J. Membrane Biol. 18, 379–397 (1974)

Ion Transport Through Liquid Membranes Facilitated by Crown Ethers and their Polymers

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Received 15 April 1974

Summary. The macrocyclic polyethers 4′-methylbenzo-15-crown-5 (15C5) and 4′-methylbenzo-18-crown-6 (18C6) as well as the corresponding crown polymers and crown-styrene copolymers were used as carriers for the transport of sodium and potassium picrate or the corresponding chlorides across a stirred chloroform membrane. The observation of pronounced bathochromic shifts in the optical spectra of picrate salts on increasing the interionic ion pair distance could be utilized in determining the nature and structure of the migrating species. These species were found to be ion pair crown complexes of at least two kinds, viz., crown-complexed tight ion pairs and crown-separated ion pairs. The feasibility to thus identify the detailed structure of the migrating ionic entity is important as solvents of low polarity such as chloroform or hexane have been used as liquid membranes to represent the interior of biomembranes. The structure of the ion pair is expected to be an important consideration in correlating properties such as membrane potentials or cation selectivities with ionic distribution equilibria. Ion pair extraction equilibrium constants were determined in the H_2O–$CHCl_3$ system for the various crown species. The values for 18C6 with sodium and potassium picrate are nearly the same as those for the corresponding polymers. The same was found with 15C5 and sodium picrate; but the potassium forms, in addition to a 1:1 complex, a 1:2 complex with 15C5, making the corresponding polymer a more effective extracting agent. The ionic distribution data were interpreted in terms of the salt partition coefficients and the complex formation constants of the ion pair crown complexes in chloroform. The salt migration across the liquid membrane was found to be controlled by the diffusion of the ion pair complex in the chloroform, the extraction equilibrium across the interphase being rapidly established. The thickness of the diffusion layer adjacent to the water-chloroform interphase was estimated to be 50 μ. The ratios of the salt fluxes under otherwise identical conditions were found to be governed by the extraction equilibrium constants, the selectivity ratio for the potassium-to-sodium picrate with 18C6 being 118. This ratio, which was also determined for other crown species, was found to be anion dependent.

Ion transport across membranes is known to be augmented by macrocyclic antibiotics such as monactin and valinomycin [1, 6, 7, 9, 15, 28]. This

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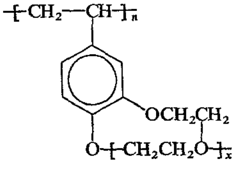
carrier-facilitated ionic permeability can also be induced by the synthetic macrocyclic polyethers, a class of compounds commonly referred to as crown ethers [3, 5, 10, 17–20]. The crown compounds as well as the macrobicyclic ligands recently synthesized by Lehn [16], are effective chelating agents of alkali and alkaline earth cations, capable of selectively transporting cations across natural and nonaqueous membranes [6, 21, 22].

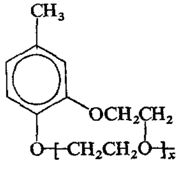
In recent years we have carried out a series of studies dealing with the structure and properties of ion pairs and their coordination complexes with solvents and ligands such as crown ethers [25]. Spectrophotometric measurements on ethereal solutions of carbanion salts revealed the existence of tight and loose (solvent-separated) ion pairs [11], and addition of crown ethers to tight ion pairs resulted in the formation of crown-coordinated tight ion pairs or crown-separated loose ion pairs, depending on the polarity of the medium, the temperature and the nature of the cation and anion [26, 27]. In the course of this work, macromolecules were synthesized containing the crown moiety as pendent group, the objective being to compare their ion binding characteristics with those of the monomeric crown ligands and to explore their usefulness as selective cation chelating materials [12, 13].

Results reported in this paper deal with salt extraction equilibria and ion transport properties of homopolymers and styrene copolymers of two vinylbenzo crown ethers (I) and their corresponding monomeric analogs (II), viz., 4′-methylbenzo-15-crown-5 and 4′-methylbenzo-18-crown-6.



I

$x=3$ P15C5
$x=4$ P18C6



II

$x=3$ 15C5
$x=4$ 18C6

Chloroform was used as the nonaqueous medium, and the electrolytes transported were sodium and potassium picrate, and, in some cases, the corresponding chlorides. The use of picrate salts in chloroform permitted us to draw certain conclusions regarding the structure of the ion pairs extracted into or carried across the organic phase by the various crown ligands. This structure, inferred from spectral changes observed when crown ethers complex to picrate salts, can be a significant factor in determining the cation selectivity of crown ethers.

Materials and Methods

Preparation of Compounds and Solutions

Crown Ethers. The preparation of 4′-methylbenzo-15-crown-5 and of 4′-methylbenzo-18-crown-6 has been described elsewhere [17, 26]. The synthesis of the two corresponding 4′-vinylbenzo crown ethers and their subsequent conversion to polymers by a radical type polymerization has also been published [12]. The only change in the preparation of the vinyl monomers concerns the synthesis of the intermediate 3′,4′-dihydroxyacetophenone, which was obtained by demethylation of 4′-hydroxy-3′-methoxyacetophenone (acetovanillone, Aldrich) with $AlCl_3$ in methylene chloride [14]. The number average molecular weights of poly(vinylbenzo-15-crown-5) and of poly(vinylbenzo-18-crown-6), as determined by high speed membrane osmometry, were found to be 40,000. Copolymers of styrene and the two vinylbenzo crown ethers containing twenty mole percent of the latter monomer were prepared by radical polymerization. Their composition, determined by proton nmr was nearly identical to that of the starting monomer mixture. For reason of conciseness we shall denote the respective crown ether species by 15C5, 18C6, P15C5, P18C6, P15C5(20%) and P18C6(20%), the notation P referring to the respective polymers.

