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The Chromatographic Behavior of Alkali and Alkaline Earth Metal Cations on Crown Ether-Modified Silica Gels and Polymer Matrices

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Alkali and alkaline earth metal cations were chromatographed over silica gels and polymer matrices which had been modified by the addition of benzo-15-crown-5, benzo-18-crown-6, and benzo-21-crown-7, using water as the mobile phase. The retention sequences of the cations agreed closely with the stability sequences of the corresponding crown-ether complexes. The best separation was attained on the silica gels modified by the use of benzo-18-crown-6. The retention times increased in this sequence: $Li^+<Na^+<Rb^+<Cs^+<K^+$; $Mg^{2+}<Ca^{2+}<Sr^{2+}<Ba^{2+}$. The retention sequences on the benzo-15-crown-5 and benzo-21-crown-7 columns were $Li^+<Na^+\approx Cs^+<Rb^+<K^+$ and $Li^+\approx Na^+<K^+<Rb^+\approx Cs^+$ respectively. The resin-based columns showed similar retention sequences, but were inferior in their separation ability to the silica-based ones. The retention times were affected by many factors, such as the cation concentration, the species of the counter anions, the kind and composition of the second solvents in the mixed mobile phase, and the column temperature.

Crown ethers are attractive to analytical chemists because of their selective cation-binding ability. In the field of chromatography, these substances have frequently been used as stationary phases. Four types of stationary phases have so far been developed depending on the method of crown-ether immobilization and on the kind of supporting material. Kimura et al.[1)] chromatographed alkali metal cations over ODS–silica gels coated with dodecyl-18-crown-6 or decyl-cryptand 221. Igawa et al.[2–4)] showed that silica gels coated with polyamide crown resins were useful for separating anions rather than cations. The stationary phases of this type are easy to prepare, but the loss of the crown ethers by elution is inevitable. The loss can be avoided by bonding them onto a certain supporting material. Blasius et al.[5,6)] investigated extensively the chromatographic separation of many cations on crown ether- or cryptand-containing polymer matrices. Nakajima et al.[7–9)] also studied the separation of alkali metal cations on crown-modified silica gels.

This paper will describe the immobilization of different crown ethers on silica gels and polymer matrices and the chromatographic separation behavior of the alkali and alkaline earth metal cations on these columns. Factors affecting the retention behavior were also investigated.

Experimental

Syntheses of Amino Crown Ethers. Benzo-15-crown-5 (B15C5), benzo-18-crown-6 (B18C6), and benzo-21-crown-7 (B21C7) were synthesized from catechol and 1,11-dichloro-3,6,9-trioxaundecane, 1,14-dichloro-3,6,9,12-tetraoxatetradecane, and 1,17-dichloro-3,6,9,12,15-pentaoxaheptadecane respectively by the method of Pedersen.[10)] The dichloro compounds were prepared as follows: Polyethylene glycol (average mol. wt.=400) was treated with thionyl chloride in the presence of a small quantity of pyridine, and the product was fractionated by vacuum distillation. The crown ethers thus obtained were nitrated and then reduced to their respective amino compounds according to the method of Ungaro et al.[11)]

Preparation of Crown-Modified Packings. Wakogel LC-5H (particle size: 5 µm, pore size: 60 nm) of an irregular type (Wako Chemical Industries, Ltd.) and LiChrosorb Si-100 (particle size: 5 µm, pore size: 100 nm) of a spherical type (Merck) were used as the supporting materials. The silica gels were activated by 6 M hydrochloric acid (1 M=1 mol dm^{-3}) under reflux with stirring for 8 h, washed thoroughly with water, and finally dried under a vacuum. A mixture of 5 g of the silica gels, 2 g of 6,7-epoxy-4-oxohexyltrimethoxysilane, and 100 cm^3 of dry toluene was heated under reflux with stirring for 10 h. After being separated from the mixture, the epoxy-modified silica gels were suspended in 100 cm^3 of dry toluene and then heated in the same manner in the presence of 3 g of the amino derivatives. The amount of crown ether moiety immobilized on the silica gels was determined to be 0.1—0.3 mmol per g of the dried crown-modified silica gels, judging from the weight loss on heating at 800 °C. Finally, the silica gels were treated with trimethylchlorosilane in order to endcap the residual silanol group. The estimated silica surface is shown in Fig. 1 (above).

