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Separation of lanthanides and actinides using magnetic silica particles bearing covalently attached tetra-CMPO-calix[4]arenes

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Calix[4]arene tetraethers in the cone conformation bearing four –NH–CO–CH_2–P(O)Ph_2 (= CMPO) residues on their wide rim and one, two or four ω-amino alkyl residues of various lengths at the narrow rim were synthesized. Reaction with dichlorotriazinyl (DCT) functionalized magnetic particles led to complete coverage of the available surface by covalently linked CMPO-calix[4]arenes in all cases. Magnetically assisted removal of Eu(III) and Am(III) from acidic solutions was distinctly more efficient with these particles in comparison to analogous particles bearing the same amount of analogous single-chain CMPO-functions. The best result, an increase of the extraction efficiency by a factor of 140–160, was obtained for attachment *via* two propyl spacers. The selectivity Am/Eu was in the range of 1.9–2.8. No decrease of the extraction ability was observed, when the particles were repeatedly used, after simple back extraction with water.

Introduction

The recovery of actinides from liquid nuclear wastes, generated as a result of the nuclear fuel cycle, and the development and production of nuclear weapons, is an area of world-wide concern. Current approaches are based on the TRUEX process which utilises the highly efficient, neutral, organophosphorus ligand octyl phenyl *N*,*N*-diisobutyl carbamoylmethyl phosphine oxide (CMPO).[1] Previously, we have reported calix[4]arene based extractants bearing four CMPO groups at the wide[2,3] or narrow rim.[4] Such pre-organisation of the chelating functions leads to a drastic increase[2] of the extraction efficiency (>100 fold) combined with an enhanced selectivity for actinides and lighter lanthanides.[5–7]

Solvent extraction methods using either simple extractants or highly efficient systems such as calix[4]arene based ligands, need very sophisticated facilities to be implemented for the recovery of actinides from high activity wastes. However, reprocessing operations or, more generally, nuclear facilities generate medium activity wastes bearing actinides for which solvent extraction is not adapted because it is too complex in its implementation. Recently interest has focused on the use of magnetic fluidised bed separation technology and the development of magnetically assisted chemical separation (MACS) systems for nuclear waste remediation.[8] These techniques avoid the use of large volumes of organic solvent, but combine the selectivity of solvent extraction with improved phase separation in the magnetic field, resulting in a system providing only a small volume of high level waste. The magnetic particles can be directly vitrified or stripped, to enable their re-use in an automated process. Particles coated with a solution of CMPO in tri-n-butylphosphate (TBP) have been prepared by treatment of crosslinked acrylamide particles with CMPO/TBP using hexane or ethanol as volatile diluent.[9–12]

As recently reported our approach is based on the covalent attachment of CMPO derivatives on the surface of functionalised magnetic particles.[13] Such chemically modified particles should show increased long-term stability as the ligands cannot be desorbed or leached. In addition, this covalent attachment takes advantage of the pre-organisation of the CMPO chelating sites on various (macrocyclic) platforms like calix[4]arenes. In the present study we have varied the length and the number of linkers between the calixarene and the particle surface to optimise the extraction capacity of magnetic silica particles coated with tetra-CMPO calix[4]arenes.

Syntheses

4,6-Dichloro-1,3,5-triazin-2-yl (DCT) functionalized magnetic particles[14] were chosen to attach the ligands by reaction with amino groups, as outlined in Scheme 1.

This requires calix[4]arenes **1**–**3**, bearing four CMPO-functions on their wide rim and aminoalkyl groups at the narrow rim. Here we varied the number of these linkers (one, two and four) as well as their length. The synthetic pathway is exemplified in Scheme 2 for the 1,3-derivatives **2a**–**c**.

Starting with the known 1,3-dipropylether of *tert*-butylcalix-[4]arene (**5**) the remaining hydroxyl groups were alkylated with ω-bromoalkyl-phthalimides in DMF at r.t. using NaH as base. Yields of the pure product in the cone conformation (**6a**–**c**)[15] range between 50–65% since the formation of partial cone and 1,3-alternate conformers cannot be entirely avoided. The required ω-bromoalkylphthalimides (commercially available for $n = 3$) were obtained with yields of 70% by alkylation of phthalimide with an excess of the respective α,ω-dibromoalkane ($n = 5$, 10) and chromatographic work up. The following steps, *ipso*-nitration of the tetra-ether derivatives (100% HNO_3, CH_2Cl_2, rt, 90% of **7a**–**c**), reduction of the nitro groups ($SnCl_2$/ethanol, 90% of **8a**–**c**) and acylation of the so-formed amino functions by the active ester (*p*-nitrophenyl(diphenylphosphoryl)acetate, 70–75% of **9a**–**c**) were done in close analogy to similar examples.[2,3] Cleavage of the phthalimide groups by hydrazine in refluxing ethanol finally led with yields of 85–95% to the wide rim tetra-CMPOs **2a**–**c**, functionalized by two aminoalkyl groups at their narrow rim.

Tetra-CMPO calixarenes bearing one aminopentyl group (**1**) or four aminopropyl groups (**3**) at the narrow rim were synthesised analogously in three steps from the tetra-ethers **14** and **17**, respectively. **17** was directly obtained by *O*-alkylation of *tert*-butylcalix[4]arene (70%), while **10** should be available in two steps from *tert*-butylcalix[4]arene either *via* the *syn*-tripropylether or *via* the monoether formed with *N*-bromopentylphthalimide. However, having the monopropylether at hand a mixed 1,3-di-ether was prepared with *N*-bromopentylphthalimide (40%) which finally was exhaustively *O*-alkylated with propylbromide to yield **14** (51%).

