then they were put into the capillary with a vacuum system. An aqueous solution containing 1×10^{-5} mol dm^{-3} DB18C6, 3% ethanol, and an equal concentration of M$^+$ to the migrating solutions was used as an analyte solution. The analyte solution was introduced into the capillary from an anodic end for 3 s by the vacuum system (injection volume: about 9 nl). After that, a voltage of 10 kV was applied, and then electrophoresis was started. The analyte, DB18C6, was detected at 200 nm on the cathodic end of the capillary. Electroosmotic flow (EOF) was monitored with ethanol contained in the analyte solution as a neutral marker. More than three measurements were done, and were averaged to obtain accurate mobility. Throughout the experiments, the capillary was held in a thermostatted compartment controlled at 35 °C. Under the migrating conditions, the effect of Joule's heat was well depressed, though electric currents in the capillary increased linearly with increasing amounts of MCl in the migrating solutions. The apparent mobility of DB18C6 and the velocity of EOF were calculated by using the migration time of DB18C6 and ethanol, respectively.

CZE Measurements for the Study of Ion Association. The aqueous solution containing DB18C6, ethanol, and M$^+$ was also used as the analyte solution. Migrating solutions consisted of the phosphate buffer, alkali metal chloride, and alkali metal perchlorate or alkali metal picrate; the total concentration of alkali metal ion was adjusted to 2.75×10^{-2} mol dm^{-3} and the concentrations of the pairing anion, perchlorate or picrate, were varied. The applied voltage, the injection time of the analyte solution, the capillary temperature, and the detection wavelength were the same as in the previous section.

Results and Discussion

Electrophoretic Migration of DB18C6 in the Presence of Various Alkali Metal Ions. The crown ether, DB18C6, used as an analyte is electrically neutral, and essentially does not migrate by electrophoresis; that is, its migration time may be identical to that of ethanol, a marker of electroosomotic flow, when DB18C6 is present as it is. The electropherogram (a) in Fig. 1 obtained with lithium salts shows that the migration time of DB18C6 is almost identical to that of EOF. This result also indicates that lithium ion, even at the concentration of 2.75×10^{-2} mol dm^{-3}, does not form any detectable complex with DB18C6. However, DB18C6 migrated faster than the EOF in the presence of M$^+$ except for Li$^+$, as shown in Fig. 1(b)—(f). It suggests that some parts of DB18C6 are positively charged in the migrating buffer; that is, DB18C6 can react with M$^+$ to form positively charged complexes. Differences in migration time between DB18C6 and the neutral marker were largest of all alkali metal ions when the migrating solution contained K$^+$, and they were smallest in a Li$^+$ solution. The difference in the migration time between DB18C6 and the EOF increased with increasing K$^+$ concentrations, as shown in the electropherograms (c) and (d) in Fig. 1.

