Solvent extraction of heavy metals with macrocyclic ligands based on calix[4]arenes

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Ligand **1**, a calix[4]arene-based compound with a crown-6 moiety, efficiently extracts the heavy metal ions Hg^{2+} and Pb^{2+} from weakly acidic solutions due to their compatible ion radius. The CO$_2$H groups are essential for the metal extraction, as seen from a comparison with the corresponding ester compound **2**. Ligand **3** as a crown-5 is also capable of extracting smaller cations such as Zn^{2+} and Cd^{2+} from weakly acidic solutions. Compound **5**, bearing four CO$_2$H groups, shows quantitative extraction for Hg^{2+} and Pb^{2+} at pH values above 2.5 and 2.8, respectively. Extraction takes place to some extent even if water-soluble organic complexing reagents are present in the aqueous phase, such as EDTA. Quantitative back-extraction is achieved by using 0.75 M HNO$_3$.

New extractants with high selectivity for metal ions are of interest for analytical purposes as well as for the recycling of resources and for waste water treatment, for example, the removal of rare or toxic heavy metals. Calixarenes[1–3] and similar macrocyclic compounds such as cyclophanes in general have proved their worth as a hydrophobic platform for the synthesis of selective ligands for solvent extraction, because the use of template effects and protective groups can effectively control the synthesis.

Previously, we reported the synthesis of calix[*n*]arenes ($n = 4$–6) bearing mixed functionalities including carboxylic acid groups, as well as their selective extraction behaviour towards noble metal ions[4] and f-element ions.[5] It was noted that the cavity size, the position and kind of donor groups and the ligand's hydrophobicity have a pronounced impact on the extraction power and selectivity. The variety of possible structures and the distinct coordination properties promoted our interest in calixarenes for solvent extraction.[6] It has been reported that calixarenes bearing 2-mercaptoethoxy or 2-*N*,*N*-dimethyldithiocarbamoylethoxy groups can extract Hg(II), Pb(II), Cd(II), Ag(I) and Au(III).[7] Thiophosphorylated calix[6]arenes with a Pb/Cd selectivity have aroused interest for use in electrodes,[8] while calixarene-based thioamides extract copper, silver, cadmium and lead.[9] In the extraction of Ag$^+$, Hg$^+$, and Hg^{2+} a metal ion-induced azo/hydrazone tautomerism in calixarenes was observed.[10] Recently, the extraction of Hg(II) and Ag(I) by calix[4]arene *N*-(X) sulfonylcarboxamides at pH 2.5 was shown to take place selectively,[11] while an acyclic polyether with pseudo-18-crown-6 structure was shown to extract Pb(II) selectively over smaller heavy metal ions.[12] The substitution of the methylene bridges in a calix[4]arene by sulfide linkages results in a high extractability towards divalent transition metal ions,[13] and introduction of diphenylphosphino groups into calix[4]arenes promotes the extraction of transition metals, as well as Cd(II) and Hg(II).[14] Selective cobalt extraction by a calix[6]arene for analytical purposes was reported,[15] and selective lead/zinc separation is achieved with a calix[4]arene-based resin.[16] Selective silver/palladium extraction with a ketone derivative of calix[4]arene,[17] and specific interaction of Ag(I) with the cavity of a calix[4]arene-based amide[18] result in higher selectivity compared with non-cyclic analogues. Owing to the recent growing interest in heavy metal extraction, we would like to present our results on the extraction of heavy metal ions by calix[4]arenes in the pH range of 2.4 to 4.

In this work we describe the extraction of divalent Pb, Hg, Cd, Zn and Co from weakly acidic media into toluene by using the extractants shown in Scheme 1. The compounds (with the exception of **2**) contain CO$_2$H groups to facilitate extraction by cation exchange, a cavity of defined diameter in order to selectively bind heavy metal ions, and branched alkyl chains to make them insoluble in water. Ligands **1**, **2** and **3**[19] are characterized by a crown linkage at the 'lower rim' of the molecule. This linkage has two functions: (*i*) it restricts the conformational freedom of the calixarene thus defining the cavity size and (*ii*) it shields the encapsulated cation from solvent molecules. The idea behind this work was to extract small cations such as Co^{2+} and Cd^{2+} with a crown-5, and larger cations with the crown-6 derivative. It will be shown that extraction is achieved even in the absence of sulfur as donor atom and that the selectivity is governed by the relationship between ion and cavity radius.

