Uncommon Complex Stoicheiometry in Solvent Extraction: Solution-phase Dicationic Complex Formation of Crown Ethers[†]

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A solvent extraction study with 18-crown-6, 24-crown-8, and their dibenzo-derivatives has revealed that the following ligand–cation combinations give dicationic complexes in the solution phase: 18-crown-6 with Li^+; 24-crown-8 with Li^+, Na^+, K^+; dibenzo-24-crown-8 with Na^+, K^+, Ag^+, Sr^{2+}. The facile formation of dicationic complexes in the solvent extraction is attributed to the effective charge-shielding co-ordination by the bulky, lipophilic picrate anions in the contact ion-pair complex extracted.

The complexation stoicheiometry of a guest cation and a host crown ether has long been the subject of extensive investigations ever since the very first preparation of crown ethers by Pedersen.[1] The observed complex stoicheiometry of simple crown ethers has been discussed from the viewpoint of the size-fit concept, in which the relationship between the cation and cavity sizes plays an important role.[2,3,‡] The size-matched combinations of cations and ligands yield the 1:1 complexes, while cations larger in size than the ligand cavity lead to the 1:2 sandwich complexes. On the other hand, large-sized ligands with sufficient flexibility bind small cations in the induced three-dimensional cavity, giving rise to the 1:1 encapsulating complexes as is the case with the some natural antibiotic ionophores.[3]

In the crystalline state, yet another stoicheiometry has been found for two large-sized, somewhat rigid crown ethers, dibenzo-24-crown-8 and dibenzo-30-crown-10, which preferentially form binuclear complexes with two sodium and, in the former case, potassium ions, in which two cations, nesting in the same cavity of one ligand molecule, accept bridging co-ordination by the counter anions from both sides of the ligand plane.[4] By contrast, it has been reported also that these combinations merely gave 1:1 complexes upon solvent extraction and/or homogeneous-phase complexation without any indication of dicationic complex formation.[5] This apparent discrepancy has not been explained, although all of the other complex stoicheiometries, *i.e.* regular 1:1, sandwich-like 1:2, encapsulating 1:1 cation:ligand ratios, have been demonstrated to exist in both solution and solid phases. However, any of the above results do not immediately exclude the possibility of all dicationic complexes of small cations with large-sized ligands, since the encapsulating complexation is the only process competing with the dicationic complexation and is considered to be sensitive to the ligand rigidity and the environmental conditions including the phase, solvent, and counter anion employed.

In the present paper we report a quantitative solvent extraction study of dicationic complex formation in the solution phase; extensive screening was carried out with all alkali and some alkaline-earth and heavy metal picrates, using common 18-crown-6, 24-crown-8, and their dibenzo-derivatives as ligands. The present work reveals that, contrary to the previous reports,[5] several crown ethers, not restricted to those of large size, do form dicationic complexes with small-to medium-sized cations in the solution phase, suggesting that dicationic complexation is one of the prime modes of complexation for size-mismatched cation–ligand combinations.

Experimental

Materials.—Ligands. Commercially available 18-crown-6 (Nisso), dibenzo-18-crown-6 (Merck), and dibenzo-24-crown-8 (Merck) were used without further purification. 24-Crown-8 was synthesized in 7% yield by the reaction of tetraethylene glycol ditosylate with tetraethylene glycol in the presence of excess potassium hydroxide in tetrahydrofuran under similar conditions to those reported previously.[6]

Metal picrates.[§] All metal picrates, except for lithium picrate, were synthesized and purified according to the procedures reported previously.[6,7]

Lithium picrate. Picric acid (2.5 g, 11 mmol), recrystallized from water and dried *in vacuo* at room temperature in the dark, was dissolved in hot ethanol (30 cm^3), to which lithium carbonate (0.4 g, 5.3 mmol) was added portionwise. The mixture was stirred for 10 min and then filtered while hot. The filtrate was cooled in an ice-bath to give a crystalline precipitate, which was recrystallized from ethanol: yield 1.1 g (43%). The lithium picrate obtained was the monohydrate (Found: C, 28.4; H, 1.65; N, 16.35. Calc. for $C_6H_2LiN_3O_7{\cdot}H_2O$: C, 28.5; H, 1.60; N, 16.60%). U.v.: $\lambda_{max.}(\varepsilon)$ 357 (13 500) in H_2O; 376 nm (16 600 dm^3 mol^{-1} cm^{-1}) in CH_2Cl_2–CH_3CN (1:1).