Salt Solutions. Sodium and potassium picrate were prepared and purified as described by Coplan and Fuoss [4]. They were stored in the dark under vacuum. All solutions were made in distilled water saturated with chloroform.

Extraction and Transport Measurements

Extraction equilibrium constants were obtained in water-chloroform by repeatedly shaking a 10-ml aqueous solution of a picrate salt with a 10-ml chloroform solution of a crown ether [6, 8, 18]. The concentration of the crown-complexed picrate salt was determined spectrophotometrically in a Cary 14 spectrophotometer. The principal absorption maximum of the complex was carefully recorded as its position (between 355 nm and 380 nm) depends on the cation and the type and concentration of the crown ether. Molar absorptivities were determined by dissolving a known amount of picrate salt in chloroform containing a small excess of the crown compound.

Transport measurements were carried out in a modified Schulman bridge [24] described in detail by Reusch and Cussler [21, 22]. A known volume ($\sim$8 ml) of water-saturated chloroform containing a weighed quantity of crown ether (concentration between 10^{-4} and 10^{-2} M, depending on whether picrates or chlorides were used) was placed in a small U-shaped tube of 10 to 12 mm diameter. A 10-ml salt solution was then carefully placed in the right arm of the tube, while simultaneously the left arm was filled with 10 ml of chloroform-saturated water. During the measurements, all three solutions were stirred vigorously at a constant rate of speed ($\sim$120 rpm) by means of three Teflon stirring bars. The total amount of electrolyte transported to the left compartment of the tube generally amounted to less than 5% of the initial salt concentration present in the right arm.

The flux of picrate salt across the chloroform barrier was measured spectrophotometrically at 354 nm (ε_m 1.45×10^4) by drawing, at regular intervals, small aliquots from the left compartment. Each time the sample was immediately placed back in the side arm to maintain constant volume. At the end of the flux measurement a sample from the chloroform layer was taken and the absorption maximum and concentration of the picrate complex in the organic phase determined.

A few flux experiments were carried out with sodium and potassium chloride, using 1 M salt solutions, the crown concentration being 10^{-2} M. The amount of salt transported was measured as a function of time by means of a conductance cell which was present in the left compartment [21, 22]. Other experiments were carried out in which mixtures of sodium and potassium picrates were used, or the corresponding chlorides. In these cases the alkali content of the transported salt mixture was obtained by means of a Unicam SP90 flame spectrophotometer. Blank experiments show that the alkali content due to impurities in the distilled water or from contamination of the glass can amount to approximately 10^{-4} M [2]. With mixtures of picrates the alkali ion with the lowest concentration was obtained as the difference between the concentration of picrate and that of the alkali ion with the highest concentration in order to minimize the blank correction. For chlorides, experimental conditions were chosen such that the concentrations of the transported salts were significantly above the blank values.

Results

Optical Spectra

Purified sodium and potassium picrate, nearly insoluble in chloroform, dissolve more or less readily in this solvent on addition of certain crown compounds. The absorption maxima of the respective crown picrate complexes, and values of the molar absorptivities, are collected in Table 1. The data in the absence of crown were obtained in tetrahydrofuran, a solvent in which the salts are much more soluble.

Table 1. Absorption maxima and molar absorptivities of picrate salts in chloroform at 25 °C in the presence of excess crown ethers

Salt	Crown	λ_m(nm)	$\varepsilon \times 10^{-4}$ ($\mathrm{cm}^{-1}\,\mathrm{M}^{-1}$)
Na^+	–	351 [a]	1.65 [a]
	15C5	356	1.61
	P15C5	362	1.65 [b]
	P15C5(20%)	362	1.60
	18C6	362	1.63
	P18C6	369	1.61
	P18C6(20%)	362	1.65
K^+	–	357 [a]	1.65 [a]
	15C5	378 [c]	1.81
	P15C5	378	1.65 [b]
	P15C5(20%)	378	1.65 [b]
	18C6	365	1.65
	P18C6	370	1.70
	P18C6(20%)	365	1.65

[a] These values refer to tetrahydrofuran solutions of the picrate salts.

[b] Some difficulty was experienced in obtaining accurate absorptivity values due to solubility problems, and the listed values were estimated.

[c] The λ_m value of the 15C5 complex varies with the 15C5/KPi ratio; the λ_m 378 nm is the value for the 2:1 15C5/KPi complex which is formed when 15C5 is present in large excess.

The λ_m values of Table 1 clearly reveal the dependence of the absorption maxima of the crown complexes on the nature of the cation and the structure of the crown ether. It is interesting in this respect to note that a second transition which can be identified as a clearly distinct maximum at 420 nm in complexes with λ_m between 350 and $\sim$365 nm, is not affected by a change in cation or crown ether. It becomes merely a shoulder in the spectra of complexes with a λ_m above 370 nm due to overlap caused by the bathochromic shift of the main band.