Results and discussion

Fig. 1 shows the results of Hg(II) extraction by the series of macrocyclic ligands **1** and **3**–**6** in the pH range of 2.4 to 3.7. The conformation of the ligands is a cone as concluded from their NMR spectra, and with the exception of ligand **6** the conformation is fixed. Ligand **5** is the best extractant for Hg(II) with more than 99% extraction above pH 2.5. Removing two of the four CO$_2$H groups results in a significant drop in extractability, as seen for the Bu^t analogue **6**. This decrease is partially offset by the crown-6 moiety in ligand **1**. On the other hand, the crown-5 moiety in ligand **3** further reduces the extractability of Hg(II) compared with **1** and **6**, probably because of the smaller size of the rigid cavity in **3**, formed by the 'lower' rim of the calix, the crown and the CO$_2$H groups. The steric requirements of the amide and the Oct^t groups of **4** reduce cavity size and molecular flexibility compared with **5** and **6**, resulting in a much lower extraction. The extraction, expressed as the distribution ratio D ($D = c_{\text{metal, org}}/c_{\text{metal, aq.}}$)

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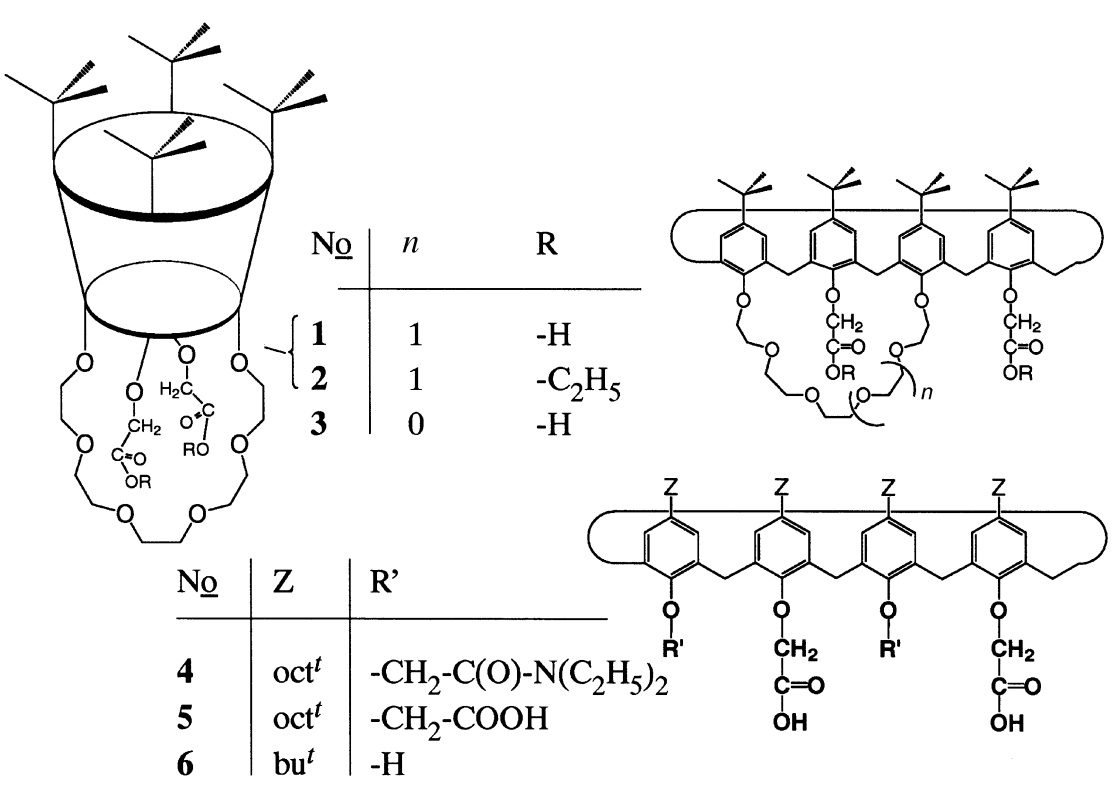

No	n	R
1	1	-H
2	1	$-C_2H_5$
3	0	-H

No	Z	R'
4	oct^t	$-CH_2-C(O)-N(C_2H_5)_2$
5	oct^t	$-CH_2-COOH$
6	bu^t	-H

(oct^t = 1,1,3,3-tetramethylbutyl)

Scheme 1 Structures of the extractants.

increases with a slope of about 0.5 in the plot of log D_{Hg} *vs.* pH for all ligands. This value is lower than expected for divalent ions and can be explained by the extraction of hydrolyzed Hg(II) species (*ca.* 50% hydrolyzed at pH 4 in the absence of ligands other than OH^-), and the extraction of nitrate anions at lower pH.

