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Transport of Uranyl Ion through Liquid Membrane Mediated by Macrocyclic Polycarboxylate in Combination with Hydrophobic Quaternary Ammonium Cation

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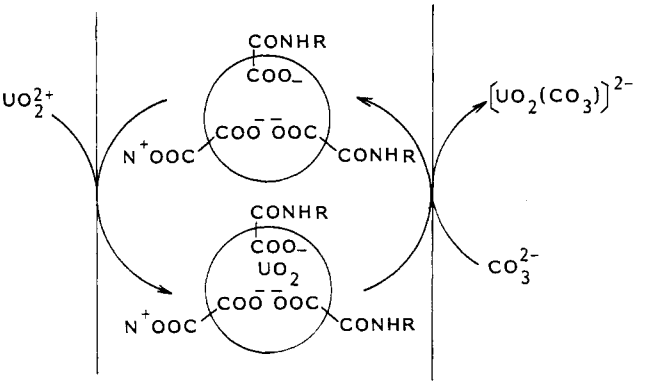
Macrocyclic polycarboxylates affording planer hexadentation to uranyl ion were prepared from a hexaester of 27-membered carboxylic acids. One to three *tert*-butyl moieties were introduced systematically into the macrocyclic skeleton by using ethyl *tert*-butyl malonate in the synthesis. The *tert*-butyl ester functionality was selectively cleaved and converted into the amide of hydrophobic aliphatic amines. The remaining three to five ethyl esters were then hydrolyzed into carboxylic acids that satisfy the hexadentation by three carboxylates attached to different carbon atoms in the macrocycle. These polycarboxylates were combined with hydrophobic quaternary ammonium salts to form complexes with each other, which partitioned preferentially into the organic phase. The 1:1 complex functioned as the real carrier molecule for the uranyl transport through the chloroform liquid membrane. The uranyl ion was transported smoothly against the concentration gradient by the use of carbonate gradient. The efficiency of quaternary salts followed a decreasing order of hydrophobicity: trioctylmethyl > cetyltrimethyl > lauryltrimethyl > benzyltrimethyl > tetraethyl. Among the series of amide carriers, diamide tetracarboxylate **3h** gave the fastest transport rate; then the relative order **3l > 3g > 3m > 3i** was observed, illustrating the combined effect of hydrophobic–hydrophilic balance and stereochemical requirement.

Introduction

Since the discovery of ionophores, the transport of ionic species through the membrane[1] mediated by these ionophores has gained special attention that covers a wide range of interest, including mimicking biologically important phenomena, development of ion-selective electrodes, separation of metal ions or amino acids, applications to a waste water treatment, and others.[2-7]

One of the least studied but most important examples of such ions might be uranium, especially that present in seawater as an extremely dilute solution. The total amount, 4×10^9 tons, is ca. 1000-fold of the amount existing in the mines all over the free world.[8] However, the concentration, 3.3 ppb almost uniformly in all oceans, is too low to be easily extracted and efficient ways of concentrating uranyl species are now under current investigations.[9-11] The most successful approach so far is adsorption onto chelating resins.[12-18] The problem is a small overall adsorption rate mainly limited by the low uranyl concentration and a small equilibrium adsorption by the competing metal ions sometimes in a large excess. Membrane transport may give an attractive alternative. Here, the uranyl ion is transferred into a membrane phase by complexation with appropriate "uranophile"[19-26] type carrier molecules and moves across the membrane and then is liberated into another aqueous phase by the dissociation. For efficient UO_2^{2+} concentration it is necessary to transport UO_2^{2+} against its own concentration gradient across the membrane by applying other chemical potential differences in the opposite direction across the membrane (see Scheme I). Then, the uranyl species is accumulated into the other receiving aqueous phase. This procedure may be promising for the spontaneous concentration of

Scheme I



† Deceased March 22, 1987.

(1) McMurry, W.; Begg, R. W. *Arch. Biochem. Biophys.* **1959**, *84*, 546–548.
(2) Lehn, J. M. *Struct. Bonding (Berlin)* **1973**, *16*, 1–69.
(3) Simon, W.; Morf, W. E.; Meier, P. C. *Struct. Bonding (Berlin)* **1973**, *16*, 113–160.
(4) Pressman, B. C. *Annu. Rev. Biochem.* **1976**, *45*, 501–530.
(5) Izatt, R. M., Christensen, J. J., Ed. *Synthetic Multidentate Macrocyclic Compounds*; Academic Press: New York, 1978.
(6) Ovchinnikov, Y. A. *Eur. J. Biochem.* **1979**, *94*, 321–336.
(7) Wright, J. K.; Seckler, R.; Overath, P. *Annu. Rev. Biochem.* **1986**, *5*, 225–248.
(8) Davies, R.; Kennedy, J.; McIlroy, R.; Spence, R. *Nature (London)* **1964**, *203*, 1110–1115.
(9) Tabushi, I.; Kobuke, Y. *Mem. Fac. Eng. Kyoto Univ.* **1984**, *46*, 51–60.
(10) Tabushi, I.; Kobuke, Y. *Israel J. Chem.* **1985**, *25*, 217–227.
(11) Tabushi, I.; Kobuke, Y.; Nishiya, T. *Nature (London)* **1979**, *280*, 665–666.

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uranyl ion. Here we report the fundamental research directed to the membrane accumulation of uranyl by using macrocyclic polycarboxylates.

Experimental Section

General. Commercially available chemicals were used as received unless otherwise described. Diethyl malonate was distilled prior to use. Ethyl *tert*-butyl malonate was prepared from monoethyl malonate, bp 98–100 °C/44 mm.[27] 1,8-Dibromooctane was prepared by the action of 37% HBr with 1,8-octanediol, which was obtained by $LiAlH_4$ reduction of diethyl suberate. 1,8-Diiodooctane was prepared from the above dibromide through the action of NaI. Tetrahydrofuran (THF) was dried over Na metal under reflux and distilled. A magnetic bar was kept stirring vigorously to expose the metallic surface of sodium flakes. For the preparation of macrocyclic compounds, this dry THF was redistilled over $LiAlH_4$ directly into the reaction flask. Diazomethane was generated from *N*-nitrosomethylurea and trapped into ether. The yellow solution was used directly for the esterification without further distillation. HCl gas was generated by the addition of concentrated H_2SO_4 onto NaCl. The gas was dried by being passed through concentrated sulfuric acid.

Column chromatography was carried out on E. Merck silica gel 60 (70–230 mesh). Analytical thin-layer chromatography (TLC) was carried out on E. Merck silica gel 60F-254 precoated glass plates (0.25 mm).

^1H NMR spectra were recorded with Varian EM-360 or JEOL PMX-60 instruments. Coupling constants are in hertz. Infrared spectra were recorded on a Hitachi 215 spectrophotometer. Mass spectra (MS) were obtained by a JEOL JMS-DX300 instrument. pH measurements were performed on a Toa Electronics Model HM-5B instrument. Melting points (mp) were measured by a Yanagimoto apparatus and were corrected. Microanalyses were obtained from Kyoto University Elemental Analysis Center.

Diethyl α,α-Bis(8-bromooctyl)malonate (1a). A slight excess of an NaH dispersion (60%, 1.76 g, 0.044 mol) was added to a solution of diethyl malonate (6.41 g, 0.04 mol) in 300 mL of dry THF. The mixture was refluxed for 30 min and then cooled to room temperature. Dibromooctane (43.5 g, 0.16 mol) was added in one portion and the solution was heated to 50–55 °C for 3 h. Then the mixture was cooled again to room temperature and another portion of the NaH dispersion (60%, 1.76 g, 0.044 mol) was added, and the solution was heated to 50–55 °C for 1.5 h. THF was distilled off and the residue was poured into saturated NaH_2PO_4, extracted with ether (40 mL × 4), and dried over Na_2SO_4. After evaporation of ether, excess dibromooctane was recovered by distillation under reduced pressure. The residue was subjected to a column chromatography using ether–hexane (1:1, v/v) as eluent to give 1.17 g (54%) of **1a** as an oil: TLC R_f = 0.56 (ether–hexane, 1:1, v/v); ^1H NMR (CCl_4) δ 4.17 (4 H, q, J = 7.0), 3.37 (4 H, t, J = 6.5), 2.1–1.1 (34 H, m); IR (film) 2900, 2830, 1715, 1450, 1350, 1220, 1180, 1010, 850, 710 cm^{-1}. Anal. Calcd for $C_{23}H_{42}Br_2O_4$: C, 50.93, H, 7.80; Br, 29.46. Found: C, 50.82; H, 7.82; Br, 29.25.