To ascertain that the shifts did not result from the presence of free picrate anions, we measured the conductance of a chloroform solution of the PiK–18C6 complex. At a concentration of 3.7×10^{-5} M the equivalent conductance at 20 °C was found to be 0.65 $\text{cm}^2\ \text{equiv}^{-1}\text{ohm}^{-1}$. Assuming $\Lambda_0 \approx 100$ (the Λ_0 in methanol, a solvent with nearly the same viscosity as chloroform, was reported to be 99 [4]), the fraction of free ions is calculated to be $\alpha = \Lambda/\Lambda_0 \approx 0.0065$, hence $K_d \approx 10^{-9}$ M. This is an upper limit as interionic interactions are neglected. The value as compared in methylene chloride ($K_d \approx 10^{-5}$ [8]) is lower by a factor of 10^4. This is reasonable considering the difference in dielectric constants, which at 20 °C is 4.80 for $CHCl_3$ and 9.08 for CH_2Cl_2. The K_d in a "sphere in continuum model" is proportional to $\exp(-e^2/aDkT)$. Assuming identical interionic distances a for the ion pair complex KPi–18C6 in the two solvents (the nearly identical value for the absorption maxima in the two media makes this assumption plausible) one calculates that $\log K_d(CHCl_3) = (9.08/4.80 \log K_d(CH_2Cl_2)$, or $K_d(CHCl_3) \approx 3.10^{-10}$ M. The equivalent conductance measured at 3.7×10^{-5} M was only slightly higher when water-saturated chloroform was used. Hence, under our experimental conditions (i.e., a complex concentration of $\sim 5 \times 10^{-5}$ M or higher), the ionic species in the organic phase are present in the form of ion pairs.

Extraction Equilibrium Constants

Since the complex is present as an ion pair, the overall extraction equilibrium may be written as

$$M^+ + Pi^- + n\,\text{Crown}^* \rightleftarrows M^+, Pi^-, (\text{Crown})_n^* \ldots K_e \tag{1}$$

where the asterisk refers to species in the chloroform layer. The sodium salt forms 1:1 complexes with all crown species used in this investigation. The potassium ion is known to form a 1:1 complex with the 18C6 moiety, but a 2:1 crown-cation complex can be formed with 15C5 [12]. For 1:1 com-

Table 2. Extraction equilibrium constants of *sodium* picrate in the presence of crown ethers for the system H_2O–$CHCl_3$ at 20 °C

Crown	$[\text{Crown}]_0$ ($\times 10^3$ M)	$[\text{Picrate}]_0$ ($\times 10^3$ M)	λ_m (nm)	$\frac{[\text{Crown}]_{\text{compl.}}}{[\text{Crown}]_0}$ [a]	K_e ($\times 10^{-3}$ M^{-2})
15C5	0.100	10.0	356	0.227	3.7
	0.350	10.0	356	0.212	3.7
P15C5	0.100	10.0	362	0.310	5.4
	0.350	10.0	362	0.312	5.7
P15C5(20%)	0.100	10.0	356	0.233	3.9
	0.350	10.0	356	0.250	4.2
18C6	0.100	20.0	362	0.388	2.2
	0.200	20.0	362	0.400	2.3
	0.406	20.0	362	0.403	2.4
P18C6	0.200	10.0	369	0.33	6.2
	0.350	10.0	369	0.29	5.1
P18C6(20%)	0.100	10.0	362	0.124	1.8
	0.342	10.0	362	0.112	1.6

[a] This ratio is equal to $[\text{complex}]/[\text{crown}]_0$ since in all systems a 1:1 crown-picrate complex is formed.

plexes the K_e was calculated from the expression

$$K_e = \frac{[\text{complex}]}{\gamma_{\pm}^2 [\text{M}^+][\text{Pi}^-]\{[\text{crown}]_0 - [\text{complex}]\}} \tag{2}$$

where $\gamma_{\pm}$ denotes the mean activity coefficient of the salt in water and $[\text{crown}]_0$ refers to the initial crown concentration. In the system PiK–15C5 it was necessary to use a low 15C5 concentration to avoid formation of the 2:1 crown-PiK complex. The observed λ_m of 362 nm (Table 3) is evidence that only the 1:1 complex was present (*see* Discussion). The close proximity of 15C5 moieties in P15C5 and P15C5(20%) results in the formation of 2:1 complexes (λ_m 378 nm!). However, the same equation for K_e can be used if the reasonable assumption is made that the pair of closely adjacent crown units in the two polymers can be considered as a single kinetic entity. The only change is that the expression $[\text{crown}]_0$–[complex] for the free crown concentration in Eq. (2) must be replaced by $[\text{crown}]_0$–2[complex].

The respective K_e values are listed in Tables 2 and 3. In most systems K_e appears to be reasonably constant on varying the crown or salt concentration. Lower K_e values are frequently found at high picrate concentrations or in the presence of excess base, a problem which was also encountered

Table 3. Extraction equilibrium constants of *potassium* picrate in the presence of crown ethers for the system H_2O–$CHCl_3$ at 20 °C

Crown	$[\text{Crown}]_0$ $(\times 10^3\ \text{M})$	$[\text{Picrate}]_0$ $(\times 10^3\ \text{M})$	λ_m (nm)	$\frac{[\text{Crown}]_{\text{compl.}}{}^{a}}{[\text{Crown}]_0}$	K_e $(\times 10^{-5}\ \text{M}^{-2})$
18C6	0.100	1.00	365	0.18	2.3
	0.200	1.00	365	0.225	3.1
	0.100	3.00	365	0.63	2.3
	0.200	10.0	365	0.95	2.4
	0.350	10.0	365	0.943	2.1
	0.350	10.0[b]	365	0.97	(1.2)
P18C6	0.100	1.00	370	0.25	5.6 (3.5)[c]
	0.350	1.00	370	0.25	6.5 (3.7)
	0.350	3.00	370	0.43	4.4 (1.1)
	0.350	10.0	370	0.44	– (0.11)
	0.350	10.0[b]	370	0.47	– (0.027)
	0.200	10.0	370	0.47	– (0.11)
P18C6(20%)	0.100	1.00	365	0.15	1.9
	0.350	1.00	365	0.14	1.7
	0.350	3.00	365	0.51	1.6
	0.100	3.00	365	0.52	1.4
	0.350	1.00	365	0.89	1.0
	0.350	1.00[b]	365	0.94	(0.5)
15C5[d]	0.100	20	360	0.107	0.0042
	0.350	20	362	0.107	0.0042
P15C5	0.175	10	378	0.263	0.022
	0.350	10	378	0.267	0.023
P15C5(20%)	0.100	10	378	0.79	0.24
	0.500	10	378	0.85	0.35
	0.100	5	378	0.65	0.45

[a] This ratio is equal to $[\text{Complex}]/[\text{Crown}]_0$ in systems forming 1:1 crown-cation complexes. For P15C5 and P15C5(20%) the complex contains two crown groups per cation, and the ratio $[\text{Crown}]_{\text{compl}}/[\text{Crown}]_0 = 2\,[\text{Complex}]/[\text{Crown}]_0$.