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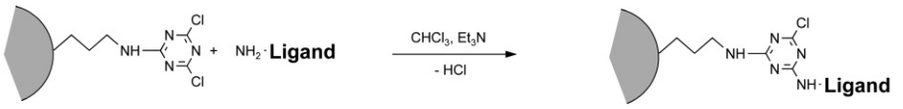
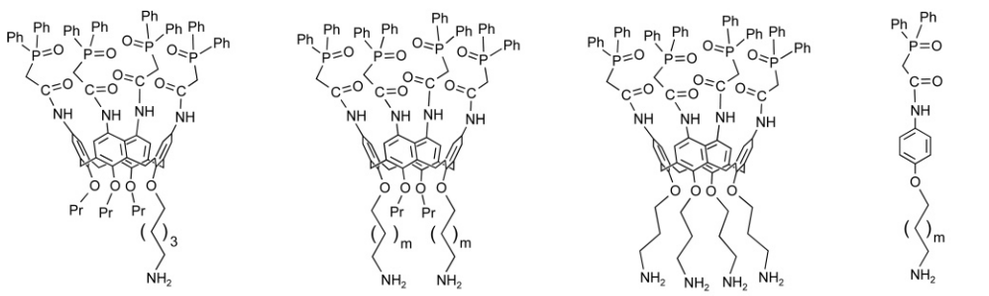
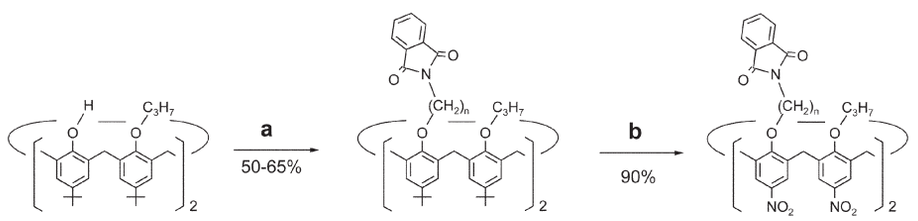




1 **2a** m = 1 **2b** m = 3 **2c** m = 8 **3** **4a** m = 1 **4b** m = 3

Scheme 1



5 **6a** n = 3 **6b** n = 5 **6c** n = 10 **7a** n = 3 **7b** n = 5 **7c** n = 10

2a n = 3 **2b** n = 5 **2c** n = 10 **9a** n = 3 **9b** n = 5 **9c** n = 10 **8a** n = 3 **8b** n = 5 **8c** n = 10

a) Bromoalkyl-phthalimide / NaH / DMF b) HNO_3 (100%)/CH_2Cl_2 c) $SnCl_2$ / Ethanol

d) Active Ester / $CHCl_3$ e) NH_2-NH_2 / Ethanol

Scheme 2

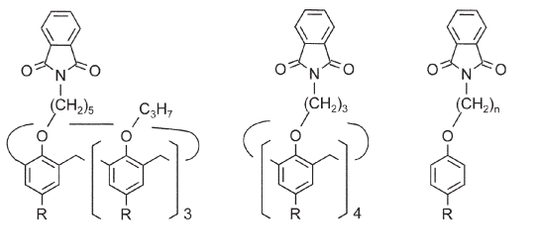
Model compounds **4a**,**b**, consisting of a single CMPO-substituted aromatic unit were prepared in four steps from *p*-nitrophenol by *O*-alkylation with the respective bromoalkylphthalimide (85% of **18a**,**b**), reduction of the nitro groups to **19a**,**b**, *N*-acylation with the active ester (70–75% of **20a**,**b**) and finally, cleavage of the phthalimide by hydrazine (80–85% of **4a**,**b**).

Magnetic silica particles were prepared by encapsulation of iron oxide into highly porous silica particles followed by introduction of amino groups on the particle surface. These primary aliphatic amino groups were derivatised with cyanurchloride to provide DCT groups on the particle surface. For the attachment of aminofunctionalised calix[4]arenes **1**–**3** and model compounds **4** according to Scheme 1

Table 1 Extraction of europium and americium by magnetic particles with covalently bound ligands **1–4**

Compound	Number of linkers	Spacer length $n = m + 2$	K_D(Eu)/ml g^{-1}	K_D(Am)/ml g^{-1}	K_D(Am)/K_D(Eu)
1	$z = 1$	$n = 5$	121	226	1.87
2a	$z = 2$	$n = 3$	253	549	2.17
2b	$z = 2$	$n = 5$	130	310	2.38
2c	$z = 2$	$n = 10$	58	132	2.28
3	$z = 4$	$n = 3$	69	193	2.80
4a	$z = 1$	$n = 3$	1.6	3.8	2.38
4b	$z = 1$	$n = 5$	16	26	1.63

Extraction conditions: 3 M HNO_3 + ^{152}Eu + ^{241}Am; volume of aqueous phase: 10 ml; mass of particles: 300 mg; stirring time: 1 h; $T = 25$ °C.



R = $C(CH_3)_3$	**10**	**14**	
R = NO_2	**11**	**15**	**18**
R = NH_2	**12**	**16**	**19**
R = NH–C(=O)–P(=O)(Ph)–Ph	**13**	**17**	**20**

these DCT functionalised magnetic silica particles were suspended in chloroform and shaken at room temperature in the presence of a stoichiometric quantity of triethylamine to neutralize/capture the hydrogen chloride. The amount of CMPO-calixarene bound to the surface in this step was determined by monitoring its disappearance from the liquid phase by UV-spectrometry. Thus, it was found, that for all calix[4]arenes (25 ± 3) μmol g^{-1} were bound to the magnetic particles. This result is surprising since obviously there is no measurable influence either of the number of linkers (one, two or four in compounds **1**–**3**) or of the length of the spacer (3, 5 and 10 C-atoms in **2a**–**c**). The available surface of the particles, determined by the BET-method,[16] is 3.3×10^{19} nm^2 g^{-1}. This leads to an average area of 2.2 nm^2 per calix[4]arene molecule which corresponds more or less exactly to the area estimated by molecular modelling. Therefore we can conclude that the surface is completely covered by densely packed calix[4]arenes which correlates with the observation that the number and the length of the linkers have no influence on the amount of calix[4]arene attached to the surface. Similarly it could be shown that 110 ± 5 μmol g^{-1} of the model compounds **4a**,**b** were bound to the particle surface, in agreement with the fact that four single phenolic units can be slightly closer packed than in a calix[4]arene in the cone-conformation.