Hitachi COOH type gels (No. 3011-C, 10—15 µm) were used as the polymer matrices. The crown ether moieties were introduced as follows: 2.6 g of the dry resins were dispersed in 40 cm^3 of toluene and treated with 4 cm^3 of thionyl chloride under reflux for 6 h. The resulting resins were washed well with dry toluene and then treated with 25 cm^3 of a pyridine solution containing 2.1 g of 4′-aminobenzo-18-crown-6 by occasional gentle swirling for two days at room temperature. The amount of the crown moiety immobilized was estimated to be 0.6 mmol per g of the crown-modified resin by measuring the amount of potassium picrate adsorbed on it. The estimated structure

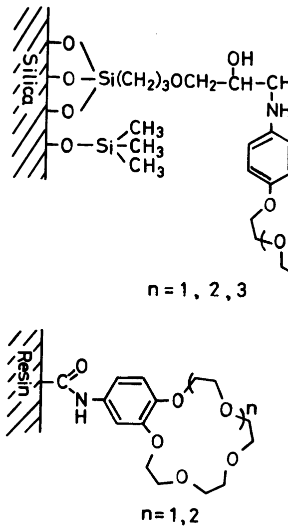

Fig. 1. Estimated structures of the crown-modified silica gel (above) and resin (below).

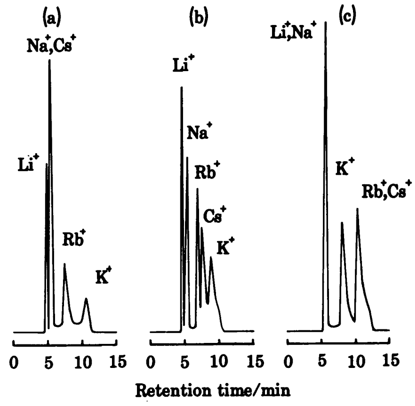

Fig. 2. Chromatograms of equimolar mixtures of alkali metal chlorides over the silica-based crown columns. (a): B15C5 ($n=1$), (b): B18C6 ($n=2$), (c): B21C7 ($n=3$).
Sample size: (a) 0.5 M, 3 μl (1l$=$1000 cm^3); (b) 0.05 M, 5 μl; (c) 0.01 M, 5 μl.
Mobile phase: water, Flow rate: 0.5 ml min^{-1}.

is also shown in Fig. 1 (below).

Packing to Columns. The crown-modified silica-based packings were made balanced-density slurries by ultrasonic mixing with a Chemco C-type slurry solvent (Chemco Scientific Co., Ltd.) and pumped into stainless-steel columns (4 mm i.d., 250 mm length) with methanol according to a given pressure program by using a Model 124 Chemco Slurry-Packing Apparatus. The crown-modified resin-based packings were packed in a similar manner by using a methanol–chloroform mixture as the slurry solvent. The columns thus obtained were conditioned by elution with methanol and then a large quantity of water.

Materials. The alkali and alkaline earth metal salts were of an analytical grade. The water was purified by the use of an Auto Still (Model WAG-28, Yamato Scientific Co., Ltd.) equipped with ion-exchange resins and a glass-made distilling apparatus. The resulting water was distilled again with an all-quartz-made, non-boiling type distilling apparatus (HF-200, Fujiwara Seisakusho Co., Ltd.), preventing contamination of the water with CO_2 in the air.

Chromatographic Measurements. An assembly consisting of a pump (Shimadzu LC-5A), a sample injector (Rheodyne 7125), a conductometric detector (LDC conducto Monitor), and a recorder (YHP Reporting Integrator 3390A) was used for high-performance liquid chromatography. Freshly distilled water was used as the mobile phase. For the silica-based columns, the pressure drops were about 50 kg cm^{-2} at a flow rate of 0.5 cm^3 min^{-1} and for the resin-based ones, less than 20 kg cm^{-2} at a flow rate of 1.0 cm^3 min^{-1}. Chromatography was performed at 25 °C unless otherwise stated.