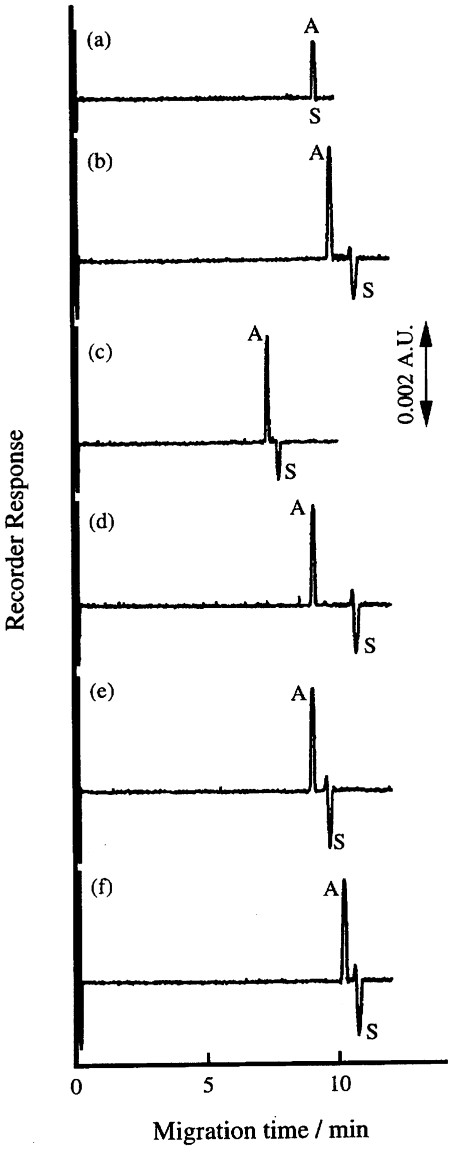

Fig. 1. Typical electropherograms of DB18C6 in the presence of alkali metal ions. CE Conditions and analyte solutions are cited in the text. Migrating solution: (a), (b), (d), (e), and (f), 5.0×10^{-3} mol dm^{-3} (M,H)MHPO$_4$ + 2.0×10^{-2} mol dm^{-3} MCl; (c), 5.0×10^{-3} mol dm^{-3} (M, H)MHPO$_4$. M$^+$: (a), Li$^+$; (b), Na$^+$; (c) and (d), K$^+$; (e), Rb$^+$; (f), Cs$^+$. A, analyte (DB18C6); S, neutral marker (ethanol).

Analysis of Complex Formation Based on Mobility Change of DB18C6. Changes in apparent electrophoretic mobility of DB18C6, $\mu'_{\mathrm{ep,L}}$, were examined by varying the concentrations of alkali metal ions in the migrating solution and were plotted against the concentrations of M$^+$; Figure 2

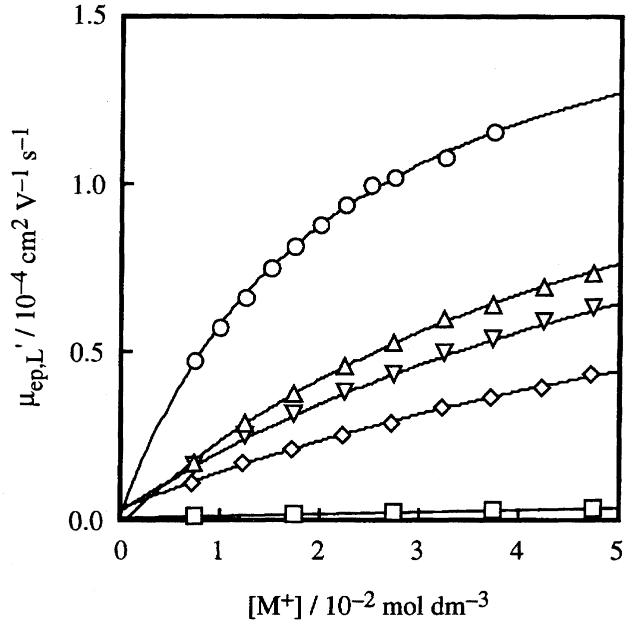

Fig. 2. Change in electrophoretic mobility of DB18C6 by increasing M$^+$ concentrations. Experimental conditions, except for MCl concentrations, are the same as in Fig. 1. M$^+$: □, Li$^+$; △, Na$^+$; ○, K$^+$; ▽, Rb$^+$; ◇, Cs$^+$.

shows the results. The mobility increased with increasing concentrations of alkali metal ions. Such increases in the mobility indicate the increased reactivity of DB18C6 with alkali metal ions. Previously, we proposed an analysis for ion-associate formation in aqueous solutions by using the electrophoretic mobility, and used it to calculate ion association constants.[7,8] In this study, a modified analysis was proposed to measure the complex formation constants, K_{ML}, for alkali metal ions with DB18C6. A 1 : 1 complex was expected to form between M$^+$ and DB18C6, as shown in reaction (1), with an equilibrium constant given by Eq. 2.

$$\mathrm{M^+ + L \rightleftarrows ML^+} \quad K_{\mathrm{ML}} \tag{1}$$

$$K_{\mathrm{ML}} = \frac{[\mathrm{ML^+}]}{[\mathrm{M^+}][\mathrm{L}]}. \tag{2}$$

The apparent electrophoretic mobility of DB18C6, $\mu_{\mathrm{ep,L}}'$, can be written by Eq. 3.

$$\mu_{\mathrm{ep,L}}' = \frac{\mu_{\mathrm{ep,L}}[\mathrm{L}] + \mu_{\mathrm{ep,ML}}[\mathrm{ML^+}]}{[\mathrm{L}] + [\mathrm{ML^+}]}, \tag{3}$$

where $\mu_{\mathrm{ep,L}}$ and $\mu_{\mathrm{ep,ML}}$ are the electrophoretic mobility of DB18C6 and that of 1 : 1 complex, respectively. Equation 3 can also be expressed as in Eq. 4, which can be derived from the mass balance for DB18C6 and the complex formation constant expressed in Eq. 2.