Diethyl α,α-Bis(8-iodooctyl)malonate (1b). The bromo derivative **1a** (4.3 g, 7.9 mmol) was mixed with sodium iodide (3.55 g, 24 mmol) in 20 mL of 2-butanone. The mixture was heated to 80–85 °C for 17 h, where the triplet centered at δ 3.37 (α to bromo) in the ^1H NMR spectrum completely disappeared and a new triplet due to HC α to iodine appeared at δ 3.22. Most of 2-butanone was distilled off and the product was partitioned between ether and water (20 mL each). The organic layer was separated and the aqueous layer was further extracted twice with ether (each 10 mL). Combined ether extracts were washed with 5% $NaHSO_3$ solution (10 mL), dried over Na_2SO_4, and evaporated to give 5 g (99%) of a yellow oil. The oily product was dried overnight in vacuo and used directly for the subsequent reaction.

Ethyl *tert*-Butyl α,α-Bis(8-bromooctyl)malonate (1c). Similar to the preparation of **1a**, ethyl *tert*-butyl malonate (1.65 g, 8.8 mmol) was treated with two portions of an NaH dispersion (50%, 0.49 g × 2, total 20.4 mmol) and 1,8-dibromooctane (15.3 g, 56 mmol) in dry THF (60 mL). After workup, the product was isolated through a column eluted with ether–hexane (1:5, v/v) as a colorless oil of 2.28 g (46%); IR (film) 2900, 2830, 1720, 1440, 1385, 1360, 1240, 1140, 1020, 840 cm^{-1}; ^1H NMR (CCl_4) δ 4.20 (2 H, q, J = 7.0), 3.30 (4 H, t, J = 6.5), 2.1–1.1 (40 H, m). Anal. Calcd for $C_{25}H_{46}Br_2O_4$: C, 52.64; H, 8.13. Found: C, 52.78; H, 8.24.

Ethyl *tert*-Butyl α,α-Bis(8-iodooctyl)malonate (1d). The bromo derivative (4 g, 7 mmol) was treated with sodium iodide (5 g, 33 mmol) in 25 mL of 2-butanone. The product (4.34 g, 95% recovery) separated by extraction was pure enough to be used for the next cyclization reaction without further purification.

Tetraethyl *n*-Decane-1,1,10,10-tetracarboxylate (2a). Into a 50-mL three-necked flask fitted with a dropping funnel and a reflux condenser attached with a $CaCl_2$–P_2O_5 tube on the top was placed 200 mL of absolute ethanol. Sodium (8.35 g, 0.36 mol) was added in small pieces and then diethyl malonate (64 g, 0.4 mol) was added slowly through the dropping funnel. The mixture was heated under reflux for 1 h to complete the formation of malonate anion and then a solution of 1,8-diiodooctane (33.2 g, 0.09 mol) in 20 mL of ethanol was added and heated under reflux for a further 4 h. After distilling off the solvent, 50 mL of water was added to the residue and the mixture was neutralized by the addition of NH_4Cl. The product was extracted with ether (50 mL × 4). The combined ethereal extracts were dried over Na_2SO_4 and concentrated into a small volume. The product was distilled in vacuo. The fraction boiling at 194–196 °C (0.4 mm) was collected, 26.3 g (67%): IR (film) 2900, 2830, 1725, 1465, 1380, 1360, 1290–1080, 1020, 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ 4.00 (8 H, q, J = 7.0), 3.14 (2 H, t, J = 7.0), 2.7–1.1 (28 H, m).

Diethyl Di-*tert*-butyl *n*-Decane-1,1,10,10-tetracarboxylate (2b). A sodium hydride dispersion (50%, 2.4 g, 0.05 mol) was added to a solution of ethyl *tert*-butyl malonate (18.8 g, 0.1 mol) in 100 mL of dry THF and the mixture was refluxed for 30 min. Dibromooctane (8.97 g, 0.033 mol) was added dropwise in a period of 1 h with stirring under reflux. The mixture was refluxed for a further 4 h. Then most of THF was distilled off. The residue was partitioned between ether and an aqueous saturated NaH_2PO_4 solution (30 mL each). The organic layer was separated and the aqueous layer was extracted with ether (30 mL × 3). Combined ether extracts were washed with water and dried over Na_2SO_4 and then the ether was evaporated. After removal of excess ethyl *tert*-butyl malonate by a distillation under reduced pressure, the residue was column chromatographed (ether–hexane, 1:3, v/v) to give 7.5 g (47%) of **2b**: TLC R_f = 0.34 (ether–hexane, 1:3, v/v); IR (film) 2900, 2830, 1720, 1450, 1380, 1360, 1240, 1130, 1020, 840 cm^{-1}; ^1H NMR (CCl_4) δ 4.24 (4 H, q, J = 7.0), 3.24 (2 H, t, J = 7.0), 2.1–1.1 (40 H, m). Anal. Calcd for $C_{26}H_{46}O_8$: C, 64.17; H, 9.53. Found: C, 64.30; H, 9.65.

1,1,10,10,19-Pentacarbethoxy-19-carbo-*tert*-butoxycycloheptacosane (3a). Into a 2-L three-necked flask protected from moisture by a $CaCl_2$–P_2O_5 tube were placed tetraester **2a** (1.28 g, 3 mmol) and diiodide **1d** (1.99 g, 3 mmol). Dry THF (1000 mL)

(12) Egawa, H.; Harada, H. *J. Chem. Soc. Jpn.* **1979**, 958–959.
(13) Egawa, H.; Harada, H.; Nonaka, T. *J. Chem. Soc.* Jpn. **1980**, 1767–1772.
(14) Egawa, H.; Harada, H.; Shuto, T. *J. Chem. Soc. Jpn.* **1980**, 1773–1776.
(15) Sugasaka, K.; Katoh, S.; Takai, N.; Takahashi, H.; Umezawa, Y. *Sep. Sci. Technol.* **1981**, *16*, 971–985.
(16) Schwochau, K.; Astheimer, L.; Schenk, H. J.; Witte, E. G. *Z. Naturforsch.* **1982**, *37b*, 214–216.
(17) Astheimer, L.; Schenk, J. J.; Witte, E. G.; Schwochau, K. *Sep. Sci. Technol.* **1983**, *18*, 307–339.
(18) Kobuke, Y.; Tabushi, I.; Aoki, T.; Kamaishi, T.; Hagiwara, I. *Ind. Eng. Chem. Res.* **1988**, *27*, 1461–1466.
(19) Tabushi, I.; Kobuke, Y.; Nishiya, T. *Tetrahedron Lett.* **1979**, 3515–3518.
(20) Tabushi, I.; Kobuke, Y.; Ando, K.; Kishimoto, M.; Ohara, E. *J. Am. Chem. Soc.* **1980**, *102*, 5947–5948.
(21) Tabushi, I.; Kobuke, Y.; Yoshizawa, A. *J. Am. Chem. Soc.* **1984**, *106*, 2481–2482.
(22) Bismondo, A.; Casellato, U.; Sitran, S.; Graziani, R. *Inorg. Chim. Acta* **1985**, *110*, 205–210.
(23) Fux, P.; Lagrange, J.; Lagrange, P. *J. Am. Chem. Soc.* **1985**, *107*, 5927–5031.
(24) Shinkai, S.; Koreishi, H.; Ueda, K.; Manabe, O. *J. Chem. Soc., Chem. Commun.* **1986**, 233–234.
(25) Shinkai, S.; Koreishi, H.; Ueda, K.; Arimura, T.; Manabe, O. *J. Am. Chem. Soc.* **1987**, *109*, 6371–6376.
(26) Kobuke, Y.; Tabushi, I.; Oh, K. *Tetrahedron Lett.* **1988**, *29*, 1153–1156.
(27) Breslow, D. S.; Baumgarten, E.; Hauser, C. R. *J. Am. Chem. Soc.* **1944**, *66*, 1286–1288.

was redistilled over $LiAlH_4$ directly into the flask. Two necks were then equipped with a stirrer and a reflux condenser, the top of which was attached with a $CaCl_2$–P_2O_5 tube. An NaH dispersion in oil (50%, 0.58 g, 12 mmol) was added in one portion and the mixture was stirred under reflux for 20 h. Most of THF was removed and the residue was partitioned between 30 mL each of ether and saturated aqueous NaH_2PO_4 solution. The organic layer was separated and the aqueous layer was extracted with ether (50 mL × 5). The combined ether extract was washed with water (50 mL) and dried over Na_2SO_4. After the ether was evaporated, the residue was column chromatographed. The fraction eluted with ether–hexane (1:2, v/v) gave 1.51 g (60%) of **3a** as a colorless solid. Recrystallization from *n*-hexane gave needles: mp 75–77 °C; TLC R_f = 0.38 (ether–hexane, 1:2, v/v); IR (KBr) 2900, 2830, 1720, 1460, 1360, 1290, 1260, 1245, 1205, 1140, 1110, 1080, 1020, 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ 4.18 (10 H, q, J = 7.0), 2.0–1.0 (72 H, m). Anal. Calcd for $C_{47}H_{82}O_{12}$: C, 67.27; H, 9.85. Found: C, 67.37; H, 10.12.