Extraction

For liquid/liquid extractions the distribution coefficient K_D is defined as

$$K_D = \frac{n_1/V_1}{n_2/V_2} = \frac{c_1}{c_2}$$

For solid/liquid extractions the extracted amount of substance must be related to the mass of the solid phase.

$$K_D = \frac{n_S/m_S}{n_L/V_L} = \frac{n_S/m_S}{c_L}$$

Since the extracted amount is usually determined by its decrease in the liquid phase

$$n_S = (c_{L,0} - c_L) \cdot V_L$$

this leads to

$$K_D = \frac{(c_{L,0} - c_L)}{c_L} \bullet \frac{V_L}{m_S}$$

Due to saturation phenomena, these K_D values are usually not constant and thus only values obtained under identical conditions (concentration in the liquid phase, amount of solid phase) should be compared. Therefore the distribution coefficients K_D for Eu and Am extraction with magnetic particles coated by **1**–**4** were determined under constant conditions, shaking 300 mg magnetic particles (m_S) with 10 ml (V_L) Eu and Am containing test solution of known activity ($c_{L,0}$) for one hour at room temperature. After magnetic separation of the particles the final radionuclide activity (c_L) was measured in the supernatant.

The results of the extraction experiments are summarized in Table 1. Since the amount of calixarene fixed to the surface is identical for all the calix[4]arene based particles **1**–**3**, and the amount of CMPO-functions is even slightly larger for particles with **4**, these K_D values can be directly compared. The following trends/effects can be observed:

a) The extraction is much more efficient with particles coated by calix[4]arene derivatives than for particles coated by the model compounds **4**. With a factor of >100 this is most pronounced for **2a** in comparison to **4a** (both with $n = 3$). Thus, it is clearly advantageous to pre-organize the CMPO-functions on a common platform (not necessarily a calix[4]arene), and to attach this pre-organised assembly to the particle surface.

b) The length of the spacer is obviously most crucial for the "monomeric" CMPOs **4** where K_D increases by a factor of ~10 in going from $n = 3$ to $n = 5$. This can be understood, assuming that a certain "mobility" of the CMPO-functions on the surface is necessary to allow the co-operative interaction of three bidentate ligating groups with a Eu^{3+} or Am^{3+} cation.[17] On the other hand, in the series **2a**–**c** a steady decrease of K_D is observed if the length of the two spacers increases from 3 over 5 to 10. However, this decrease occurs on a much higher extraction level, since four CMPO-functions are already pre-organized at the calix[4]arene platform. These four CMPO-functions do not necessarily complex a single cation. NMR relaxation time (T_1) studies of Gd^{3+} complexes of wide rim tetra-CMPOs suggest the formation of polymeric species under anhydrous conditions, in contrast to narrow rim tetra-CMPOs,[18] and oligomeric species might be involved also in liquid/liquid extraction. Thus, a comparison of particles coated with **2** or **4** concerns various factors and a tentative explanation for the opposite effect caused by changes in the spacer length would be merely speculative at the moment.

c) An indication of the optimum number of linkers (with the same length) can be obtained by comparison of **1** with **2b** and **2a** with **3**, respectively. The first pair suggests that there is not much difference between a one and a two point attachment, while the second pair indicates a stronger decrease of K_D for a four point attachment. This could be understood to be due to an unfavourable distortion of the calix[4]arene conformation when fixed to the surface *via* four linkers.

d) Some selectivity for Am over Eu is observed in all cases and is unaffected by alterations in spacer length or the number of points of attachment. Interestingly the values observed of between 1.6 and 2.8 are distinctly lower than those observed for wide rim tetra-CMPOs in liquid/liquid extractions.[5]

Although this was not the main goal of the present study, the potential re-use of beads was shown in a series of five successive extraction (Eu, 3 M HNO_3)/stripping cycles with magnetic particles bearing **2a**. Generally more than 90% of Eu activity was recovered by stripping twice with demineralised water. After five cycles the extraction capacity decreased by 10–15%, a value which is still within the limits of error of these small scale experiments.

Conclusion

A complete coating of the available surface of magnetic silica particles by covalently linked CMPO-derivatives is easily possible by aminolysis of 4,6-dichloro-1,3,5-triazin-2-yl groups. The CMPO-coated beads may be used in magnetically assisted extraction of lanthanides and actinides. Pre-organization of four CMPO-groups at the wide rim of calix[4]arenes leads to much better extraction results than the direct covalent attachment of the same amount of analogous single CMPO-functions. The present results suggest that the binding of wide rim tetra-CMPO calix[4]arenes *via* two short spacers of three carbon atoms gives the best results in terms of extraction efficiency.

Experimental

Starting materials

p-tert-Butylcalix[4]arene and its mono-[3] and dipropylether[19] were prepared in analogy to the literature. The synthesis of tetraether **14**[4] and of *p*-nitrophenyl(diphenylphosphoryl)acetate[2,20] has been described earlier. Compounds **8a**, **9a**, and **2a** were described in the electronic supplementary information of ref. 13 but are listed here for completeness.

4,6-Dichloro-1,3,5-triazin-2-yl functionalized magnetic silica particles (micromod, product-code: 58-39-105) were used for the covalent attachment of CMPO-derivatives.

Synthesis of calixarenes and model compounds

***N*-(5-Bromopentyl)phthalimide.** 1,5-Dibromopentane (20 ml, 0.140 mol), phthalimide (4.29 g, 0.028 mol) and K_2CO_3 (8.57 g, 0.059 mol) were added to DMF (70 ml) and stirred for 3 days under argon. The mixture was filtered and the solvent and excess reagent were removed under vacuum. The resulting brown oil was purified by column chromatography (CH_2Cl_2/hexane 4 : 1) to afford a white solid. Yield: 6.27 g, 73%; mp 85–87 °C; ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.83 (m, 2H, Phth), 7.79 (m, 2H, Phth), 3.66 (t, J = 7.1, 2H, NCH_2), 3.33 (t, J = 6.8, 2H, CH_2Br), 1.84 (m, 2H, NCH$_2$CH_2), 1.69 (m, 2H, CH_2CH$_2$Br), 1.41 (m, 2H, CH_2CH$_2$CH$_2$Br).