$$\mu_{\mathrm{ep,L}}' = \frac{1}{1 + K_{\mathrm{ML}}[\mathrm{M^+}]}\mu_{\mathrm{ep,L}} + \frac{K_{\mathrm{ML}}[\mathrm{M^+}]}{1 + K_{\mathrm{ML}}[\mathrm{M^+}]}\mu_{\mathrm{ep,ML}}. \tag{4}$$

A non-linear least-squares method was applied to Eq. 4 to obtain the values of K_{ML}, $\mu_{\mathrm{ep,L}}$, and $\mu_{\mathrm{ep,ML}}$. In the method, a series of pairs of a known concentration of M$^+$ and an experimentally obtained $\mu_{\mathrm{ep,L}}'$value was put into Eq. 4, and the values of K_{ML}, $\mu_{\mathrm{ep,L}}$, and $\mu_{\mathrm{ep,ML}}$ were optimized by the errors between the calculated and the experimental values of $\mu_{\mathrm{ep,L}}'$ being the smallest. In the case of Li$^+$, the change in mobility was small, the value of $\mu_{\mathrm{ep,ML}}$ was estimated in the range from 0.5 to 1.5×10^{-4} cm^2 V^{-1} s^{-1}, and the K_{ML} was optimized. In Fig. 2, solid lines show the simulation of the mobility change using Eq. 4 and the optimized values; each line agreed with the experimentally obtained $\mu_{\mathrm{ep,L}}'$ values. The K_{ML} and $\mu_{\mathrm{ep,ML}}$ obtained in this work are summarized in Tables 1 and 2, respectively. As can be expected, optimized values of $\mu_{\mathrm{ep,L}}$ were nearly zero (the captions in Table 1), which demonstrates that DB18C6 is electrically neutral and the equilibrium shown in Eq. 1 is reasonable. Electrophoretic mobility of the complexes, $\mu_{\mathrm{ep,ML}}$, obtained in this study are in the order of K$^+$ complex>Rb$^+$ complex>Na$^+$ complex>Cs$^+$ complex>Li$^+$ complex, while

Table 1. Complex Formation Constants and Ion Association Constants

Crown ether (L)	Pairing anion (X$^-$)	Constant	M$^+$ Li$^+$	Na$^+$	K$^+$	Rb$^+$	Cs$^+$
DB18C6[a]		$\log K_{\mathrm{ML}}$[b]	(-0.3 ± 0.2)[c]	1.18 ± 0.02	1.67 ± 0.02	1.14 ± 0.03	0.96 ± 0.06
DB18C6[a]		$\log K_{\mathrm{ML}}$[d]	(-0.3 ± 0.2)[c]	1.24 ± 0.02	1.67 ± 0.02	1.07 ± 0.02	0.94 ± 0.02
DB18C6[e]		$\log K_{\mathrm{ML}}$	0	1.16	1.67	1.08	0.83
DB18C6[f]		$\log K_{\mathrm{ML}}$	—	4.4	5.0	4.2	—
18C6[g]		$\log K_{\mathrm{ML}}$	—	0.8	2.03	1.56	0.99
B18C6[h]		$\log K_{\mathrm{ML}}$	—	1.38	1.744	1.15	(0.88)[c]
	Picrate[a]	$\log K_{\mathrm{M\cdot X}}$	—	<0.0	0.15 ± 0.12	0.47 ± 0.13	—
	Picrate[i]	$\log K_{\mathrm{M\cdot X}}$	—	1.38	1.64	1.94	2.07
DB18C6[a]	$\mathrm{ClO_4^-}$	$\log K_{\mathrm{ML\cdot X}}$	—	<0.0	0.54 ± 0.16	—	—
DB18C6[a]	Picrate	$\log K_{\mathrm{ML\cdot X}}$	—	2.23 ± 0.29	1.95 ± 0.10	—	—
B18C6[j]	Picrate	$\log K_{\mathrm{ML\cdot X}}$	—	1.54 ± 0.16	3.30 ± 0.20	3.11 ± 0.24	—

a) This study. Error: 3σ. b) Values were optimized using $\mu_{\mathrm{ep,L}}=0$. c) Estimated value. d) Optimized values of $\mu_{\mathrm{ep,L}}$ were: 0.01 ± 0.01, -0.02 ± 0.02, 0.00 ± 0.04, 0.03 ± 0.02, and 0.03 ± 0.02 in the experiments of Li$^+$, Na$^+$, K$^+$, Rb$^+$, and Cs$^+$, respectively. e) Reported values from Ref. 5, determined by spectrophotometry. f) Values in methanol as a medium (Ref. 13). g) 18-crown-6 (Ref. 14). h) Benzo-18-crown-6 (Ref. 15). i) Reported values from Ref. 16, estimated from solvent extraction constants. j) Benzo-18-crown-6. Values are cited from Ref. 17.

