concerted displacement reaction that is enforced by the absence of a significant lifetime of the oxocarbenium ion under the conditions of the experiment. It is likely that substitution reactions on sugars by carboxylate groups do occur by concerted displacement, through a dissociative, oxocarbenium-like transition state, because the cation will not have a significant lifetime in the presence of the carboxylate ion. The concerted displacement reaction of acetate ion with α-D-glucosyl fluoride was described in the preceding paper.[11] General-acid–base catalysis of such reactions will be even more significant if it is brought about by acidic and basic groups that are held in the correct position for reaction in intramolecular and enzyme-catalyzed reactions.[8,9]

**Registry No. 1**, 2106-10-7; methyl β-D-glucopyranoside, 709-50-2; glucose, 50-99-7; 1,6-anhydroglucose, 498-07-7; β-D-glucopyranose 1-(trichloromethyl)phosphonate, 135646-42-3.

# Calixcrowns as Selective Potassium Cation Carriers in Supported Liquid Membranes

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**Abstract:** Calixcrown derivatives transport potassium cations selectively through supported liquid membranes (Accurel/*o*-nitrophenyl *n*-octyl ether, NPOE). These lipophilic carriers give stable fluxes (>4 weeks) for the membrane system described. Bridging with a tetraethylene glycol unit at the lower rim is essential since simple calix[4]arenes do not transport potassium cations. The potassium/sodium cation selectivity of these carriers was compared with the selectivity of other potassium-selective carriers like valinomycin and dibenzo-18-crown-6 in both single-cation and mixed-cation experiments. In the competition experiments, the order of decreasing $K^+/Na^+$ selectivity was as follows: valinomycin > 1,3-dimethoxy-*p-tert*-butylcalix[4]arene crown-5 > dibenzo-18-crown-6 > 1,3-dihydroxy-*p-tert*-butylcalix[4]arene crown-5. The transport selectivity is not simply related to the transport rates in single-cation experiments or to association constants. Although the $K^+/Na^+$ extraction selectivity is high, the $K^+/Na^+$ transport selectivity of valinomycin and 1,3-dimethoxy-*p-tert*-butylcalix[4]arene crown-5 (**5**) is low due to a high association constant for $K^+$ in NPOE combined with a low diffusion constant. A mathematical model has been developed that predicts the observed $K^+/Na^+$ selectivities in competition experiments from the results of single-cation experiments.

Liquid membranes containing selective carriers may give higher fluxes and selectivities than conventional semipermeable porous polymeric membranes. Since bulk liquid membranes[1] require a large quantity of carrier solution in proportion to the interfacial area where phase transfer can take place, supported liquid membranes (liquid-immobilized membranes) have been developed. They consist of a carrier solution immobilized in a thin microporous support ($d \approx 100$ μm) that separates the two aqueous phases. These supported liquid membranes are of interest both for possible technological applications (hollow fibers) and for fundamental studies of the transport process.

Previously, we described the mechanism of single-cation transport of guanidinium and potassium salts through supported liquid membranes by crown ethers.[2-4] The experimental fluxes could be described by a mathematical model based on diffusion-limited transport. Since the membrane volume of a supported liquid membrane is relatively small compared to the volume of the aqueous phases, the carriers must be very lipophilic in order to avoid substantial partitioning to the aqueous phases. We have found that the membrane stability can be improved by using carriers modified with hydrophobic alkyl or aryl groups[2,3] or carriers attached to a polysiloxane backbone.[4]

So far we have only studied single-cation transport. However, membranes have been developed for separations, and consequently we have studied selective transport by macrocyclic carriers through supported liquid membranes. As a model system we have chosen the selective potassium/sodium cation transport by calixcrown derivatives. 1,3-Dimethoxy-*p-tert*-butylcalix[4]arene crown-5 (**5**) shows a high $K^+/Na^+$ selectivity in both extraction ($CHCl_3/H_2O$, $K_{K^+} = 3.0 \times 10^8$ $M^{-1}$ and $K_{Na^+} = 1.1 \times 10^5$ $M^{-1}$)[5] and in ISFET measurements (the potentiometric selectivity coefficient $K_{K^+/Na^+} = 1600$).[6] Moreover, these compounds are very lipophilic and hence may be applicable as carriers in supported liquid membranes.

So far calixarene derivatives have only been studied as carriers in bulk liquid membranes to transport alkali cations (in particular cesium cations)[7-11] or $UO_2$ cations,[12] except for one application in which $UO_2$ cations are transported by calix[6]arenes through a polymer/liquid crystal composite membrane.[12] To the best of our knowledge, we now report the first application of calixarenes as carriers in supported liquid membranes. A mathematical model

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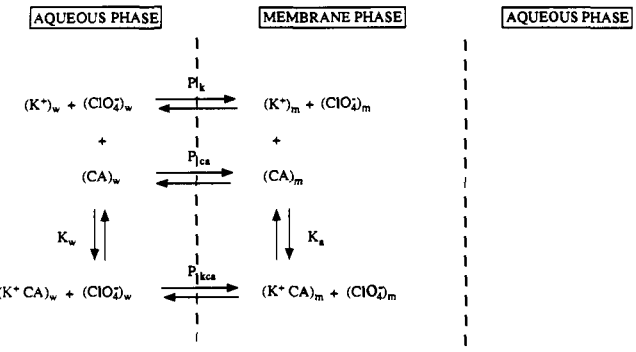