***N*-(10-Bromodecyl)phthalimide.** 1,10-Dibromodecane (40 g, 0.133 mol), phthalimide (6.18 g, 0.042 mol) and K_2CO_3 (9.6 g, 0.069 mol) were dissolved in DMF (280 ml) and stirred at room temperature for 5 days. The precipitate was filtered off and the solvent was removed under vacuum. The product was purified by column chromatography (hexane followed by CH_2Cl_2) and obtained as white crystals. Yield: 10.7 g, 70%; mp 63–65 °C; ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.85–7.80 (m, 2H, Phth), 7.70–7.66 (m, 2H, Phth), 3.66 (t, J = 7.0 Hz, 2H, CH_2N), 3.38 (t, J = 7.0 Hz, 2H, BrCH_2), 1.89–1.75 (m, 2H, CH_2), 1.73–1.60 (m, 2H, CH_2), 1.26 (br s, 12H, CH_2).

25,27-Diphthalimidopropoxy-*p-tert*-butylcalix[4]arene-26,28-diol. *p-tert*-Butylcalix[4]arene (10 g, 15.4 mmol) and K_2CO_3 (2.34 g, 17 mmol) were heated at reflux for 1 h in acetonitrile (380 ml). *N*-(3-Bromopropyl)phthalimide (9.1 g, 33.9 mmol) was then added and the mixture heated at reflux for a further 48 h. The solvent was then evaporated *in vacuo* and the residue re-dissolved in chloroform. The solution was washed twice with water and brine and then dried. Evaporation of the solvent followed by precipitation from chloroform/methanol gave the desired compound as a white solid. Yield: 10.1 g, 68%; mp 251–253 °C; ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.72 (m, 4H, Phth), 7.56 (m, 4H, Phth), 7.45 (s, 2H, O*H*), 7.03 (s, 4H Ar*H*), 6.78 (s, 4H Ar*H*), 4.30 (d, 4H, J = 13.2 Hz ArCH_2Ar), 4.09 (m, 8H, CH_2N + OCH_2), 3.31 (d, 4H, J = 13.2 Hz, ArCH_2Ar), 2.43 (quin, 4H, J = 7.3 Hz, CH_2CH$_2$N), 1.27 (s, 18H, *t*-Bu), 0.93 (s, 18H, *t*-Bu); FD-MS m/z = 1022.7 (M$^+$, 100%, calc 1022.5).

25,27-Diphthalimidopropoxy-26,28-dipropoxy-*p-tert*-butylcalix[4]arene 6a. A solution of 25,27-diphthalimidopropoxy-*p-tert*-butylcalix[4]arene-26,28-diol (4.00 g, 3.92 mmol) in DMF (60 ml) was flushed with argon, then NaH (300 mg, 11.87 mmol) was added and the mixture stirred for 30 min. Propylbromide (1.07 ml, 11.76 mmol) was added and the stirring continued for 2 days. The reaction was quenched with water (30 ml), the resulting precipitate collected by filtration, dissolved in chloroform and washed with water, 15% HCl and brine. The solution was dried and the solvent evaporated to give a yellow oil. Column chromatography (chloroform) finally gave a white solid. Yield: 3.55 g, 82%; mp 243–245 °C (Lit.[1] 241–243 °C); ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.81 (m, 4H, Phth), 7.69 (m, 4H, Phth), 6.92 (s, 4H, Ar*H*), 6.54 (s, 4H Ar*H*), 4.34 (d, 4H, J = 12.2 Hz ArCH_2Ar), 4.05 (t, 4H, J = 7.8 Hz, OCH_2), 3.89 (t, 4H, J = 7.3 Hz, CH_2N), 3.67 (t, 4H, J = 7.3 Hz, OCH_2CH$_2$CH$_3$), 3.08 (d, 4H, J = 12.7 Hz, ArCH_2Ar), 2.50 (quin, 4H, J = 7.8 Hz, CH_2CH$_2$N), 1.86 (sext, 4H, J = 7.3 Hz, CH_2CH$_3$), 1.19 (s, 18H, *t*-Bu), 0.89 (m, 24H, *t*-Bu + CH$_2$CH_3); FD-MS m/z = 1108.2 (MH$^+$, 100%, calc 1107.6).

25,27-Diphthalimidopentoxy-26,28-dipropoxy-*p-tert*-butylcalix[4]arene 6b. A suspension of the dipropylether **5** (1.8 g, 2.45 mmol) in DMF (60 ml) was stirred at room temperature for 1 h with NaH (0.143 g, 5.96 mmol). *N*-(5-Bromopentyl)phthalimide (1.75 g, 5.91 mmol) was added and the mixture was stirred for 1.5 d at room temperature. The solvent was removed under reduced pressure, and the residue taken up with CH_2Cl_2 (60 ml). After washing with saturated NaCl solution (2 × 70 ml), the organic phase was dried over $MgSO_4$, filtered and evaporated. The residue was triturated with methanol to yield **6b** as a white solid. Yield: 1.8 g, 64%; mp 190–192 °C; ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.79 (m, 4H, Phth), 7.69 (m, 4H, Phth), 6.80 (s, 4H, Ar*H*), 6.59 (s, 4H, Ar*H*), 4.37 (d, 4H, ArCH_2Ar), 3.74 (m, 12H, OCH_2 + NCH_2), 3.10 (d, 4H, ArCH_2Ar), 2.02 (m, 8H, CH_2), 1.76 (m, 4H, CH_2), 1.45 (m, 4H, CH_2), 1.10 (s, 18H, *t*-Bu), 1.00 (s, 18H, *t*-Bu), 0.95 (t, 6H, CH_3).

