CHEMISTRY LETTERS, pp. 1595-1598, 1993.

Alkali Metal Selectivity of Calix[n]aryl Acetates as Estimated by Mass Spectrometry on the Relative Stability of the 2:1 Metal/Calix[n]arene Complex

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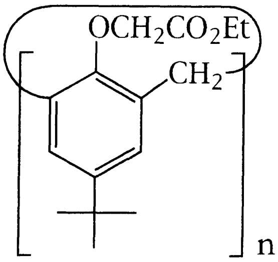
It was found that the metal selectivity of calix[n]aryl acetates (n=4, 6, and 8) can be conveniently estimated by mass spectrometry. The results have disclosed several new phenomena which cannot be found through conventional solvent extraction.

Calix[n]aryl acetates and acetamides possess an ionophoric cavity composed of $OCH_2C(=O)$ groups, which can selectively bind alkali metal cations.1) When comparing with the cation-binding properties of a crown ether family, we can raise several characteristics of a calix[n]arene family as an ionophore: (i) calix[4]aryl acetates and acetamides show the very high Na^+ selectivity,1-5) (ii) the dynamic association-dissociation process is relatively slow,6,7) and (iii) since the ionophoric cavity is situated in a deep cleft on the lower rim, they cannot form a 1:2 metal/calix[n]arene complex as crown ethers do.4) Very recently, Casnati *et al.*8) reported that in fast atom bombardment mass (FAB Mass) spectrometry a calix[6]aryl acetamide derivative gives a peak for a 2:1 metal/calix[6]arene complex in addition to a peak for a 1:1 complex. However, the report is so fragmentary that it is not clear if the mass spectrometric method is useful to estimate the alkali metal selectivity for calix[n]arene-based ionophores.9) Here, we systematically studied the metal-binding properties of calix[n]aryl acetates (**1**n), particularly from the viewpoints of (i) the effect of the ring size, (ii) the effect of the counteranion, and (iii) the relative stability of the 2:1 complex versus the 1:1 complex.



1n (n=4, 6, and 8)

The synthesis of **1**n was described previously.4) Positive secondary ion mass spectrometry (SIMS) was performed on a Hitachi M-2500 mass spectrometer. **1**n (50 mmol dm^{-3}, 1 μl in chloroform), 1 μl of *m*-nitrobenzyl alcohol, and alkali metal halide (MX: 50 mmol dm^{-3}, 2 μl in methanol) were mixed. After 10 min the mixture was loaded on the silver target. Xe^+ was employed as a primary ion, which was accelerated at 6.0 kV. Secondary ions were accelerated at 2.5

kV. In most cases we could observe both peaks for $[\mathbf{1}_n + \mathrm{M}]^+$ and $[\mathbf{1}_n + 2\mathrm{M} + \mathrm{X}]^+$.

Figure 1 shows the relative peak intensities for $[\mathbf{1}_n + \mathrm{M}]^+$ versus $[\mathbf{1}_n + \mathrm{Na}]^+$. A number of interesting points can be raised about the data. As expected, **1**$_4$ shows the sharp selectivity for Na^+. **1**$_6$ shows the affinity with Na^+, K^+, and Cs^+ but the highest selectivity is observed for Na^+ but not for K^+ as expected from the extraction data.1-5) The trend implies that **1**$_6$ shows the *apparent* selectivity for K^+ when metal cations are solvated whereas it shows the *true* selectivity for Na^+ when metal cations are not solvated. **1**$_8$ shows the broad affinity with all metal cations, reflecting the flexibility of the ionophoric cavity.