1,1,10,19-Tetracarbethoxy-10,19-dicarbo-*tert*-butoxycycloheptacosane (3b). Diethyl di-*tert*-butyl ester **2b** (1.46 g, 3 mmol) and α,ω-diiodide **1b** (1.92 g, 3 mmol) were dissolved in 600 mL of dry THF. An NaH dispersion (60%, 0.32 g, 8 mmol) was added and the reaction mixture was refluxed for 21 h. NaH (60%, 0.08 g, 2 mmol) was added further, and the refluxing was continued for an additional 5 h. The reaction mixture was treated similarly to **3a** and the product was isolated through column chromatography by eluting with ether–hexane (1:2, v/v) to give 0.95 g (36.5%) of a colorless solid, which was recrystallized from *n*-hexane, mp 78–80 °C: TLC R_f = 0.41 (ether–hexane, 1:2, v/v); IR (KBr) 2900, 2830, 1720, 1450, 1380, 1360, 1290, 1260, 1200, 1140, 1105, 1020, 840 cm^{-1}; NMR ($CDCl_3$) δ 4.10 (8 H, q, J = 7.0), 2.0–1.0 (78 H, m). Anal. Calcd for $C_{49}H_{86}O_{12}$: C, 67.87; H, 10.00. Found: C, 67.91; H, 10.17.

1,10,19-Tricarbethoxy-1,10,19-tricarbo-*tert*-butoxycycloheptacosane (3c). Diethyl di-*tert*-butyl ester **2b** (2.77 g, 5.7 mmol) and α,ω-diiodide **1d** (3.79 g, 5.7 mmol) were dissolved in 1.2 L of dry THF. An NaH dispersion (60%, 0.72 g, 18 mmol) was added. The mixture was refluxed for 20 h. The reaction mixture was treated as above and the product was isolated through column chromatography by eluting with ether–hexane (1:3, v/v) to give 0.84 g (23.5%) of a colorless solid, which was recrystallized from *n*-hexane as needles, mp 69–71 °C: TLC R_f = 0.35 (ether–hexane, 1:3, v/v); IR (film) 2900, 2830, 1720, 1450, 1380, 1360, 1290–1080 (br), 1020, 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ 4.23 (6 H, q, J = 7.0), 2.0–1.0 (84 H, m). Anal. Calcd for $C_{51}H_{90}O_{12}$: C, 68.42; H, 10.13. Found: C, 68.15; H, 10.43.

1,1,10,10,19-Pentacarbethoxy-19-(Octadecylcarbamoyl)cycloheptacosane (3d). Macrocyclic mono-*tert*-butyl ester **3a** (270 mg, 0.33 mmol) was dissolved in 20 mL of CH_2Cl_2. Dry HCl gave was passed into the solution for 8 h, after which the starting material was confirmed to be completely disappeared by TLC. Dry air was then introduced to expel HCl gas. Evaporation of CH_2Cl_2 gave 235 mg of a waxy solid. The solid was used directly for further preparation without purification. The monoacid (235 mg, 0.3 mmol) thus obtained was refluxed with 10 mL of $SOCl_2$ for 1 h. Excess $SOCl_2$ was distilled off completely by the final application of vacuum. The residue was dissolved in 13 mL of CH_2Cl_2 and stearylamine (161 mg, 0.6 mmol) and triethylamine (83 μL, 0.6 mmol) were added. The mixture was stirred at room temperature for 30 min. CH_2Cl_2 was evaporated and water (2 mL) was added and the mixture was neutralized with 0.1 N HCl. The mixture was extracted with ether (20 mL × 3). The combined ether extracts were washed with 10 mL of water and dried over $MgSO_4$. After evaporation of ether, the residue was column chromatographed (ether–hexane, 1:3, v/v) to give 231 mg (73%) of a waxy mass: TLC R_f = 0.58 (ether–hexane, 1:1, v/v); IR (film) 2900, 2830, 1720, 1650, 1520, 1460, 1360, 1290–1140, 1080, 1020, 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.35 (1 H, br), 4.23 (10 H, q, J = 7.0), 3.27 (2 H, t, J = 7.0), 2.0–1.0 (98 H, m). Anal. Calcd for $C_{61}H_{111}NO_{11}$: C, 70.82; H, 10.81; N, 1.35. Found: C, 71.44; H, 11.05; N, 1.77.

1,1,10,19-Tetracarbethoxy-10,19-bis(octadecylcarbamoyl)cycloheptacosane (3e). Macrocyclic di-*tert*-butyl ester **3b** (375 mg, 0.43 mmol) in CH_2Cl_2 was treated with HCl gas in a similar manner to the preparation of **3d**. A waxy solid (295 mg, 91%) was used directly after drying: TLC R_f = 0.32 (ether–hexane, 3:1, v/v); IR (film) 3260, 2900, 2830, 1740–1650, 1450, 1360, 1290–1080, 1020, 925, 850 cm^{-1}; ^1H NMR ($CDCl_3$) δ 9.6 (2 H, br), 4.17 (8 H, m), 2.1–1.0 (60 H, br).

The crude diacid (90 mg, 0.12 mmol) was then treated first with $SOCl_2$ (5 mL) and with a mixture of stearylamine (129 mg, 0.48 mmol) and triethylamine (49 mg, 0.48 mmol), similarly to the preparation of **3d**. The product was isolated through column chromatography (ether–hexane, 1:1, v/v) as 101 mg (67%) of a waxy mass: TLC R_f = 0.44 (ether–hexane, 1:1, v/v); IR (film) 3350, 2800, 2830, 1720, 1650, 1530, 1460, 1260–1150, 1010, 860, 800 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.30 (2 H, br), 4.22 (4 H, q, J = 7.0), 4.20 (4 H, q, J = 7.0), 3.26 (4 H, m), 2.0–1.0 (130 H, br).

1,10,19-Tricarbethoxy-1,10,19-tris(octadecylcarbamoyl)cycloheptacosane (3f). Macrocyclic tri-*tert*-butyl ester **3c** (240 mg, 0.27 mmol) in CH_2Cl_2 was hydrolyzed into the tricarboxylic acid by the action of HCl gas to yield 190 mg (97%) of a waxy mass: TLC R_f = 0.29 (ether–hexane, 1:1, v/v); IR (film) 3200, 2900, 2830, 1740–1680, 1450, 1360, 1300–1100, 1020, 910, 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ 10.9 (3 H, br), 4.23 (6 H, br m), 2.1–1.0 (57 H, br).

The crude triacid (150 mg, 0.21 mmol) was treated with $SOCl_2$ (15 mL) and then with a mixture of stearylamine (339 mg, 1.26 mmol) and triethylamine (126 mg, 1.26 mmol) to yield 252 mg (81%) of **3f** after a column chromatographic separation (ether–hexane, 1:1, v/v); TLC R_f = 0.50; IR (film) 3300, 2900, 2830, 1720, 1700, 1650, 1520, 1450, 1360, 1300–1100, 1010, 840 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.33 (3 H, br), 4.23 (6 H, m) 3.24 (6H, br, m), 2.0–1.0 (162 H, br).