Table 2. Electrophoretic Mobility of Alkali Metal Ions and Their Complexes

Mobility	Ionic radius	Li^+	Na^+	K^+	Rb^+	Cs^+
$\mu_{ep,ML}$ a)		(1.07±0.26) b)	1.65±0.05	1.81±0.05	1.69±0.04	1.37±0.05
$\mu_{ep,M}$ c)		5.25	6.82	10.0	10.58	10.51
	r_c d)	60	97	133	147	169
	r_s e)	254	195	133	127	176

a) Ionic mobility: 10^{-4} cm^2 V^{-1} s^{-1}. b) Estimated value. c) Ionic mobility at infinite dilution. The values were cited from the literature.[21] d) Crystal ionic radii (pm).[21] e) Stokes radii (pm).[21]

the electrophoretic mobility of alkali metal ions ($\mu_{ep,M}$) are in the order of $Rb^+ > Cs^+ > K^+ > Na^+ > Li^+$, as shown in Table 2. Comparing $\mu_{ep,ML}$ with $\mu_{ep,M}$, the $\mu_{ep,ML}$ values reflect the degree of the hydration of metal ions and the increased mass in the complexed form. The ionic radius of Cs^+, as well as Rb^+, is too large to enter the hole of DB18C6. Therefore, the mobility of the complexed rubidium and caesium ion seems to be decreased compared with the complexed potassium ion.

In this work, the experiments were done with I (ionic strength)=0.01—0.05 and at 35 °C. Although the activity coefficient of the reagents might be affected by the change in ionic strength, its effect on the complex formation constant would not be serious, because both the reactant and the product contain +1 charged species in this equilibrium.

The effects of ionic strength on the electrophoretic mobility of ionic species were also investigated. The mobility change in inorganic anions was studied to estimate the effects of ionic strength by using Br^-, I^-, $NO_3{}^-$, and $IO_3{}^-$ as analyte ions and electrolytes of KH_2PO_4–K_2HPO_4 buffer and KCl present in the migrating solutions (I=0.020—0.035). The electrophoretic mobility and its relative standard deviations (R.S.D.) were almost identical: −8.78±0.10 (1.0), −8.63±0.13 (1.1), −7.89±0.08 (0.8) and −4.49±0.06 (0.9), for Br^-, I^-, $NO_3{}^-$, and $IO_3{}^-$, respectively, where the mobility values are in the dimension of 10^{-4} cm^2 V^{-1} s^{-1} and the values in the parentheses are percentage R.S.D of 18 measurements. The deviations are sufficiently small compared with the μ'_{ep} values obtained in this study. Therefore, the effects of ionic strength on the electrophoretic mobility of analyte ions studied in this work are considered to be negligible.

From the complex formation constants of alkali metal ions obtained in this study, it is noted that K_{ML} values are almost identical to the ones obtained by another method.[5] This demonstrates that the analysis proposed in this work is reliable. As can be expected, the reactivity of DB18C6 with metal ions becomes larger in the medium of methanol.[13] The reactivity of the crown ether is found to be in the order: 1,4,7,10,13,16-hexaoxacyclooctadecane (18C6)[14]>2,3-benzo-1,4,7,10,13,16-hexaoxacyclooctade-2-cene (B18C6)[15]>DB18C6.

Analysis of Ion Association Based on Mobility Change of Picrate Ion in the Presence of Alkali Metal Ions. It is necessary first to consider the ion associability of alkali metal ions with pairing anions (X^-) for analyzing the ion associability of the crown ether complexes. However, such ion associability of alkali metal ions had never been measured. Yamane et al. thought the ion associability of alkali metal ions with picrate ion (Pic^-) could be measured from a liquid–liquid distribution study.[16] In this work, the ion association of alkali metal ions with Pic^- was studied by the mobility measurement. The apparent electrophoretic mobility of picrate ion, $-\mu'_{ep,X}$, against the concentrations of metal ions is shown in Fig. 3. The mobility decreased slightly with increasing concentrations of alkali metal ions. Though the decrease in the mobility was very small, the ion associability was found to be in the order: $Na^+ < K^+ < Rb^+$. Such ion associability indicates that the non-hydration character of ions is more effective to form ion associates. The ion association reaction and its equilibrium are written as in reaction (5) and Eq. 6, respectively.