**Figure 1.** Schematic representation of equilibria at the source–membrane interface describing the transport process.

for selective cation transport through this type of membrane will also be described.[13]

## Model Description

**Model Description of Single-Cation Transport.** Previously, we proposed a mathematical model that describes carrier-mediated transport through a supported liquid membrane by the different equilibria that can be defined at both interfaces of the membrane.[2-4] These equilibria are shown in Figure 1 for the source-phase interface; all other parameters are expressed in parameters related to this interface. In this model, the initial transport rate is determined by the diffusion of the complexes through the membrane. We have made the following additional assumptions: there is thermodynamic equilibrium at the interfaces, electroneutrality in the membrane and aqueous phases, a 1:1 complexation, and linear concentration profiles of carrier and complex in the membrane phase. By applying Fick's first law, the flux can be described by[2-4]

$$J = D_m d^{-1}[K^+CA]_m \tag{1}$$

in which $J$ = flux (mol cm$^{-2}$ h$^{-1}$), $D_m$ = diffusion coefficient of the complex (cm$^2$ h$^{-1}$), $d$ = membrane thickness (cm), and $[K^+CA]_m$ = complex concentration in the membrane at the source phase (mol cm$^{-3}$).

With the equilibria described in Figure 1, the complex concentration in the membrane at the source interface $[K^+CA]_m$ can be expressed as a function of the association constant in the membrane ($K_a$), the association constant in water ($K_w$), the partition of the carrier ($P_{ca}$), and the partition of the salt ($P_k$), which were defined as

$$K_a = \frac{[K^+CA]_m}{[K^+]_m[CA]_m} \tag{2}$$

$$K_w = \frac{[K^+CA]_w}{[K^+]_w[CA]_w} \tag{3}$$

$$P_{ca} = \frac{[CA]_m}{[CA]_w} \tag{4}$$

$$P_k = \frac{[K^+]_m[ClO_4^-]_m}{[K^+]_w[ClO_4^-]_w} \tag{5}$$

where m denotes the membrane phase at the source interface and w denotes the aqueous phase. There is strong evidence that in NPOE ($\epsilon$ = 23.5) the salt is predominantly present as free ions.[2] The extraction constant ($K_{ex}$) of the salt is defined as the product of the association constant in the membrane ($K_a$) and the partition of the free salt ($P_k$).

$$K_{ex} = \frac{[K^+CA]_m[ClO_4^-]_m}{[K^+]_w[ClO_4^-]_w[CA]_m} = P_k K_a \tag{6}$$

(13) A model for the selective carrier-mediated transport of ion pairs through supported liquid membranes was described recently: Izatt, R. M.; Bruening, R. L.; Bruening, M. L.; LindH, G. C.; Christensen, J. J. *Anal. Chem.* **1989**, *61*, 1140–1148.

Previously[2-4] we derived an equation relating $[K^+CA]_m$ to the parameters in eqs 2–6:

$$[CA]_m^0 = F[K^+CA]_m + G\frac{[K^+CA]_m^2}{K_{ex}[K^+]_w^2} \tag{7}$$

in which

$$R_r = \frac{V_m}{V_r} \qquad R_s = \frac{V_m}{V_s}$$

$$F = 1 + \frac{1}{R_r P_{ca}}$$

$$G = 1 + \frac{1}{R_r P_{ca}} + \frac{1}{R_s P_{ca}} + \frac{K_w}{R_s P_{ca}}[K^+]_w$$

where s denotes the source phase and r denotes the receiving phase. When the carrier does not leach to the aqueous phases ($P_{ca} > 10^5$) and complexation in the aqueous phases can be neglected, $F$ and $G$ are approximately 1.

We used to rewrite eq 7 by defining $K_{ex}'$ as

$$K_{ex}' = \frac{[K^+CA]_m}{[K^+]_w[CA]_m} = \frac{[ClO_4^-]_w}{[ClO_4^-]_m}K_{ex} \tag{8}$$

Assuming that $[ClO_4^-]_w/[ClO_4^-]_m$ was constant, eq 7 rearranged to

$$[CA]_m^0 = F[K^+CA]_m + G\frac{[K^+CA]_m}{K_{ex}'[K^+]_w} \tag{9}$$

from which the relevant parameters were deduced by graphical methods.

Recently, we have studied the transport as a function of the salt concentration in the source phase. We found that $K_{ex}'$ is not constant under all experimental conditions. Therefore, from now on we will use the more general eq 7. In our current procedure, Fick's law and eq 7 are combined to give the cation flux due to carrier-mediated transport (with use of salt activities ($a_k$) instead of salt concentrations):

$$J = \frac{D_m}{d}\left(\frac{-F + \sqrt{(F^2 + 4T)}}{2Q}\right) \tag{10}$$

in which

$$T = \frac{G[CA]_m^0}{K_{ex}a_k^2}$$

$$Q = \frac{G}{K_{ex}a_k^2}$$

Our current procedure consists of optimizing eq 10 by least-squares analysis. The starting values for the iteration procedure are obtained from

$$\frac{[CA]_m^0}{Jd} = \frac{F}{D_m} + \frac{GJd}{D_m^2 K_{ex}a_k^2} \tag{11}$$

When the flux is measured as a function of the salt concentration in the source phase, $[CA]_m^0 J^{-1}d^{-1}$ can be plotted versus $Jd(a_k)^{-2}$, and $D_m$ can be calculated from the intercept and $K_{ex}$ from the slope of the linear correlation that is obtained. In this way, values of $D_m$ and $K_{ex}$ are obtained that are more accurate than those calculated with the method described before.[2-4]