[b] In these experiments the aqueous phase also contained 0.04 M of KOH.

[c] Values for P18C6 given in brackets were calculated on the assumption that the K_e value is independent of the ion pair population on a P18C6 chain.

[d] The 15C5 concentration is low enough to only form a 1:1 PiK–15C5 complex (λ_m 362 nm).

in previous experiments with methylene chloride [8, 12]. Considerable foam formation at the $CHCl_3$–H_2O interphase was noticeable with PiK–P15C5(20%), and prolonged standing did not remove the foam completely except at the lowest P15C5(20%) concentration. The highest K_e value reported for this system in Table 3 may, therefore, be the correct one.

There is obviously a dependence of K_e on crown and salt concentrations in the system PiK–P18C6. It appears that even with a considerable excess of picrate the ratio $[\text{crown}]_{\text{compl}}/[\text{crown}]_0$ does not exceed the value 0.47 in spite of the fact that 18C6 is not known to form a 2:1 complex with K^+. However, the cation-to-crown ratio does reach a value close to unity with the copolymer P18C6(20%), and its K_e value with potassium picrate is constant. We recalculated K_e for the homopolymer P18C6 based on a maximum cation-to-crown ratio of 0.5. These values are also listed in Table 3, together with those calculated on the basis of a 1:1 complex, the latter data being given in brackets.

Transport Measurements

Picrate diffusion across the chloroform membrane apparently occurs entirely by means of an ion pair complex with the crown carrier. Assuming that the extraction equilibrium (1) across the interphase can be maintained during the transport of salt, the steady-state flux density, F, is given by

$$F = D(C_e - C_s)/l. \tag{3}$$

The constant D denotes the diffusion constant of the ion pair complex and l refers to the thickness of the diffusion barrier which, because of the vigorous stirring, is reduced to a thin chloroform layer adjacent to the interphase. C_e and C_s refer to the complex concentration at the interphase and in the steady-state region of the chloroform layer, respectively. The accumulated salt in the left compartment is kept small compared to the initial salt concentration, hence, $C_e = 2C_s$. Combining Eqs. (2) and (3) one obtains,

$$F = \frac{DK_e\gamma_\pm^2[\mathrm{M}^+][\mathrm{Pi}^-][\mathrm{Crown}]_0}{2l\{1 + K_e\gamma_\pm^2[\mathrm{M}^+][\mathrm{Pi}^-]\}}, \tag{4}$$

an expression which resembles that derived by Ward [29] and Reusch and Cussler [22]. It is also assumed in the derivation that the diffusion rates of complex and unbound carrier across the barrier are comparable.

Our experiments confirm that for both monomeric and polymeric crown species the cumulative amount of transported salt is proportional with time, as expected from the steady-state flux (*see* Figs. 1 and 2). The initial curvature found in all the plots is caused by the time required to reach a steady-state distribution of the ion pair complex.

The flux density was calculated from the slopes of the respective plots and the cross-section of the $H_2O/CHCl_3$ interphase. The values are given in

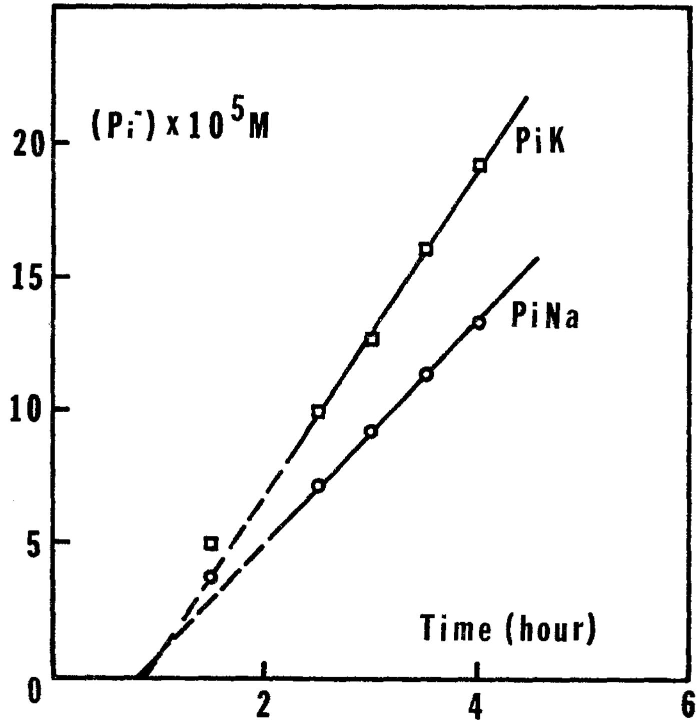


Fig. 1. Concentration of picrate accumulated (in moles/liter) as a function of time with 18C6 as carrier. $[\mathrm{PiK}]_0=2.0\times10^{-3}$ M; $[\mathrm{PiNa}]_0=2.0\times10^{-2}$ M; $[18\mathrm{C6}]_0=2.03\times10^{-4}$ M; cross-section interphase 1.43 cm^2

Table 4, together with the initial concentration of salt and crown ether, and the experimentally determined steady-state complex concentration. In the case of PiK–18C6 and PiK–P18C6(20%) it was necessary to correct the observed flux since as much as 10 to 15% salt was transported. The flux values for these systems given in Table 4 are the corrected data based on the initial salt concentrations.