Solvent Extractions.—The quantitative solvent extraction and the determination of the extraction equilibrium constants were carried out according to the following procedures.[6]

Dichloromethane solutions (10 cm^3) of a ligand of various concentration ranges (0.002—0.15 mol dm^{-3}, depending upon its extractability) and aqueous solutions (10 cm^3) of each metal picrate (fixed at 0.003 mol dm^{-3} concentration) were introduced into Erlenmeyer flasks, which were then stoppered and shaken reciprocally for 10 min in a Taiyo M100L incubator thermostatted at 25.0 ± 0.1 °C. This period of shaking was long

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[†] Abbreviations: 18-crown-6 = 1,4,7,10,13,16-hexaoxacyclo-octadecane, 24-crown-8 = 1,4,7,10,13,16,19,22-octaoxacyclotetracosane, dibenzo-24-crown-8 = 6,7,9,10,12,13,20,21,23,24,26,27-dodecahydrodibenz[*b,n*][1,4,7,10,13,16,19,22]octaoxacyclotetracosin, dibenzo-30-crown-10 = 6,7,9,10,12,13,15,16,23,24,26,27,29,30,32,33-hexadecahydrodibenzo[*b,q*][1,4,7,10,13,16,19,22,25,28]decaoxacyclotriacontin.

[‡] It has been shown that, with some flexible macrocycles and N-pivot lariat ethers, possessing additional binding sites(s) in a side arm, the hole-size relationship fails to explain cation selectivity: R. A. Schultz, B. D. White, D. M. Dishong, K. A. Arnold, and G. W. Gokel, *J. Am. Chem. Soc.*, 1985, **107**, 6659; G. Michaux and J. Reisse, *ibid.*, 1982, **104**, 6895.

[§] Caution should be exercised in the synthesis and handling of metal picrates, since they are highly sensitive to heat and shock in the crystalline state: T. Watanabe, Y. Nemoto, and H. Takahashi, *Kogyo Kayaku Kyokaishi*, 1963, **24**, 339.

Table. Extraction equilibrium constants (K_{ex}) for conventional 1:1 and dicationic 2:1 (values in italics) complexations of some crown ethers with alkali, alkaline-earth, and heavy metal picrates in a water–dichloromethane system at 25 °C

	log K_{ex}								
Ligand	Li^+	Na^+	K^+	Rb^+	Cs^+	Ag^+	Tl^+	Sr^{2+}	Ba^{2+}
18-Crown-6	*7.43*[a]	3.89	6.20	5.96	5.17	5.09	6.71	*b*	*b*
Dibenzo-18-crown-6	2.16	2.81	4.84	4.43	4.08	3.74	5.02	5.69	*b*
24-Crown-8	*8.10*[a]	*8.68*[a]	*9.44*[a]	4.83	5.17	4.70	5.65	6.77	8.54
Dibenzo-24-crown-8	*b*	*8.49*[a]	*8.99*[a]	4.33	4.54	*8.55*[a]	5.07	*11.70*[a]	7.19

[a] Values for dicationic 2:1 complexation; no 1:1 complexation observed. [b] Not determined.

enough to establish the equilibrium between the two phases, since periods of 5 or 20 min gave identical results. The resulting mixtures were allowed to stand for at least 2 h at that temperature in order to complete the phase separation. In the experiments using alkali- and heavy-metal picrates, an aliquot (usually 5 cm^3) was withdrawn from each organic phase and was diluted with dichloromethane–acetonitrile (1:1) to give a solution of appropriate concentration for spectrophotometric analysis. With alkaline-earth picrates, the aliquot withdrawn was dried *in vacuo* and the residue was diluted with acetonitrile. The picrate concentrations in the diluted solutions were determined from absorption maxima at 375—376 nm. The molar absorption coefficients of the metal picrates at the absorption maxima (375—376 nm) were 18 600 (sodium), 19 000 (potassium), 18 800 (rubidium), 18 500 (caesium), 18 800 (silver), 18 900 (thallium), 29 400 (magnesium), 29 700 (calcium), 29 500 (strontium), and 29 000 dm^3 mol^{-1} cm^{-1} (barium) in dichloromethane–acetonitrile (1:1) (monovalent metal picrates) or in acetonitrile (divalent metal picrates).

In control runs, no detectable amounts of any picrates were extracted into the organic phase in the absence of crown ethers. In some extraction experiments which gave moderate to high extractabilities, the picrate concentrations in both organic and aqueous phases were measured in order to cross-check the mass balance. The sum of the picrate concentrations in both phases (2.94—3.05 mmol dm^{-3}) was practically identical to the initial picrate concentration (3.0 mmol dm^{-3}) in the aqueous phase in every case examined.

