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New Wide Rim Phosphomethylated Calix[4]arenes in Extraction of Americium and Europium

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Abstract

A new series of the cone-shaped tetraalkoxycalix[4]arenes substituted at the wide rim with four phosphomethyl groups have been synthesized by the Arbuzov, Michaelis–Becker and Aterthon–Todd reactions of the chloromethyl or phenylhydrophosphinylmethylcalix[4]arenes. Their binding properties towards Eu^{3+} and Am^{3+} cations were investigated by the liquid–liquid extraction method. Due to the 'calixarene effect' the tetraphosphorylated calixarenes are more effective extractants for the metal cations than their acyclic analogs or some industrial extractants such as trialkylphosphinoxides, carbamoylphosphinoxide, bis-2-diethylhexyl phosphoric acid.

Introduction

The development of nuclear power has led to accumulation of a great amount of radioactive wastes of both high and medium level activity, which requires efficient methods for their reprocessing and safe disposal. The main reprocessing method is based on the liquid–liquid extraction of the toxic radionuclides with subsequent burial or transmutation [1]. An important class of extractants used for that purpose is based on organophosphoryl compounds, whose 'basic' P=O oxygen atom effectively binds actinide or lanthanide metal cations [2, 3]. Examples involve organophosphoryl compounds [tributylphosphate, bis-2-ethylhexyl phosphoric acid (DIEHPA), trialkylphosphine oxides (TAPO), carbamoylphosphine oxides (CMPO)] that are used in industrial processes for extraction of uranium, plutonium, lanthanides and actinides from spent nuclear fuel (PUREX and TRUEX processes). However, despite the achievements in this field, the problem of higher efficiency and selectivity of organophosphorus extractants remains an active field of research [4]. A promising approach in the design of efficient and selective extractants is based on the functionalization of calixarenes [5] by phosphoryl-containing fragments, which can form pseudocavities suitable to cooperatively bind the metal cations [6] (Chart 1).

A remarkable achievement concerns calix[4]arenes **1** and **2** [7] synthesized by Böhmer *et al.*, containing four carbamoylphosphine oxide groups at the macrocyclic wide or narrow rims. These calixarenes exceed the CMPO extractant (i-Bu_2N—C(O)—CH_2—P(O)Ph(Oct)) developed for the TRUEX process, by more than two orders of magnitude in the extraction of actinides (Np, Pu, Am). Calixarenes **3** containing monodentate $Ph_2P(O)CH_2$ groups at the lower rim also better extract actinides than the ungrafted Oct_3P=O or CMPO ligands do [8]. Calixarenes **4** [9] containing $Ph_2P(O)CH_2$ groups at the wide rim are less efficient than their analogues **3** with the same groups at the narrow rim and surpass only slightly trioctylphosphine oxide. However, modeling of an analogue of **4** points to the 'possible cooperative participation of its four phosphoryl groups in the complexation of hard metal cations, leading to a high ionophoric efficiency' [10].

Because liquid–liquid extraction is a multifactorial process (it depends, e.g., on the basicity of the phosphoryl oxygen, on steric and electrostatic metal–ligand interactions and on the lipophilicity of the ligands and their complexes), we decided to synthesize a series of new tetrakis-(diorganylphosphorylmethyl)tetraalkoxycalix[4]arenes bearing two identical or different substituents at the P atoms, and to examine their extraction

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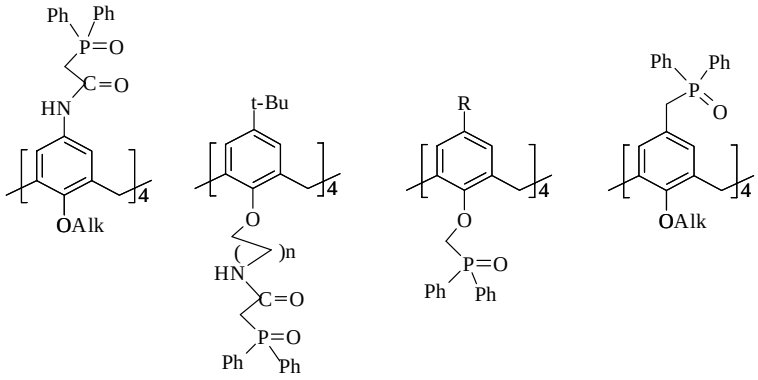


1 **2** **3** **4**

Chart 1

capabilities towards trivalent americium and europium. The following types of substituents, which differ in size and in electronic properties, were introduced and tested: AlkO, Ph, Alk, $(Alkyl)_2N$. The row of the σ^{ϕ} parameters: −0.29 (*i*-PrO), −0.48 or −0.59 (Ph), −1.22 (Bu), −1.54 (Et_2N) suggests increasing oxygen basicities and complexing properties of the phosphoryl group [11].

Experimental

Materials

All reactions were carried out under argon atmosphere. Column chromatography was performed with silica gel (0.060–0.200 mm, pore diameter ca. 6 nm) from Acros Organics. NMR spectra were obtained on a Varian (VXR-300) spectrometer. Chemical shifts are reported relative to TMS (^{1}H) (internal standard) or 85% H_3PO_4 (^{31}P) (external standard). Melting points are uncorrected.

*5,11,17,23-Tetrakis-[di(isopropyl)phosphonylmethyl]-25,26,27,28-tetrapropoxycalix[4]arene (**7**)*

The mixture of **5** (3.5 g, 4.4 mmol) and triisopropylphosphite (9.26 g, 44.0 mmol) was stirred at 180 °C for 2 h. After completion of the reaction, the excess of triisopropylphosphite was removed by evaporation under reduced pressure. The crystallization of the residue from hexane gives **7** as a white powder in 76% yield: m.p. 100–102 °C; ^{1}H NMR ($CDCl_3$): δ 0.96 (t, 12H, J_{HH} 7.2 Hz, $OCH_2CH_2CH_3$), 1.14 and 1.26 (two d, 48H, $OCH(CH_3)_2$), 1.84 (m, 8H, $OCH_2CH_2CH_3$), 2.77 (d, 8H, $^2J_{PH}$ 17.1 Hz, $ArCH_2P$), 3.06 and 4.35 (two d, 8H, $^2J_{HH}$ 13.1 Hz, $ArCH_2Ar$), 3.78 (t, 8H, J_{HH} 6.9 Hz, $OCH_2CH_2CH_3$), 4.52 (m, 8H, $OCH(CH_3)_2$), 6.52 (s, 8H, Ar*H*); ^{31}P NMR ($CDCl_3$): δ 26.97. Anal. Calcd. for $C_{68}H_{108}O_{16}P_4$: C, 62.55; H, 8.34; Found: C, 62.39; H, 8.59.