**Model Description of Two-Cation Transport.** The competitive transport of two cations and a common anion through a supported liquid membrane can also be described by this model (1:1 complexation and transport of free ions). Again, the transport can be described by the extraction coefficients (eq 6), now defined as $K_{ex,1}$ and $K_{ex,2}$, for the two different salts:

$$K_{ex,1} = \frac{[M_1^+CA]_m[ClO_4^-]_m}{[M_1^+]_w[ClO_4^-]_w[CA]_m} \quad (12)$$

$$K_{ex,2} = \frac{[M_2^+CA]_m[ClO_4^-]_m}{[M_2^+]_w[ClO_4^-]_w[CA]_m} \quad (13)$$

in which $[M_1^+]$ and $[M_2^+]$ are the concentrations of the two cations. This means that

$$\frac{[M_1^+CA]_m}{[M_2^+CA]_m} = \frac{K_{ex,1}}{K_{ex,2}} \frac{[M_1^+]_w}{[M_2^+]_w} \quad (14)$$

From eqs 2–5 and 12–14, the mass balance of the carrier,

$$V_m[CA]_m^0 = 0.5\,V_m\{[CA]_{m,s} + [M_1^+CA]_{m,s} + [M_2^+CA]_{m,s} + [CA]_{m,r} + [M_1^+CA]_{m,r} + [M_2^+CA]_{m,r}\} + V_s\{[CA]_{w,s} + [M_1^+CA]_{w,s} + [M_2^+CA]_{w,s}\} + V_r\{[CA]_{w,r} + [M_1^+CA]_{w,r} + [M_2^+CA]_{w,r}\} \quad (15)$$

and the assumptions that (i) the total carrier concentration is constant throughout the membrane

$$[CA]_{m,s} + [M_1^+CA]_{m,s} + [M_2^+CA]_{m,s} = [CA]_{m,r} + [M_1^+CA]_{m,r} + [M_2^+CA]_{m,r}$$

(ii) there is initial transport only

$$[M^+]_{w,s} = [M^+]_{w,s}^0$$

$$[M^+CA]_{m,r} = 0$$

$$[M^+CA]_{w,r} = 0$$

$$[M^+]_{w,r} = 0$$

(iii) the free-salt concentrations in the membrane phase can be neglected compared to the complex concentrations, (iv) the complex concentrations in the aqueous phase can be neglected compared to the free-salt concentrations, and (v) there is electroneutrality in the membrane and in the aqueous phases

$$[M_1^+CA]_m + [M_2^+CA]_m = [ClO_4^-]_m$$

$$[M_1^+]_{w,s}^0 + [M_2^+]_{w,s}^0 = [ClO_4^-]_{w,s}^0$$

it follows that

$$[CA]_m^0 = F[M_1^+CA]_m\left(1 + \frac{K_{ex,2}[M_2^+]_w}{K_{ex,1}[M_1^+]_w}\right) + \left(1 + \frac{K_{ex,2}[M_2^+]_w}{K_{ex,1}[M_1^+]_w}\right)\frac{G'[M_1^+CA]_m^2}{K_{ex,1}[M_1^+]_w([M_1^+]_w + [M_2^+]_w)} \quad (16)$$

in which

$$G' = 1 + \frac{1}{R_r P_{ca}} + \frac{1}{R_s P_{ca}} + \frac{[M_1^+]_w K_{w,1} + [M_2^+]_w K_{w,2}}{R_s P_{ca}}$$

From eq 16, $[M_1^+CA]_m$ can be calculated since the extraction coefficients are known from the single-cation experiments and all the other parameters are also known. From eq 16 and Fick's first law (with use of salt activities instead of salt concentrations), the expression for the flux of one cation in competition experiments can be derived:

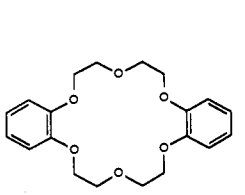
$$J_1 = \frac{D_{m1}}{d}\left(\frac{-F + \sqrt{(F^2 + 4T')}}{2Q_1'}\right) \quad (17)$$

in which

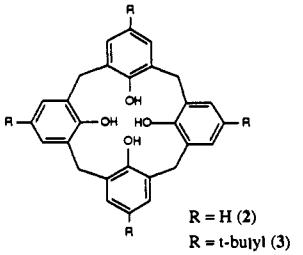
$$T' = \frac{G'[CA]_m^0}{(a_{M1}K_{ex,1} + a_{M2}K_{ex,2})(a_{M1} + a_{M2})} \quad (18)$$

$$Q_1' = \frac{G'}{(a_{M1} + a_{M2})K_{ex,1}a_{M1}} \quad (19)$$

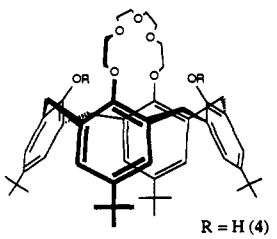
**Chart I.** Structures of Potassium-Selective Macrocycles used as Carriers in Supported Liquid Membranes