25,27-Diphthalimidodecyloxy-26,28-dipropoxy-*p-tert*-butylcalix[4]arene 6c. Prepared as described for **6b** and isolated as an oil. Yield: 50%; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.78 (m, 4H, Phth), 7.66 (m, 4H, Phth), 6.77 (s, 4H, Ar*H*), 6.70 (s, 4H, Ar*H*), 4.38 (d, 4H, ArCH_2Ar), 3.78 (t, 8H, OCH_2), 3.64 (t, 4H, NCH_2), 3.08 (d, 4H, ArCH_2Ar), 1.98 (m, 8H, CH_2), 1.64 (m, 4H, CH_2), 1.29 (m, 24H, CH_2), 1.06 (s, 18H, *t*-Bu), 1.01 (s, 18H, *t*-Bu), 0.94 (t, 6H, CH_3).

5,11,17,23-Tetranitro-25,27-diphthalimidopropoxy-26,28-dipropoxycalix[4]arene 7a. Trifluoroacetic acid (2.4 ml, 31 mM) was added to a solution of **6a** (3.0 g, 2.71 mmol) in dichloromethane (60 ml). Fuming nitric acid (2.3 ml, 5.5 mmol) was then added to the solution. After 30 min the solution was poured onto ice and diluted with 50 ml of dichloromethane. The organic layer was separated, washed with water (4 times) and brine (3 times), dried and the solvent was evaporated. Precipitation from dichloromethane/methanol gave a yellow solid which was purified by column chromatography (chloroform/methanol 30 : 1) to give the desired **7a**. Yield: 1.63 g, 65%; mp 163–167 °C (Lit.[1] 169–171 °C); ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.82 (m, 4H, Phth), 7.72 (m, 4H, Phth), 7.59 (s, 4H, Ar*H*), 7.48 (s, 4H Ar*H*), 4.50 (d, 4H, J = 14.2 Hz ArCH_2Ar), 4.11 (t, 4H, J = 7.1 Hz, OCH_2), 3.93 (t, 4H, J = 7.3 Hz, CH_2N), 3.83 (t, 4H, J = 7.1 Hz, OCH_2CH$_2$CH$_3$), 3.38 (d, 4H, J = 13.6 Hz, ArCH_2Ar),

2.50 (quin, 4H, J = 7.1 Hz, CH_2CH_2N), 1.86 (sext, 4H, J = 7.3 Hz, CH_2CH_3), 0.94 (t, 6H, J = 7.3 Hz, CH_2CH_3); FD-MS m/z = 1062.7 (M^+, 100%, calc 1062.3).

5,11,17,23-Tetranitro-25,27-diphthalimidopentoxy-26,28-dipropoxycalix[4]arene 7b. Tetraether **6b** (1.5 g, 1.29 mmol) was dissolved in dry CH_2Cl_2 (60 ml) at room temperature and mixed with 13 ml glacial acetic acid. Nitric acid (100%, 4 ml) was added dropwise with stirring. After 3.5 h, when the colour of the solution had changed from black-violet to orange-yellow, water was added and stirring continued for 1 h. The organic phase was separated, neutralized with sodium carbonate solution, washed with brine, dried ($MgSO_4$) and evaporated. The residue was dissolved in the smallest amount of $CHCl_3$, methanol was added, and the crude product precipitated as a nearly white powder. Yield: 1.28 g, 89%; mp 162–165 °C; ^{1}H NMR (200 MHz, $CDCl_3$): 7.79 (m, 4H, Phth), 7.72 (m, 4H, Phth), 7.65 (s, 4H, Ar*H*), 7.40 (s, 4H, Ar*H*), 4.49 (d, 4H, ArCH_2Ar), 3.93 (t, 8H, OCH_2), 3.69 (t, 4H, NCH_2), 3.38 (d, 4H, ArCH_2Ar), 1.88 (m, 8H, CH_2), 1.74 (m, 4H, CH_2), 1.44 (m, 4H, CH_2), 0.97 (t, 6H, CH_3).

5,11,17,23-Tetranitro-25,27-diphthalimidodecyloxy-26,28-dipropoxycalix[4]arene 7c. Prepared as described for **7b**. Yield: 87%; mp 169–170 °C; ^{1}H NMR (400 MHz, $CDCl_3$): 7.78 (m, 4H, Phth), 7.68 (m, 4H, Phth), 7.57 (s, 4H, Ar*H*), 7.51 (s, 4H, Ar*H*), 4.49 (d, 4H, ArCH_2Ar), 3.93 (m, 8H, OCH_2), 3.63 (t, 4H, NCH_2), 3.38 (d, 4H, ArCH_2Ar), 1.88 (m, 12H, CH_2), 1.63 (m, 4H, CH_2), 1.29 (m, 24H, CH_2), 0.97 (t, 6H, CH_3).

5,11,17,23-Tetraamino-25,27-diphthalimidopropoxy-26,28-dipropoxycalix[4]arene 8a. $SnCl_2{\cdot}H_2O$ (6.6 g) was added to a suspension of **7a** (1.5 g, 1.41 mmol) in ethanol (40 ml) and heated at reflux for 18 h. The mixture was poured onto ice water, diluted with dichloromethane (300 ml) and stirred for 1 h. 1 M NaOH (300 ml) was then added and stirring continued for 1 h. The organic layer was separated and washed with water and brine. After drying the solvent was evaporated to give the amine as a pale brown foam. Yield: 1.19 g, 89%; ^{1}H NMR (200 MHz, DMSO) δ 7.80 (m, 8H, Phth), 6.12 (s, 4H, Ar*H*), 5.73 (s, 4H Ar*H*), 4.3 (b, 4H, NH_2), 4.10 (d, 4H, J = 12.7 Hz ArCH_2Ar), 3.83 (t, 4H, J = 7.8 Hz, OCH_2); 3.64 (t, 4H, J = 6.8 Hz, CH_2N), 3.45 (t, 4H, J = 7.3 Hz, OCH_2CH$_2$CH$_3$), 2.75 (d, 4H, J = 12.7 Hz, ArCH_2Ar), 2.28 (m, 4H, J = 7.1 Hz, CH_2CH$_2$N), 1.66 (m, 4H, J = 7.3 Hz, CH_2CH$_3$), 0.79 (t, 6H, J = 7.3 Hz, CH$_2$CH_3); FD-MS m/z = 942.8 (M^+, 100%, calc 942.4).