*5,11,17,23-Tetrakis-(butylisopropoxyphosphonylmethyl)-25,26,27,28-tetrapropoxycalix[4]arene (**8**)*

The mixture of **5** (4.7 g, 6 mmol) and diisopropylbutylphosphonit (24.6 g, 120 mmol) was stirred at 180 °C for 2 h. After completion of the reaction, the excess of diisopropylbutylphosphonit was removed by evaporation under redused pressure. The crystallization of the residue from hexane gives **8** as a white powder in 64% yield: m.p. 124–126 °C; ^{1}H NMR ($CDCl_3$): δ 0.84–1.02 (m, 24H, $OCH_2CH_2CH_3$ and $P(CH_2)_3CH_3$), 1.15–1.47 (m, 24H, $P(CH_2)_3CH_3$), 1.29 (d, 24H, $CH(CH_3)_2$), 1.92 (m, 8H, $OCH_2CH_2CH_3$), 2.79 (d, 8H, $^2J_{PH}$ 16.4 Hz, $ArCH_2P$), 3.12 and 4.39 (two d, 8H, $^2J_{HH}$ 13.4 Hz, $ArCH_2Ar$), 3.78 (t, 8H, J_{HH} 6.9 Hz, $OCH_2CH_2CH_3$)), 4.55 (m, 4H, $OCH(CH_3)_2$), 6.50 (s, 8H, Ar*H*); ^{31}P NMR ($CDCl_3$): δ 55.00. Anal. Calcd. For $C_{72}H_{116}O_{12}P_4$: C, 64.93; H, 9.94; Found: C, 64.85; H, 9.74.

*5,11,17,23-Tetrakis-[(diethylamido)butylphosphonylmethyl]-25,26,27,28-tetrapropoxycalix[4]arene (**9**)*

The mixture of **5** (3.68 g, 4.70 mmol) and (Et_2N)BuPOPr-*i* (20.53 g, 93.60 mmol) was warmed at 160 °C for 3 h. After completion of the reaction, the excess of (Et_2N)BuPOPr-*i* was removed by evaporation under reduced pressure. The obtained residue was purified by column chromatography (CH_2Cl_2-methanole, 3:1) to give product **9** as a yellow glass in 85% yield: m.p. > 72 °C; ^{1}H NMR ($CDCl_3$): δ 0.90 (m, 48H, $OCH_2CH_2CH_3$, NCH_2CH_3 and $PCH_2CH_2CH_2CH_3$), 1.25–1.60 (m, 24H, $PCH_2CH_2CH_2CH_3$), 1.85 (m, 8H, $OCH_2CH_2CH_3$), 2.75 (d, 8H, $^3J_{PH}$ 14.4 Hz, $ArCH_2P$), 2.89 (m, 16H, NCH_2CH_3), 3.07 and 4.35 (two d, 8H, $^2J_{HH}$ 12.9 Hz, $ArCH_2Ar$), 3.76 (t, 8H, $^3J_{HH}$ 7.5 Hz, $OCH_2CH_2CH_3$), 6.48 (s, 8H, Ar*H*); ^{31}P NMR ($CDCl_3$): δ 47.43; ^{13}C NMR ($CDCl_3$): δ 10.37 (s, $OCH_2CH_2CH_3$), 13.72 (s, $PCH_2CH_2CH_2CH_3$), 14.52 (s, NCH_2CH_3), 23.12 (s, $PCH_2CH_2CH_2CH_3$), 23.58 (s, $OCH_2CH_2CH_3$), 24.11 (d, $^2J_{PC}$ 14.8 Hz, $PCH_2CH_2CH_2CH_3$), 27.53 (d, $^1J_{PC}$ 84.9 Hz, $PCH_2CH_2CH_2CH_3$), 31.03 (s, $ArCH_2Ar$), 36.86 (d, $^1J_{PC}$ 75.9 Hz, PCH_2Ar), 38.18 (s, NCH_2CH_3), 76.70 (s, $OCH_2CH_2CH_3$), 125.77 (d, $^2J_{PC}$ 8.8 Hz, *p*-

C_{Ar}), 129.51 (d, $^3J_{PC}$ 5.5 Hz, *m*-C_{Ar}), 134.86 (s, *o*-C_{Ar}), 155.59 (d, $^5J_{PC}$ 3.4 Hz, *ipso*-C_{Ar}),. Anal. Calcd. for $C_{76}H_{128}N_4O_8P_4$: C, 67.63; H, 9.56; Found: C, 67.24; H, 9.32.

*5,11,17,23-Tetrakis-(dibutylphosphinylmethyl)-25,26,27,28-tetrapropoxy-calix[4]arene (**10**)*

(a) *iso*-Propyldibutylphosphinyte (38.8 g, 190.4 mmol) was added to a stirred solution of chloromethylcalixarene **5** (3.7 g, 4.7 mmol) in toluene (120 mL). The mixture was stirred and refluxed for 4 h. After completion of the reaction, the mixture was cooled to room temperature and the solvent and excess of isopropyldibutylphosphinyte were removed by evaporation under reduced pressure. The obtained residue was purified by column chromatography ($CHCl_3$-methanole, 20:1) to give product **10** as a yellow glass in 60% yield: m.p. 48–53 °C; ^{1}H NMR ($CDCl_3$): δ 0.89 (m, 36H, $OCH_2CH_2CH_3$ and $PCH_2CH_2CH_2H_3$), 1.25–1.60 (m, 48H, $PCH_2CH_2CH_2CH_3$), 1.89 (m, 8H, OCH_2CH_2-CH_3), 2.78 (d, 8H, $^3J_{PH}$ 13.8 Hz, $ArCH_2P$), 3.08 and 4.38 (two d, 8H, $^2J_{HH}$ 13.35 Hz, $ArCH_2Ar$), 3.81 (t, 8H, $^3J_{HH}$ 7.1 Hz, $OCH_2CH_2CH_3$), 6.46 (s, 8H, Ar*H*); ^{31}P NMR ($CDCl_3$): δ 47.41. Anal. Calcd. for $C_{76}H_{124}O_8P_4$: C, 70.99; H, 9.72; Found: C, 70.01; H, 9.63.

(b) To a solution of potassium dibutylphosphinyte [from Bu_2PHO (8.28 g, 51.05 mmol) in DMSO (60 mL) and 50% solution of potassium hydroxide in water (6 mL), 30 min at room temperature] calixarene **5** (5.02 g, 6.38 mmol) was added. The mixture was stirred at 80 °C for 70 h. After completion of the reaction, water (60 mL) was added and the mixture was stirred for 30 min. The obtained suspension was taken up in $CHCl_3$ (150 mL) and after separation the organic layer was washed with water to neutral reaction. The organic layer was dried over Na_2SO_4, the solvent was removed by evaporation under reduced pressure. Sublimation of excess of Bu_2PHO *in vacuo* (160 °C, 0.04 mm Hg) gave pure **10** in 80% yield. NMR spectra confirmed that the species was the same as that described above.

*5,11,17,23-Tetrakis-(diphenylphosphinylmethyl)-25,26,27,28-tetrapropoxycalix[4]arene (**12**)*

The mixture of **5** (2.88 g, 3.6 mmol) and isopropyldiphenylphosphinite (17.80 g, 73 mmol) was stirred at 180 °C for 2 h. After completion of the reaction, the excess of isopropyldiphenylphosphinite was removed by evaporation under redused pressure. The crystallization of the residue from hexane gives **12** as a white powder in 98% yield: m.p. > 250 °C; ^{1}H NMR ($CDCl_3$): δ 0.91 (t, 12H, J_{HH} 7.2 Hz, $OCH_2CH_2CH_3$), 1.75 (m, 8H, $OCH_2CH_2CH_3$), 2.74 and 4.10 (two d, 8H, $^2J_{HH}$ 13.3 Hz, $ArCH_2Ar$), 3.21 (d, 8H, $^2J_{PH}$ 13.2 Hz, $ArCH_2P$), 3.65 (t, 8H, $OCH_2CH_2CH_3$), 6.13 (s, 8H, Ar*H*), 7.36 and 7.59 (two m, 40H, P*Ph*); ^{31}P NMR ($CDCl_3$): δ 29.05. Anal. Calcd. For $C_{76}H_{124}O_8P_4$: C, 70.99; H, 9.72; Found: C, 70.01; H, 9.63.