1,1,10,10,19-Pentacarboxy-19-(octadecylcarbamoyl)cycloheptacosane (3g). Pentaester monoamide **3d** (200 mg, 0.19 mmol) was added to an aqueous alcoholic solution (30 mL, 1:5) of 85% KOH (2 g) and the mixture was refluxed with magnetic stirring for 4 h. Ethanol was removed and the residue was acidified (pH <1) with dilute HCl and then extracted with ether (10 mL × 3). The combined ether extracts were washed with water (5 mL × 2) and dried (Na_2SO_4). Evaporation of ether gave 151 mg (89%) of a colorless solid, which was chromatographed (ether–methanol, 9:1, v/v) to afford colorless needles: mp 55–57 °C; TLC R_f = 0.25; IR (KBr) 3330, 2920, 2850, 1720, 1610, 1550, 1470, 1370, 1290–1090, 1030, 920 cm^{-1}; ^1H NMR ($CDCl_3$) δ 9.67 (5 H, br), 7.90 (1 H, br), 3.27 (2 H, br), 2.0–1.0 (83 H, br). Anal. Calcd for $C_{51}H_{91}NO_{11}$: C, 68.50; H, 10.26; N, 1.57. Found: C, 68.65; H, 10.44; N, 1.64.

1,1,10,19-Tetracarboxy-10,19-bis(octadecylcarbamoyl)cycloheptacosane (3h). Tetraester diamide **3e** (70 mg, 0.056 mmol) was treated with an aqueous alcoholic solution (15 mL, 1:5) of 0.75 g of 85% KOH to yield 54 mg (84%) of a waxy mass: TLC R_f = 0.44 (ether–methanol, 9:1, v/v); IR (KBr) 3250, 2900, 2830, 1700, 1580, 1530, 1460, 1420, 1370, 1260 cm^{-1}; ^1H NMR ($CDCl_3$) δ 10.5 (4 H, br), 7.8 (2 H, br), 3.3 (4 H, br), 2.0–1.0 (118 H, br). Anal. Calcd for $C_{69}H_{128}N_2O_{10}$: C, 72.33; H, 11.26; N, 2.44. Found: C, 72.37; H, 11.26; N, 2.60.

1,10,19-Tricarboxy-1,10,19-tris(octadecylcarbamoyl)cycloheptacosane (3i). Triester triamide **3f** (150 mg, 0.1 mmol) was treated with alcoholic KOH to yield 134 mg (95%) of a waxy mass: TLC R_f = 0.47 (ether–methanol, 9:1, v/v); IR (film) 3300, 2900, 2830, 1700, 1580, 1530, 1470, 1360, 1220–1100, 900 cm^{-1}; ^1H NMR ($CDCl_3$) δ 10.6 (3 H, br), 7.9 (3 H, br), 3.4 (6 H, br), 2.0–1.0 (162 H, br). Anal. Calcd for $C_{87}H_{165}N_3O_9$: C, 74.79; H, 11.90; N, 3.01. Found: C, 74.64; H, 12.00; N, 2.72.

The following compounds were prepared according to the procedures described in detail for the related compounds **3e**, **3f**, **3h**, or **3i**.

1,1,10,19-Tetracarbethoxy-10,19-bis(dodecylcarbamoyl)cycloheptacosane (3j): yield 75%; TLC R_f = 0.49 (ether–hexane, 1:1, v/v); IR (film) 3330, 2900, 2830, 1720, 1645, 1520, 1290–1150, 1090, 1010, 860 cm^{-1}; ^1H NMR ($CDCl_3$) δ 4.17 (8 H, m), 3.25 (4 H, m), 2.0–1.0 (106 H, br). Anal. Calcd for $C_{65}H_{120}N_2O_{10}$: C, 71.65; H, 11.10; N, 2.57. Found: C, 71.40; H, 11.20; N, 2.46.

1,10,19-Tricarbethoxy-1,10,19-tris(dodecylcarbamoyl)cycloheptacosane (3k): yield 83%: TLC R_f = 0.68 (ether–hexane, 2:1, v/v); IR (film) 3330, 2900, 2830, 1720, 1650, 1530, 1290–1090, 1010, 860 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.33 (3 H, br), 4.25 (6 H, m), 3.30 (6 H, br, q, J = 7.0), 2.0–1.0 (126 H, br). Anal. Calcd for $C_{75}H_{141}N_3O_9$: C, 73.30; H, 11.56; N, 3.42. Found: C, 73.05; H, 11.60; N, 3.28.

Table I. Uranyl Transport through Chloroform Liquid Membrane Mediated by Polycarboxylate–Hydrophobic Ammonium Complex

entry	$CHCl_3$ carboxylate,[a] 10^{-5}M		$CHCl_3$ ammonium,[b] 10^{-5}M		aq I UO_2^{2+}, 10^{-5}M	aq I pH initial	aq I pH final	aq II $NaHCO_3$, M	aq II pH initial	aq II pH final	rate, $\mu M \cdot h^{-1} \cdot cm^{-2}$
1	**3h**	10			3.3	5.05	[c]	1.0	8.50	[c]	0
2			**4a**	10	3.3	5.05	[c]	1.0	8.50	[c]	0
3	**3h**	10	**4a**	10	3.29	5.05	[c]	1.0	8.65	[c]	1.94
4	**3h**	10	**4b**	10	3.29	5.05	[c]	1.0	8.62	[c]	0.0
5	**3h**	10	**4c**	10	3.29	4.92	[c]	1.0	8.22	[c]	0.26
6	**3h**	10	**4d**	10	3.29	4.92	[c]	1.0	8.62	[c]	1.45
7	**3h**	10	**4e**	10	3.29	5.05	[c]	1.0	8.65	[c]	1.76
8	**3g**	10	**4a**	10	3.29	5.07	4.84	1.0	8.60	9.00	1.19
9	**3i**	10	**4a**	10	3.29	5.07	[c]	1.0	8.50	[c]	0.62
10	**3l**	10	**4a**	10	3.29	5.05	[c]	1.0	8.65	[c]	1.41
11	**3m**	10	**4a**	10	3.29	[c]	5.20	1.0	8.27	8.82	0.97
12	**3g**	5	**4a**	5	6.20	5.07	4.62	1.0	8.60	8.87	1.76
13	**3h**	5	**4a**	5	6.20	4.95	4.65	1.0	8.40	8.85	2.03
14	**3i**	5	**4a**	5	6.20	5.00	4.76	1.0	8.40	8.84	1.37
15	**3l**	5	**4a**	5	6.20	5.00	4.83	1.0	8.40	8.87	1.81
16	**3m**	5	**4a**	5	6.20	5.00	6.00	1.0	8.40	8.77	1.67
17	**3h**	5	**4a**	2.5	6.92	5.0	5.4	1.0	8.5	9.0	0.70
18	**3h**	5	**4a**	5	6.92	4.6	5.0	1.0	8.5	8.9	2.03
19	**3h**	5	**4a**	15	6.92	4.6	5.4	1.0	8.5	9.1	1.81
20	**3h**	5	**4a**	20	6.92	4.6	5.2	1.0	8.5	9.0	1.85
21	**3h**	5	**4a**	50	6.92	5.0	5.6	1.0	8.4	9.0	2.03
22	**3h**	5	**4a**	5	5.34	5.07	4.48	1.0	8.80	9.00	2.03
23	**3h**	5	**4a**	5	2.0	[c]	4.58	1.0	[c]	8.95	0.88
24	**3h**	10	**4a**	10	6.92	5.00	4.20	1.0	8.40	9.00	2.51
25	**3h**	20	**4a**	20	6.92	5.00	5.38	1.0	8.53	8.83	2.73
26	**3h**	1	**4a**	1	3.29	5.05	[c]	1.0	8.65	[c]	0.57
27	**3h**	10	**4a**	10	3.24[d]	8.2	[c]	1.0	8.65	[c]	0.84
28	**3h**	10	**4a**	10	3.41[e]	8.2	[c]	1.0	8.65	[c]	0.87

[a] See Scheme II for structures of macrocycles **3**. [b] **4a** (trioctylmethylammonium chloride), **4b** (tetraethylammonium bromide), **4c** (benzyltriethylammonium chloride), **4d** (lauryltrimethylammonium chloride), and **4e** (cetyltrimethylammonium chloride). [c] pH value not measured. [d] $UO_2(OAc)_2$ was added to natural seawater. See the text for metal ion concentrations. [e] Aq I contains 1.0×10^{-2} M Ca^{2+} as a coexisting metal ion.