Evidence for the extraction of Hg(II) by **1** is also seen in the NMR spectra of the complex, which was prepared by extracting $Hg(NO_3)_2$ into a $CDCl_3$ solution: new ^1H peaks for H_{Ar} at δ 7.0 and H_{Bu^t} at δ 1.16, and sharpening of the ^{13}C signals for HC_{Ar} and CH_2–C_{Ar}.

Fig. 2 shows the extraction data for Pb(II). The values of log *D vs.* pH for ligands **1**, **4** and **5** lie on straight lines with a slope of two, corresponding to the cation charge. Also included are the results with the bis(ethoxycarbomethoxy) derivative **2**, which is the precursor of **1** and which can extract ion pairs only. Comparing the extractability of **1** and **2** clearly shows that the presence of the two CO_2H groups promotes the extraction at pH above 3. The highest extractability is again observed for ligand **5**. In fact, the extraction by **5** is quantitative above pH 2.8 for Pb(II) and above pH 2.5 for Hg(II), and can be applied for analytical purposes. This result is in agreement with the adsorption of Pb(II) above pH 2,[16] on a resin with an immobilized calix[4]arene having a similar structure and with the high extraction from neutral solutions by the Bu^t analogue of **5**.[19] In the acidic region below pH 3, the crown-5 compound **3** extracts Pb(II) better than the crown-6 ligand **1**. However, the slope is only 0.5 and it is concluded that **3** preferably extracts the ion pair with NO_3^-, in contrast to **1** which extracts Pb(II) due to cation exchange

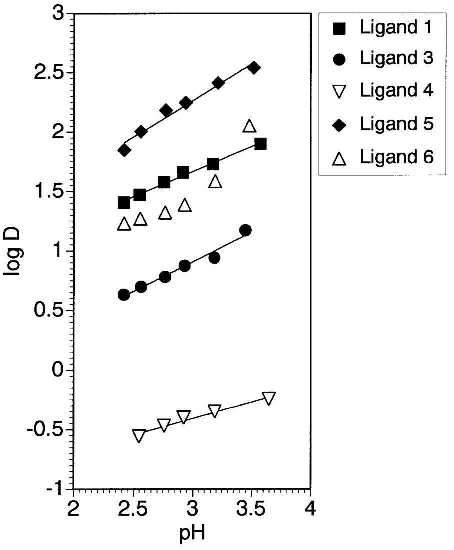

Fig. 1 Solvent extraction of Hg(II) by the ligands **1** and **3**–**6** from aqueous to toluene solutions. Extraction conditions: aqueous phase: HNO_3 containing 5×10^{-5} M metal nitrate (single metal ion extraction); organic phase: 5×10^{-3} M ligand.

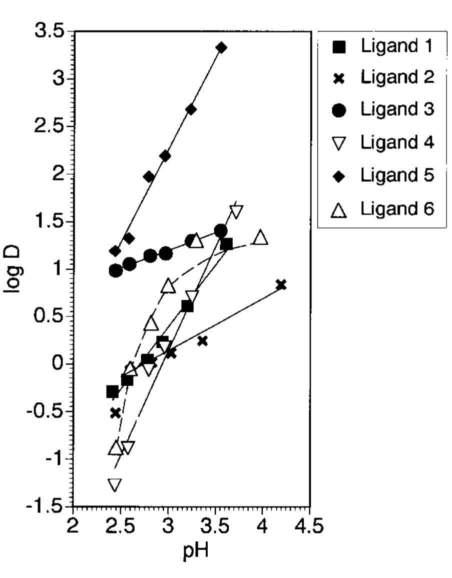

Fig. 2 Solvent extraction of Pb(II) by the ligands **1**–**6** from aqueous to toluene solutions. For extraction conditions see Fig. 1.