*5,11,17,23-Tetrakis-(diphenylphosphinylmethyl)-25,26,27,28-tetrahexoxy-calix[4]arene (**13**)*

The mixture of **5** (1.55 g, 1.6 mmol) and isopropyl diphenylphosphinite (7.92 g, 32 mmol) was stirred at 180 °C for 2 h. After completion of the reaction, the excess of isopropyldiphenylphosphinite was removed by evaporation under reduced pressure. The crystallization of the residue from hexane gives **13** as a white powder in 97% yield: m.p. 131–133 °C; ^{1}H NMR ($CDCl_3$): δ 0.88 (t, 12H, J_{HH} 7.3 Hz, $OCH_2(CH_2)_4CH_3$), 1.29 (m, 24H, $(CH_2)_3CH_3$), 1.72 (m, 8H, $OCH_2CH_2(CH_2)_3CH_3$), 3.17 (d, 8H, $^2J_{PH}$ 13.2 Hz, $ArCH_2P$), 2.67 and 4.07 (two d, 8H, $^2J_{HH}$ 13.3 Hz, $ArCH_2Ar$), 3.65 (t, 8H, OCH_2), 6.11 (s, 8H, Ar*H*), 7.36 and 7.59 (two m, 40H, P*Ph*); ^{31}P NMR ($CDCl_3$): δ 30.44. Anal. Calcd. For $C_{104}H_{116}O_8P_4$: C, 77.42; H, 7.23; Found: C, 76.91; H, 7.16.

*5,11,17,23-Tetrakis-(phenylmethylphosphinylmethyl)-25,26,27,28-tetrapropoxy-calix[4]arene (**13**)*

(a) CH_3I (0.4 g, 2.81 mmol) was added to a stirred solution of **14** (0.4 g, 0.35 mmol) in DMSO (5 mL) and 50% solution of potassium hydroxide in water (0.26 mL) at room temperature. The mixture was stirred at 60–80 °C for 11 h. After completion of the reaction 1 M solution of HCl (10 mL) was added to the mixture, the obtained suspension was taken up in CH_2Cl_2 (75 mL) and after separation the organic layer was washed with water to neutral reaction. The organic layer was dried over Na_2SO_4, the solvent was removed by evaporation under reduced pressure. The obtained residue was purified by column chromatography (eluent CH_2Cl_2-acetone, 1:1, and then CH_2Cl_2-methanole, 10:3) to give **15** as a yellow glass in 74% yield: m.p. 109–113 °C; ^{1}H NMR ($CDCl_3$): δ 0.99 (m, 12H, $OCH_2CH_2CH_3$), 1.36 (m, 8H, $OCH_2CH_2CH_3$), 1.92 (m, 12H, PCH_3), 2.84 (m, 8H, PCH_2Ar), 3.02 and 4.34 (two m, 8H, $ArCH_2Ar$), 3.80 (m, 8H, $OCH_2CH_2CH_3$), 6.42 (m, 8H, Ar*H*), 7.35–7.6 (m, 20H, P*Ph*); ^{31}P NMR ($CDCl_3$): δ 33.79. Anal. Calcd. for $C_{72}H_{84}O_8P_4$: C, 71.98; H, 7.05; P, 10.31; Found: C, 71.90; H, 7.05, P, 9.40.

(b) NaH (0.63 g, 26.20 mmol) was added to a solution of **14** (3.0 g, 2.62 mmol) in dry THF (50 mL), and the mixture was stirred at room temperature for 30 min. The solution of $MeOSO_2C_6H_4CH_3$-p (3.9 g, 20.96 mmol) in THF (10 mL) was added and the reaction mixture was stirred at 60–65 °C for 8 h. After completion of the reaction the mixture was treated as described above. The crystallization of the residue from benzene-hexane gives **15** as a white powder in 81% yield. NMR spectra confirmed that the compound was the same as that described above.

*5,11,17,23-Tetrakis-(phenylbutylphosphinylmethyl)-25,26,27,28-tetrapropoxy-calix[4]arene (**16**)*

NaH (0.21 g, 8.76 mmol) was added to a solution of **14** (0.83 g, 0.73 mmol) in dry THF (15 mL) and the mixture was stirred 5 min at room temperature. C_4H_9Br

(0.79 g, 5.83 mmol) was added and the reaction mixture was stirred at 60–70 °C for 22 h. After completion of the reaction 1 M solution of HCl (5 mL) was added to the mixture. The obtained suspension was taken up in CH_2Cl_2 (75 mL) and after separation the organic layer was washed with water to neutral reaction. The organic layer was dried over Na_2SO_4, the solvent was removed by evaporation under reduced pressure. The obtained residue was purified by crystallization (benzene-hexane) to give **16** as a white powder in 72% yield: m.p. 137–142 °C; ^{1}H NMR ($CDCl_3$): δ 0.70–0.86 (m, 12H, $P(CH_2)_3CH_3$), 0.86–1.02 (m, 12H, $OCH_2CH_2CH_3$), 1.18–1.38 (m, 12H, $PCH_2CH_2CH_2CH_3$), 1.72 (m, 8H, $PCH_2CH_2CH_2CH_3$), 1.85 (m, 8H, $OCH_2CH_2CH_3$), 2.88 and 4.26 (two m, 8H, $ArCH_2Ar$), 2.93 (m, 8H, PCH_2Ar), 3.60–3.85 (m, 8H, $OCH_2CH_2CH_3$), 6.10–6.45 (m, 8H, Ar*H*), 7.30–7.62 (m, 20H, P*Ph*); ^{31}P NMR ($CDCl_3$): δ 38.91. Anal. Calcd. for $C_{84}H_{108}O_8P_4$: C, 73.66; H, 7.95; P, 9.05; Found: C, 72.95; H, 7.79, P, 8.55.