$$M^+ + X^- \rightleftarrows M^+{\cdot}X^- \quad K_{M\cdot X} \tag{5}$$

$$K_{M\cdot X} = \frac{[M^+{\cdot}X^-]}{[M^+][X^-]}, \tag{6}$$

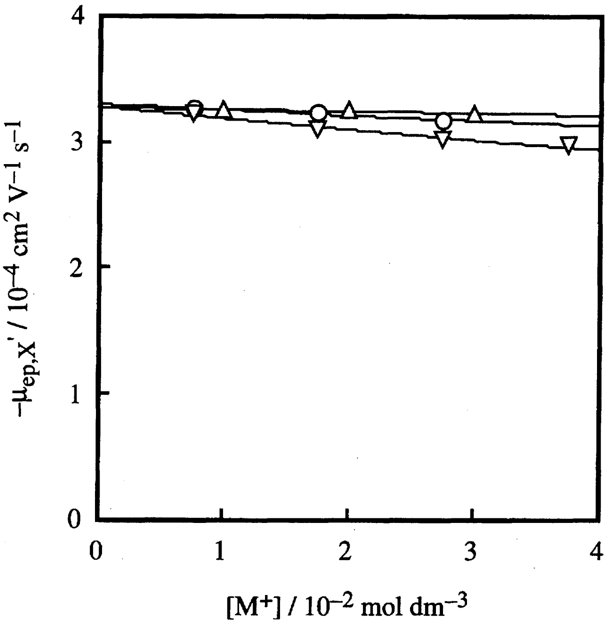

Fig. 3. Change in electrophoretic mobility of picrate ion by increasing M^+ concentrations. CE conditions: applied voltage, 10 kV; injection volume, 3 s (about 9 nl); detection wavelength 350 nm; capillary temperature, 35 °C. Migrating solution: 5×10^{-3} mol dm^{-3} phosphate buffer (pH 7.0)+MCl (K^+ and Rb^+); 5×10^{-3} mol dm^{-3} borax (pH 9.2)+MCl (Na^+). Analyte solution: 2×10^{-5} mol dm^{-3} NaPic. △, Na^+; ○, K^+; ▽, Rb^+.

where $K_{M\cdot X}$ is a 1 : 1 ion association constant. The constant $K_{M\cdot X}$ can be related to the apparent mobility of picrate, $-\mu'_{ep,X}$, as in Eq. 7.

$$-\mu'_{ep,X} = \frac{1}{1+K_{M\cdot X}[M^+]}(-\mu_{ep,X}) + \frac{K_{M\cdot X}[M^+]}{1+K_{M\cdot X}[M^+]}(-\mu_{ep,M\cdot X}), \quad (7)$$

where $-\mu_{ep,X}$ and $-M_{ep,M\cdot X}$ are the electrophoretic mobility of analyte anion, picrate ion in this case, and of its ion associate with M^+, respectively. In this study, the ion associate, $M^+\cdot X^-$, is electrically neutral; therefore, the value of $-\mu_{ep,M\cdot X}$ may be assumed to be zero. A non-linear least-squares analysis method was used to calculate the constants based on Eq. 7, and the values of $K_{M\cdot X}$ and $-\mu_{ep,X}$ were obtained by the optimization of the values of $K_{M\cdot X}$ obtained are summarized in Table 1. From the ion association constants obtained, it is found that the constants obtained are smaller than those expected in our previous paper.[16] This is probably because the distribution coefficients of the ion associates, $K_{D,M\cdot X}$, were estimated to be smaller than they are. From the constants obtained in this study, it was found that most of M^+ and Pic^- can dissociate at their concentration levels of 10^{-2} mol dm^{-3}.

Analysis of Ion Association Based on the Mobility Change of DB18C6 in the Presence of Both Alkali Metal Ion and Pairing Anion. Ion associability of the M^+–DB18C6 complexes with hydrophobic pairing anions was examined on the basis of the mobility measurements of DB18C6 at a constant M^+ concentration of 2.75×10^{-2} mol dm^{-3} (I=0.03). A counter anion with less ion associability with alkali metal ion is suitable for ion association study between the M^+–DB18C6 complexes and the pairing ion in an aqueous solution, because the side reaction of ion association between M^+ and its counter anion can be negligible. As the counter ion of alkali metal ion, chloride ion was selected because of its low ion associability.