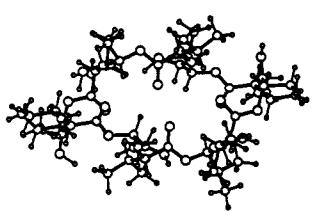
dibenzo-18-crown-6 (1)



R = H (2)
R = t-butyl (3)
calix[4]arene



R = H (4)
R = $CH_3$ (5)
calix[4]crown-5



valinomycin (6)

When only one cation is transported ($a_{M2} = 0$), eq 17 changes to the relation for single-cation transport (eq 10). In the same way, an expression for the flux of the second cation can be derived:

$$J_2 = \frac{D_{m2}}{d}\left(\frac{-F + \sqrt{(F^2 + 4T')}}{2Q_2'}\right) \quad (20)$$

in which

$$Q_2' = \frac{G'}{(a_{M1} + a_{M2})K_{ex,2}a_{M2}} \quad (21)$$

From eqs 17 and 20, it can be seen that

$$\frac{J_1}{J_2} = \frac{D_{m,1}}{D_{m,2}} \frac{K_{a,1}}{K_{a,2}} \frac{P_{M1}}{P_{M2}} \frac{a_{M1}}{a_{M2}} \quad (22)$$

This means that the transport selectivity in competition experiments is determined by the diffusion constants of the complexes, the association constants in the membrane phase, the salt concentration in the source phase, and the partition of the transported salts.

## Results and Discussion

**Single-Cation Transport.** Several potassium-selective receptor molecules were used as carriers in a supported liquid membrane (see Chart I). The membrane consisted of a $10^{-2}$ M carrier solution in NPOE (*o*-nitrophenyl *n*-octyl ether) immobilized in a porous polymeric support (Accurel). The membrane separates the aqueous salt-containing source phase (sp) from the aqueous receiving phase (rp), which initially contains no salt. Initial transport was measured in all cases (unless stated otherwise).

Firstly, we have used 1,3-dimethoxy-*p-tert*-butylcalix[4]arene crown-5 (**5**), the synthesis of which has been described in literature,[5] as a carrier for potassium and sodium perchlorate. The influence of the carrier concentration on the potassium and sodium cation fluxes in single-cation experiments is shown in Figure 2. In agreement with carrier-mediated transport, the cation fluxes increase with increasing carrier concentration. The potassium cation flux is higher than the sodium cation flux, which was expected on the basis of the complexation constants measured in $CHCl_3$ (vide supra).

A second calixcrown (**4**), having two hydroxy groups at the lower rim, was also used as a carrier. In order to compare the performance of these calixcrown derivatives, potassium and sodium

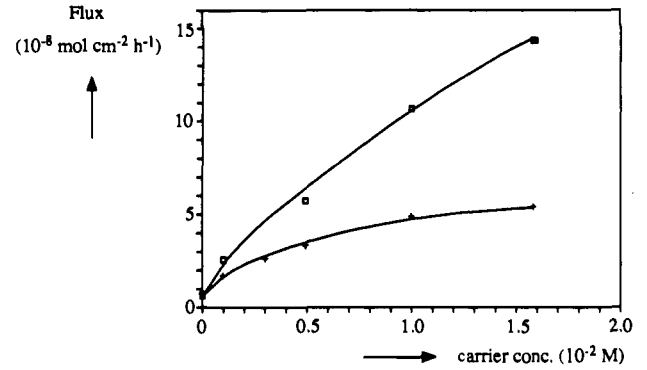



**Figure 2.** $KClO_4$ and $NaClO_4$ flux as a function of the calixcrown **5** concentration in NPOE; [alkali perchlorate] = 0.1 M, $T$ = 298 K (+ = $NaClO_4$, □ = $KClO_4$).

**Table I.** Potassium and Sodium Cation Fluxes for Different Carriers in Single-Cation Transport[a]

| carrier | $K^+$ flux ($10^{-8}$ mol cm$^{-2}$ h$^{-1}$) | $Na^+$ flux ($10^{-8}$ mol cm$^{-2}$ h$^{-1}$) |
|---|---|---|
| **1** | 26.1 | 4.7 |
| **2** | ≤0.4 | |
| **3**[b] | | |
| **4** | 5.4 | 2.0 |
| **5** | 10.3 | 4.9 |
| **6** | 26.5 | 9.5 |

[a] [alkali perchlorate] = 0.1 M; $[carrier]^0_m = 10^{-2}$ M; $T$ = 298 K. [b] Only poorly soluble in NPOE.