1,1,10,19-Tetracarboxy-10,19-bis(dodecylcarbamoyl)-cycloheptacosane (3l): yield 71%; TLC R_f = 0.42 (ether–methanol, 9:1, v/v); IR (film) 3270, 2900, 2830, 1720, 1690, 1580, 1530, 1470, 1420, 1360, 1220–1140 cm^{-1}; ^1H NMR ($CDCl_3$) δ 10.6 (4 H, br), 7.7 (2 H, br), 3.30 (4 H, br), 2.0–1.0 (94 H, br).

1,10,19-Tricarboxy-1,10,19-tris(dodecylcarbamoyl)cycloheptacosane (3m): yield 70%; TLC R_f = 0.44 (ether–methanol, 9:1, v/v); IR (KBr) 3300, 2900, 2830, 1700, 1580, 1530, 1460, 1360, 1200–1080 cm^{-1}; ^1H NMR ($CDCl_3$) δ 8.50 (3 H, br), 7.70 (3 H, br), 3.37 (6 H, br), 2.0–1.0 (117 H, br).

Transport. Transport experiments were conducted by using U-shaped cells, where two cylinders (each i.d. = 16 mm, height = 10 cm) with flat bottoms were connected by a small bridge (i.d. = 6 mm, length = 5 mm) near the bottom. The cells were placed in a thermostated (25.0 ± 0.1 °C) bath, below which magnetic motors were equipped as described below. In the cell, aqueous phase I (aq I) containing uranyl acetate and aqueous phase II (aq II) containing sodium bicarbonate were separated by an intervening chloroform solution containing the carrier molecule (8 mL each). The pH of aq I was adjusted carefully by the addition of 0.1 N HCl and/or NaOH solution. Buffer was not used throughout the transport experiments in order to avoid any possible undesired interactions with uranyl ion, which forms stable complexes with weak acid anions. Therefore, a slight pH change was observed before and after the transport experiment, the data of which were included in the Table I. This may reflect a subtle shift of the equilibrium of ionic species in the aqueous phase but not influence the results significantly, because of the small pH change observed. The concentrations of both aqueous phases were determined by the Arsenazo III method[28] for aliquots taken out at specified time intervals.

Transport Equipment. We have constructed special equipment for stirring magnetic bars inside the U-tube as described below. Figure 1 illustrates five rotors as well as an additional driving rotor on the front side. Here model motors (Mabuchi motor, RE 140) were employed just for bearing blocks of rotating magnets. All of the electric coil system and magnets inside the motor were taken out and the cover was sealed again. A stainless steel bar (2 mm i.d. = 70 mm in length) was passed through the central hole of each rotor. Ten such rotors were attached to a stainless steel plate (40 mm × 440 mm, 1.2 mm in the thickness) by using pedestals attached to the original motor so that a pair may stand opposite to the stainless steel plate to afford five sets of magnetic stirrers. Near the bottom end of the stainless steel bar on the front side, three model plastic wheels (20, 40, and 40 mm i.d., from the top to the bottom) were fixed. To the steel bar on the rear side, only one wheel (20 mm i.d.) was attached at the top level of the corresponding one on the front side. Front and rear wheels of each set were connected together by a loop of string. In addition to this connection, a sheet of polyethylene (15 mm × 300 mm) connected five front wheels to each other by passing additional small stainless steel bars (10 mm in length) extending down from the lowest wheels. This polyethylene sheet assured all rotors of a certain identical rotation rate. An additional motor set attached on the front side was directly driven by a set of electric motor, Oriental PS425-201, and a gear, Oriental 4GK3.6K, which gave a speed control in the range of 25–470 rpm. At each top end of the steel bar, small magnets were attached on the small wheel (20 mm i.d.). The front and rear wheel set was used to stir a pair of magnetic bars in the U-shaped transport cell.

The equipment described above gives a frictionless rotation without noise and assured a required identical rpm for all sets of the magnet. The latter condition is essential for experiments studying the effect of stirring rates on the transport rate.

Two-Phase Experiment. Two-phase experiments were undertaken in vials of appropriate sizes. Aqueous I contains uranyl of appropriate concentrations as a donating phase. The receiving phase, aq II, contains sodium carbonate. The aqueous phase, I or II, was placed on a chloroform phase, which contains the carrier molecule. The chloroform phase was continuously stirred with a magnetic bar that was driven with a speed controlled by using

(28) Ohnishi, K.; Hori, Y.; Tomari, Y. *Bunseki Kagaku* **1977**, *26*, 74–77.

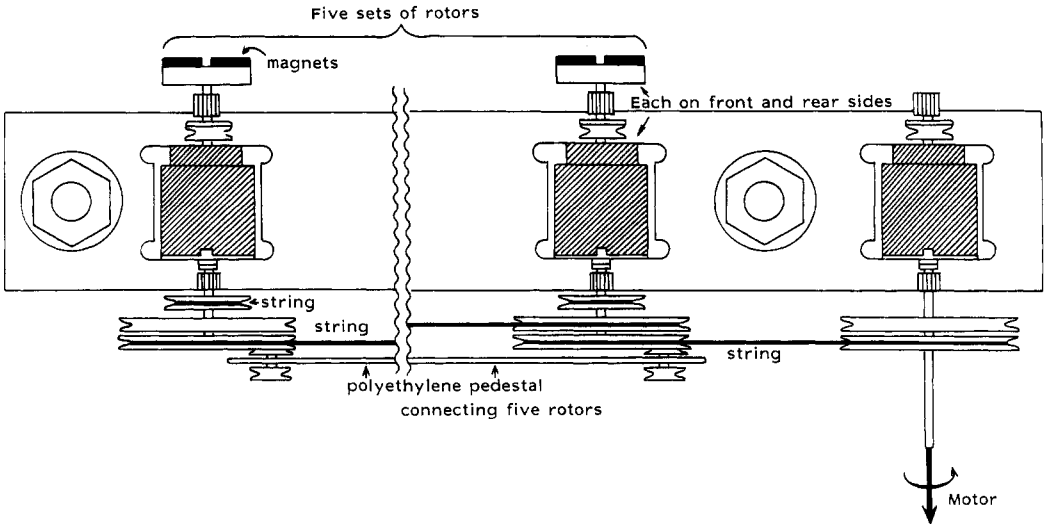


Figure 1. Specially designed transport equipment assuring an identical rotation rate for all transport cells.

the equipment described above. An aliquot of the aqueous phase was sampled out from time to time to analyze the uranyl concentration.

Results and Discussion

Preparation of Carriers. The macrocyclic hexacarboxylic acid was chosen as a starting material to prepare the specific carrier molecule recognizing uranyl ion based on the following reasons. As described in the preceding communication[20,26] three of six carboxylates are expected to give a specific and strong binding site for the uranyl ion, each carboxylate providing a bidentate coordination. Then, the other three may be converted for certain desired functions. Appropriate lipophilicity is one of the possibilities by considering that the carrier must be partitioned favorably into the membrane phase. At the same time, a part of the molecule should reasonably be hydrophilic to achieve rapid association–dissociation rates at the interphase. Thus, one, two, or at most three long alkyl chains were introduced into the molecule via amide bond formation in order to gain an appropriate lipophilic–hydrophilic balance.

The preparation of the macrocyclic skeleton was carried out by the use of *tert*-butyl ethyl malonate instead of diethyl malonate employed in the synthesis of the hexacarboxylic acid.[20] The resulting *tert*-butyl ester in the macrocycles **3a–c** was converted selectively to the corresponding carboxylic acid under a mild acidic condition without a concomitant hydrolysis of other ethyl ester moieties. The carboxylic acid was then converted to the acyl chloride, which was treated further with stearyl- or laurylamine to give the mixed amide ester. The ester functionality was then selectively and cleanly hydrolyzed under an alkaline condition to the corresponding amide carboxylic acid, where the amide grouping remained unchanged under these conditions. According to this procedure, a pentaacid monoamide, tetraacid diamides, and triacid triamides were prepared. The preparation scheme is summarized in Scheme II.