Results and Discussion

Separation of Alkali and Alkaline Earth Metal Cations. Typical chromatograms of the alkali metal cations on the crown-modified silica-gel columns are shown in Fig. 2. Li$^+$, Na$^+$, K$^+$, Rb$^+$, and Cs$^+$ were separated satisfactorily from each other on the B18C6-modified silica-gel (B18C6–Si) column. Na$^+$ was not separated from Cs$^+$ on the B15C5-Si column. Two pairs of ions, Li$^+$/Na$^+$ and Rb$^+$/Cs$^+$, were not separated on the B21C7–Si column. Figure 2 also shows that the retention sequences vary greatly according to the ring size of the crown ether moieties; the retention times on the B15C5–Si, B18C6–Si, and B21C7–Si columns increased in this sequence: $\mathrm{Li^+<Na^+\approx Cs^+<Rb^+<K^+}$; $\mathrm{Li^+<Na^+<Rb^+<Cs^+<K^+}$; and $\mathrm{Li^+\approx Na^+<K^+<Rb^+\approx Cs^+}$ respectively.

Crown ethers are known to form 'metal-in-the-hole'-type complexes with many cations. Cations which fit into the hole of the crown ether form stable complexes of 1:1 stoichiometry. On the other hand, cations which are too large to fit into the molecular hole tend to form 1:2 (cation:crown) complexes, which are, in most cases, more stable than the 1:1 complexes. It is natural to consider that cations which can form more stable complexes are retained more strongly. The retention sequence on the B15C5-Si column can be elucidated on the basis of the stability sequence by assuming the 1:2 interactions for K$^+$ and Rb$^+$ (Table 1). The retention sequence on the B21C7–Si column was consistent with the stability sequence. For the B18C6–Si columns, both sequences agreed well; however, it was found that, in certain columns, Cs$^+$ appeared in the eluents before Rb$^+$, whereas, in other columns, it appeared as late as K$^+$. Nakajima et al.[8] indicated that poly(benzo-18-crown-6)- and bis(benzo-18-crown-6)-modified silica-gel columns possessing neighboring crown ether moieties were favorable for forming 1:2 complexes with Cs$^+$ and retained it most strongly among the alkali metal cations. Taking into account the fact that the densities of the crown ether moieties

Table 1. Stability Constants (logarithmic unit) of Crown Ether Complexes with Alkali and Alkaline Earth Metal Cations

Cation	r/nm[a)]	B15C5[b)] in 70% MeOH	18C6[c)] in H_2O	21C7[d)] in MeOH
Li^+	0.068			
Na^+	0.097	1.99	0.8	
K^+	0.133	1.5, 4.15[e)]	2.03	4.41
Rb^+	0.147	1.8, 3.77[e)]	1.56	
Cs^+	0.167	1.7	0.99	5.02
Ca^{2+}	0.099		<0.5[f)]	
Sr^{2+}	0.112		2.72	
Ba^{2+}	0.134		3.87	

a) Ionic radii, Ref. 12. b) Benzo-15-crown-5, Ref. 13. c) 18-Crown-6, Ref. 14. d) 21-Crown-7, Ref. 15. e) 1:2 (Cation : crown) complex. f) Ref. 15.

of the present columns are as high as those of their columns (0.3 mm g^{-1}), it is probable that, even in the present columns, Cs^+ forms the 1:2 complexes to an appreciable extent, though the spatial arrangement of the crown ether moieties is less favorable than that of their columns. It seems, therefore, natural to consider that the columns with a high crown density retain Cs^+ longer.

The pore size of the silica gels showed no appreciable effect on the elution behavior of the cations.

Separation of Alkaline Earth Metal Cations. Chromatograms of the alkaline earth metal cations on the B15C5- and B18C6-Si columns are shown in Fig. 3((a) and (b)). The retention sequence on the former column was $Mg^{2+} \approx Ca^{2+} < Sr^{2+} < Ba^{2+}$; Mg^{2+} was not separated from Ca^{2+}. On the other hand, the retention sequence on the latter column was $Mg^{2+} < Ca^{2+} < Sr^{2+} < Ba^{2+}$; the separation of Mg^{2+} from Ca^{2+} was still unsatisfactory.