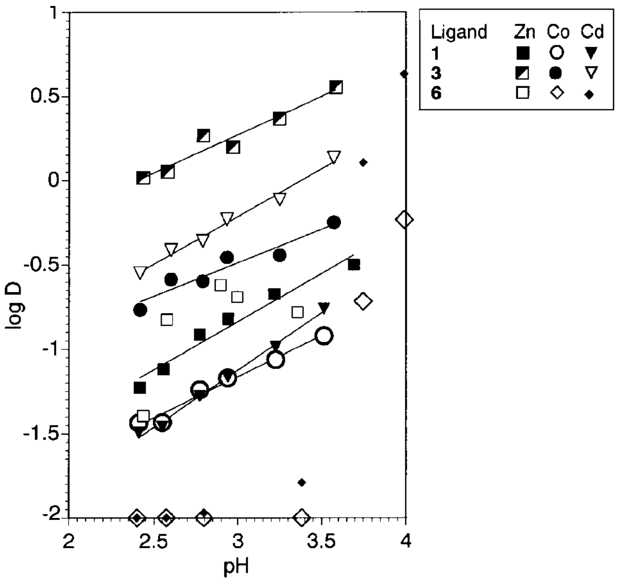

Fig. 3 Solvent extraction of Co(II), Zn(II), and Cd(II) by the ligands **1**, **3**, and **6** from aqueous to toluene solutions. Extraction conditions: aqueous phase: HNO_3 containing 5×10^{-5} M (Zn) or 1×10^{-4} M (5×10^{-5} M each of Co and Cd) metal nitrate; organic phase: 5×10^{-3} M ligand.

only. Further studies on the stoichiometry are under way in order to clarify the composition of the extracted complexes. Ligands **3** and **4** extract Pb(II) better (over 50% at pH 3) than all the other investigated metal ions. Extraction of Pb(II) by the bis(carboxymethoxy)dihydroxy derivative **6** depends non-linearly on pH, which is probably due to a change in the extraction mechanism. The good extraction by **3** as well as by **6** from less acidic media is in agreement with the high extractability from neutral solutions.[19]

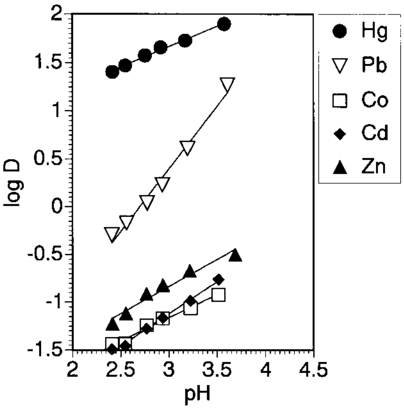

Fig. 4 Solvent extraction of divalent metal ions by ligand **1**.

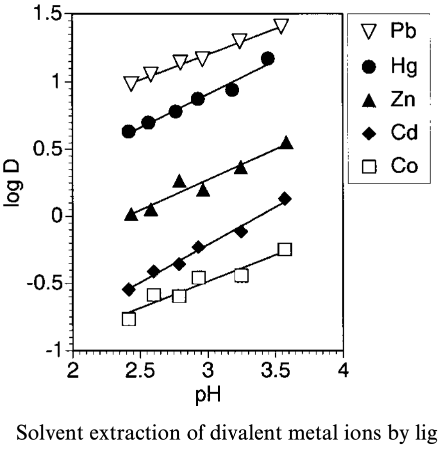

Fig. 5 Solvent extraction of divalent metal ions by ligand **3**.

Fig. 3 depicts the results of the extraction of Zn(II), Co(II), and Cd(II) by ligands **1**, **3**, and **6**. Although various commercial ligands such as acetylacetonates, amines, carboxylic acids and P-donor ligands can extract Co(II) and Zn(II), these metal ions were included in order to study the influence of the ligand structure on the extraction of divalent ions having similar radii (Zn 0.074, Co 0.072, Cd 0.094 nm). In contrast to Hg(II) (0.11 nm radius) and Cd(II), which are 'soft' Lewis acids, Pb(II) (0.12 nm), Co(II) and Zn(II) are of intermediate nature according to the hard and soft acids and bases (HSAB) principle. Although our extractants contain O-donor atoms, there is no clear discrimination between hard and soft Lewis acids. This is explained by the cavity size of the macrocycle being the governing factor for cation extraction in the investigated system. Among the ions, Co^{2+}, Zn^{2+} and Cd^{2+} are smaller than the cavity size of calix[4]arenes (about 0.2 nm diameter[1] defined by the phenolic O atoms) and their complexes are therefore less stable, as seen in the low extraction by ligand **1** for example. Only ligand **3**, with a rigid cavity and a sufficient number of donor atoms, can extract these ions well (*e.g.*, 24% Co and 64% Zn at pH 3). Moreover, ligand **3** can provide a coordination sphere suitable for Zn(II), that is square pyramidal. The higher extraction of Zn(II) compared with Co(II) is in agreement with the ligand field stabilization energy (LFSE). The extraction of Cd(II) lies in between, but a surprisingly high extraction of Cd(II) and also Co(II) is possible at pH > 3.5 with ligand **6**. Not shown are the results for **4** and **5**, due to the low extraction ($\log D < -1.5$) within the pH range of 2.4–3.5. An exception is Cd(II) extracted at 50% by ligand **5** pH 3.5. In the course of the back-extraction experiments it was noted that the presence of a water-soluble organic ligand such as EDTA (5×10^{-3} M) does not prevent the extraction of Hg(II), Pb(II), Cd(II) and Co(II) from neutral solutions. Instead, 0.75 M HNO_3 was used for quantitative back-extraction, except in the case of ligand **1** from which only 40% Hg(II) is back-extracted in the first stage.