According to the extraction equilibrium indicated in the Results and Discussion section, the concentration of free crown ether (L) in the organic phase, $[\mathrm{L}]_{\mathrm{org}}$, was calculated by equation (1), where $[\mathrm{L}]_i$ is the initial concentration of crown

$$[\mathrm{L}]_{\mathrm{org}} = [\mathrm{L}]_i - n[\mathrm{M}_k\mathrm{L}_n\mathrm{A}_{km}]_{\mathrm{org}} - [\mathrm{L}]_{\mathrm{aq}} \qquad (1)$$

ether dissolved in the organic phase. The distribution of free crown ether between the two phases is expressed as in equation (2). From three independent runs, the distribution coefficients

$$\mathrm{L}_{\mathrm{org}} \xrightleftharpoons{K_d} \mathrm{L}_{\mathrm{aq}}$$
$$K_d = [\mathrm{L}]_{\mathrm{aq}}/[\mathrm{L}]_{\mathrm{org}} \qquad (2)$$

(K_d) of crown ethers between aqueous and organic phases were determined gravimetrically at 25 °C as 0.289 and 0.162 for 18-crown-6 and 24-crown-8, respectively, according to the method reported.[6a] Although the distributions of dibenzo-derivatives were examined by spectrophotometric analyses of the aqueous and organic phases separated from the equilibrated mixture, the K_d values were shown to be $\ll 0.0$ and were therefore taken as zero in the calculation.

Substitution of $[\mathrm{L}]_{\mathrm{aq}}$ in equation (1) by equation (2) leads to equation (3), which was actually used to calculate the $[\mathrm{L}]_{\mathrm{org}}$ values.

$$[\mathrm{L}]_{\mathrm{org}} = ([\mathrm{L}]_i - n[\mathrm{M}_k\mathrm{L}_n\mathrm{A}_{km}]_{\mathrm{org}})/(1 + K_d) \qquad (3)$$

Subsequent analysis of the results, described in the following section, gave the K_{ex} values, and the complex stoicheiometries for the specific combinations of metal picrate and ligand.

The continuous variation method[8] was employed in the solvent extraction of aqueous sodium and caesium picrates with dibenzo-24-crown-8 in dichloromethane; the sum of initial metal ion and picrate concentrations, $[\mathrm{M}^+]_i + [\mathrm{A}^-]_i$, was varied, while the total concentration, $[\mathrm{M}^+]_i + [\mathrm{A}^-]_i + [\mathrm{L}]_i$, was kept constant at 0.01 mol dm^{-3}. Each extract was diluted with the same amount of dichloromethane–acetonitrile (1:1) to an appropriate concentration to fit into the measuring range of the spectrometer (absorbance <2.0).

Results and Discussion

Assuming only one extracted species, the overall extraction equilibrium between an aqueous (aq) solution of metal picrate (MA_m) and an organic (org) solution of ligand (L) is expressed in the general form of equation (4), where the ratio $k:n$ denotes

$$k\mathrm{M}^{m+}{}_{\mathrm{aq}} + km\mathrm{A}^-{}_{\mathrm{aq}} + n\mathrm{L}_{\mathrm{org}} \rightleftharpoons [\mathrm{M}_k\mathrm{L}_n\mathrm{A}_{km}]_{\mathrm{org}} \qquad (4)$$

the cation:ligand stoicheiometry. The equilibrium constant (K_{ex}) is given by equations (5) and (6), since $[\mathrm{M}^{m+}]_{\mathrm{aq}} = [\mathrm{A}^-]_{\mathrm{aq}}/m$ in the present system. Modification of equation (5) leads to equation (7) with $[\mathrm{L}]_{\mathrm{org}}$ as a variant. The extraction

$$K_{ex} = \frac{D_{\mathrm{M}}}{(k/m^{k-1})[\mathrm{A}^-]_{\mathrm{aq}}^{km+k-1}[\mathrm{L}]_{\mathrm{org}}^{n}} \qquad (5)$$

$$D_{\mathrm{M}} = \frac{k[\mathrm{M}_k\mathrm{L}_n\mathrm{A}_{km}]_{\mathrm{org}}}{[\mathrm{M}^{m+}]_{\mathrm{aq}}} \qquad (6)$$

$$\log\{D_{\mathrm{M}}/(k/m^{k-1})[\mathrm{A}^-]_{\mathrm{aq}}^{km+k-1}\} = n\log[\mathrm{L}]_{\mathrm{org}} + \log K_{ex} \qquad (7)$$

equilibrium constant K_{ex} and the complex stoicheiometry were determined by using equation (7). From the slope, the 1:2 sandwich complex can be discriminated easily from the 1:1 complex. The involvement of an unusual dicationic complex is merely implied by systematic deviations in the plots for the normal 1:1 and sandwich-like 1:2 stoicheiometries, but is verified unequivocally by fitting to the theoretical line for 2:1 dicationic complexation.