*5,11,17,23-Tetrakis-(phenyoctylphosphinylmethyl)-25,26,27,28-tetrapropoxy-calix[4]arene (**17**)*

NaH (0.60 g, 25 mmol) was added to a solution of **14** (1.50 g, 1.31 mmol) in dry THF (30 mL) and the mixture was stirred 5 min at room temperature. $C_8H_{17}Br$ (2.02 g, 10.48 mmol) was added and the reaction mixture was stirred at 60–70 °C for 24 h. After completion of the reaction 1 M solution of HCl (10 mL) was added to the mixture, the obtained suspension was taken up in CH_2Cl_2 (150 mL) and after separation the organic layer was washed with water to neutral reaction. The organic layer was dried over Na_2SO_4, the solvent was removed by evaporation under reduced pressure. The obtained residue was purified by crystallization (heptane) to give **17** as a yellow powder in 62% yield: m.p. 125–128 °C; ^{1}H NMR ($CDCl_3$): δ 0.78–0.92 (m, 12H, $P(CH_2)_7CH_3$), 0.92–1.06 (m, 12H, $OCH_2CH_2CH_3$), 1.06–1.40 (m, 48H, $PCH_2(CH_2)_6CH_3$), 1.71–2.00 (m, 16H, $PCH_2(CH_2)_6CH_3$ and $OCH_2CH_2CH_3$), 2.88–3.11 and 4.15–4.50 (two m, 8H, $ArCH_2Ar$), 2.93 (m, 8H, PCH_2Ar), 3.60–4.00 (m, 8H, $OCH_2CH_2CH_3$), 6.00–6.45 (m, 8H, Ar*H*), 7.20–7.70 (m, 20H, P*Ph*); ^{31}P NMR ($CDCl_3$): δ 39.03 Anal. Calcd. for $C_{100}H_{140}O_8P_4$: C, 75.34; H, 8.86; P, 7.77; Found: C, 74.28; H, 8.24, P, 7.25.

*General procedure for synthesis of phenyamido phosphonylmethylcalix[4]arenes (**18–21**)*

The mixture of **14** (1 g), amine (5 mL) and CCl_4 (5 mL) was stirred at 80 °C for 5 h. After completion of the reaction 1 M solution of HCl (10 mL) was added to the mixture. The obtained suspension was taken up in CH_2Cl_2 (150 mL) and after separation the organic layer was washed with water to neutral reaction. The organic layer was dried over Na_2SO_4, the solvent was removed by evaporation under reduced pressure.

*5,11,17,23-Tetrakis-(phenydiethylamidophosphonylmethyl)-25,26,27,28-tetrapropoxycalix[4]arene (**18**)*

The obtained residue was purified by column chromatography (eluent CH_2Cl_2-methanole, 10:3) to give **18** as a white powder in 61% yield: m.p. 180–182 °C; ^{1}H NMR ($CDCl_3$): δ 0.92 (m, 36H, $OCH_2CH_2CH_3$ and $N(CH_2CH_3)_2$), 1.79 (m, 8H, $OCH_2CH_2CH_3$), 2.44–3.48 (m, 28H, $ArCH_2P$, $N(CH_2CH_3)_2$ and $ArCH_2Ar$), 3.72 (t, 8H, $^3J_{HH}$ 7.1 Hz, $OCH_2CH_2CH_3$), 4.12 (d, 4H, $^2J_{HH}$ 13.3 Hz, $ArCH_2Ar$), 6.46 (m, 8H, Ar*H*); 7.15–7.95 (m, 20H, P*Ph*); ^{31}P NMR ($CDCl_3$): δ 29.81. Anal. Calcd. for $C_{84}H_{112}N_4O_8P_4$: C, 70.57; H, 7.97; Found: C, 69.43; H, 7.51.

*5,11,17,23-Tetrakis-(phenydibutylamidophosphonylmethyl)-25,26,27,28-tetrapropoxycalix[4]arene (**19**)*

The crystallization of the residue from ethylacetate gives **19** as a yellow powder in 61% yield: m.p. 157–159 °C; ^{1}H NMR ($CDCl_3$): δ 0.78 (m, 36H, $OCH_2CH_2CH_3$ and $N(CH_2CH_2CH_2CH_3)_2$), 1.25–1.60 (m, 32H, $N(CH_2CH_2CH_2CH_3)_2$), 1.79 (m, 8H, $OCH_2CH_2CH_3$), 2.64 (m, 24H, $ArCH_2P$ and $N(CH_2\text{-})_2$), 2.81 and 4.21 (two d, 8H, $^2J_{HH}$ 13.35 Hz, $ArCH_2Ar$), 3.67 (t, 8H, $OCH_2CH_2CH_3$), 6.33 (s, 8H, Ar*H*); 7.15–7.65 (m, 20H, P*Ph*); ^{31}P NMR ($CDCl_3$): δ 26.03. Anal. Calcd. for $C_{100}H_{144}N_4O_8P_4$: C, 72.61; H, 8.77; Found: C, 72.43; H, 8.65.

*5,11,17,23-Tetrakis-[pheny(phenylethylamido)phosphonylmethyl]-25,26,27,28-tetrapropoxycalix[4]arene (**20**)*

The obtained residue was purified by column chromatography (eluent $CHCl_3$-methanole, 10:3) to give **20** as a white powder in 57% yield: m.p. 204–208 °C; ^{1}H NMR ($CDCl_3$): δ 0.91 (m, 24H, $OCH_2CH_2CH_3$ and NCH_2CH_3), 1.84 (m, 8H, $OCH_2CH_2CH_3$), 2.22–3.37 (m, 20H, NCH_2CH_3, $ArCH_2Ar$ and $ArCH_2P$), 3.72 (t, 8H, $OCH_2CH_2CH_3$), 4.01–4.23 (m, 4H, $ArCH_2Ar$), 6.42–8.19 (m, 48H, Ar*H*, P*Ph* and N*Ph*)); ^{31}P NMR ($CDCl_3$): δ 34.21. Anal. Calcd. for $C_{100}H_{112}N_4O_8P_4$: C, 67.91; H, 7.06; Found: C, 67.7; H, 7.65.

*5,11,17,23-Tetrakis-(phenymorpholidophosphonylmethyl]-25,26,27,28-tetrapropoxycalix[4]arene (**21**)*

The obtained residue was purified by column chromatography (eluent $CHCl_3$-methanole, 10:3) to give **21** as a white powder in 67% yield: m.p. 152–156 °C; ^{1}H NMR ($CDCl_3$): δ 0.88 (m, 12H, $OCH_2CH_2CH_3$), 1.78 (m, 8H, $OCH_2CH_2CH_3$), 2.44–3.38 (m, 20H, $O(CH_2CH_2)_2N$, $ArCH_2Ar$), 3.38–4.01 (m, 32H, $ArCH_2P$, $OCH_2CH_2CH_3$ and $O(CH_2CH_2)_2N$), 4.01–4.23 (m, 4H, $ArCH_2Ar$), 6.38 (m, 8H, Ar*H*); 7.18–7.90 (m, 20H, P*Ph*); ^{31}P NMR ($CDCl_3$): δ 34.82. Anal. Calcd. for $C_{84}H_{104}N_4O_{12}P_4$: C, 67.91; H, 7.06, Found: C, 67.78; H, 6.82.