The relationships between the apparent electrophoretic mobility of DB18C6, $\mu'_{ep,L}$, and the concentrations of pairing ions, X^-, are shown in Fig. 4. Rubidium was also investigated under similar conditions as for Na^+ and K^+. The solubility of $Rb^+\cdot Pic^-$, however, was not sufficient to measure the mobility changes. In the case of the lithium and caesium complex, the ratio of the complexes formed were insufficient for our purpose, to examine the ion association reaction. From Fig. 4, it can be seen that the decreases in $\mu'_{ep,L}$ are very slight with increasing concentrations of perchlorate ion, compared with Pic^-. These results indicate that the ion associability of Pic^- is larger than that of perchlorate ion. The small mobility change of DB18C6 with the increase in the concentrations of perchlorate ion also indicates that the coexisting ion, such as Cl^-, $H_2PO_4{}^-$, or $HPO_4{}^{2-}$, will not associate with ML^+ complexes.

The ion association reaction between the complex ML^+ and a pairing anion X^- and the equilibrium constant are written in reaction (8) and Eq. 9, respectively.

$$ML^+ + X^- \rightleftarrows ML^+\cdot X^- \qquad K_{ML\cdot X} \qquad (8)$$

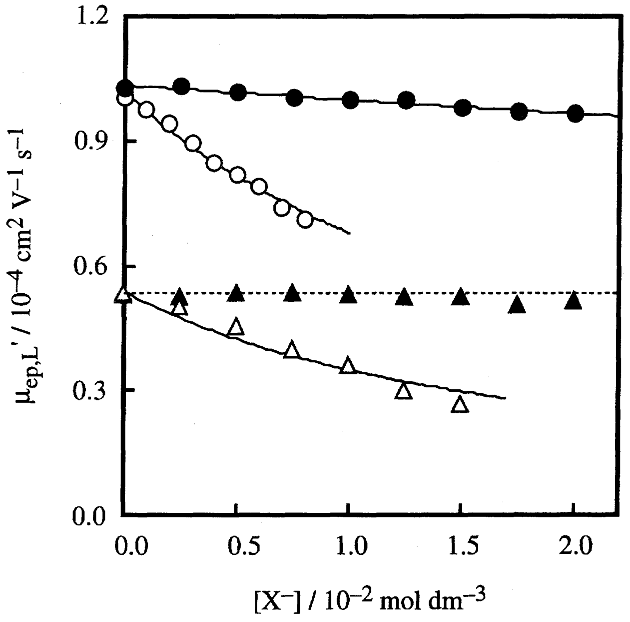

Fig. 4. Change in electrophoretic mobility of DB18C6 in the presence of M^+ and pairing anion. CE conditions are the same as in Fig. 1. Migrating solution: 5×10^{-3} mol dm^{-3} phosphate buffer (pH 7.0)+MCl+MX (ionic strength: 0.03). Concentration of M^+ was adjusted to 2.75×10^{-2} mol dm^{-3} with MCl. Analyte solution: 1×10^{-5} mol dm^{-3} DB18C6+ 5×10^{-3} mol dm^{-3} phosphate buffer (pH 7.0)+MCl+MX+ 3(v/v)% ethanol. M^+: ○ and ●, K^+; △ and ▲, Na^+. Pairing anion: open symbol, Pic^-; solid symbol, $ClO_4{}^-$.

$$K_{ML\cdot X} = \frac{[ML^+\cdot X^-]}{[ML^+][X^-]}, \qquad (9)$$

where $K_{ML\cdot X}$ is an ion association constant. The apparent electrophoretic mobility of DB18C6, $\mu'_{ep,L}$, in the presence of both alkali metal ion and a pairing anion is shown in Eq. 10, when the ion association between M^+ and X^- is negligible.

$$\mu'_{ep,L} = \frac{\mu_{ep,L} + K_{ML}[M^+]\mu_{ep,ML} + K_{ML}K_{ML\cdot X}[M^+][X^-]\mu_{ep,ML\cdot X}}{1 + K_{ML}[M^+] + K_{ML}K_{ML\cdot X}[M^+][X^-]}, \quad (10)$$

where $\mu_{ep,ML\cdot X}$ is the electrophoretic mobility of the ion associate $ML^+\cdot X^-$. In this case, DB18C6 and the ion associates are expected to be electrically neutral; therefore, the values of $\mu_{ep,L}$ and $\mu_{ep,ML\cdot X}$ are assumed to be zero.

$$\mu'_{ep,L} = \frac{K_{ML}[M^+]\mu_{ep,ML}}{1 + K_{ML}[M^+] + K_{ML}K_{ML\cdot X}[M^+][X^-]}. \qquad (11)$$