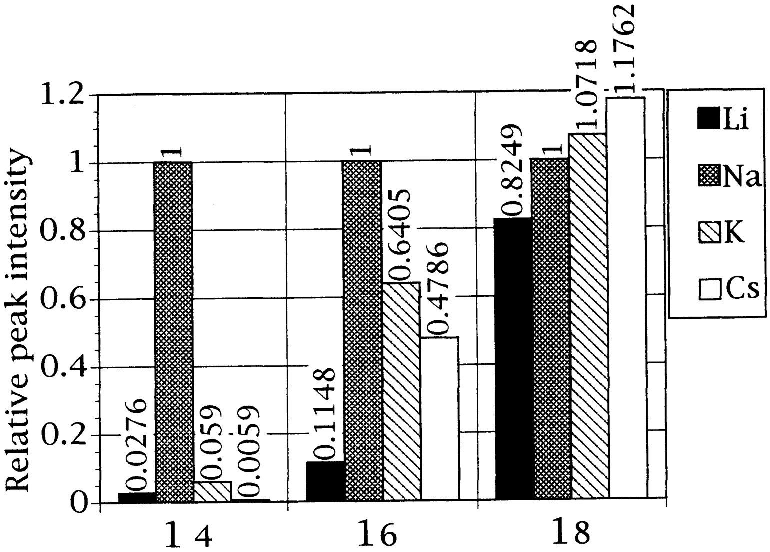


Fig. 1. Relative peak intensities for $[\mathbf{1}n + \mathrm{M}]^+/[\mathbf{1}n + \mathrm{Na}]^+$ obtained from the mixture of **1**n and an equimolar amount of NaI and MI.

In Fig. 1, one can compare the data for the same calixarene but cannot compare them for other calixarene. We measured the peak intensities for NaI in the presence of an equimolar amount of **1**$_4$, **1**$_6$, and **1**$_8$. The relative intensity for $[\mathbf{1}_n + \mathrm{Na}]^+$ was 1.000:0.0595:0.0194. This ratio can be regarded to be the "absolute ionophoricity" of these three homologs. The data in Fig. 1 can be normalized by multiplying these factors. We thus obtained Fig. 2 in which all the data can be discussed under the normalized condition. It is clearly seen from Fig. 2 that calix[n]aryl acetates are characterized by the high affinity and specificity of **1**$_4$ toward Na^+.

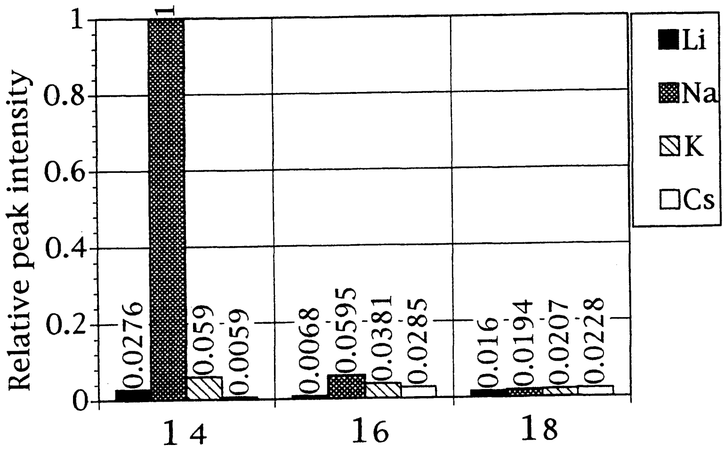


Fig. 2. Metal affinity of **1**n under the normalized condition.

Next, we estimated the stability of 2:1 metal/calix[n]arene complexes by the ratio of $[\mathbf{1}_n + 2\mathrm{M} + \mathrm{X}]^+/[\mathbf{1}_n + \mathrm{M}]^+$. As shown in Fig. 3, **1**$_6$ and **1**$_8$ with a large ionophoric cavity form the 2:1 complexes in a significant stability with respect to the 1:1 complexes. Although the $[\mathbf{1}_n + \mathrm{M}]^+$ was scarcely affected by the counteranion, the $[\mathbf{1}_n + 2M + X]^+$ was significantly affected. For X^-=Cl^- the stable 2:1 complexes were observed with $\mathbf{1}_6$ whereas for X^-=I^- they were observed with $\mathbf{1}_8$. How can we rationalize this counteranion effect?

It is reasonable to consider that to reduce the electrostatic repulsion two metal cations and X^- form a sandwich structure as in Fig. 4. The metal selectivities shown in Fig. 3 manifest that the ionophoric cavity of $\mathbf{1}_6$ has the spectrum from $2Li^+ + Cl^-$ (x=6.38 Å) to $2Na^+ + Cl^-$ (x=7.42 Å) whereas that of $\mathbf{1}_8$ has the spectrum from $2Li^+ + I^-$ (x=7.16 Å) to $2K^+ + I^-$ (9.64 Å). On the other hand, these calixarene cannot efficiently bind $2M^+ + X^-$ with the larger x values: for example, $\mathbf{1}_6$ only weakly includes $2M^+ + X^-$ with x>8.8 Å(*e.g.*, $2K^+ + Cl^-$ (x=8.86 Å) and $2K^+ + I^-$ (x=9.64 Å)) and $\mathbf{1}_8$ scarcely includes $2Cs^+ + X^-$ with x>10 Å(*e.g.*, $2Cs^+ + Cl^-$ (x=10.14 Å) and $2Cs^+ + I^-$ (x=10.94 Å)). The results indicate that the inclusion of two metal cations is basically controlled by the hole-size selectivity although the selectivity is not so high probably because of the ring flexibility.