5,11,17,23-Tetraamino-25,27-diphthalimidopropoxy-26,28-dipentoxycalix[4]arene 8b. Calixarene **7b** (0.95 g, 0.85 mmol) was heated under reflux with $SnCl_2{\cdot}H_2O$ (3.2 g, 4.5 mol per mol NO_2) in ethanol/dioxane (1 : 1; 40 ml) for 10 h. NaOH (10%) was then added and the stirring continued for additional 1 h. The aqueous solution was extracted with CH_2Cl_2 (2 × 70 ml) and the organic phase was washed with brine and water, dried ($MgSO_4$) and evaporated. Precipitation from $CHCl_3$/hexane gave **8b** as a pale yellow powder. Yield: 0.76 g, 90%; mp 155–156 °C; ^{1}H NMR (200 MHz, $CDCl_3$): 7.79 (m, 4H, Phth), 7.66 (m, 4H, Phth), 6.07 (s, 4H, Ar*H*), 5.95 (s, 4H, Ar*H*), 4.27 (d, 4H, ArCH_2Ar), 3.68 (t, 8H, OCH_2), 3.17 (t, 4H, NCH_2), 2.90 (d, 4H, ArCH_2Ar), 1.84 (m, 8H, CH_2), 1.44 (m, 8H, CH_2), 0.97 (t, 6H, CH_3).

5,11,17,23-Tetraamino-25,27-diphthalimidopropoxy-26,28-didecyloxycalix[4]arene 8c. Prepared as described for **8b**. Yield: 87%; 154–157 °C; ^{1}H NMR (400 MHz, $CDCl_3$): 7.78 (m, 4H, Phth), 7.67 (m, 4H, Phth), 6.06 (s, 4H, Ar*H*), 5.96 (s, 4H, Ar*H*), 4.28 (d, 4H, ArCH_2Ar), 3.67 (m, 12H, NCH_2 + OCH_2), 3.10 (b, 8H, NH_2), 2.88 (d, 4H, ArCH_2Ar), 1.81 (m, 12H, CH_2), 1.63 (m, 4H, CH_2), 1.5 (m, 24H, CH_2), 0.88 (t, 6H, CH_3).

5,11,17,23-Tetra-CMPO-25,27-diphthalimidopropoxy-26,28-dipropoxycalix[4]arene 9a. *p*-Nitrophenyl(diphenylphosphoryl)-acetate (2.54 g, 6.66 mmol) was added to a solution of tetraamine **8a** (1.05 g, 1.11 mmol) in toluene (30 ml). The mixture was heated to 50 °C for 18 h. The solvent was then evaporated and the residue re-dissolved in dichloromethane. The solution was washed repeatedly with 10% NaOH, dried and the solvent evaporated. Column chromatography (chloroform/methanol 30 : 1) followed by precipitation from dichloromethane/diethylether gave the desired compound as a white solid. Yield: 1.43 g, 68%; mp 179–182 °C; R_f = 0.53 (chloroform/methanol 9 : 1); ^{1}H NMR (200 MHz, DMSO-d$_6$) δ 9.77 (s, 2H, N*H*), 9.34 (s, 2H, N*H*), 7.43–7.84 (m, 48H, Phth + Ph$_2$P), 6.93 (s, 4H, Ar*H*), 6.39 (s, 4H Ar*H*), 4.23 (d, 4H, J = 12.7 Hz ArCH_2Ar), 3.93 (m, 4H, OCH_2), 3.59–3.76 (m, 16H, OCH_2CH$_2$CH$_3$ + CH_2N + POCH_2CO), 3.00 (d, 4H, J = 13.2 Hz, ArCH_2Ar), 2.12 (m, 4H, CH_2CH$_2$N), 1.66 (m, 4H, CH_2CH$_3$), 0.83 (t, 6H, J = 7.0 Hz, CH$_2$CH_3); FD-MS m/z = 1911.9 (MH^+, calc 1911.6).

5,11,17,23-Tetra-CMPO-25,27-diphthalimidopropoxy-26,28-dipentoxycalix[4]arene 9b. *p*-Nitrophenyl(diphenylphosphoryl)-acetate (0.8 g, 2.1 mmol) was stirred with **8b** (0.35 g, 0.35 mmol) in $CHCl_3$ (25 ml) containing 0.2 g of triethylamine for 18 h. Additional $CHCl_3$ (10 ml) was added, the solution was washed repeatedly with 10% aq. NaOH, dried and the solvent evaporated. The residue was further purified by column chromatography ($CHCl_3$/methanol) and precipitation from $CHCl_3$/hexane to give a pale yellow powder. Yield: 1.13 g, 72%; mp 165–167 °C; ^{1}H NMR (400 MHz, DMSO-d$_6$): 9.50 (s, 2H, CONH), 9.41 (s, 2H, CONH), 7.69 (m, 24H, Ph$_2$P + Phth), 7.43 (m, 24H, Ph$_2$P), 6.62 (s, 4H, Ar*H*), 6.53 (s, 4H, Ar*H*), 4.14 (d, 4H, ArCH_2Ar), 3.61 (m, 16H, COCH_2PO + OCH_2), 3.50 (t, 4H, NCH_2), 2.90 (d, 4H, ArCH_2Ar), 1.69 (m, 8H, CH_2), 1.56 (m, 4H, CH_2), 1.31 (m, 4H, CH_2), 0.81 (t, 6H, CH_3).