Quantitative solvent extraction studies were carried out at a variety of ligand concentrations to determine the extraction equilibrium constant K_{ex} and the complex stoicheiometry. A set of data obtained for each cation–ligand combination were first analysed assuming the conventional 1:1 stoicheiometry. Some were successful but evidently others were not. Typical examples of both cases are shown in Figure 1(*a*), for dibenzo-24-crown-8

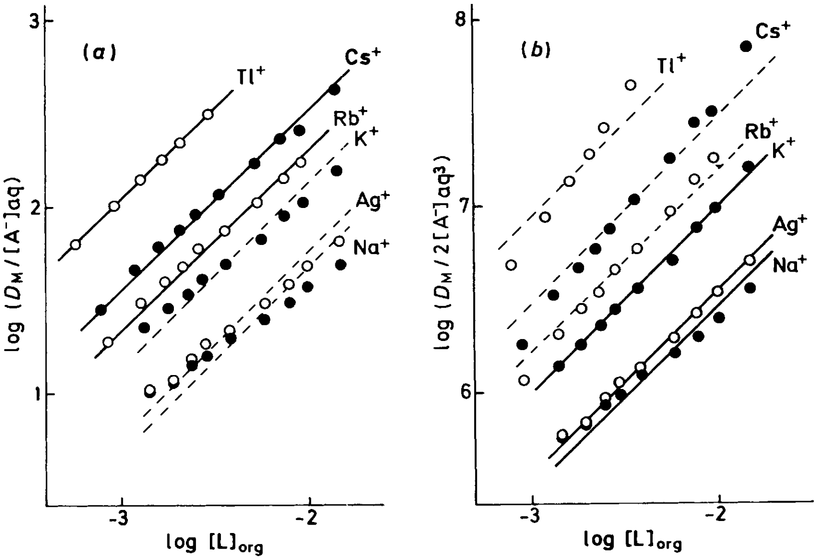

Figure 1. Typical plots for solvent extraction of some alkali and heavy metal picrates of fixed initial concentration (0.003 mol dm^{-3}) with dibenzo-24-crown-8 of varied initial concentrations (0.001—0.015 mol dm^{-3}): (*a*) conventional 1:1 or (*b*) dicationic 2:1 stoicheiometry assumed

with some alkali and heavy metal picrates. Rubidium, caesium, and thallium picrates give good straight lines of unit slope, whereas sodium, potassium, and silver picrates deviate significantly from the theoretical line. Similar analyses reveal that the combinations listed below fit into the conventional 1:1 stoicheiometry; their equilibrium constants are listed in the Table.

18-Crown-6 with Na$^+$, K$^+$, Rb$^+$, Cs$^+$, Ag$^+$, Tl$^+$
Dibenzo-18-crown-6 with Li$^+$, Na$^+$, K$^+$, Rb$^+$, Cs$^+$, Ag$^+$, Tl$^+$, Sr^{2+}
24-Crown-8 with Rb$^+$, Cs$^+$, Ag$^+$, Tl$^+$, Sr^{2+}, Ba^{2+}
Dibenzo-24-crown-8 with Rb$^+$, Cs$^+$, Tl$^+$, Ba^{2+}

For the cation–ligand combinations that showed systematic deviation from the theoretical line for 1:1 complexation, the dicationic 2:1 stoicheiometry was then examined.* As exemplified in Figure 1(*b*), the 2:1 stoicheiometry explains well the extraction behaviour of the otherwise unsuccessful combinations of cations and ligands shown below;† their equilibrium constants are listed in italics in the Table.