Effect of Hydrophobic Ammonium on Transport. Aqueous phase I containing uranyl acetate (3.3×10^{-5} M, 8 mL) was brought in contact (rpm = 150) with a solution of di-C_{18}-amide tetracarboxylate **3h** in chloroform (1.0×10^{-4} M, 8 mL), which was again in contact with aqueous phase II containing sodium bicarbonate (1.0 M, 8 mL) as a uranyl receiving agent. The transport was negligibly slow under these conditions. The addition of trioctylmethylammonium chloride (**4a**) to the chloroform phase ($1.0 \times$

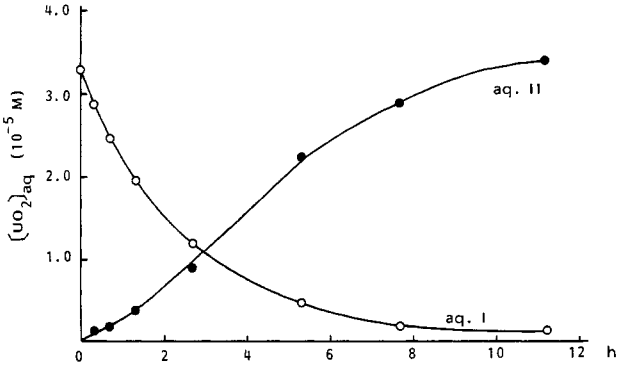
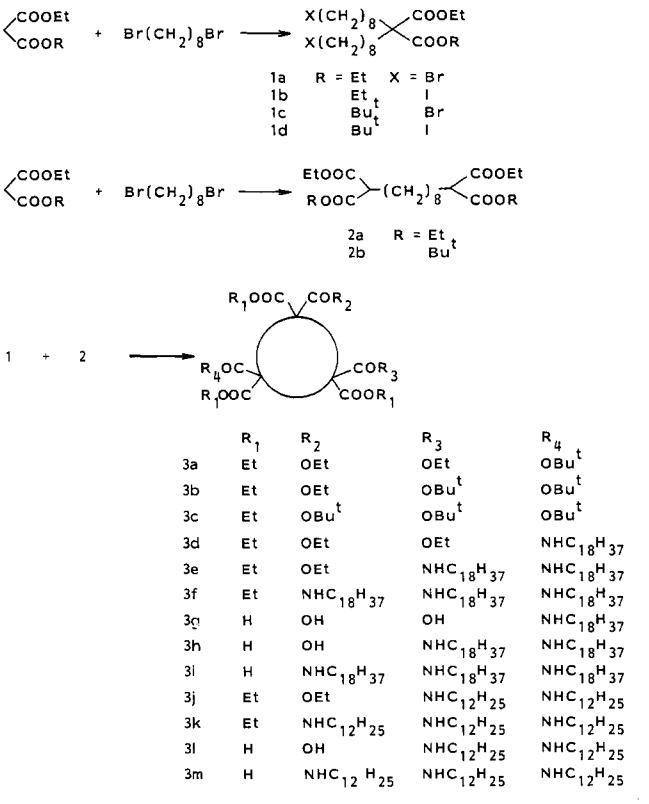


Figure 2. Transport of uranyl by a combination of diamide tetracarboxylate (**3h**) and trioctylammonium chloride (**4a**) in a 1:1 composition.

Scheme II



	R_1	R_2	R_3	R_4
3a	Et	OEt	OEt	OBu^t
3b	Et	OEt	OBu^t	OBu^t
3c	Et	OBu^t	OBu^t	OBu^t
3d	Et	OEt	OEt	$NHC_{18}H_{37}$
3e	Et	OEt	$NHC_{18}H_{37}$	$NHC_{18}H_{37}$
3f	Et	$NHC_{18}H_{37}$	$NHC_{18}H_{37}$	$NHC_{18}H_{37}$
3g	H	OH	OH	$NHC_{18}H_{37}$
3h	H	OH	$NHC_{18}H_{37}$	$NHC_{18}H_{37}$
3i	H	$NHC_{18}H_{37}$	$NHC_{18}H_{37}$	$NHC_{18}H_{37}$
3j	Et	OEt	$NHC_{12}H_{25}$	$NHC_{12}H_{25}$
3k	Et	$NHC_{12}H_{25}$	$NHC_{12}H_{25}$	$NHC_{12}H_{25}$
3l	H	OH	$NHC_{12}H_{25}$	$NHC_{12}H_{25}$
3m	H	$NHC_{12}H_{25}$	$NHC_{12}H_{25}$	$NHC_{12}H_{25}$

Table II. Effect of Trioctylmethylammonium Chloride (4a) on the Uptake of Uranyl Ion in Two-Phase Experiments[a]

3h, 10^{-5} M	4a, 10^{-5} M	time, h	$[UO_2]_{aq}$, 10^{-5} M	extractn, %
10.0	0	0	3.30	
10.0	0	4	1.77	44
10.0	0	18	1.54	46
10.0	10.0	0	3.57	
10.0	10.0	0.3	1.82	41
10.0	10.0	1	0.64	74
10.0	10.0	2	0.41	81

[a] Equal volumes (3 mL) of aqueous and chloroform solutions were used.

10^{-4} M, 1:1 molar ratio with **3h**), however, accelerated the transport dramatically as shown in Figure 2. The uranyl concentration in aq I decreased smoothly in accord with its appearance in aq II. After 3 h of transport, the concentrations in the two phases reached the same level and still the transport continuously proceeded against the concentration gradient between two aqueous phases giving rise to a complete reversal of the uranyl concentrations in the two aqueous phases. The transport rate, estimated from a linear increase of $[UO_2]$ in aq II against time, was 1.52 $\mu M \cdot h^{-1} \cdot cm^{-2}$ (entry 3 in Table I).

The presence of trioctylmethylammonium chloride in the chloroform phase obviously plays a key role in the transport, although tetraalkylammonium ion itself cannot transport any trace of uranyl ion (entry 2, Table I). The uptake of uranyl from aqueous to chloroform phases by **3h** was examined in the presence or absence of the quarternary ammonium salt **4a** (Table II), to gain further insights into the three-phase transport. The uranyl uptake is slow and stops at the level of ca. 45% by the use of **3h** alone. The addition of **4a** in a 1:1 equivalent ratio greatly enhances the uranyl uptake into the chloroform phase. When the chloroform solution of **3h** was washed with $NaHCO_3$ solution (1 N) before the extraction experiments, the uranyl extraction from the aqueous solution drops to an almost zero level. A similar treatment of the chloroform solution of **3h** in the presence of ammonium salt, however, in a sharp contrast, exhibits the identical extraction as the original solution before the $NaHCO_3$ washing. The $NaHCO_3$ washings from the above extraction experiments were acidified and extracted with ether separately. The residue obtained on the evaporation of ether was treated with diazomethane. The former sample recovered from the aqueous phase containing **3h** alone gave a predominant spot on TLC near the corresponding spot of **3e**. The recovered product (ca. 70% of **3h** initially added) is assignable to tetramethyl ester distearylamide by its behavior on TLC as well as from the comparison of its IR spectrum with that of **3e** (tetraethylester distearylamide). However, no corresponding spot was observed for the latter sample recovered from the aqueous phase containing both **3h** and **4a**. These results suggest that **3h** is lost into $NaHCO_3$ during the transport experiments but that the phase transfer of **3h** from the oil to the water phase is suppressed by the addition of a quarternary ammonium salt like **4a**, probably by the formation of a stable hydrophobic ion pair in the organic phase.

Dependence of pH in Aq I. In order to determine the active phase-transfer species, pH dependence of the uptake rates was examined by the use of a two-phase system. Aqueous phase I was prepared so as to contain 3.57×10^{-5} M of uranyl acetate at pH 3.0, 5.0, or 8.0. The pH adjustment was carried out carefully by the addition of 0.1 N HCl and/or NaOH solution. No buffering agent was added so as to avoid any competing uranyl complexation.