Inspection of the flux values shows that over a fourfold concentration range of crown ether the flux density is proportional to the total crown concentration (at least for 18C6), in accordance with Eq. (4). Reusch and Cussler [22] found a similar result for sodium and potassium chloride transport facilitated by dicyclohexyl-18-crown-6, and also established the proportionality of the flux with the square of the salt concentration.

The agreement between calculated and observed values for the steady-state complex concentration (Table 4) confirms the relationship $C_s=1/2\,C_e$. This is depicted in a different way in Fig. 3, the flux being proportional to C_e, in accordance with Eq. (3).

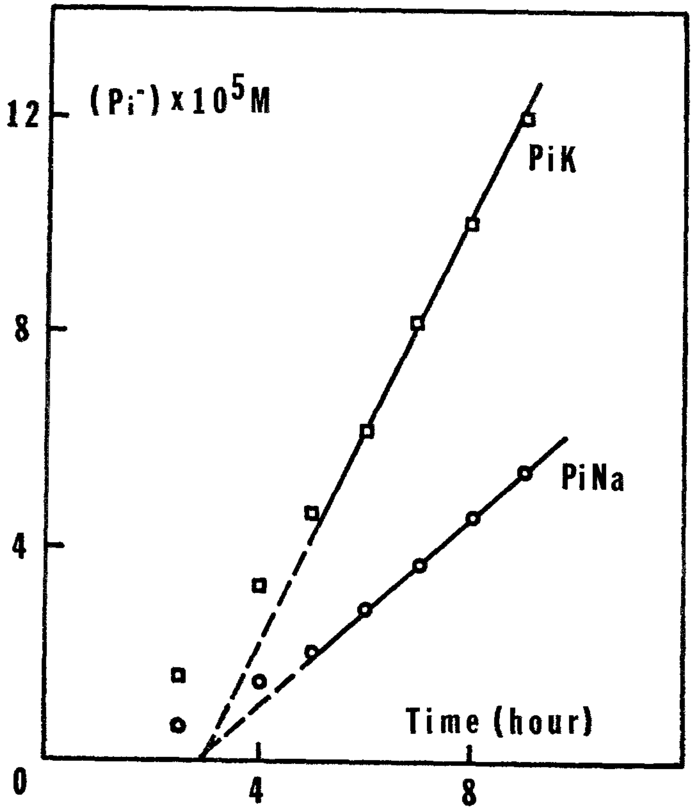


Fig. 2. Concentration of picrate accumulated (in moles/liter) as a function of time with P18C6(20%) as carrier. $[\mathrm{PiK}]_0 = 2.0 \times 10^{-3}$ M; $[\mathrm{PiNa}]_0 = 2.0 \times 10^{-2}$ M; $[\mathrm{P18C6(20\%)}]_0 = 3.42 \times 10^{-2}$ M (expressed in terms of crown units); cross-section interphase 1.43 cm^2

Further proof for the correctness of the assumption that the extraction equilibrium (1) is rapid with respect to the diffusion across the chloroform barrier can be obtained by calculating K_e from the flux density Eq. (4), and comparing these values with those obtained from extraction experiments. Since D can only be estimated, we determined instead the ratio:

$$\frac{K_e'}{K_e''} = \frac{F'[\mathrm{Na}^+][\mathrm{Pi}^-]''[\mathrm{Crown}_0 - 2C_s]''}{F''[\mathrm{K}^+][\mathrm{Pi}^-]'[\mathrm{Crown}_0 - 2C_s]'} \tag{5}$$

the notation "prime" referring to PiK–18C6 and the "double prime" referring to PiNa–18C6. Identical diffusion constants are assumed for the two ion pair complexes. Combining experiments at the three different crown concentrations (Table 4) one obtains an average ratio of 118 ± 3. The same ratio from extraction data (*see* Tables 2 and 3) has the value 104 ± 10. The

Table 4. Flux density of sodium and potassium picrate across a $CHCl_3$ membrane in the presence of crown ethers

Crown	$[\text{Picrate}]_0$ ($\times 10^3$ M)	$[\text{Crown}]_0$ ($\times 10^3$ M)	$[\text{Complex}]_s$ ($\times 10^4$ M)	$[\text{Complex}]_{s,\text{calc}}$[a] ($\times 10^4$ M)	F ($\times 10^7$ M hr^{-1} cm^{-2})
			A. Sodium Picrate		
18C6	20.0	1.00	0.19	0.20	1.36
	20.0	2.03	0.34	0.40	2.90
	20.0	4.06	0.80	0.80	5.85
P18C6(20%)	20.0	1.00	0.15	0.16	0.272
	20.0	1.71	0.22	0.28	0.300
	20.0	3.42	0.47	0.56	0.600
			B. Potassium Picrate		
18C6	2.00	1.00	0.21	0.21	2.02
	2.00	2.03	0.35	0.43	4.21
	2.00	4.06	0.91	0.87	8.20
P18C6(20%)	2.00	1.00	0.20	0.19	0.706
	2.00	1.71	0.33	0.32	1.05
	2.00	3.42	0.63	0.64	1.38

[a] The calculated steady-state complex concentration was obtained from the equilibrium complex concentration $C_e = 2C_s$, where C_e was calculated from the corresponding K_e values of Tables 2 and 3.