*5,11,17,23-Tetrakis-(phenylhydroxyphosphonylmethyl)-25,26,27,28-tetrapropoxycalix[4]arene (**22**)*

Trimethylbromosilane (14.80 g, 96.63 mmol) was added to a stirred solution of **11** (6.65 g, 4.83 mmol) in $CHCl_3$ (35 mL). The mixture was stirred for 48 h at room

temperature. After evaporation of the solvent under reduced pressure, the absolute methanol (20 mL) was added to the residue and the reaction mixture was refluxed for 6 h. The solvent was removed by evaporation under reduced pressure. The obtained residue was purified by crystallization (acetone) to give **22** as a light-brown powder in 75% yield: m.p. 177–181 °C; ^{1}H NMR ($CDCl_3$): δ 0.99 (t, 12H, $OCH_2CH_2CH_3$), 1.87 (m, 8H, $OCH_2CH_2CH_3$), 2.92 and 4.26 (two d, 8H, $^2J_{HH}$ 13.3 Hz, $ArCH_2Ar$), 3.12 (d, 8H, $^3J_{PH}$ 15.6 Hz, $ArCH_2P$), 3.74 (t, 8H, $OCH_2CH_2CH_3$), 6.58 and 7.2–7.5 (m, 28H, Ar*H*), 10.78 (s, 4H, O*H*); ^{31}P NMR ($CDCl_3$): δ 34.51. Anal. Calcd. for $C_{68}H_{76}O_{12}P_4$: C, 67.54; H, 6.34; P, 10.25; Found: C, 67.43; H, 6.23; P, 9.88.

Molecular modeling

Calculations in the gas phase were performed using the MacroModel-5.5 program and the incorporated AMBER*force field. Electrostatic potential charge were initially calculated for the fragment of **10** with the SPARTAN 5.0 program using the 6-31G*basis set. Calculations have been performed in two steps: (1) modelbuilding of the initial structures with constrained distance Ca^{2+}—O = 2.6 Å, and (2) with full optimization using a Monte-Carlo conformational search followed by molecular mechanics energy minimization of the most stable structure. The cation was modeled with a +2 charge, in order to somewhat mimic the charge transfer from the ligands and avoid overestimation of coulombic interactions. For instance, according to quantum mechanical calculations on trivalent lanthanide complexes with amide ligands, the europium Mulliken charge ranges from about 1.4 to 2.5 e [12]. On the other hand, the Eu^{3+}, Am^{3+} and Ca^{2+} cations have similar ionic radii (1.087, 1.115 and 1.14 Å, respectively [13]).

Extraction

The distribution coefficients *D* were determined as follows: 1.5 mL of a 0.01 M solution of appropriate calix[4]arene in *m*-nitro(trifluoromethyl)benzene was mixed with 1.5 mL of a 10^{-5} M solution of europium nitrate in aqueous nitric acid, containing trace amounts of ^{152}Eu or ^{241}Am. The mixture was vigorously stirred at 22–24 °C for 5 min. The phases were separated by centrifuging and the metal content was determined in both phases by radiometry through γ-emission of corresponding isotope.

To measure the static sorption coefficients *D*, 0.2 g of the solid extractant and 5 mL of the aqueous phase were placed into the plugged test tube and stirred for 24 h at 22–24 °C, followed by a centrifuging to separate the solid and the liquid phases. The radiometric measurements were performed by the scintillation γ-spectrometer «DeskTop InSpector» based on NaJ-detector 51 × 51 mm with a well ('Canberra' Co). The time taken for the measurement of samples was set in such a manner that the error of radiometric measurements be no more than 15%.

Results and discussion

Synthesis and stereochemistry

The synthesis of the phosphorus derivatives of the upper rim functionalized calix[4]arenes was based on the Arbuzov, Michaelis–Becker and Aterthon–Todd reactions.

Tetraalkoxycalixarenes **7–13** bearing four diisopropoxyphosphoryl, butylisopropoxyphosphonyl, butyldiethylamidophosphonyl, dibutylphosphinyl, phenylisopropoxyphosphonyl, and diphenylphosphinyl groups respectively were synthesized by the Arbuzov reaction of tetrakis-(chloromethyl)-tetraalkoxycalix[4]arenes **5, 6** with isopropyl esters of P^{III} phosphorus acids [14] (Scheme 1).

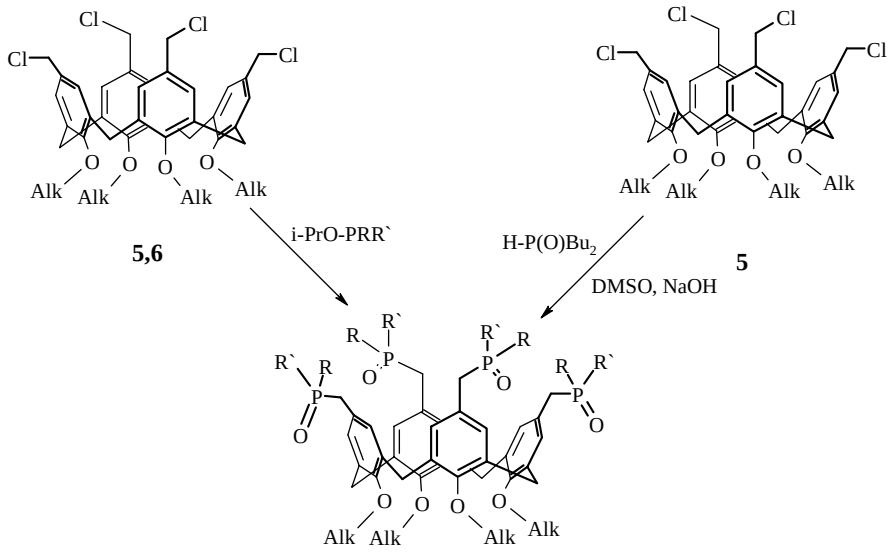
High temperature (110–180 °C) and a great excess of the P^{III} esters [14] were needed to reach the satisfactory yields (64–97%) of **7–13**. Isolation and purification of these calixarenes from the esters in excess turned out to be difficult. In order to increase the yield of calixarene **10**, the Michaelis–Becker reaction of chloromethylcalixarene **5** with dibutylphosphinoxyde (1:6 ratio) in THF/NaH medium or in the DMSO–NaOH high basic medium [15] was successfully applied (Scheme 1). Attempts to expand this DMSO–NaOH medium for the synthesis of **7–9** or **11** failed, however, due to the hydrolytical cleavage of P—OPr-*i* bond or due to difficulties in the synthesis of the starting P(O)—H reagents.

The Michaelis–Becker reaction was successfully used for the synthesis of the calix[4]arenes **15–17**. Calix[4]arene **14** [16] bearing highly reactive P(O)—H groups (synthesized by the reduction of **11** with $LiAlH_4$ [16]) was used as substrate in this reaction. The alkylation of **14** with MeI, MeOTos, BuBr and OctBr in THF–NaH or DMSO–NaOH medium gives calixarenes **15–17** with 62–81% yield (see Experimental).

Calix[4]arene **14** was also used as starting material to synthesise a series of phenylamido derivatives **18–21** by the Aterthon–Todd reaction. The reaction takes place in the secondary amine – carbon tetrachloride solution at 80 °C within 5 h and gives 57–67% yields of calixarenes **18–21** (Schem 2).