**Table II.** Influence of the Partition Coefficient $P$ of Different Carriers on the Potassium Cation Flux[a] Stability

| carrier | log $P$ octanol/water | log $P$ NPOE/water | flux: no. of replacements[b] 0 | 1 | 2 |
|---|---|---|---|---|---|
| **1** | 3.1 | 3.3 | 26.0 | 21.6 | 18.3 |
| **2** | 4.0 | 4.0 | ≤0.4 | | |
| **5** | 15 | 13 | 10.3 | 10.4 | 11.1 |
| **6** | 8.6[c] | 7.9 | 25.9 | 26.6 | 26.1 |

[a] $10^{-8}$ mol cm$^{-2}$ h$^{-1}$; $[KClO_4] = 0.1$ M; $[carrier]^0_m = 10^{-2}$ M; $T$ = 298 K. [b] Of the receiving phase after 24 h. [c] See ref. 21.

perchlorate fluxes were also measured for other potassium-selective compounds. Valinomycin (**6**) is a natural potassium ionophore that binds potassium cations very selectively ($K_{K^+} = 7.9 \times 10^4$ $M^{-1}$, $K_{Na^+} = 4.7$ $M^{-1}$, measured in MeOH,[14] $K_{K^+/Na^+} = 5000$ in ISFET measurements[6]). Dibenzo-18-crown-6 (**1**) is a synthetic potassium ionophore with a relatively low selectivity ($K_{K^+} = 1.0 \times 10^5$ $M^{-1}$, $K_{Na^+} = 2.3 \times 10^4$ $M^{-1}$, measured in MeOH,[14] $K_{K^+/Na^+} = 40$ in ISFET measurements[6]). In addition, simple calixarene derivatives (**2** and **3**) were used as carriers. Table I shows that the simple calix[4]arene (**2**), which is not bridged, is a very poor carrier of potassium cations compared with the calixcrown derivatives **4** and **5**. Valinomycin and dibenzo-18-crown-6 showed high potassium fluxes.

Carriers in supported liquid membranes must be very lipophilic to prevent leaching to the aqueous phases. As a measure of lipophilicity, we use the partition coefficient ($P$) NPOE/water (the concentration of a species in NPOE divided by the concentration in water). This partition coefficient can be measured from extraction experiments or can be estimated from hydrophobic fragmental constants for different functional groups according to Rekker.[15,16] These hydrophobic fragmental constants are known for the octanol/water system. The partition coefficients

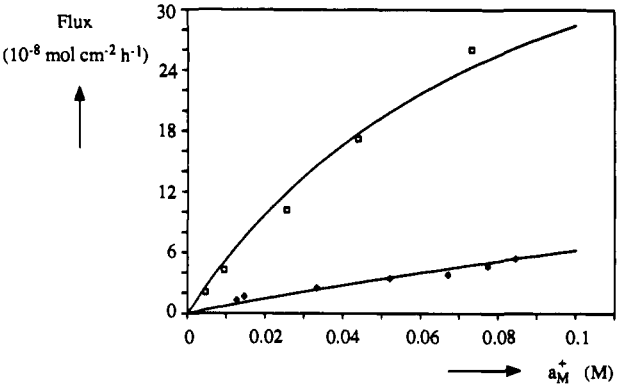



**Figure 3.** $KClO_4$ and $NaClO_4$ flux as a function of the salt activity in the source phase for dibenzo-18-crown-6 (**1**); $[carrier]^0_m = 10^{-2}$ M, $T$ = 298 K (◇ = $NaClO_4$, □ = $KClO_4$). The lines drawn are calculated according the model, the points are measured values.

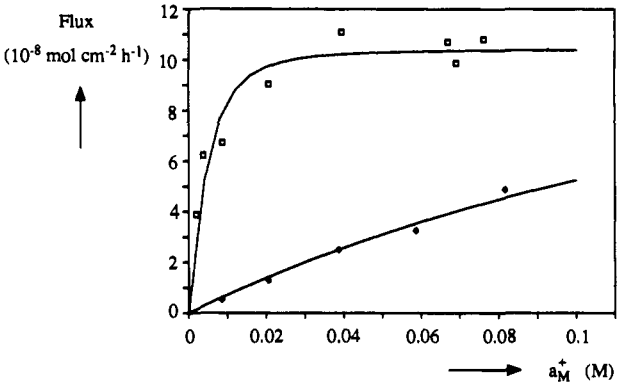



**Figure 4.** $KClO_4$ and $NaClO_4$ flux as a function of the salt activity in the source phase for calixcrown **5**; $[carrier]^0_m = 10^{-2}$ M, $T$ = 298 K (◇ = $NaClO_4$, □ = $KClO_4$). The lines drawn are calculated according the model, the points are measured values.

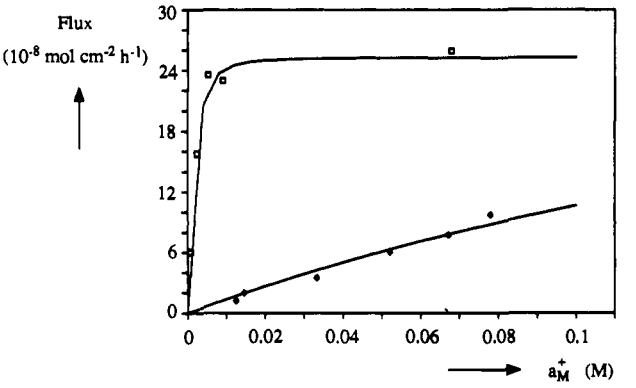



**Figure 5.** $KClO_4$ and $NaClO_4$ flux as a function of the salt activity in the source phase for valinomycin **6**; $[carrier]^0_m = 10^{-2}$ M, $T$ = 298 K (◇ = $NaClO_4$, □ = $KClO_4$). The lines drawn are calculated according the model, the points are measured values.