A mixture of the alkali and alkaline earth metal cations was chromatographed over the B18C6-Si column (Fig. 3(c)). Na^+, Sr^{2+}, and Rb^+ were separated from each other almost satisfactorily. The separation of Ca^{2+} from Li^+ was not achieved. The retention sequence agreed with the stability sequence. Sr^{2+}, however, was retained more weakly than had been expected from its stability constant.

A few univalent cations other than the alkali metal cations were chromatographed over the B18C6-Si column. Tl^+ was retained longer than K^+. Ag^+ was not detected as a peak. Quarternary ammonium salts were all eluted so rapidly that they were only poorly separated, the retention sequence being: benzyltrimethylammonium<trimethylammonium≈ammonium ions.

Counter Anions. Many investigators[3–8)] have pointed out that the retention times of cations on crown-modified columns were affected markedly by the anion species also present. In the present work, the effect of anions was investigated by using the B18C6- and B21C7-Si columns. The retention times obtained are summarized in Table 2, together with the anionic radii. From Table 2, it is clear that the retention times increase with an increase in the ionic size: $Cl^- < Br^- < NO_3^- < I^- < SCN^-$. This sequence

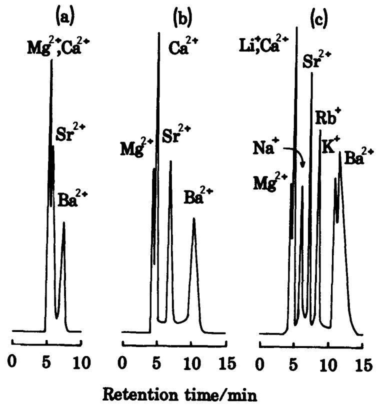

Fig. 3. Chromatograms of alkaline earth metal chlorides over the silica-based crown columns.
(a): B15C5, (b): B18C6, (c): B18C6.
Sample size: (a) 0.05 M (equimolar mixture), 3 μl; (b) 0.05 M (equimloar mixture), 5 μl; (c) 0.05 M (Li : Na : K : Rb = 1 : 1 : 2 : 2 , Mg : Ca : Sr : Ba = 1 : 1 : 2 : 2)., 5 μl.
Mobile phase: water, Flow rate: 0.5 ml min^{-1}.

Table 2. The Effect of Counter Anions on the Retention Time on the Silica-Based Columns[a)]

Anion	B18C6		B21C7		r_{cryst}[b)]
	Na^+	K^+	Na^+	K^+	
Cl^-	7.43	12.32	5.51	7.69	1.81
Br^-	7.55	12.50	5.69	8.13	1.96
I^-	8.17	14.97	6.34	9.71	2.20
NO_2^-	7.48		5.66		
NO_3^-	7.77	12.63	5.83	8.42	1.89[c)]
$HCOO^-$	7.45		5.49		
CH_3COO^-	7.53		5.52		
ClO_2^-	7.48		5.52		
ClO_3^-	7.70	12.65	5.76	8.29	2.00[c)]
ClO_4^-	8.85	15.93	7.22	11.88	2.36[c)]
BrO_3^-		11.95		7.67	
IO_3^-		11.30		7.36	
SCN^-	9.97				
Pic^-[d)]	21.83		18.71		
SO_4^{2-}	7.87	16.15	5.43	8.63	
$[Fe(CN)_6]^{3-}$		11.07		19.92	
$[Fe(CN)_6]^{4-}$		11.12		21.46	

a) Mobile phase: water, Flow rate: 0.4 cm^3 min^{-1}, Sample size: 0.1 mol dm^{-3}, 5 μl (1 l = 1000 cm^3), Temp: 20 °C. b) Ref. 12. c) Ref. 16. d) 0.05 mol dm^{-3} picrate.