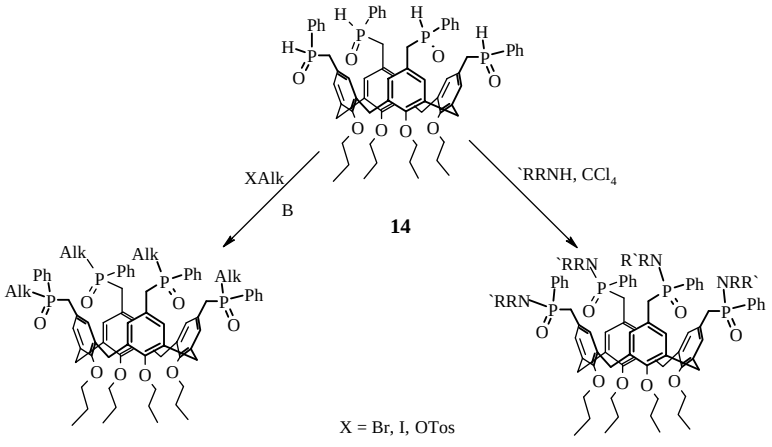
The consecutive treatment of **11** with bromotrimethylsilane and methanol leads to phenylhydroxy derivative **22** (Scheme 3). **22** can be considered as a calixarene analogue of the phosphinic acids (or DIEHPA) which extract lanthanides and actinides [3].

The phosphorylated calixarenes are white crystals or viscous yellow glasses quite soluble in non-polar solvents. The AB spin system in the ^{1}H NMR spectra with $\Delta\delta$ 1.30–1.50 ppm for axial and equatorial protons



	Alk	R	R`
5	Pr	-	-
6	Hexyl	-	-
7	Pr	i-PrO	i-PrO
8	Pr	Bu	i-PrO
9	Pr	Bu	NEt_2
10	Pr	Bu	Bu
11	Pr	Ph	i-PrO
12	Pr	Ph	Ph
13	Hexyl	Ph	Ph

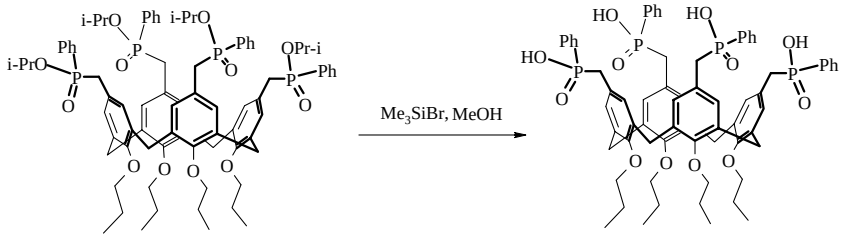
Scheme 1



	Alk
15	Me
16	Bu
17	Oct

	R	**R`**
18	Et	Et
19	Bu	Bu
20	Et	Ph
21	$(CH_2)_2O$	

Scheme 2



11 **22**

Scheme 3

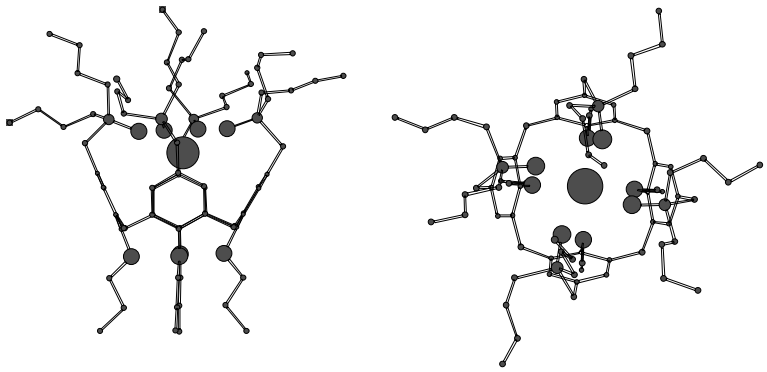
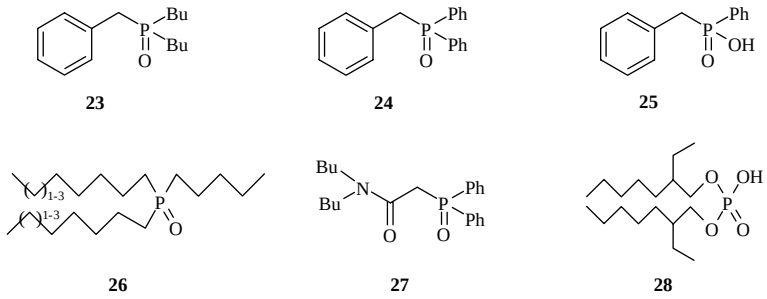


Figure 1. The lowest energy structure of the calixarene **10** – Ca^{2+} complex obtained from Monte–Carlo conformational search.



23 **24** **25**

26 **27** **28**

Chart 2

of the $ArCH_2Ar$ methylene links confirms the *cone* conformation [15] of calixarenes **5–22**. Further confirmation comes from the ^{13}C NMR shifts of the methylene links at 30–31 ppm [17].

As calixarenes **8**, **9**, **11**, **15–21** with four chiral phosphorus atoms can exist as a mixture of stereoisomers (up to six forms: two *meso*-forms and two pairs of enantiomers), their ^1H NMR spectra are rather complicated, especially for the diastereotopic protons of the methylene links.

Molecular modeling simulations

Monte Carlo simulations were performed on the Ca^{2+} complex of **10** in the gas phase, assuming a 1:1 stoichiometry and sampling the different orientations of the four grafted arms. They show that **10** is capable to encapsulate Ca^{2+} in the pseudocavity formed by all four phosphoryl groups at the wide rim (Figure 1), leading to four $Ca^{2+}\cdots O{=}P$ distances of 2.5 Å. We notice that, in solution, the cation binding mode and stoichiometry may be influenced by other effects, such as solvation forces, counterions and other ligands, and thus differ from the gas phase.

Extraction

The extraction of Eu^{3+} and Am^{3+} ions from HNO_3 solutions by the calixarenes dissolved in *meta*-nitrobenzotrifluoride (NBTF) solution was investigated. Acyclic analogs (dibutylbenzylphosphinoxide **23**, diphenylbenzylphosphinoxide **24**, phenylbenzylphosphinic acid **25**) as well as ungrafted industrial extractants such as heteroradical trialkylphosphine oxide **26** (HRPO) [2, 18], *N*,*N*-dibutylcarbamoylmethyldiphenylphosphine oxide **27** (CMPO), di-2-ethylhexylphosphoric acid **28**

Table 1. Extraction of Am^{3+} and Eu^{3+} from HNO_3 solution by solution of L in NBTF