(octanol/water) of dibenzo-18-crown-6[2] and the ethylene glycol unit[15] have been measured. The partition coefficients of the calixarene derivatives were estimated from the hydrophobic fragmental constants; the log $P$ values are given in Table II. The NPOE/water partition can be calculated from the octanol/water partition with eq 23.[3,4,17] When log $P_{NPOE/water}$ is higher than

$$\log P_{NPOE/water} = 0.84 \log P_{octanol/water} + 0.66 \quad (23)$$

5, the leaching of the carrier to the aqueous phases is negligible in our experiments. We found that flux measurements were fully in line with the estimated log $P$ values given in Table II. This

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**Table III.** Calculated Diffusion and Extraction Coefficients for Different Carriers in NPOE[d]

| complex | $D_m$[a] ($cm^2\ h^{-1}$) | $K_{ex}$ ($M^{-1}$) | $K_{ex,K^+}/K_{ex,Na^+}$ |
|---|---|---|---|
| $1{\cdot}K^{+b}$ | $7.0 \times 10^{-4}$ | $1.3 \times 10^{0}$ | $6.6 \times 10^{1}$ |
| $1{\cdot}Na^{+b}$ | $7.0 \times 10^{-4}$ | $1.9 \times 10^{-2}$ | |
| $5{\cdot}K^{+c}$ | $1.0 \times 10^{-4}$ | $5.6 \times 10^{2}$ | $1.3 \times 10^{3}$ |
| $5{\cdot}Na^{+c}$ | $1.0 \times 10^{-4}$ | $4.2 \times 10^{-1}$ | |
| $6{\cdot}K^{+c}$ | $2.4 \times 10^{-4}$ | $2.3 \times 10^{3}$ | $5.1 \times 10^{3}$ |
| $6{\cdot}Na^{+c}$ | $2.4 \times 10^{-4}$ | $4.5 \times 10^{-1}$ | |

[a] The diffusion coefficients of the potassium and sodium cation complexes were assumed to be equal. The correct value was calculated with the help of linear regression analysis. [b] $K_{w,K^+} = 40$, $K_{w,Na^+} = 14$.[14] [c] $K_{w,K^+} = K_{w,Na^+} = 0$. [d] $T = 298$ K.

table also shows that the potassium cation flux for dibenzo-18-crown-6 is diminished (about 15%) after replacement of the receiving phase after 24 h, while calixarene carriers and valinomycin result in a constant flux. This means that dibenzo-18-crown-6 leaches to the aqueous phases; the flux dropped after each replacement because of a lower net carrier concentration in the membrane. The calixarenes and valinomycin do not leach out, so a stable flux was obtained.

We have also varied the potassium and sodium perchlorate concentrations in the source phase by using dibenzo-18-crown-6 (**1**), 1,3-dimethoxy-*p-tert*-butylcalix[4]arene crown-5 (**5**), and valinomycin (**6**) as carriers in order to determine the $D_m$ and $K_{ex}$ values. The results of the measurements are given in Figures 3–5. They show that, in the case of potassium cation transport by 1,3-dimethoxy-*p-tert*-butylcalix[4]arene crown-5 and valinomycin, the flux becomes independent of the salt concentration above a certain concentration in the source phase. This is not observed for sodium cation transport with these carriers. Since this effect is not observed for potassium cation transport with dibenzo-18-crown-6, it can not be due to saturation of the membrane with salt.

To obtain more insight about this effect, we have calculated the diffusion and extraction coefficients with eq 11 from the variation of the salt concentration (see Table III). The diffusion coefficients of valinomycin and the calixcrown derivative are lower than for dibenzo-18-crown-6.[18] This implies that changing the structure of the carrier may have a large effect on the diffusion coefficients and therefore on the transport. Table III also shows that valinomycin forms the strongest complex with potassium cations and is the most selective carrier, followed by calixcrown **5** and dibenzo-18-crown-6. The extraction selectivities ($K_{ex,K^+}/K_{ex,Na^+}$) shown in Table III agree nicely with the selectivities observed in ISFET measurements (vide supra).[6] By using these diffusion and extraction coefficients, the percentage carrier that is complexed at the source interface can be calculated. For valinomycin and calixcrown **5** (potassium perchlorate transport) this percentage is very high (>90%) for potassium perchlorate transport even at low salt concentrations (0.01 M $KClO_4$). For dibenzo-18-crown-6, this percentage is lower than 10% with 0.01 M $KClO_4$. This means that for valinomycin and calixcrown **5**, even at low potassium perchlorate concentrations, the source interface is almost saturated with complex because of high extraction constants combined with a slow diffusion of the complex. In this way, the potassium cation flux is limited by the carrier concentration; increasing the salt concentration does not result in an increase in flux. Since the extraction constants for sodium perchlorate and for the dibenzo-18-crown-6 complexes are much lower, this saturation effect is not observed in these cases. By using the calculated values for the diffusion and extraction constants, the observed fluxes could be simulated very well.