The data for ligands **1** and **3** are summarized in Fig. 4 and 5, respectively. It is seen that the crown-6 derivative preferably extracts the cations with larger ion radii, with a preference for Hg(II) over Pb(II). On the other hand, the crown-5 not only extracts the larger cations, but the smaller ones as well. In conclusion, macrocyclic hydrophobic extractants with O-donor atoms are capable of selectively recognizing the heavy metal cations Hg^{2+}, Pb^{2+}, Cd^{2+}, and Zn^{2+} due to size compatibility, as shown for calixarenes with different crown moieties.

Experimental

Synthesis

Solvents for synthesis under nitrogen were dried and freshly distilled. Work-up includes washing of the raw product dissolved in $CHCl_3$ with HCl to remove template cations, drying, and recrystallization. NMR spectra (in ppm) were recorded at room temperature at 250 MHz (^1H) and 60 MHz (^{13}C). Mass spectra were recorded in FAB mode using 3-nitrobenzyl alcohol as matrix. TLC was performed on silica gel plates $60F_{254}$.

5,11,17,23-Tetrabutyl-25,27-bis(carboxymethoxy)calix[4]-arene-26,28-crown-6, 1, in two steps. Tetrabutyl-calix[4]arene-tetrol[1] was converted to the diester precursor 5,11,17,23-tetrabutyl-25,27-bis[(ethoxycarbonyl)methoxy]calix[4]arene-26,28-diol, **1a**, in the presence of a weak base.[20,21] **1a** (1 equiv.) was treated in a manner similar to that described in ref. 22 with pentaethylene glycol di-*p*-toluenesulfonate (1 equiv.) in THF (150 ml) in the presence of NaH (3.5 equiv.) to give after work-up the intermediate 5,11,17,23-tetrabutyl-25,27-bis-[(ethoxycarbonyl)methoxy]calix[4]arene-26,28-crown-6, **2**. Yield 75%; TLC ($CHCl_3$–MeOH 5 : 1): R_f 0.62; mp 123–126 °C; IR (KBr, cm^{-1}): 1757 (ν_{CO}), 1123 [vs, (w in **1a**), ν_{as}, C–O–$C_{aliphat.}$]; ^{1}H NMR ($CDCl_3$): δ 0.82 (s, 18H), 1.32 (br, 24H), 3.22 (br d, 4H, Ar–CH_2–Ar), 3.6–4.8 (br, 32H), 6.56 (s, 4H), 7.14 (s, 4H); selected ^{13}C NMR: δ 30.80 and 31.42 (Bu^t), 66.44, 69.66, 70.43 (–CH_2), C_{Ar} 125.0, 132.0, 134.7, 144.8, 150.2 (br), 170.34 (CO); MS (FAB$^+$) m/z: 1020 (L − H_2), 1005 (L − H_2O), 1042 (L + H_2O); Anal. calcd for $C_{62}H_{86}O_{12}$: C, 72.77; H, 8.47; found: C, 71.86; H 8.15%.

Hydrolysis of **2** (1 equiv.) in THF (40 ml) with 25% $N(Me)_4OH$ (20 ml) for 1 day, drying, washing (0.5 M HCl–$CHCl_3$) and recrystallization from MeOH gave **1**. Mp 100–103 °C; ^{1}H NMR ($CDCl_3$–CD_3OD 1 : 2): δ 0.83 (18H), 1.34 (18H Bu^t), 3.21 (d, 4H, Ar–CH_2–Ar), 4.86 (s, 4H, O–CH_2–, v br in $CDCl_3$), 3.6–4.8 (m, 24H), 6.56 and 7.15 (8H_{Ar}); selected ^{13}C NMR ($CDCl_3$): δ 30.2, 30.9, 31.5, 32.6, 34.1, 69.8, 70.5, 125.1, 125.4, 125.7, 132.2, 134.9, 171.3; MS (FAB$^-$) m/z: 966 (L − H), 907 (L − CH_2CO_2H), 895 (L − CH_2CO_2H and OH), 849 (L − 2 CH_2CO_2H), 795 [L − $CH_2O(C_2H_4O)_3CH_2$], 761 (L − crown), 705 (L − CH_2CO_2H − crown), 647 (backbone of L); trace of $N(Me)_4OH$ observed (if product is not thoroughly washed with HCl) in NMR [^{1}H (δ 1.8, br) and ^{13}C (δ 25.9)] and in MS {1056 [L + $N(Me)_4OH$]}; Anal. calcd for $C_{58}H_{78}O_{12}$: C, 72.02; H, 8.13; found: C, 71.55; H, 8.14%.