L	D	$[HNO_3]$ (M)				
		0.1	0.3	1.0	3.0	6.0
9	D_{Eu}	0.03	0.05	0.03	0.03	< 0.01
	D_{Am}	0.02	0.03	0.02	< 0.01	< 0.01
10	D_{Eu}	4.0	3.5	0.68	0.03	< 0.01
	D_{Am}	1.5	1.3	0.27	0.01	< 0.01
15	D_{Eu}	0.5	0.5	1.1	0.07	0.06
	D_{Am}	0.26	0.28	0.34	0.03	< 0.01
16	D_{Eu}	0.16	0.23	0.2	0.13	0.03
	D_{Am}	0.25	0.4	0.4	0.15	0.04
17	D_{Eu}	0.1	0.18	0.13	0.07	0.02
	D_{Am}	0.09	0.11	0.11	0.04	0.01
18	D_{Eu}	0.09	0.08	0.06	0.02	0.01
	D_{Am}	0.06	0.06	0.04	0.02	0.01
19	D_{Eu}	2.43	0.47	0.14	0.03	0.01
	D_{Am}	0.8	0.24	0.08	0.02	0.01
21	D_{Eu}	0.04	0.04	0.05	0.02	0.01
	D_{Am}	0.03	0.03	0.03	0.01	0.01
22	D_{Eu}	11.7	0.8	0.07	0.012	0.04
	D_{Am}	10.6	0.61	–	0.005	–
23 (0.4 M)	D_{Eu}	0.01	0.023	0.01	< 0.01	< 0.01
	D_{Am}	0.004	0.008	< 0.01	< 0.01	< 0.01
24 (0.04 M)	D_{Eu}	0.005	0.006	0.008	0.013	0.006
	D_{Am}	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
25	D_{Eu}	0.006	0.007	0.009	0.005	0.008
	D_{Am}	0.005	0.005	0.004	0.004	0.002
26 (0.04 M)	D_{Eu}	0.057	0.054	0.006	< 0.01	–
27	D_{Eu}	0.02	0.07	0.26	0.47	0.36
28 (0.04 M)	D_{Eu}	0.12	0.003	< 0.01	–	–

Distribution coefficient as a function of HNO_3 concentration. If not specified, [L] = 0.01 M. Distribution coefficient for L: **7, 8, 11, 12** and **13** less than 0.01.

(DIEHPA) (Chart 2) were tested for comparison. The results are given in Table 1 and on Figures 2 and 3.

It is found that the Eu^{3+} and Am^{3+} distribution coefficients markedly depend on the electronic features of phosphorus atom substituents and vary in the order: $Bu_2P(O)$ > Ph(Alk)P(O) > Bu(RR′N)P(O) > $Ph_2P(O)$ ≅ Ph(*i*-PrO)P(O) ≅ $(i\text{-PrO})_2P(O)$, which follows the extraction order of similar non-cyclic phosphoryl compounds.

In addition, when compared to the acyclic analogue, the extraction efficiency of dibutylphosphinylcalixarene **10** over a wide range of acidity of the aqueous phase ($[HNO_3]$ 0.1–6.0 M) is more than by two orders of magnitude superior to that of HRPO **23**. In the range of $[HNO_3]$ 0.1–1.0 M, it is also superior to CMPO **27** (Figure 2). The high extraction efficiency points to a cooperative involvement of phosphoryl groups into binding of metal cation. Similar increase of distribution coefficients is observed when going from DIEHPA **28** to

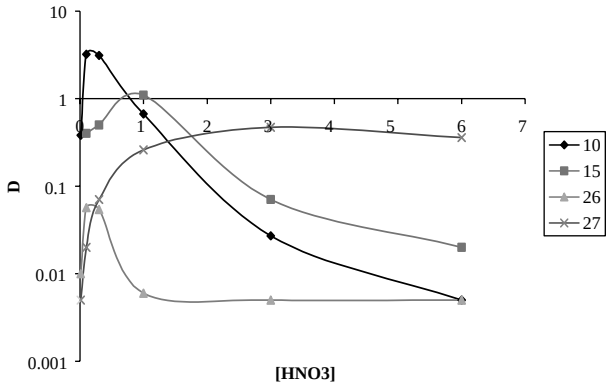


Figure 2. Extraction of Eu ($[10^{-5}$ M]) by calixarenes **10**, **15** (0.01 M), **26** (0.04 M) and **27** (0.01 M) in NBTF. Distribution coefficient as a function of HNO_3 concentration.

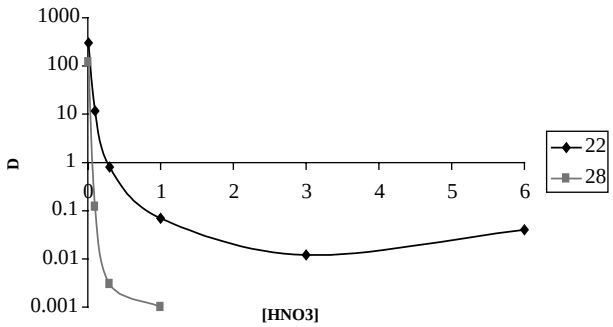


Figure 3. Extraction of Eu ($[10^{-5}$ M]) by calixarene acid **22** (0.01 M) and DIEHPA **28** (0.04 M) in NBTF. Distribution coefficient as a function of HNO_3 concentration.

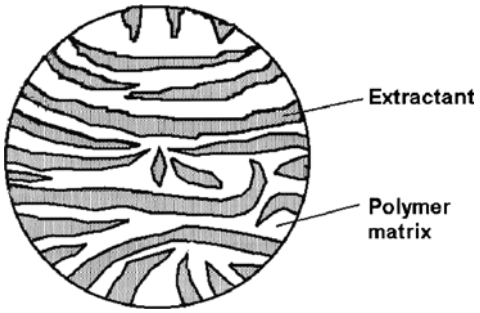


Figure 4. Schematic view of SE grain.

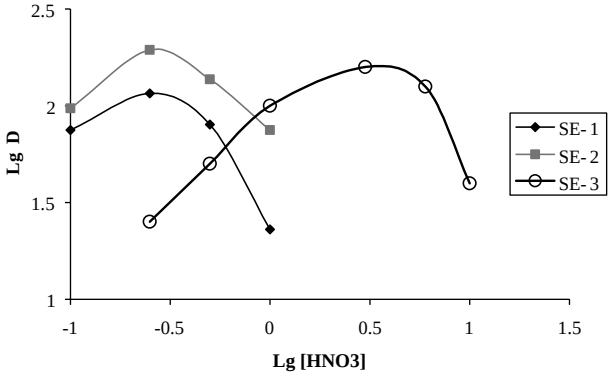


Figure 5. Extraction of Eu ([10^{-5} M]) by SEs. Distribution coefficient as a function of HNO_3 concentration.

Table 2. Properties of the solid extractants

Extractant	Composition	Extraction mixture content in SE, (% wt)	Extractant content in SE, (% wt)
SE-1	100% HRPO **26**	50	50
SE-2	0.12 M solution of calixarene **10** in *meta*-nitrobenzotrifluoride	44	5
SE-3	0.6 M solution of CMPO **27** in *ortho*-$C_8H_{17}OC_6H_4NO_2$	45	10

calixarene **22** (Figure 3). Comparing now the europium *versus* americium selectivity, one sees that europium is extracted somewhat better than americium by all calixarenes studied.

In the processing of the liquid radioactive wastes, in addition to the classic liquid–liquid extraction, utilization of the solid extractants (SEs) is considered as an alternative technique [19]. SEs belongs to a class of sorbents containing a great amount of extractant (up to 50% of mass) in macroporous matrices like styrene-divinylbenzene ones (Figure 4). The extractant can be introduced into the polymeric matrix either as a concentrated solution or in a pure form. The use of SEs combines the simplicity of the sorption processes with potential of the liquid–liquid extraction. So far, preparation of SEs was mostly based on trialkylphosphine oxides [19] and, to our knowledge, calixarenes have not been investigated as extractant component of SEs. We thus prepared and tested three SEs based on the divinylbenzene-styrol polymeric matrix: SE-2 contains the calixarene **10**, while SE-1 and SE-3 contain HRPO **26** and CMPO **27** extractants, respectively. Their composition is given in Table 2.