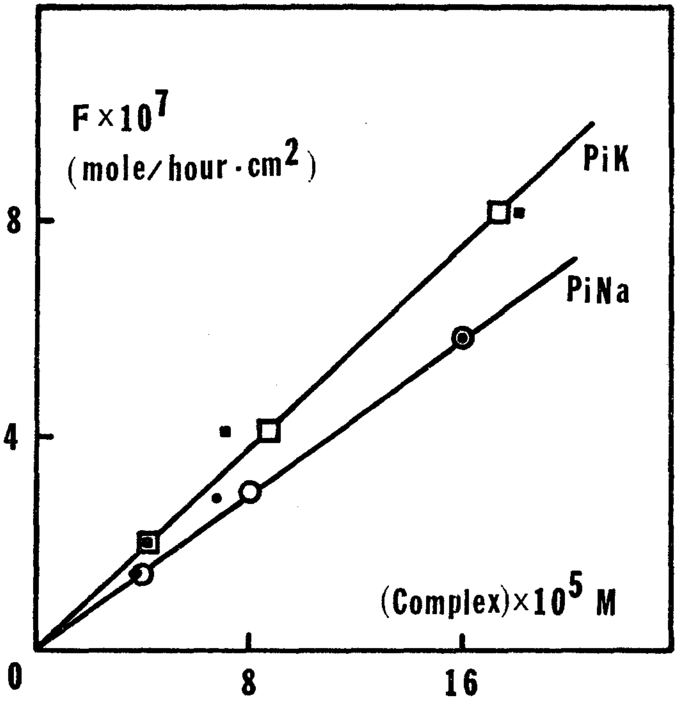


Fig. 3. Plot of flux density versus equilibrium concentration of 18C6 complex in chloroform at the interphase. ○, □, equilibrium concentrations of PiNa and PiK complexes calculated from the respective K_e values; ●, ■, equilibrium concentrations of PiNa and Pik complexes taken as twice the experimental steady-state complex concentrations

agreement is remarkable and shows indeed that the diffusion within the membrane is the rate-controlling step.

The thickness l of the diffusion layer adjacent to the interphase can be estimated from Eq. (3), using a plausible estimate for D of 10^{-5} cm^2 sec^{-1} [23]. An average length of $l = 47 \pm 5$ μ is obtained from the six experiments of 18C6 with the two picrate salts. Although this value may be off by a factor of two, it nevertheless appears to be reasonable as indicated from the work of Rosano *et al.* [23] who found for such systems an experimental estimate for l of 30 μ.

The flux experiments with sodium and potassium chloride were only carried out with 18C6 at one salt (1 M) and crown concentration (10^{-2} M). The accumulated amount of salt as measured by conductance again shows proportionality with time after the initial time lag, and the fluxes for KCl and NaCl were found to be 7.2×10^{-7} M hr^{-2} cm^{-1} and 2.2×10^{-8} M hr^{-1} cm^{-2}, respectively. Since Eq. (4) was found to be valid for chloride transport with crown ethers [22] one can calculate the K_e values of the two chlorides from the fluxes and K_e values of the respective picrates, assuming again the same D and l values for the two salts. The calculations yield K_e(KCl) = 4.6×10^{-2} M^{-2} and K_e(NaCl) = 2.0×10^{-3} M^{-2}, the ratio being 23. The same ratio calculated directly from the fluxes has the value 33.

Discussion

The interpretation of our extraction and transport data for the respective crown-salt systems hinges to a considerable degree upon our findings with regard to the nature of the ionic species present in the chloroform layer. We, therefore, shall first discuss the results of our spectral measurements.

Optical Spectra and Ion Pair Structures

Recent work on crown complexes of fluorenyl alkali and alkaline earth salts revealed that in low polarity media at least two kinds of ion pair crown complexes may exist, viz., a crown-complexed tight ion pair and a crown-separated ion pair (the latter species may contain more than one crown ether [8, 20, 26]. The two kinds of ion pairs possess distinctly different absorption maxima, the respective optical transitions of the carbanion showing a bathochromic shift with increasing interionic ion pair distance. While a difference in the absorption maximum of picrate-crown complexes was reported when CH_2Cl_2 was used as solvent (λ_m 370 nm) as compared to

$CFCl_2CF_2Cl$ (λ_m 350 nm), it was not associated with a difference in ion pair structure [8]. Preliminary data on complex formation of picrate salts with crown ethers in tetrahydrofuran (THF) can indeed be rationalized in terms of ion pair equilibria of the type:

$$\mathrm{Pi^-, M^+ + Crown \rightleftarrows Pi^-, M^+, Crown \rightleftarrows Pi^-, Crown, M^+} \tag{6}$$

and

$$\mathrm{Pi^-, M^+, Crown + Crown \rightleftarrows Pi^-, Crown, M^+, Crown.} \tag{7}$$

The second equilibrium denotes the formation of 2:1 crown-cation complexes which are prevalent in systems where the cation radius exceeds that of the crown cavity [8, 26, 27].

The spectral data of Table 1 can be interpreted as follows: The absorption maxima of sodium and potassium picrate in THF are those of the tight ion pairs. The same maxima and the same species would probably be found in chloroform if the solubility were high enough, as the solvent interaction with alkali ions is expected to be less than in THF. The presence of 15C5 in $CHCl_3$ solubilizes the sodium salt in the form of a crown-complexed tight ion pair, PiNa, 15C5 (λ_m 357 nm), the crown interaction resulting in a small increase in the Pi^- Na^+ interionic distance. The spectrum of this complex is not affected by addition of more 15C5. On the other hand, addition of a considerable excess of 15C5 to the potassium salt converts the 1:1 complex PiK, 15C5 (λ_m 362 nm) to a loose ion pair Pi^-, 15C5, K^+, 15C5 (λ_m 378 nm). Such 2:1 complexes have been found in other K–15C5 systems [8, 26], and are the only species formed when P15C5 or P15C5(20%) is used.