The value of K_{ML} obtained in this work and the several couples of the measured values of $\mu'_{ep,L}$ and the concentrations of M^+ and X^+ were put into Eq. 11, and the optimization of $K_{ML\cdot X}$ was done by using the non-linear least-squares method. The $K_{ML\cdot X}$ values obtained are summarized in Table 1. From the constants in Table 1, it is found that the ion association constants are larger in Pic^- than $ClO_4{}^-$. These results indicate that the hydrophobic character of the pairing anion acts on the ion associability in an aqueous solution. Furthermore, the interaction between the benzene rings of the complexed DB18C6 and Pic^- will increase the ion associability of Pic^- with the complexes, where the pairing ion can form a stacked ion association,[17] as it is illustrated in Fig. 5. It is very interesting that the ion associability of the sodium complex is larger than that of the potassium complex. Probably, the electrostatic interaction between the complexed alkali metals and the deprotonated hydroxyl group is stronger in Na^+ than in K^+ because the ionic radius of Na^+ is smaller than that of K^+. Compared with the case of B18C6, the ion associability of the complexed K^+ with B18C6 is larger than that of Na^+; these were obtained by a liquid–liquid distribution study.[17] Such a reverse ion associability is very interesting, but the reason cannot be explained at this stage.

Distribution Behavior of Ion Associates between an Aqueous and an Organic Phase. It has been often reported that alkali metal–crown ether complexes can be extracted into the organic phase with various pairing anions or ion association reagents. Picrate ion has often been used as a pairing ion.[11,17—19] The overall reaction, the ion-association extraction reaction, is expressed as in reaction (12) and its equilibrium (13) could be determined.

$$M^+ + L_{(o)} + X^- \rightleftarrows ML^+{\cdot}X^-_{(o)} \qquad K_{ex} \tag{12}$$

$$K_{ex} = \frac{[ML^+{\cdot}X^-]_{(o)}}{[M^+][X^-][L]_{(o)}}, \tag{13}$$

where the subscripts (o) denote the species present in the organic phase. The diagram concerning overall liquid–liquid distribution equilibria is shown in Fig. 6. The fundamental reaction steps dominating the extraction reaction are complex formation between alkali metal ions and crown ether in an aqueous solution {reaction (1)}, formation of ion associate between the complex and pairing anion {reaction (8)} and distribution of the ion associate from aqueous phase to organic phase, as is presented in reaction (14).

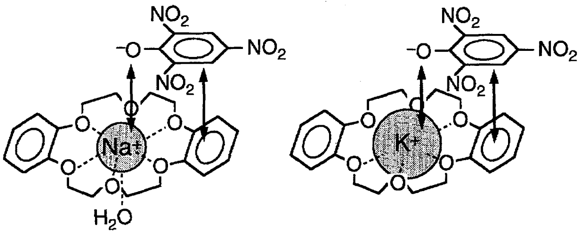

Fig. 5. Ion association models of alkali metal ions. The crown ether complexes and picrate will be stacked with each other.

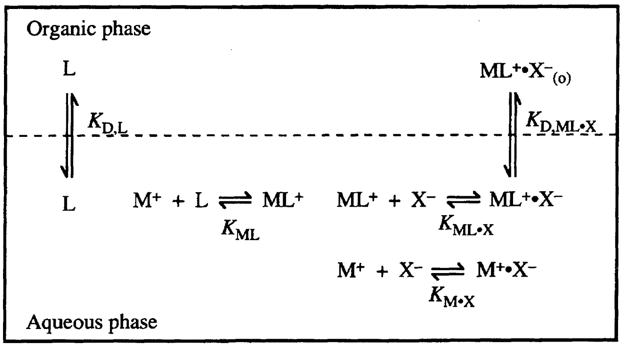

Fig. 6. Diagram concerning liquid–liquid distribution equilibria. In aqueous phase: $K_{M\cdot X} = \frac{[M^+{\cdot}X^-]}{[M^+][X^-]}$; $K_{ML} = \frac{[ML^+]}{[M^+][L]}$; $K_{ML\cdot X} = \frac{[ML^+{\cdot}X^-]}{[ML^+][X^-]}$. Distribution of chemical species between aqueous and organic phases: $K_{D,L} = \frac{[L]_{(o)}}{[L]}$; $K_{D,ML\cdot X} = \frac{[ML^+{\cdot}X^-]_{(o)}}{[ML^+{\cdot}X^-]}$. M^+: alkali metal ion; L: crown ether; X^-: pairing ion. ML^+: crown ether complex. $M^+{\cdot}X^-$, $ML^+{\cdot}X^-$, $ML^+{\cdot}X^-_{(o)}$: ion associate.