5,11,17,23-Tetrabutyl-25,27-bis(carboxymethoxy)calix[4]-arene-26,28-crown-5, 3.[19] **3** was synthesized in analogy to **1**, giving the same products as described in ref. 19. The intermediate 5,11,17,23-tetrabutyl-25,27-bis[(ethoxycarbonyl) methoxy]-calix[4]arene-26,28-crown-5, **3a**, was obtained in 80% yield and identified: TLC ($CHCl_3$–MeOH 5 : 1): R_f 0.62; IR (KBr, cm^{-1}): 1757 (ν_{CO}), 1124 (vs, ν_{as}, C–O–$C_{aliphat.}$); ^{1}H NMR ($CDCl_3$): δ 0.83 (s) and 1.33 (br s) (42H), 3.21 (br d, 4H, Ar–CH_2–Ar), 3.56–4.78 (m, 28H), 6.57 and 7.13 (8H); selected ^{13}C NMR: δ 14.99, 30.89, 31.38, 33.54, 34.02, 66.48, 69.66, 70.43, 72.03, 75.4 (br, C_{Ar}), 172.32 (CO).

Ligand **3** was obtained by hydrolysis of **3a** and confirmed by NMR,[19] MS (FAB$^-$) m/z: 921 (L − H), 863 (L − CH_2CO_2H), 805 (L − 2 CH_2CO_2H), 763 (L − crown), 705 (L − crown − CH_2CO_2H), 647 (backbone of L), and elem. anal. (calcd for $C_{56}H_{74}O_{11}$: C, 72.85; H, 8.08; found: C, 71.40; H, 7.98%).

5,11,17,23-Tetrakis(1,1,3,3-tetramethylbutyl)-25,27-bis(carboxy-methoxy)-26,28-bis[(*N*,*N*-diethylcarbamoyl)methoxy]-calix-[4]arene, 4, in three steps. 5,11,17,23-Tetrakis(1,1,3,3-tetrakismethylbutyl)-25,26,27,28-tetrahydroxycalix[4]arene[23,24] (1 equiv. in 100 ml acetone) was converted to 5,11,17,23-tetrakis-(1,1,3,3-tetramethylbutyl)bis[(ethoxycarbonyl)methoxy]calix[4] arene-26,28-diol, **4a**, with ethyl bromoacetate (2.2 equiv.) in the presence of K_2CO_3 (1.1 equiv.), similarly to the Bu^t analogue.[20,21] **4a**: Yield 92%, TLC ($CHCl_3$–ether 9 : 1) R_f = 0.9; mp 151 °C; ^{1}H NMR ($CDCl_3$): δ 0.27 (s, 18H), 0.71 (s, 18H), 1.09 (s, 12H), 1.31–1.36 (m, –CH_3), 1.66 (s, 4H, –CH_2), 3.30 (d, 4H, Ar–CH_2–Ar, J = 13 Hz), 4.30 (q, 4H, –CH_2–CH_3), 4.43 (d, 4H, Ar–CH_2–Ar, J = 13 Hz), 4.66 (s, 2H, –OCH_2–), 6.83 (s, 4H, H_{Ar}), 6.99 (s, 4H, H_{Ar}), 7.29 (s, 2H, –OH); ^{13}C NMR: δ 14.1, 30.79–32.01 (m), 37.67, 37.73, 57.19, 57.53, 61.15, 72.1, 72.62, 73.1, 125.74–127.31 (m), 132.11, 140.14, 145.76, 150.28, 150.44, 169.0; MS (FAB$^+$): m/z: 1085 (L + K), 1069 (L + Na), 1046 (L); Anal. calcd for $C_{68}H_{100}O_8$: C, 78.11; H, 9.64; found: C, 77.56; H, 9.37%.