agreed with that reported by Igawa et al.[3] In the present experiment, however, SO_4^{2-} was not eluted so fast as they reported. The retention sequence for some oxyacid anions was $IO_3^- < BrO_3^- < ClO_3^-$, the sequence being difficult to explain from the size effect alone. In Fig. 4, the retention time is plotted against the lyotropic number,[17] which reflects the hydrophobic nature of anions. The higher the hydrophobicity, the longer the retention time becomes. It should be noted that ClO_4^- is retained much longer on the stationary phase. In Fig. 5, the retention time is plotted against the *A* value introduced by Motomizu.[18] He indicated that the extraction constants, K_{ex}, for the chloroform extraction of ion pairs could be divided into two terms: $\log K_{ex} = C + A$, where *C* and *A* represent the extractabilities of the cation and anion species respectively. The *A* value further reflects the hydrophobicity and the ion-pair formation ability of the anion. Figure 5 shows that, for many anions, the retention times are closely related to the *A* values. It is of interest to note that, in Fig. 5, the plot of ClO_4^- falls on a curve, unlike as in Fig. 4. It can be concluded that so-called soft anions are retained strongly on the crown-modified silica-gel columns. Table 2 shows that $[Fe(CN)_6]^{3-}$ and $[Fe(CN)_6]^{4-}$ are retained very weakly on the B18C6-Si column, whereas they are retained very strongly on the B21C7-Si column. The reason for this is not clear.

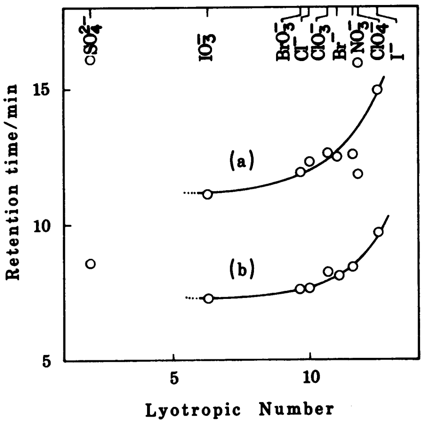

Fig. 4. Plots of retention time on the silica-based columns vs. the lyotropic number of anions.
(a): B18C6, (b): B21C7, Counter ion: K^+, Chromatographic conditions: see Table 2.

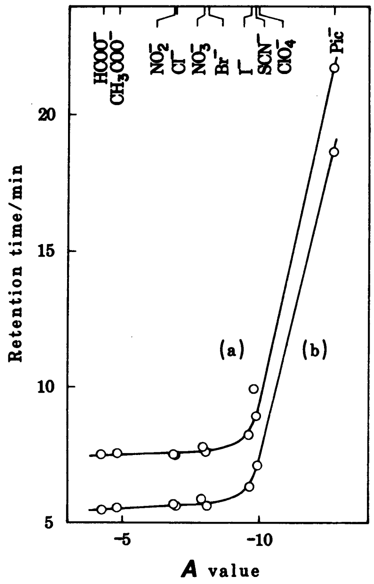

Fig. 5. Plots of retention time on the silica-based columns vs. the *A* value of anions.
(a): B18C6, (b): B21C7, Counter ion: Na^+, Chromatographic conditions: see Table 2.

Cation Concentration. The alkali metal cations were chromatographed separately over the B18C6-Si column by varying their concentrations (Fig. 6). The peak area yielded a straight line when plotted against the concentration, the linear range being from about 0.005 to 0.06 mol dm^{-3}. The lower concentration limit differed slightly with different cations; the limit appeared at somewhat higher concentrations for strongly retained cations (K^+, Cs^+, and Rb^+). Just outside the lower limit, the peak heights decreased rapidly with a decrease in the concentration, until finally the peak disappeared below the very broad, irregularly shaped background peak. The background peaks of this type were observed for all the cations tested, regardless of the species of the crown ether moieties. Therefore, the base-line separation among the strongly retained cations was not achieved (Figs. 2 and 3). Figure 7 shows that the retention time increases with a decrease in the cation concentration, the rate of increase being greater at lower concentrations. The peak assignment of the chromatograms must be made carefully because the