5,11,17,23-Tetra-CMPO-25,27-diphthalimidopropoxy-26,28-didecyloxycalix[4]arene 9c. Prepared as described for **9b**. Yield: 75%; mp 150–152 °C; ^{1}H NMR (400 MHz, $CDCl_3$): 8.91 (s, 2H, CON*H*), 8.85 (s, 2H, CON*H*), 7.77 (m, 24H, Ph$_2$P + Phth), 7.43 (m, 24H, Ph$_2$P), 6.57 (s, 4H, Ar*H*), 6.48 (s, 4H, Ar*H*), 4.29 (d, 4H, ArCH_2Ar), 3.71 (m, 8H, CH_2), 3.63 (t, 4H, NCH_2), 3.40 (d, 8H, COCH_2PO), 3.01 (d, 4H, ArCH_2Ar), 1.77 (m, 8H, CH_2), 1.63 (m, 4H, CH_2), 1.23 (m, 24H, CH_2), 0.85 (t, 6H, CH_3).

5,11,17,23-Tetra-CMPO-25,27-bis(aminopropoxy)-26,28-dipropoxycalix[4]arene 2a. Hydrazine hydrate (1.48 ml) was added to a suspension of 300 mg (0.16 mmol) of **9a** in ethanol (10 ml). The mixture was heated to reflux for 1 h and the solvent evaporated. The residue was re-dissolved in a mixture of dichloromethane and water. The aqueous layer was then separated and washed four times with dichloromethane. The combined organic layers were then washed with brine and the solvent evaporated to give a light yellow foam. Yield: 254 mg, 96%; mp 207–212 °C (slow decomp.); ^{1}H NMR (200 MHz, DMSO-d$_6$) δ 9.68 (s, 2H, N*H*), 9.47 (s, 2H, N*H*), 7.45–7.82 (m, 40H, Ph$_2$P), 6.80 (s, 4H, Ar*H*), 6.54 (s, 4H Ar*H*), 4.25 (d, 4H, J = 13.2 Hz ArCH_2Ar), 3.62–3.78 (m, 16H, OCH_2CH$_2$CH$_3$ + POCH_2CO + OCH_2CH$_2$NH$_2$), 3.50 (br, 8H, NH_2), 3.01 (d, 4H, J = 13.2 Hz, ArCH_2Ar), 2.72 (t, 4H, J = 6.8 Hz, CH_2N), 1.85 (m, 8H, CH_2CH$_3$ + CH_2CH$_2$N), 0.88 (t, 6H, J = 7.3 Hz, CH$_2$CH_3).

5,11,17,23-Tetra-CMPO-25,27-bis(aminopentyloxy)-26,28-dipropoxycalix[4]arene 2b. Hydrazine hydrate (1.4 ml) was added to a solution of **9b** (0.2 g) in ethanol (15 ml) and the mixture refluxed for 2 h. After evaporation the residue was dissolved in a mixture of CH_2Cl_2 and water. The aqueous layer was extracted three times with CH_2Cl_2, the combined organic layers were then washed with brine, dried with $MgSO_4$ and evaporated to give **2b** as a white solid. Yield: 0.15 g, 89%; mp 187–190 °C; (Found: C, 69.27; H, 6.49; N, 5.02; $C_{100}H_{106}N_6O_{12}P_4{\cdot}H_2O$ requires C, 69.59; H 6.31; N 4.87%). ^{1}H NMR (400 MHz, DMSO-d$_6$): 9.45 (b, 4H, CON*H*), 7.71–7.43 (m, 40H, Ph$_2$P), 6.61 (b, 8H, Ar*H*), 4.21 (d, 4H, ArCH_2Ar), 3.64 (b, 16H, COCH_2PO + OCH_2), 2.97 (d, 4H,

ArCH_2Ar), 2.50 (m, 4H, NCH_2), 1.74 (m, 8H, CH_2), 1.37 (m, 8H, CH_2), 0.89 (t, 6H, CH_3).

5,11,17,23-Tetra-CMPO-25,27-bis(aminodecyloxy)-26,28-dipropoxycalix[4]arene 2c. Obtained as a pale yellow powder as described for **2b**. Yield: 87%; mp 180–182 °C; (Found: C, 71.01; H, 7.21; N, 4.76; $C_{110}H_{126}N_6O_{12}P_4{\cdot}H_2O$ requires C, 70.80; H 6.91; N, 4.50%). ^{1}H NMR (400 MHz, $CDCl_3$): 8.92 (s, 2H, CON*H*), 8.79 (s, 2H, CON*H*), 7.72 (m, 16H, Ph_2P), 7.39 (m, 24H, Ph_2P), 6.64 (s, 4H, Ar*H*), 6.46 (s, 4H, Ar*H*), 4.32 (d, 4H, ArCH_2Ar), 3.76 (m, 4H, OCH_2), 3.65 (b, 4H, NH_2), 3.41 (m, 12H, COCH_2PO + CH_2), 3.02 (d, 4H, ArCH_2Ar), 2.66 (t, 4H, NCH_2), 1.78 (m, 8H, CH_2), 1.42 (m, 4H, CH_2), 1.26 (m, 24H, CH_2), 0.90 (t, 6H, CH_3).

25-Phthalimidopentyloxy-27-propoxy-*p*-*tert*-butylcalix[4]-arene-26,28-diol. A suspension of *tert*-butylcalix[4]arene monopropylether (3.0 g, 4.38 mmol), and K_2CO_3 (0.42 g, 3.04 mmol) in acetonitrile (120 ml) was stirred under reflux for 1 h. 5-Bromopentylphthalimide (1,43 g, 4.83 mmol) was added and the mixture was refluxed for 2.5 days. After cooling it was filtered and evaporated. The oily residue was triturated with methanol and the white solid finally recrystallised from $CHCl_3$/methanol: Yield 1.7 g, 39%; mp 139–142 °C. ^{1}H NMR (400 MHz, $CDCl_3$): 7.76 (s, 2H, O*H*), 7.70 (m, 2H, Phth), 7.60 (m, 2H, Phth), 7.01 (s, 2H, Ar*H*), 6.99 (s, 2H, Ar*H*), 6.83 (s, 4H, Ar*H*), 4.25, 4.15 (2 × d, 4H, ArCH_2Ar), 3.97 (t, 2H, OCH_2), 3.91 (t, 2H, OCH_2), 3.78 (t, 2H, NCH_2), 3.30, 3.20 (2 × d, 4H, ArCH_2Ar), 2.07–2.01 (m, 4H, CH_2), 1.87–1.83 (m, 4H, CH_2), 1.29–1.25 (m, 21H, CH_3 + *t*-Bu), 1.00 (s, 18*H*, *t*-Bu).