With 18C6 both salts form 1:1 complexes (λ_m 362 to 365 nm). The presence of the 420-nm transition (which does not shift) makes it difficult to decide whether the observed spectrum constitutes a superposition of two ion pair spectra or whether these complexes represent only one kind of ion pair with the cation protruding partially from the crown cavity. The λ_m values of the 1:1 complexes of P18C6 and of P15C5 are higher than for the corresponding monomeric crown ethers. The close proximity of the crown moieties may prevent a close approach of anion and cation, or the presence of adjacent crown oxygen atoms may favor a higher fraction of loose ion pairs. Both factors are less important in the copolymers, and the λ_m found in these systems imply that the structure of the complexes are similar to those found with the monomeric crown ethers.

All our observations lead to the conclusion that ion pairs are the migrating species in chloroform, at least down to complex concentrations of

10^{-5} M. Some recently reported results [6] on transport of crown picrate complexes across a hexane membrane which imply that free ions are involved appear, therefore, questionable. In these experiments, the complex concentration was about 10^{-5} to 10^{-6} M. The dissociation constant in hexane should be at least two orders of magnitude lower than found in chloroform ($<10^{-9}$ M, *see above*), hence the fraction of free ions should be negligible. Also, the reported λ_m 348 nm of the complex in hexane is consistent with that of a tight ion pair complex.

In methylene chloride the dissociation constants of the complexes are in the order of 10^{-5} M, and at complex concentration between 10^{-5} and 10^{-4} M migration occurs by a mixture of free ions and ion pairs [8, 12]. A closer examination of the spectra in this solvent indicates a similar dependence of λ_m on cation and crown ether as in $CHCl_3$, although most λ_m values are higher by a few nanometers. While CH_2Cl_2 is a better ionizing medium than $CHCl_3$, the structure of the ion pair complex is not much different in the two solvents. This is different from what is found in cation coordinating media (e.g., THF, tetrahydropyran), where the equilibrium

$$A^-, M^+, \text{Crown} \rightleftarrows A^-, \text{Crown}, M^+$$

is very sensitive to solvent structure [26].

Extraction Equilibria

Extraction equilibrium constants for sodium picrate in the presence of crown ethers are nearly identical for all six crown species, the values for the homopolymers being slightly higher (Table 2). The same observation can be made for the K_e values of potassium picrate with the three 18C6 species (Table 3). Three equilibria can be used to analyze the overall extraction equilibrium.

$$\begin{gathered} M^+ + \text{Crown} \overset{Ks}{\rightleftarrows} M^+, \text{Crown} \\ \text{Crown}^* \overset{Pe}{\rightleftarrows} \text{Crown} \\ M^+, \text{Crown} + A^- \overset{P_c}{\rightleftarrows} M^+, A^-, \text{Crown}^* \end{gathered} \tag{8}$$

the asterisk again referring to species in the organic phase [8]. The constant K_e is given by $K_e = K_s P_e P_c$. The extraction may also be analyzed by the following sequence of reactions [22]:

$$\begin{gathered} M^+ + A^- \overset{k}{\rightleftarrows} M^+, A^{-*} \\ M^+, A^{-*} + \text{Crown}^* \overset{K_c}{\rightleftarrows} M^+, A^-, \text{Crown}^* \end{gathered} \tag{9}$$

where $K_e = kK_c$.

Our results appear to indicate that the second sequence is preferred. Potentiometric measurements of the binding of sodium ions to crown ethers in THF/H_2O mixtures give nearly identical K_s values for 15C5 and P15C5, and for 18C6 and P18C6 [12]. On the other hand, the partition coefficients, P_e, for the homopolymers are about two orders of magnitude lower than for the corresponding monomeric crown ethers [12], and the copolymers were found to be lower by a factor of nearly 10^3. Unfortunately, the partition coefficients for the complexes, P_c, cannot be measured, but it seems unlikely that in all cases the large variations in P_e between monomeric and polymeric crown ethers would be counter-balanced by corresponding variations in P_c as required by the identical K_e and K_s values. The nature of the species involved (neutral and ionic, low and high molecular weight) are entirely different.

The second alternative, with $K_e = kK_c$, only requires that for the sodium salt K_c is the same with 18C6 and P18C6(20%), and slightly higher for P18C6. In view of the above-mentioned potentiometric data, this is very reasonable. The higher value for the homopolymers may be interpreted as increased participation of adjacent crown moieties as is also indicated by the λ_m values. The much higher K_e values for the K–18C6 systems as compared to the corresponding Na systems (nearly a factor of 100) are most likely due to a much higher partition coefficient, k, for the potassium picrate. The crown ether dibenzo-18-crown-6 intrinsically appears to bind Na^+ ions better than K^+ ions, although this is reversed in the better cation solvating media such as oxetane or methanol [8, 30].

The peculiar dependence of K_e on crown and picrate concentration for the system potassium picrate-P18C6 is most likely caused by the dependence of K_e on the ion pair population. This, in turn, may be the result of electrostatic repulsion between the bound cations or of steric hindrance beyond an ion pair to crown ratio of 0.5. This dependence of the complex formation constant on the cation population has also become apparent from conductance measurements on systems such as potassium tetraphenylboron/P18C6 in acetone or methylethylketone. The cation-to-crown ratio can exceed 0.5 in K^+/P18C6 systems when the formation constants are very high, such as in the system fluorenyl potassium/P18C6/THF [13], but even here the ratio does not exceed 0.8. In the copolymer, repulsion or steric effects are reduced, and the cation-to-crown ratio approaches unity (Table 3).