Next, **4a** (1 equiv.) was dissolved in acetonitrile (100 ml) and converted to 5,11,17,23-tetrakis(1,1,3,3-tetramethylbutyl) bis(ethoxycarbonyl)methoxy-26,28-bis[(*N*,*N*-diethylcarbamoyl)-methoxy]calix[4]arene, **4b**, by treatment with *N*,*N*-diethylchloroacetamide (6.7 equiv.) in the presence of K_2CO_3 (7.55 equiv.) and NaI (5 equiv.).[4] **4b**: Yield 90.1% (recryst. from MeOH); mp 111–113 °C; ^{1}H NMR ($CDCl_3$): δ 0.62 (s, 18H), 0.71 (s, 18H), 0.89 (s, 12H), 1.11–1.21 (m, 24H), 1.38 (s, 4H, –CH_2 of Oct^t), 1.63 (s, 4H, –CH_2 of Oct^t), 3.14 (d, 4H, Ar–CH_2–Ar, J = 13 Hz), 3.34 (m, 8H, N–CH_2), 4.08 (q, 4H, –CH_2 ester, J = 7.2 Hz), 4.60 (s, 4H, –OCH_2–), 4.88 (d, 4H, Ar–CH_2–Ar, J = 13 Hz), 4.98 (s, 4H, –OCH_2–), 6.51 (s, 4H, H_{Ar} at Ar with ester), 6.88 (s, 4H, H_{Ar} at Ar with amide); ^{13}C NMR: δ 13.24, 14.48, 14.77, 31.18–32.64 (m), 38.03, 38.20, 40.40, 41.81, 57.33, 57.77, 60.22, 71.22, 72.89, 126.13, 126.72, 132.49, 134.46, 144.42, 153.91, 154.01, 168.63, 171.51; MS (FAB$^+$) m/z: 1294 (L + Na), 1272 (LH$^+$); Anal. calcd for $C_{80}H_{122}O_{10}N_2$: C, 75.55; H, 9.67; N, 2.20; found: C, 75.19; H, 9.51; N, 2.24%.

Finally, **4b** was hydrolyzed with $N(Me)_4OH$ and worked up[4] to give ligand **4**. Yield 95%; mp 155–158 °C; NMR (^{1}H, $CDCl_3$): δ 0.40 (s, 18H), 0.70 (s, 18H), 0.95 (s, 12H), 1.12 (m, 6H), 1.30 (s, 12H), 1.34 (s, 4H), 1.64 (s, 4H), 3.24 (d, 4H, Ar–CH_2–Ar, J = 12.8 Hz), 3.34 (m, 4H, N–CH_2), 4.59 (s, 4H, –OCH_2–), 4.74 (d, 4H, Ar–CH_2–Ar, J = 12.8 Hz), 4.77 (s, 4H, –OCH_2–), 6.67 (s, 4H, H_{Ar}), 7.05 (s, 4H, H_{Ar}); the 1 : 1 complex with Na^+ was characterized: MS (FAB$^+$): 1238 (L + Na), 1216 (LH), trace 1306 [L + $N(Me)_4OH$]; Anal. calcd for $C_{76}H_{113}O_{10}N_2$ + Na: C, 73.75; H, 9.20; N, 2.26; found: C, 72.6; H, 9.22; N, 2.01%.

Ligands **5**[24] and **6**,[19] the latter prepared by hydrolysis of **1a**, are reference compounds bearing only four or two CO_2H as ionophilic groups [**6** was identified as a 1 : 1-complex with Na^+: MS (FAB$^+$) m/z: 764 (L), 787 (L + Na), trace 854 (L + $N(Me)_4OH$), trace 877 (L + Na + $N(Me)_4OH$); Anal. calcd for $C_{48}H_{60}O_8Na$: C, 73.15; H, 7.68; found: C, 73.52; H, 7.83%].

Metal extraction

The chemicals were of analytical grade and water was ion-exchanged and bidistilled. Toluene was washed and equilibrated with water before use. The experiments were carried out at 298 K with equal phase volumes in an overhead shaker. The aqueous phase contained 5 × 10^{-5} M of metal nitrate in the single metal ion extraction (Hg, Pb, Zn), or 5 × 10^{-5} M each of Co and Cd nitrate, as well as various amounts of HNO_3.

The organic phase contained 5 × 10^{-3} M ligand in toluene. In the case of ligand **3**, formation of an emulsion was observed at the liquid/liquid interface in the absence and presence of metal ions, resulting in slow phase coalescence. It indicates the amphiphilic nature of this ligand and it is planned in subsequent work to substitute Bu^t in **3** with 1,1,3,3-tetramethylbutyl in order to improve the hydrophobicity. Back-extraction was quantitatively achieved with 0.75 M HNO_3 [except of Hg(II) from **1**]. The equilibrium pH of the aqueous phase was measured by using a combination glass electrode (Orion). Metal analysis was done with an ICP-AES (IRIS AP, TJA), using commercially available standard solutions.