The ratio of the diffusion coefficients of calixcrown **5** and valinomycin can be directly seen from Figures 4 and 5. In these cases, the percentage complex at the source phase at high salt concentrations is nearly 100%. So when the same initial carrier concentrations are used, the ratio of the fluxes at high salt concentrations should be

$$\frac{J_1}{J_2} = \frac{D_{m1}d^{-1}[K^+CA]_{m1}}{D_{m2}d^{-1}[K^+CA]_{m2}} = \frac{D_{m1}}{D_{m2}} \qquad (24)$$

The data in Table I show that the ratio of the valinomycin–$K^+$ and the calixcrown **5**–$K^+$ fluxes at high salt concentrations is 2.6, which agrees very well with the ratio of calculated diffusion coefficients (2.4; see Table III).

These results show that a model description can be very helpful in explaining and understanding phenomena observed in complex systems like membranes.

**Table IV.** Potassium and Sodium Cation Fluxes[a] for Different Potassium-Selective Carriers in Combined Experiments

| carrier | source phase $[K^+]$–$[Na^+]$[b] | $K^+$ flux | $Na^+$ flux | $K^+$ flux/ $Na^+$ flux |
|---|---|---|---|---|
| **1** | 0.08–0.08[c] | 26.4 | ≤0.4 | ≥66 |
| | $10^{-2}$–$10^{-1}$ | 10.2 | 1.4 | 7.3 |
| | $10^{-3}$–$10^{-1}$ | 2.6 | 1.9 | 1.4 |
| **4** | 0.08–0.08[c] | 7.9 | ≤0.4 | ≥20 |
| | $10^{-2}$–$10^{-1}$ | 2.0 | 1.0 | 2.0 |
| | $10^{-3}$–$10^{-1}$ | ≤0.4 | 2.7 | ≤0.1 |
| **5** | 0.08–0.08[c] | 9.2 | ≤0.4 | ≥23 |
| | $10^{-2}$–$10^{-1}$ | 9.2 | ≤0.4 | ≥23 |
| | $10^{-3}$–$10^{-1}$ | 4.6 | 1.7 | 2.7 |
| **6** | 0.08–0.08[c] | 23.7 | ≤0.4 | ≥59 |
| | $10^{-2}$–$10^{-1}$ | 21.8 | ≤0.4 | ≥55 |
| | $10^{-3}$–$10^{-1}$ | 12.4 | 1.4 | 8.9[d] |

[a] $10^{-8}$ mol $cm^{-2}\ h^{-1}$; $[carrier]^0_m = 10^{-2}$ M; $T = 298$ K. [b] Molar. [c] Maximum concentration of a mixture of $KClO_4$ and $NaClO_4$. [d] The actual selectivity is higher since in 24 h more than 75% of the potassium cations is already transported (no initial flux); after 8 h the potassium cation flux was $50 \times 10^{-8}$ mol $cm^{-2}\ h^{-1}$ and the sodium cation flux $0.5 \times 10^{-8}$ mol $cm^{-2}\ h^{-1}$ so the selectivity in fluxes was 100. Also, the selectivities for compounds **1** and **5** may be higher for the lowest salt concentration. In these cases after 24 h 15% and 25% of the potassium cations were transported, respectively.

**Competitive or Two-Cation Transport.** The transport selectivity in competitive transport experiments was measured with mixtures of potassium and sodium perchlorate; the sodium perchlorate concentration was kept constant while the potassium perchlorate concentration was varied. Four potassium-selective carriers (**1**, **4**, **5**, and **6**) were used, and the results of these experiments are given in Table IV. Table IV shows that the transport selectivity for valinomycin and calixcrown **5** is rather low at high potassium perchlorate concentrations in comparison with what was expected from the extraction coefficients. This is again caused by the fact that at high potassium perchlorate concentrations the carriers at the source-phase side are nearly 100% complexed by potassium cations, and the potassium cation flux is limited for this carrier concentration. Since the lower detection limit of the sodium cation flux measurements is $0.4 \times 10^{-8}$ mol $cm^{-2}\ h^{-1}$,[19] the transport selectivity is limited by these two fluxes. Because saturation at these salt concentrations is not observed for dibenzo-18-crown-6 and the diffusion of this carrier is fast, the transport selectivity at higher potassium perchlorate concentrations is unexpectedly high for this carrier. However, at lower potassium perchlorate concentrations (<0.01 M $KClO_4$) when there is no saturation effect for any of these carriers, the data in Table IV show that the transport selectivity is much higher with valinomycin and calixcrown **5** compared to dibenzo-18-crown-6. This agrees with what was expected from the extraction coefficients. The effect on the selectivity of two methoxy instead of two hydroxy groups at the lower rim of the calixcrown compounds is quite large; the methoxy compound transport of potassium cations is much more selective.

The fluxes in the competition experiments were calculated from eqs 17 and 20 and the values of the extraction and diffusion

(18) The diffusion coefficient calculated for dibenzo-18-crown-6 from eq 11 is lower than that calculated before with $K_{ex}'$ ($1.1 \times 10^{-3}$ $cm^2\ h^{-1}$).[2]

(19) The low sodium fluxes ($<0.4 \times 10^{-8}$ mol $cm^{-2}\ h^{-1}$) were difficult to measure accurately. Therefore, the real fluxes might be lower than the reported values.