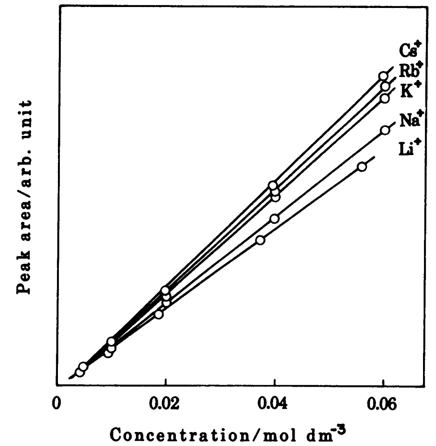

Fig. 6. Calibration curves of alkali metal chlorides on the silica-based B18C6 column.
Sample size: 5 μl, Flow rate: 0.2 ml min^{-1}.

retention time depends not only on the species of the counter anion, but also on the cation concentration.

Water-Methanol as the Mobile Phase. The stability constants of crown ether complexes are known to be three to four decades higher in methanol than in water.[19)] Izatt et al.[13)] showed clearly that the stability constants of benzo-15-crown-5 complexes increased regularly as the methanol portion of water-methanol mixtures was increased. Figure 8 shows that the retention times of the alkali metal cations increase with an increase in the methanol fraction, in accordance with the observation of Izatt et al. This figure also shows that the retention-time differences between any two cations become greater as the methanol portion increases; this finding implies that the addition of methanol improves the separation of the cations. With this in mind, the alkali metal cations were chromatographed over the B18C6-Si column by using a water-methanol (20% v/v) mixture as the mobile phase. However, little improvement was observed because of the broadening of the peaks. Pure water, therefore, is recommended as the mobile phase from the practical point of view.

Crown-Modified Resin Columns. The chromatographic behavior of the alkali metal cations was investigated on the resin-based B15C5 and B18C6 columns. Some typical chromatograms are shown in Fig. 9. The retention sequences of the cations on the B15C5- and B18C6-resin columns were $Li^+ < Na^+ \approx Cs^+ < Rb^+ < K^+$ and $Li^+ < Na^+ < Cs^+ \approx Rb^+ < K^+$ respectively. The retention behavior was very similar to that observed on the corresponding silica-based column (cf. Fig. 2 (a) and (b)). The separation patterns, however, were not so good as the silica-based columns. Na^+ was also not separated from Cs^+ on the B15C5-resin column. A linear relation between the peak area and the cation concentration was also observed with the resin-based columns in the range from about 0.01 to 0.1 M; the lower limit of the linear range was slightly higher than that of the silica-based column. It was noted that the retention time on the resin-based columns increased with an increase in the cation concentration, unlike the case with the silica-based columns.

Figure 10 shows that the retention time of the alkali metal cations depends to a considerable extent on the second solvent species. The addition of methanol increased the retention times, as has been mentioned above. On the other hand, the addition of

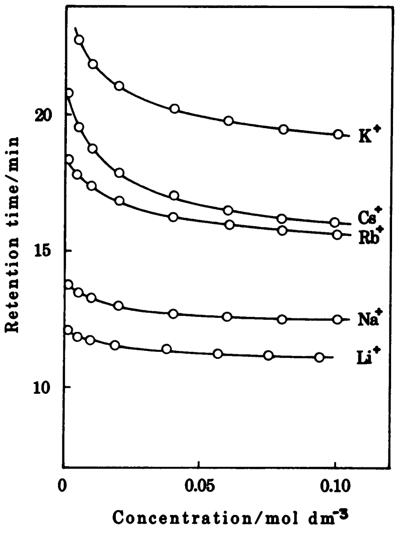

Fig. 7. Concentration dependence of the retention times of alkali metal cations on the silica-based B18C6 column.
Sample size: 5 μl, Flow rate: 0.2 ml min^{-1}.