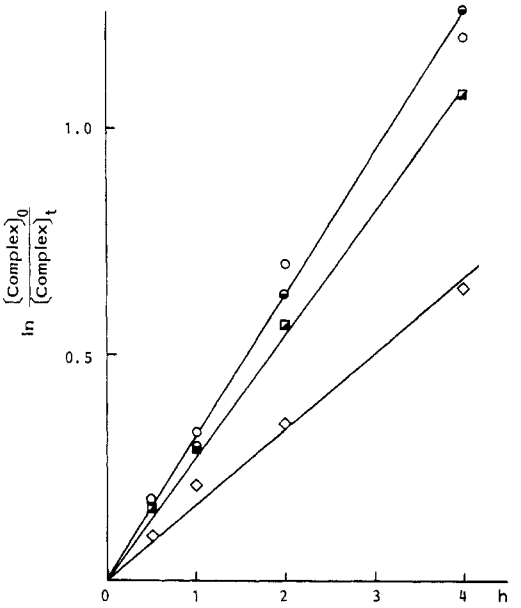


Figure 3. First-order plot for the release of uranyl–carboxylate complex into $NaHCO_3$ solution. [$NaHCO_3$]: (○) 1.0 M; (●) 0.1 M; (■) 0.025 M; (◇) 0.01 M.

Table III. pH Dependence of the Uranyl Uptake

	$[UO_2]_{aq}$, 10^{-5} M			
pH of aq I	0.33 h	1 h	2 h	4 h
3	3.82	3.74	3.82	3.58
5	2.11	0.94	0.69	0.66
8	2.27	1.04	0.65	0.63

The carrier solution was brought in contact with the uranyl solution (150 rpm). The time course of uranyl concentrations on contacting with the carrier solution is shown in Table III.

When the pH of aq I was adjusted to 3.0, no significant uptake of uranyl ion was observed. At pH 5.0 or 8.0, the uptake rate was followed by a second-order rate equation:

$$\frac{-d[UO_2]_{aq}}{dt} = k[UO_2]_{aq}[\mathbf{3h}]_{org}$$

until ca. 70% of the uranyl ion was extracted into the chloroform phase. The rate constants at pH 5.0 and 8.0 were the same order, being 1.61×10^4 and 1.46×10^4 $M^{-1} \cdot h^{-1}$, respectively. In the following transport experiments, the pH of aq I was therefore adjusted at 5.0, except in a series of experiments using seawater. A higher pH (8.0) was not employed in order to avoid a concomitant precipitation of insoluble uranyl species which was sometimes observable at higher pH in the absence of strongly coordinating species such as carbonate.

Effect of $NaHCO_3$ Concentration on Release Process. In order to gain insights into the release process, a uranyl–carboxylate complex in a chloroform solution was treated with carbonate solutions of different concentrations. Thus a 1:1 mixture of **3h** and **4a** in chloroform (5×10^{-5} M, each 30 mL) was treated with a uranyl acetate solution (5.18×10^{-5} M, 30 mL) to extract uranyl–carboxylate complex (3.70×10^{-5} M) into the chloroform phase. This solution was treated again with a $NaHCO_3$ solution of several different concentrations. The release rate of uranyl ion from chloroform to aqueous phase was found to be pseudo first order with respect to the complex concentration in the organic phase, as shown in Figure 3. Apparent first-order rate constants increase with the concentration of $NaHCO_3$ in a lower concentration range.

Table IV. Effect of Stirring Rate on Uptake and Release Rates

stirring rate, rpm	$CHCl_3$ 3h = 4a, 10^{-5} M	$CHCl_3$ $[UO_2]$, 10^{-5} M	aq I $[UO_2]$, 10^{-5} M	aq II $[NaHCO_3]$, M	rate const
100	10		3.34		0.4×10^3 M^{-1} h^{-1}
150	10		2.80		1.8×10^3 M^{-1} h^{-1}
200	10		2.96		5.2×10^3 M^{-1} h^{-1}
150	10	2.29		1.0	0.97 h^{-1}
200	10	2.52		1.0	1.62 h^{-1}

At higher carbonate concentrations, the rate is apparently saturated.

Effect of Stirring Rate. In the analysis of two-phase kinetics, the rate constants for uptake and release processes were evaluated at different stirring rates. The rate constants shown in Table IV are demonstrated to depend sharply on the stirring rate. It is clear that the phase-transfer rates are also important factors determining the rates of overall three-phase transport. In three-phase as well as two-phase experiments, the stirring rates were fixed at a constant value of 150 rpm. This value was selected because very rapid stirring (200 rpm) sometimes induced swirling of the upper aqueous phase into the chloroform phase. This range, however, still showed a stirring rate dependence. Therefore, the stirring rate was carefully controlled for all experiments by using the stirring control equipment described in detail in the Experimental Section.

Ammonium Structure and Transport Rates. As already discussed briefly, the quarternary ammonium salt has a significant role in keeping the polycarboxylate carrier within the organic phase and in enhancing the carrier activity remarkably. The transport experiments have been carried out by using **4a**, tetraethylammonium bromide (**4b**), benzyltriethylammonium chloride (**4c**), lauryltrimethylammonium chloride (**4d**), or cetyltrimethylammonium chloride (**4e**) in a 1:1 molar ratio with **3h**. Initial conditions and results are summarized in Table I, entries 3–7. The uranyl concentration in aq I decreased smoothly and that in aq II increased linearly with time except the very last stage. Transport rates were evaluated from their linear slopes in aq II. The rate of transport increased with the increasing carbon number of the quarternary ammonium salt. Tetraethylammonium (C_8) did not play any role, the benzyltrimethyl derivative (C_{13}) had a slight effect, lauryltrimethyl (C_{15}) a moderate one, and cetyltrimethyl (C_{19}) and trioctylmethyl (C_{25}) were most effective. As was suggested, the role of the quarternary ammonium salt is expected to keep the carrier of polycarboxylates in the organic phase by the anion exchange of halide into carboxylate. Hydrophobic ammonium cation is considered desirable in this respect.

Structural Effect of Macrocyclic Polycarboxylates. Five different polycarboxylate derivatives have been tested for transport carriers in a combination with a 1:1 equivalent ratio of the quarternary ammonium salt **4a**. Two different concentrations were employed for uranyl in aqueous and carrier in organic phases. Results and conditions employed are listed in entries 3 and 8–16 of Table I.

The transport rates obtained from linear slopes of the time plot of $[UO_2]_{aq\,II}$ show the same relative order for two different transport conditions, i.e., **3h** (di-C_{18}-amide) > **3l** (di-C_{12}-amide) > **3g** (mono-C_{18}-amide) > **3m** (tri-C_{12}-amide) > **3i** (tri-C_{18}-amide). This order does not show such a simple relationship between the hydrophobicity and the transport rates as observed for a series of quarternary ammonium salts. Instead, the order seems to reflect a structural change of the carboxylates, i.e., di- > mono- > triamide. Polycarboxylates provide the direct binding sites

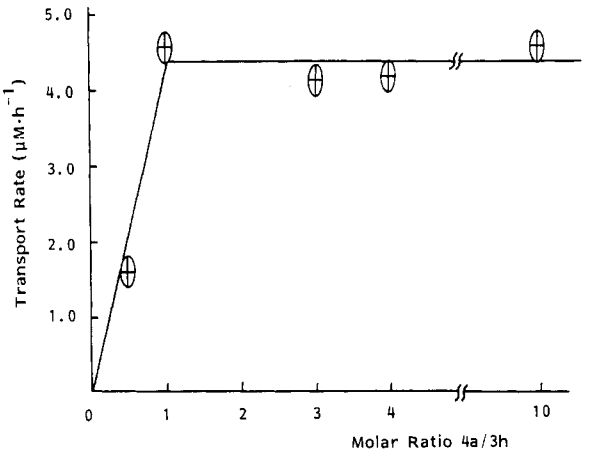


Figure 4. Dependence of transport rate on the molar ratio of ammonium to carboxylate. See Table I for the detailed conditions.

of uranyl ion and their structural changes may reasonably perturb the binding phenomena to a greater extent. The decreased capacity of triamide compared with diamide may reasonably be accounted for by the following idea. Uranyl ion should be stabilized by the coordination of three carboxylates. The presence of additional carboxylates on the same carbon atoms, however, may contribute significantly to enhancing the stability constant by affording the chance of choosing carboxylates in an appropriate stereochemical configuration. According to this expectation, the binding capacity should decrease by a higher substitution by amide groups to give rise to a decreasing order: mono- > di- > triamide. Monoamide, however, cannot be hydrophobic enough to be held in the organic phase. The alternative idea may be a favorable release rate of uranyl from diamide–uranyl compared to monoamide–uranyl complex because of the decreased stability. The observed order, di- > mono- > triamide, seems to be a compromise of these competing factors.