18-Crown-6 with Li$^+$
24-Crown-8 with Li$^+$, Na$^+$, K$^+$
Dibenzo-24-crown-8 with Na$^+$, K$^+$, Ag$^+$, Sr^{2+}

Qualitatively the complex stoicheiometry can also be determined by the continuous variation method,[8],‡ employed frequently in the homogeneous phase. In the solvent extractions of alkali-metal picrates with dibenzo-24-crown-8, the initial fraction of aqueous picrate, ([M$^+$]$_i$ + [A$^-$]$_i$)/([M$^+$]$_i$ + [A$^-$]$_i$ + [L]$_i$), was varied continuously while maintaining the total concentration of both components, [M$^+$]$_i$ + [A$^-$]$_i$ + [L]$_i$, constant. In Figure 2, the amount of metal picrate extracted, as indicated by the absorbance, was plotted as a

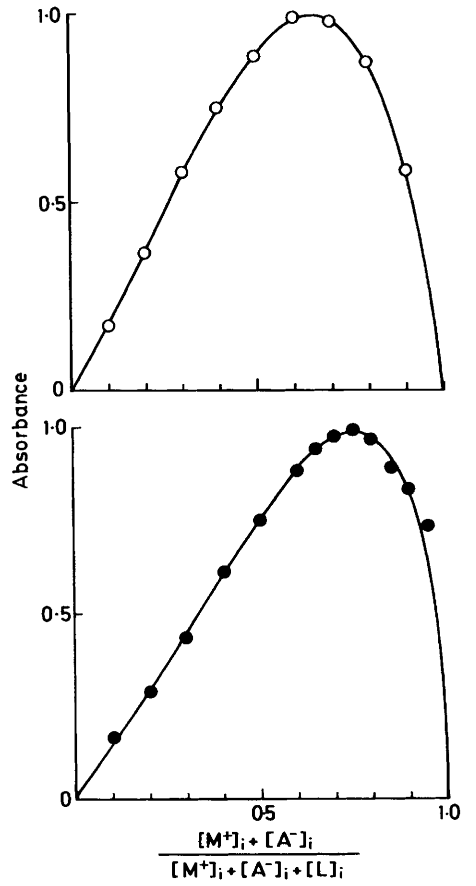

Figure 2. Continuous variation method applied to the solvent extraction of sodium (●) and caesium (○) picrates with dibenzo-24-crown-8; the absorbance (arbitrary units) of picrate extracted into the organic phase is plotted as a function of initial mole fraction of metal picrate

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* The 1:2 stoicheiometry for a sandwich complex was also examined; serious deviation from the theoretical line was found.

† The case of sodium picrate with dibenzo-24-crown-8, shown in Figure 1(*b*), is the only one where there still remains small deviations from the 2:1 theoretical line, for which we have no rationalization at present.

‡ This method may be applied only to the water-insoluble ligands like benzo-, dibenzo-, or alkylated-crown ethers, since the significant distribution of ligand into the aqueous phase makes strict analysis difficult.

function of mole fraction of the picrate used. Caesium picrate shows the peak intensity between 0.6 and 0.7 as expected for the conventional 1:1 stoicheiometry, whereas sodium picrate gives the peak around 0.75—0.80, which again confirms the unusual 2:1 stoicheiometry.

Inconsistent with the general understanding based on the preceding papers,[5] a wide variety of cation–ligand combinations, including those reported in the *X*-ray crystallographic studies,[3,4] are demonstrated to form the 2:1 dicationic complexes in the solvent extraction. It is interesting that the complexation behaviour in the solid phase and the solvent extraction share an unexpected resemblance relating to stoicheiometry. In dichloromethane, since little solvation is available as in the crystalline state, the positive charge(s) of the complexed cation(s) should be effectively shielded. This is achieved either by encapsulating the cation with a flexible ligand or by making a contact ion pair with bulky counter anion(s), if available. In the present case, we infer that the extraction of size-mismatched small cations is facilitated by the bridging co-ordination of highly lipophilic picrate anions from both sides of the ligand plane as shown in the crystalline complex.[4] In the solvent extraction, the lipophilicity of the complex produced is the decisive factor determining complex stoicheiometry as well as extractability. On the other hand, the complexation behaviour in the homogeneous phase is not affected by the nature of the counter anion, since the complex formation occurs in principle between the solvated cation and ligand and no intimate incorporation of the counter anion is needed.

The present results suggest that the cation–ligand combinations, with which the 2:1 stoicheiometry is verified in the solvent extraction but for which any *X*-ray data are not available yet, give binuclear complexes in the crystalline state, although the same stoicheiometry may not be found in the homogeneous-phase complexation. It is further suggested that the other stoicheiometries demonstrated for the crystalline complexes[3] may be also found in the solvent extraction, for which work is continuing.

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