$$ML^+{\cdot}X^- \rightleftarrows ML^+{\cdot}X^-_{(o)} \qquad K_{D,ML\cdot X} \tag{14}$$

The equilibrium corresponding to reaction (14) is written as,

$$K_{D,ML\cdot X} = \frac{[ML^+{\cdot}X^-]_{(o)}}{[ML^+{\cdot}X^-]}. \tag{15}$$

From the stepwise reactions and the equilibria, the extraction constant is represented as Eq. 16.

$$K_{ex} = \frac{K_{ML}K_{ML\cdot X}K_{D,ML\cdot X}}{K_{D,L}}, \tag{16}$$

where $K_{D,L}$ is the distribution coefficient of L between an aqueous and an organic phase.

In the liquid–liquid distribution study, all of the stepwise equilibrium constants mentioned above could not be measured. The analysis of the complex formation reaction (1) has been done, and the reaction is well investigated, as is discussed in the introduction. However, the direct analysis of the ion association reaction (8) had never been done, because there was not any analysis method. The analysis of reaction (8) is very interesting and important to clarify the mechanism of the liquid–liquid distribution of alkali metal ions and the contribution of each equilibrium. In this study, we succeeded in the measurement of $K_{ML\cdot X}$ values, and the value of $K_{D,ML\cdot X}$ can be calculated using the values of K_{ex}, K_{ML}, and

Table 3. Equilibrium Constants Related to Ion-Association Extraction Constants of Alkali Metal Ions

Crown ether	Pairing anion	Constant	M^+					
(L)	(X^-)		Li^+	Na^+	K^+	Rb^+	Cs^+	
DB18C6	Picrate	$\log K_{ex}$ [a)]	—	2.21[b)]	4.65	3.75	3.07	
DB18C6		$\log K_{D,L}$ [c)]						2.9
DB18C6		$\log K_{ML}$ [d)]	−0.3[b)]	1.24±0.02	1.67±0.02	1.07±0.02	0.94±0.02	
DB18C6	Picrate	$\log K_{ML\cdot X}$ [d)]	—	2.23±0.29	1.95±0.10	—	—	
DB18C6	Picrate	$\log K_{D,ML\cdot X}$ [e)]	—	1.7	3.9	—	—	

a) Ion-association extraction constants with picrate to benzene (Ref. 18). b) Estimated values. c) Reported value from Ref. 18. d) This study. Error: 3σ. e) Distribution coefficient of ion associate, $ML^+{\cdot}X^-$, calculated by $K_{D,ML\cdot X} = (K_{ex} \times K_{D,L})/(K_{ML} \times K_{ML\cdot X})$.

$K_{\mathrm{ML\cdot X}}$; each value is summarized in Table 3. Although the constants obtained in this study were measured at 35 °C, the constants at 25 °C would be close to the ones obtained in this study because complex formation constants are almost identical between the reported values and the ones obtained in this study and 1 : 1 ion association constants between monovalent cations and monovalent anions are only slightly affected by the temperature.(20) By comparing the values between $K_{\mathrm{ML\cdot X}}$ and $K_{\mathrm{D,ML\cdot X}}$, it is noted that the $K_{\mathrm{D,ML\cdot X}}$ value is more predominant than the $K_{\mathrm{ML\cdot X}}$ value on the extraction constant of K^+, but the $K_{\mathrm{ML\cdot X}}$ value is more predominant in Na^+. These results suggest the hydrophobic character of the K^+ complex, which is considered less hydrated than the Na^+ complex.(17) The ion associate of the complexed Na^+ with Pic^- seems to be very hydrated in an aqueous solution as is illustrated in Fig. 5, which can decrease the extractability of the ion associates into an organic phase. The greater hydrophobicity of K^+ complex is also suggested by comparing $K_{\mathrm{D,ML\cdot X}}$ values; the value of $KL^+\cdot Pic^-$ is larger than that of $NaL^+\cdot Pic^-$.

Conclusion. The proposed analysis can be used for the measurement of complex formation constants and ion association constants for an UV-absorbing crown ether. The method is especially advantageous for the reaction analysis of such compounds in aqueous solution when they are slightly soluble in water. The ion association constants in an aqueous solution analyzed by the proposed method will offer interesting information about ion association mechanisms as well as much information about the extractability and extraction mechanisms of ion associates in liquid–liquid distributions.

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