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References

1 C. D. Gutsche, *Calixarenes*, The Royal Society of Chemistry, Cambridge, UK, 1989.
2 C. D. Gutsche, *Calixarenes Revisited*, The Royal Society of Chemistry, Cambridge, UK, 1998.
3 *Calixarenes. A Versatile Class of Macrocyclic Compounds*, eds. J. Vicens and V. Böhmer, Kluwer Academic Publishers, Dortrecht/ Boston/London, 1990.
4 R. Ludwig and S. Tachimori, *Solv. Extr. Res. Dev., Jpn.*, 1996, **3**, 244.
5 R. Ludwig, K. Kunogi, T. K. D. Nguyen and S. Tachimori, *Chem. Commun.*, 1997, 1985; R. Ludwig, T. K. D. Nguyen, K. Kunogi and S. Tachimori, *Technical Report JAERI-Conf. 99-04*

[Proceedings of the 2nd NUCEF International Symposium, Ibaraki (Japan) Nov. 16–17, 1998], 1999, in press; T. K. D. Nguyen, K. Kunogi and R. Ludwig, *Bull. Chem. Soc. Jpn.*, 1999, **72**, in press.

6 R. Ludwig, *JAERI-Review 95-022*, 1995.

7 A. T. Yordanov and D. M. Roundhill, *New J. Chem.*, 1996, **20**, 447.

8 W. Wroblewski, Z. Brzozka, R. G. Janssen, W. Verboom and D. N. Reinhoudt, *New J. Chem.*, 1996, **20**, 419.

9 F. Arnaud-Neu, G. Barrett, D. Corry, S. Cremin, G. Ferguson, J. F. Gallagher, S. J. Harris, M. A. McKervey and M.-J. Schwing-Weill, *J. Chem. Soc., Perkin Trans. 2*, 1997, 575.

10 E. Nomura, H. Taniguchi and Y. Otsuji, *Bull. Chem. Soc. Jpn.*, 1993, **66**, 3797.

11 G. G. Talanova, H.-S. Hwang, V. S. Talanov and R. A. Bartsch, *Chem. Commun.*, 1998, 1329.

12 T. Hayashita, H. Sawano, T. Higuchi, M. Indo, K. Hiratani, Z. Zhang and R. A. Bartsch, *Anal. Chem.*, 1999, **71**, 791.

13 N. Iki, H. Kumagai, N. Morohashi, K. Ejima, M. Hasegawa, S. Miyanari and S. Miyano, *Tetrahedron Lett.*, 1998, **39**, 7559.

14 F. Hamada, T. Fukugaki, K. Murai, G. W. Orr and J. L. Attwood, *J. Incl. Phenom. Molec. Recog. Chem.*, 1991, **10**, 57.

15 A. Gupta and S. M. Khopkar, *Value Adding Through Solvent Extraction* (Proceedings of ISEC'96), eds. D. C. Shallcross, R. Paimin and L. M. Prvcic, The University of Melbourne, Australia, 1996, pp. 1609.

16 K. Ohto, Y. Tanaka and K. Inoue, *Chem. Lett.*, 1997, 647.

17 K. Ohto, E. Murakami, K. Shiratsuchi, K. Inoue and M. Iwasaki, *Chem. Lett.*, 1996, 173; K. Ohto, E. Murakami, T. Shinohara, K. Shiratsuchi, K. Inoue and M. Iwasaki, *Anal. Chim. Acta*, 1997, **341**, 275.

18 K. Ohto, H. Yamaga, E. Murakami and K. Inoue, *Talanta*, 1997, **44**, 1123.

19 R. Ungaro, A. Pochini and G. D. Andreetti, *J. Incl. Phenom.*, 1984, **2**, 199.

20 E. M. Collins, M. A. McKervey, E. Madigan, M. B. Moran, M. Owens, G. Ferguson and S. J. Harris, *J. Chem. Soc., Perkin Trans. 1*, 1991, 3137.

21 V. Böhmer, A. Wolff and W. Vogt, *J. Chem. Soc., Chem. Commun.*, 1990, 968.

22 P. J. Dijkstra, J. A. J. Brunink, K. E. Bugge, D. N. Reinhoudt, S. Harkema, R. Ungaro, F. Ugozzoli and E. Ghidini, *J. Am. Chem. Soc.*, 1989, **111**, 7567.

23 J. W. Cornforth, P. D'Arcy Hart, G. A. Nicholls, R. J. W. Rees and J. A. Stock, *Br. J. Pharmacol.*, 1955, **10**, 73.

24 K. Ohto, M. Yano, K. Inoue, T. Yamamoto, M. Goto, F. Nakashio, S. Shinkai and T. Nagasaki, *Anal. Sci.*, 1995, **11**, 893.

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