The effect of hydrophobicity should be demonstrated more clearly by the comparison of transport rates of compounds having stearyl and lauryl chains to the compounds having the same number of amide functionality (**3h** vs **3l**). The stearyl chain is superior to lauryl in the diamide series (entries 3 vs 10 and 13 vs 15), but the reverse tendency is observed for the triamide series (entries 9 vs 11 and 14 vs 16). This may indicate that the appropriate balance between hydrophobicity and hydrophilicity is an important factor in determining the transport rate. Excess hydrophilic carrier is partitioned into the aqueous phases to simply lose the transporting capacity. On the other hand, excess hydrophobic carrier is located deep inside the organic phase and it is difficult for uranyl or carbonate ions in bulk aqueous phases or aqueous–organic interphases to approach. Both extremes give a decreased rate of uptake or release of uranyl ion and a decreased overall transport rate results.

Concentration Dependences of Carrier and Uranyl Ion. Transport rates were measured at different molar ratios of **4a** to **3h** (entries 17–21). The rates obtained were plotted as a function of the ratio (Figure 4). The transport rate increases almost linearly with the ratio up to a 1:1 molar composition of **4a** and **3h**. After this specific point, the rate becomes constant, independent of the presence of excess amounts of the ammonium cation. A linear increase of the transport rate strongly suggests that the equilibrium (1) is shifted far to the right in chloroform, giving rise to the formation of the complex **5** (Scheme III). The complex **5** partitions preferentially into the chloroform phase and acts as a true carrier of uranyl ion. The presence

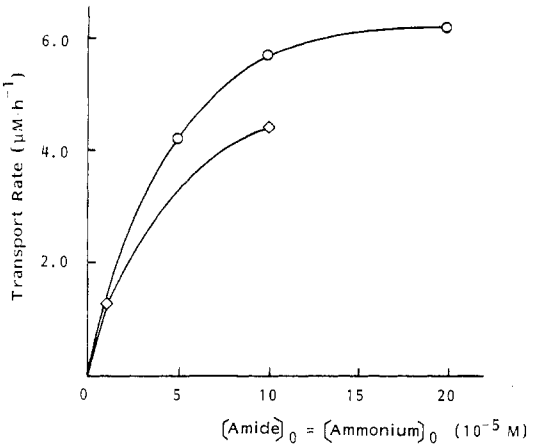
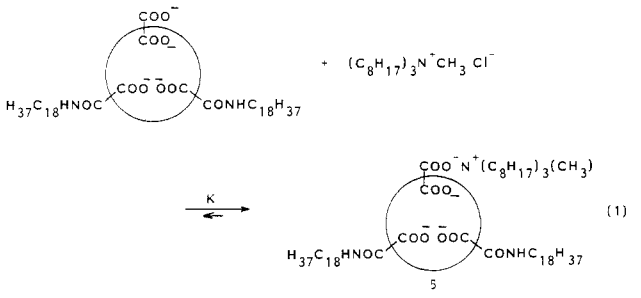


Figure 5. Dependence of transport rate on carboxylate–ammonium concentration. $[UO_2]_{initial}$: (○) 6.92×10^{-5} M; (◇) 3.29×10^{-5} M.

Scheme III



of excess ammonium cation may not contribute to the interaction with other remaining carboxylates, since the latter carboxylates in **5** should contribute principally to the binding of uranyl ion itself.

The transport rates at different concentrations of the 1:1 carrier composite mixture (entries 18, 24–26) were plotted as a function of the concentration in Figure 5. The rate increased with an increasing concentration of the carrier composite but apparently became saturated at higher values. A similar tendency was observable for the variation of uranyl concentrations in aq I. Figure 6 summarizes original time profiles of $[UO_2]_{aq\,II}$ at different initial concentrations of $[UO_2]_{aq\,I}$ (entries 13, 18, 22, and 23 in Table I). The lowest initial concentration gives the smallest transport rate, but three other runs employing higher concentrations are not discernible with each other. These results may suggest that the overall rate is determined by the rate of complex formation at lower initial concentrations of uranyl as well as carrier concentrations, but that the rate determining step is shifted to a mass transport of the complex through the liquid membrane or an interphasical transport of uranyl or carrier at their higher concentrations.

Selectivity for Uranyl Ion. Finally, the uranyl transport rate was obtained in the presence of other metal cations. Entry 27 in Table I lists the transport rate when aq I was prepared by adding uranyl acetate (3.24×10^{-5} M) to seawater, which contains typically 4.68×10^{-1} M Na^+, 5.3×10^{-2} M Mg^{2+}, 1.0×10^{-2} M K^+, 1.0×10^{-2} M Ca^{2+}, and others. The transport rate was decreased by a factor of 2.5 compared with the run in a simple uranyl solution (entry 3). Since the difference of pH in aq I is

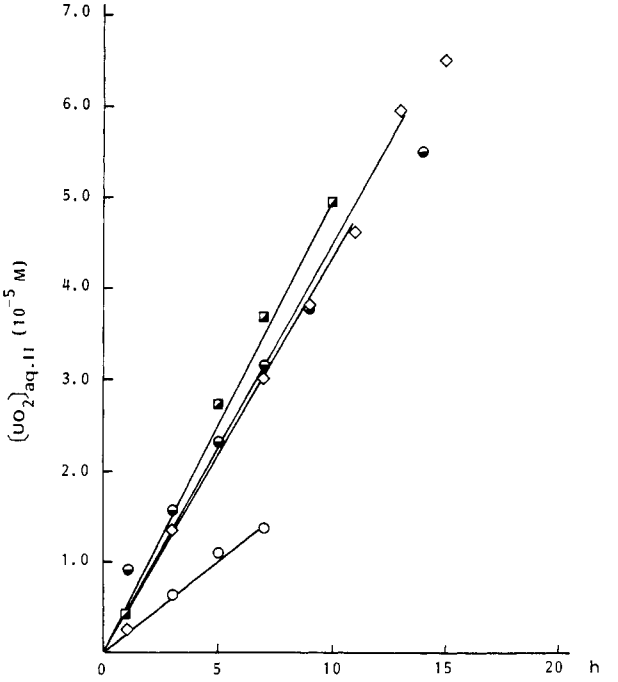


Figure 6. Dependence of transport rate on uranyl concentration. [carrier]: 5×10^{-5} M. $[UO_2]$: (○) 2×10^{-5} M; (◪) 5.34×10^{-5} M; (◒) 6.20×10^{-5} M; (◇) 6.92×10^{-5} M.

already shown not to influence significantly the uptake rate, the decrease must be ascribed to the presence of competing metal ions. In order to assign what metal ion is responsible for decelerating the transport, the same concentration of Ca^{2+} as in seawater was added to aq I (entry 28). Almost the same uranyl transport rate as in seawater was observed. Therefore the most competitive metal ion in seawater must be Ca^{2+}, which is known to have a very similar ionic radius as uranyl. Other metals are therefore concluded not to be competitive with uranyl. In other words, the macrocyclic carboxylate is highly selective in a kinetic sense for transporting uranyl ion. Even for the most competitive Ca^{2+}, the presence of a 300-fold excess caused only a 2.5-fold decrease of the transport rate.

In summary, macrocyclic polycarboxylates were prepared starting from 27-membered hexacarboxylates by a systematic introduction of long alkyl chains via amide bond formation. Polycarboxylates combined with quarternary ammonium salts having hydrophobic alkyl chains complexed with three carboxylates to give real carriers which partition preferentially into the organic phase. Without the addition of the ammonium salt, polycarboxylates were eluted into the aqueous phase, losing the ability to transport uranyl ion. On the basis of carrier-mediated transport mechanism, the uranyl ion initially present in one aqueous phase was transferred completely into the other receiving phase. The energy required to drive the transport against the concentration gradient across the membrane was supplied by a carbonate concentration rich in the receiving phase. Considering the extremely low concentration of uranium and a huge volume of seawater to be treated, a liquid membrane procedure may need some modifications to be used for direct uranium recovery from seawater. However, an interesting synergism between the polycarboxylates and hydrophobic ammoniums observed here may find several interesting applications for uranyl accumulation through the membrane process.