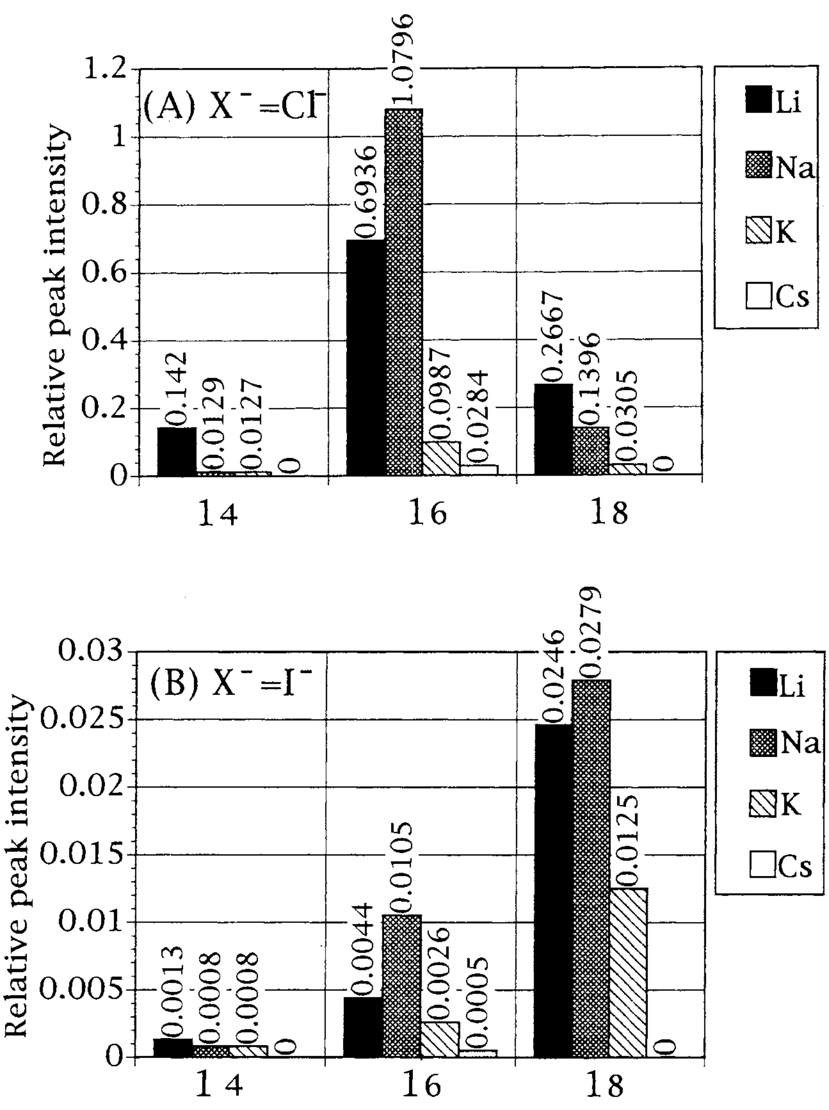


Fig. 3. Peak intensity for $[\mathbf{1}n + 2M + X]^+/[\mathbf{1}n + M]^+$: (A) X^-=Cl^-, (B) X^-=I^-.

In conclusion, the present study demonstrated that the controlling factors for the stability of 1:1 and 2:1 metal/calix[n]arene complexes can be conveniently estimated by mass spectrometric techniques. The results have disclosed the formation of 2:1 complexes, solvation effects, counteranion effects, *etc.* which cannot be estimated through conventional solvent extraction.

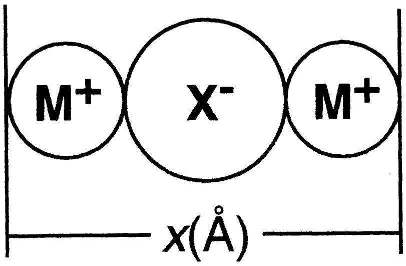


Fig. 4. Distance for the sandwich structure of $2M^+ + X^-$.

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(Received June 10, 1993)