Table V. Comparison of Measured and Calculated Fluxes[a] in Combined Experiments

| carrier | source phase $[K^+]$-$[Na^+]$[b] | measured $K^+$ flux | measured $Na^+$ flux | calculated $K^+$ flux | calculated $Na^+$ flux |
|---|---|---|---|---|---|
| **1** | 0.08–0.08[c] | 26.4 | ≤0.4 | 25.8 | 0.4 |
| | $10^{-2}$–$10^{-1}$ | 10.2 | 1.4 | 9.8 | 1.3 |
| | $10^{-3}$–$10^{-1}$ | 2.6 | 1.9 | 2.3 | 2.8 |
| **5** | 0.08–0.08[c] | 9.2 | ≤0.4 | 10.0 | 0.008 |
| | $10^{-2}$–$10^{-1}$ | 9.2 | ≤0.4 | 9.7 | 0.06 |
| | $10^{-3}$–$10^{-1}$ | 4.6 | 1.7 | 8.0 | 0.5 |
| **6** | 0.08–0.08[c] | 23.7 | ≤0.4 | 24.3 | 0.005 |
| | $10^{-2}$–$10^{-1}$ | 21.8 | ≤0.4 | 24.1 | 0.04 |
| | $10^{-3}$–$10^{-1}$ | 12.4 | 1.4 | 22.7 | 0.4 |

[a] $10^{-8}$ mol cm$^{-2}$ h$^{-1}$; $[carrier]_m^0 = 10^{-2}$ M; $T$ = 298 K. [b] Molar. [c] Maximum concentration of a mixture of $KClO_4$ and $NaClO_4$.

coefficients as obtained from the single-cation fluxes. The calculated fluxes agree well with the measured fluxes (Table V). From eq 22 it can be seen that the ratio of $K^+/Na^+$ fluxes for one carrier must be directly proportional to the ratio of the salt activities in the source phase. This was not always observed from the measured fluxes. This can be partly explained by the fact that the predicted sodium cation fluxes are lower than measured since the lower detection limit in measuring is about $0.4 \times 10^{-8}$ mol cm$^{-2}$ h$^{-1}$.[19] The predicted potassium cation fluxes for $10^{-3}$ M $KClO_4$ in the case where valinomycin or calixcrown **5** are used as carriers are higher than measured since in this case no initial transport is observed anymore (the concentration of potassium cations in the source phase is not constant; see also Table IV).

## Conclusions

Calixcrown derivatives can be used as potassium-selective carriers in supported liquid membranes, while calix[4]arenes do not result in potassium cation transport. Because of a high lipophilicity, these carriers give stable fluxes. Although the extraction selectivity is high, the transport selectivity is low. This is caused by a limitation of the potassium cation flux at higher salt concentrations (at a certain carrier concentration); because of a slow diffusion combined with a strong complexation there is a complex saturation at the source-phase side. The same effect is observed for valinomycin but not for dibenzo-18-crown-6 or sodium cation transport. The transport selectivity for potassium/sodium cations in competition experiments is as follows: valinomycin > 1,3-dimethoxy-*p-tert*-butylcalix[4]arene crown-5 > dibenzo-18-crown-6 > 1,3-dihydroxy-*p-tert*-butylcalix[4]arene crown-5. The transport selectivity in competition experiments is not the same as the transport selectivity in single-cation experiments. The transport selectivity is not only determined by the extraction coefficients but also by the diffusion coefficients of the complexes and the aqueous salt concentrations (eq 22). This means that the transport selectivities cannot be simply estimated from extraction experiments, and fluxes in competition experiments cannot be simply predicted from single-cation experiments. By using a mathematical model, the fluxes in competitive experiments can, however, be calculated with parameters from single-cation experiments. This model is also helpful in explaining unexpected phenomena observed in single-cation transport (complex saturation) and combined-cation transport (high extraction selectivity, low transport selectivity). The model description may be useful in predicting transport selectivities for different carriers and may therefore be helpful in optimizing selective membrane transport.

## Experimental Section

**Materials.** The synthesis of the calixarene compounds **2–5** has been described before.[5,20] Compounds **1** and **6** were commercially available (Merck-Schuchardt and Fluka respectively). Potassium and sodium perchlorate were obtained from Janssen Chimica and were used without further purification. The polymeric film Accurel was obtained from Enka Membrana. *o*-Nitrophenyl *n*-octyl ether was obtained from Fluka and used without further purification.

**Transport Measurements.** The transport experiments were carried out in a permeation cell consisting of two identical cylindrical compartments (half-cell volume: 50 mL; effective membrane area 12.4 cm$^2$) previously described.[2,4] The supported liquid membrane consisted of a thin, microporous polypropylene film (Accurel; thickness, $d$ = 100 μm, porosity, $\Theta$ = 64%) immobilizing the solution of carrier in *o*-nitrophenyl *n*-octyl ether (NPOE). Aqueous potassium and/or sodium perchlorate solutions were used as the source phase, and doubly distilled and deionized water was used as the receiving phase. The measurements were performed at a constant temperature of 25 °C at least two times. The transported perchlorate salts were determined by monitoring the conductivity of the receiving phase as a function of time (Philips PW 9527 conductivity meter and a Philips PW 9512/61 electrode with a cell constant of 0.76 cm$^{-1}$) in the case of single-cation transport or by atomic absorption measurements of samples taken after 24 h in the case of competitive transport. The standard deviation in the transport measurements is about 15%.

**Acknowledgment.** Financial support from the Koninklijke/Shell-Laboratorium Amsterdam (KSLA) is gratefully acknowledged.

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