The results of the extraction studies with SE-1–SE-3 are presented in Figure 5 as plots of Log *D* (*D* is the *static sorption coefficients*) *versus* HNO_3 concentration. They show that SE-2 which contains smallest amount of complexing agent **10** has *higher D* values than SE-1 and SE-3. The trends of D/C_{HNO_3} are similar to those obtained from the liquid–liquid extraction data (Figure 2).

Conclusion

Calix[4]arenes (*cone* conformation) bearing four 'basic' phosphoryl groups linked by one methylene spacer to the wide rim effectively transport trivalent europium and americium ions from an aqueous HNO_3 solution to an organic phase. The increase in Eu^{3+} and Am^{3+} distribution coefficients by a factor of up to 200 for calixarenes **10** and **22** compared to model compounds **26** (HRPO) and **28** (DIEHPA) is consistent with a cooperative binding of the phosphoryl groups to the metal cations, as suggested by molecular modeling.

Acknowledgements

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References

1. *Actinide and Fission Product Partitioning and Transmutaion*, Fifth Int. Inform. Meet, Belgium (1998); C. Davies (ed.), *Radioactive Waste Management Strategies and Issue*, Eur. Com., Luxembourg (2000).
2. M. Baaden, F. Berny, C. Boehme, N. Muzet, R. Schurhammer, and G. Wipff: *J. Alloys Comp*. **303–304**, 104 (2000).
3. V.V. Babain and A.Yu. Shadrin: In: *Chemical Separation Technologies and Related Methods of Nuclear Wastes Management*, Kluwer Academic Publishers, The Netherlands (1999), p. 135.

4. M. Hugon (ed.), *Overview of the EU Research Projects on Partitioning and Transmutation of Long-lived Radionuclides*, Euroatom, Brussels (2000).
5. V. Böhmer: *Angew. Chem.*, Int. Ed. Engl. **34**, 713 (1995); C.D. Gutsche: *Calixarenes Revisited*, RSC, Cambridge (1998); D. Diamond and M.A. McKervey: *Chem. Soc. Rev.* 15 (1996); G.J. Lumetta, R.D. Rogers, and A.S. Gopalan (eds.), *Calixarenes for Separations,* ACS, Washington (2000); L. Mandolini and R. Ungaro (eds.), *Calixarenes in Action*, Imperial College Press, Singapore (2000).
6. J.F. Dozol, M.J. Schwing-Weill, F. Arnaud-Neu, V. Boehmer, R. Ungaro, F.C.J.M. van Veggel, G. Wipff, A. Costero, J.F. Desreux, and J. de Mendoza: *Final Report FI4W-CT96-0022,* Eur. Com., Nuclear Science and Technology, (2000).
7. F. Arnaud-Neu, V. Böhmer, J.F. Dozol, C. Grüttner, R.A. Jakobi, D. Kraft, H. Mauprivez Rouquette, M.J. Schwing-Weill, N. Simon and W. Vogt: *J. Chem. Soc., Perkin Trans.* **2**, 1175 (1996); L.H. Demau, N. Simon, M.J. Schwing-Weill, F. Arnaud-Neu, J.F. Dozol, S. Eymard, B. Tournois, V. Böhmer, C. Grüttner, C. Musigmann, and A. Tunayar: *Chem. Commun.* 1627 (1998); S.E. Matthews, M. Saadioui, V. Böhmer, S. Barboso, F. Arnaud-Neu, M.J. Schwing-Weill, A.G. Carrera, and J.F. Dozol: *J. Prakt. Chem.* **341**, 264 (1999); A. Arduini, V. Böhmer, L. Delmau, J.F. Desreux, J.F. Dozol, M.A.G. Carrera, B. Lambert, C. Musigmann, A. Pochini, A. Shivanyuk, and F. Ugozzoli: *Chem. Eur. J.* **6**, 2135 (2000).
8. F. Arnaud-Neu, J.K. Browne, D. Byrne, D.J. Marrs, M.A. McKervey, P. O'Hagan, M.J. Schwing-Weill, and A. Walker: *Chem. Eur. J.* **5**, 175 (1999); J.F. Malone, D.J. Marrs, M.A. McKervey, P. O'Hagan, N. Thomson, A. Walker, F. Arnaud-Neu, O. Mauprivez, M.J. Schwing-Weill, J.F. Dozol, H. Rouquette, and N. Simon: *J. Chem. Soc.*, Chem. Commun. 2151 (1995).
9. M.J. Schwing-Weill and F. Arnaud-Neu: *Gazz. Chim. Ital.* **127**, 687 (1997); J.F. Dozol, V. Boehmer, M.A. McKervey, F. Lopez-Calahorra, D. Reinhoudt, M.J. Schwing-Weill, R. Ungaro, and G. Wipff: *Report EUR. 17615EN*, Eur. Com., Nuclear Science and Technology (1997).
10. A.V. Solovyov, L.I. Atamas, O.V. Klimchuk, V.L. Rudzevich, A.B. Drapailo, V.I. Kalchenko, A.A. Varnek, and G. Wipff: In C. Davies (ed.), *EURADWASTE 1999. Radioactive Waste Management Strategies and Issues*, Eur. Com., Luxembourg (2000), p. 523.
11. T.A. Mastryukova and M.I. Kabachnik: *Uspekhi Khimii* (*Russ. J. Chem.*) **38**, 1751 (1969).
12. F. Berny, N. Muzet, L. Troxler, A. Dedieu, and G. Wipff: *Inorg. Chem.* **38**, 1244 **(**1999).
13. *Inorganic Chemistry*: Principles of Structure and Reactivity, 4th edn. Harper Collins, New York, USA, (1993).
14. M. Almi, A. Arduini, A. Casnati, A. Pochini, and R. Ungaro: *Tetrahedron* **45**, 2176 (1989); T. Arimura, T. Nagasaki, S. Shinkai, and T. Matsuda: *J. Org. Chem.* **54**, 3766 (1989); S. Ozegowski, B. Costisella, and J. Gloede: *Phosphorus*, *Sulfur*, *Silicon* **119**, 203 (1996).
15. E.N. Tsvetkov, N.A. Bondarenko, I.G. Malakova, and M.I. Kabachnik: *Synthesis* 198 (1986).
16. L. Atamas, O. Klimchuk, V. Rudzevich, V. Pirozhenko, V. Kalchenko, I. Smirnov, V. Babain, T. Efremova, A. Varnek, G. Wipff, F. Arnaud-Neu, M. Roch, M. Saadioui, and V. Böhmer: *J. Supramol., Chem.* **2**, 421 (2002).
17. J.O. Magrans, J. de Mendoza, M. Pons, and P. Prados: *J. Org. Chem.* **62**, 4518 (1997).
18. N.G. Feschenko and G.K. Gorbatenko: *J. Gen. Chem.* (*Russia*) **62**, 1481 (1992).
19. B.N. Zaitsev, I.B. Kvasnitskiy, and V.P. Popik: *Radiochemistry* (*Russia*), **27**(4), 445 (1985).
20. S. Kanamathareddy and C.D. Gutsche: *J. Org. Chem.* **57**, 3160 (1992).