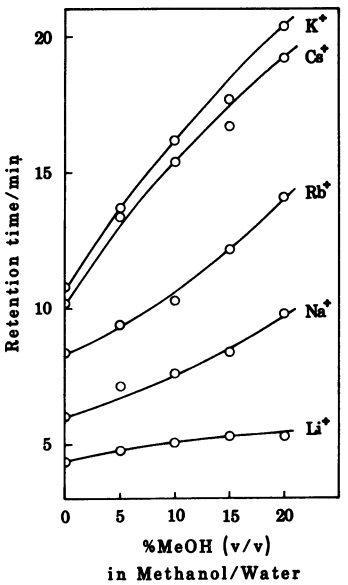

Fig. 8. Effect of methanol content on the retention times of alkali metal cations on the silica-based B18C6 column.
Sample size: 0.05 M, 1.5 μl, Flow rate: 0.5 ml min^{-1}.

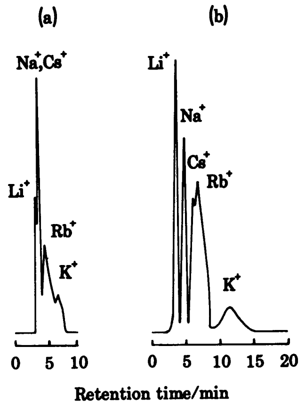

Fig. 9. Chromatograms of equimolar mixtures of alkali metal cations over the resin-based crown columns. (a): B15C5, (b): B18C6.
Sample size: 0.1 M, 5 μl, Mobile phase: water, Flow rate: 1.2 ml min^{-1}.

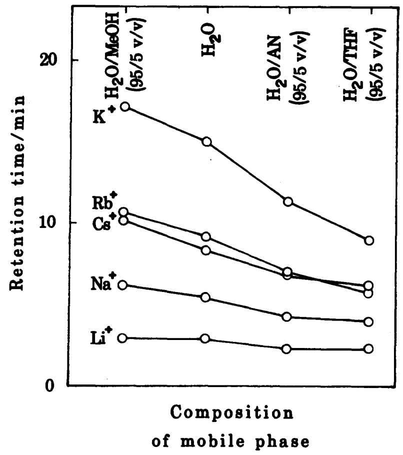

Fig. 10. Effect of the composition of mobile phase on the retention times of alkali metal cations.
AN: acetonitrile, THF: tetrahydrofuran.
Column: resin-based B18C6, Sample size: 0.1 M, 5 µl, Flow rate: 1 ml min^{-1}.

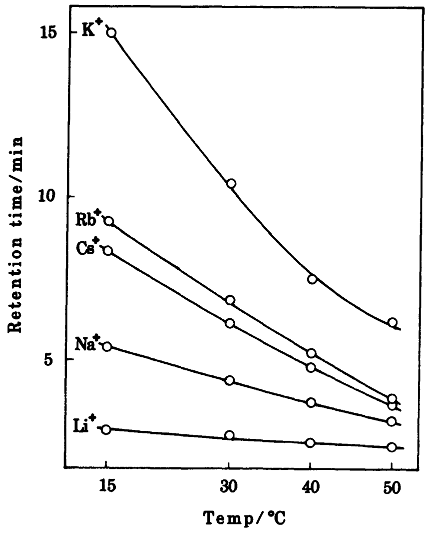

Fig. 11. Temperature dependence of the retention times of alkali metal cations.
Column: resin-based B18C6, Sample size: 0.1 M, 5 µl, Flow rate: 1 ml min^{-1}.

acetonitrile or tetrahydrofuran decreased the retention times. This phenomenon can not be elucidated in terms of the stability of the complexes, for the alkali metal–B18C6 complexes are more stable in these solvents than in water.[20,21]

The effect of the temperature on the retention times can be seen from Fig. 11. It was observed that, at lower temperatures, the separation was slightly improved. However, Cs$^+$ was not separated successfully from Rb$^+$, not even at 15 °C.

Silica- and Resin-Based Columns. The alkali and alkaline earth metal cations were most successfully separated on the B18C6-modified columns, without distinction of the matrices. However, a detailed comparison of the matrices of different types is difficult because conditions, such as the particle size, the pore size, and the density of the crown moiety, are not the same for both types of matrices. The separation ability of the resin-based columns seems to be inferior to that of the silica-based ones. However, further research on the resin-based columns is not hopeless if the fact that the chromatographic peaks on these columns show a better symmetry is taken into account.

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