The formation of 2:1 crown-K^+ complexes in PiK–P15C5 and P15C5(20%) makes the polymers more effective complexing agents than 15C5. Much higher 15C5 concentrations are needed to change the 1:1 PiK, 15C5 complex into the 2:1 separated ion pair complex as indicated by the measurements in THF. The copolymer is considerably more effective than P15C5 itself, as formation of the sandwich type complexes with K^+ ions may be hindered by the close proximity of the 15C5 moieties in the homopolymer. It is also interesting that in CH_2Cl_2 the K_e for P15C5 is more than a hundred times larger than in $CHCl_3$, probably because of the necessity to separate the PiK ion pairs on bonding. This should require more energy in a less polar solvent. In contrast, K_e values in systems that form 1:1 crown-coordinated tight ion pair complexes do not change much when $CHCl_3$ is replaced by CH_2Cl_2, although the total fraction of picrate salt extracted in CH_2Cl_2 under identical conditions is considerably higher than in $CHCl_3$ due to free ion formation [12].

Transport Measurements

The results of our flux measurements are consistent with the assumption that the rate-controlling step in the migration of picrate and chloride salts is the ion pair diffusion in the chloroform layer after rapid establishment of the extraction equilibrium across the two interphases. This agrees with findings of Reusch and Cussler on chloride transport [22], but is contrary to those of Rosano *et al.* [23], who claim transport of alkali chlorides across a butanol membrane to be governed by migration across the interphase.

The lower diffusion constants of the polymeric ion pair complexes decrease the salt flux. Assuming the same layer thickness one calculates from the flux data that D for PiNa–P18C6(20%) is approximately six times smaller than that for PiNa–18C6. For the potassium salt the factor is about three to five. A higher cation population on the chain will decrease the average ion pair complex diffusion constant. In the system PiK–P18C6(20%) the chain ($DP \approx 250$, about 50 crown units) contains on the average 10 potassium ions. With PiNa experimental conditions are such that about seven cations are bound to the chain. Not only is D affected by the number of ions per chain, but also by the chain conformation which certainly varies with the ion pair population.

As long as diffusion is the rate-determining step, the cation selectivity in migrating a mixture of two salts is determined by the ratio of the two extraction equilibrium constants (assuming identical D's for the two ion pair complexes). The crown compound 18C6, as well as the corresponding polymer and copolymer should be effective in separating K^+ and Na^+ ions. A few experiments were performed in which an equimolar mixture of sodium and potassium picrate was used with 18C6, 15C5 and P15C5 as the respective carriers. The selectivity ratios K^+/Na^+ (i.e., the ratio of the concentrations of the two salts accumulated in the left compartment of the Schulman bridge) were found to be 50, 0.14 and 0.55, respectively, as compared to the calculated ratio's (from K_e values) 104, 0.11 and 0.4. The agreement is reasonable considering the difficulty in determining the low alkali content from emission spectroscopy. As expected, the value for 15C5 is concentration dependent, since at higher 15C5 concentration relatively more K^+ migrates due to formation of 2:1 crown-K^+ complexes. For example, experiments with an equimolar mixture of sodium and potassium chloride at 10^{-4}, 10^{-3} and 10^{-2} M concentration of 15C5 yielded K/Na ratios of 0.12, 0.32 and 0.70, respectively. That same ratio for the chlorides is concentration independent when 18C6 is used as carrier, and found to be 24.0. This value is lower than for picrates, and is generally expected to be anion dependent, since the constants k and K_c will both depend on the structure of the ion pair. This is especially the case with the planar crown ethers where complexation can lead to different ion pair structures for the two salts. The selectivity ratio in such mixtures is also likely to be solvent dependent [30]. However, the differences are found to be small when complexing agents such as macrotetralide actin antibiotics are used [7]. The cations are completely sequestered by the latter type of carriers (as in the cryptates; *see* ref. [16]) and the ion pair complexes are probably all of the separated kind, having similar size and shape.

Conclusions

Facilitated salt transport across a chloroform layer with macrocyclic polyethers (crown ethers) or their polymers as carriers involves ion pair crown complexes, the structure of which can be deduced spectrophotometrically when picrate salts are used. The structure of the ion pair (e.g., tight and loose ion pairs) depends on the type of cation and anion, on the crown species (especially the diameter of the crown cavity with respect to that of the cation) and on the spacing between crown moieties when polymers are used. The migration of salt is diffusion controlled, the extraction equilibrium across the water-chloroform interphase being rapidly established. For a particular crown species the selectivity in cation transport is determined by the extraction equilibrium constants. These constants are nearly identical for the monomeric and polymeric crown species except in systems where 2:1 crown cation complexes prevail. Also, when homopolymers are used the closeness of the crown moieties causes repulsion between complexed cations or steric hindrance on binding cations when the cation-to-crown ratio exceeds certain values, making the extraction equilibrium constants to be dependent on the number of cations bound to a chain.

The cation chelating properties of macrocyclic polyethers has stimulated their use as model compounds for ion carriers across biomembranes. In these studies a hydrocarbon phase such as chloroform or hexane has frequently been employed to represent the barrier to migration of ions across such a membrane. In correlating membrane properties such as membrane potential with salt distribution equilibria, or in determining the cation selectivity of ion carriers, it is important that the nature and structure of the migrating ionic species can be identified, and the sensitivity of the optical transitions of picrate salts provides, therefore, a distinct advantage in the study of these properties.

The authors gratefully acknowledge the generous support of the National Science Foundation (PO 37799) and of the Petroleum Research Fund administered by the American Chemical Society. They also wish to thank S. Kopolow for synthesizing the vinylbenzo crown ethers.

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