25-Phthalimidopentyloxy-26,27,28-tripropoxy-*p*-*tert*-butylcalix[4]arene 10. A suspension of the mixed diether described above (1.7 g, 1.88 mmol) in DMF (60 ml) was stirred at RT for 1 h with NaH (0.122 g, 4.83 mmol). Bromopropane (0.53 g, 4.31 mmol) was then added and the mixture was stirred for 2 d at room temperature. The solvent was removed under reduced pressure, and the residue taken up with CH_2Cl_2 (60 ml). After washing with brine (2 × 40 ml), the organic phase was dried ($MgSO_4$) and evaporated. Trituration with methanol gave **10** as a white solid. Yield: 0.65 g, 51%; mp 160–163 °C; ^{1}H NMR (400 MHz, $CDCl_3$): 7.85 (m, 2H, Phth), 7.72 (m, 2H, Phth), 6.79 (s, 4H, Ar*H*), 6.77 (s, 2H, Ar*H*), 6.76 (s, 2H, Ar*H*), 4.43, 4.37 (2 × d, 4H, ArCH_2Ar), 3.88–3.73 (m, 8H, NCH_2 + OCH_2), 3.13, 3.09 (2 × d, 4H, ArCH_2Ar), 2.08–1.98 (m, 4H, CH_2), 1.87–1.83 (m, 8H, CH_2), 1.84–1.76 (m, 2H, CH_2), 1.53–1.47 (m, 2H, CH_2), 1.10 (s, 27H, *t*-Bu), 1.10 (s, 9H, *t*-Bu), 1.00 (t, 9H, CH_3).

5,11,17,23-Tetranitro-25-phthalimidopentyloxy-26,27,28-tripropoxycalix[4]arene 11. Tetraether **10** (1.0 g) was dissolved in dry CH_2Cl_2 (60 ml) at room temperature and mixed with glacial acetic acid (11 ml). Then 100% nitric acid (3.2 ml) was added dropwise with stirring. After 4 h, when the colour of the solution had changed from black-violet to orange-yellow, water was added and stirring continued for 1 h. The organic phase was separated, neutralized with Na_2CO_3 solution, washed with brine, dried ($MgSO_4$) and evaporated. The residue was dissolved in the smallest amount of $CHCl_3$, methanol was added to precipitate **11** as a nearly white powder. Yield: 0.5 g, 88%; mp 164–167 °C; ^{1}H NMR (400 MHz, $CDCl_3$): 7.84 (m, 2H, Phth), 7.75 (m, 2H, Phth), 7.62 (s, 2H, Ar*H*), 7.61 (s, 2H, Ar*H*), 7.54 (s, 2H, Ar*H*), 7.51 (s, 2H, Ar*H*), 4.54, 4.50 (2 × d, 4H, ArCH_2Ar), 4.00–3.92 (m, 8H, OCH_2), 3.72 (t, 2H, NCH_2), 3.42, 3.39 (2 × d, 4H, ArCH_2Ar), 1.96–1.87 (m, 8H, CH_2), 1.81–1.74 (m, 2H, CH_2), 1.50–1.43 (m, 2H, CH_2), 1.03–0.99 (m, 9H, CH_3).

5,11,17,23-Tetraamino-25-phthalimidopentyloxy-26,27,28-tripropoxycalix[4]arene 12. A solution of **11** (0.5 g) in ethanol/dioxane (1 : 1, 35 ml) was heated under reflux for 10 h with $SnCl_2{\cdot}H_2O$ (1.98 g, 4.5 mole per mole NO_2). NaOH (10%) was then added at room temperature and stirring was continued for 1 h. The aqueous solution was extracted with CH_2Cl_2 (2 × 50 ml) and the organic phase was washed with water and brine, dried ($MgSO_4$) and evaporated. The residue was precipitated from $CHCl_3$/hexane to give **12** as a light yellow powder. Yield: 0.71 g, 81%; mp 155–158 °C; ^{1}H NMR (400 MHz, $CDCl_3$): 7.83 (m, 2H, Phth), 7.72 (m, 2H, Phth), 6.06 (s, 4H, Ar*H*), 6.05 (s, 2H, Ar*H*), 6.03 (s, 2H, Ar*H*), 4.32, 4.29 (2 × d, 4H, ArCH_2Ar), 3.80–3.70 (m, 10H, NCH_2 + OCH_2), 3.14 (br s, 8H, NH_2), 2.93 (d, 4H, ArCH_2Ar), 1.90–1.81 (m, 8H, CH_2), 1.78–1.71 (m, 2H, CH_2), 1.45–1.40 (m, 2H, CH_2), 0.97–0.90 (m, 9H, CH_3).

5,11,17,23-Tetra-CMPO-25-phthalimidopentyloxy-26,27,28-tripropoxycalix[4]arene 13. *p*-Nitrophenyl(diphenylphosphoryl)-acetate (0.90 g) was stirred with **12** (0.30 g) in $CHCl_3$ (25 ml) containing triethylamine (0.1 g) for 18 h. Additional $CHCl_3$ (10 ml) was added, the solution was washed repeatedly with 10% aq. NaOH, dried ($MgSO_4$) and evaporated. The pale yellow residue was purified by column chromatography ($CHCl_3$/methanol) and precipitation from chloroform/hexane to give a white powder. Yield: 0.54 g, 83%; mp 185–187 °C; ^{1}H NMR (400 MHz, $CDCl_3$): 8.95 (s, 4H, CON*H*), 7.81 (m, 2H, Phth), 7.74–7.68 (m, 16H, Ph_2P), 7.55–7.41 (m, 26H, Phth + Ph_2P), 6.58 (s, 2H, Ar*H*), 6.55 (s, 6H, Ar*H*), 4.32, 4.29 (2 × d, 4H, ArCH_2Ar), 3.81–3.68 (m, 10H, NCH_2 + OCH_2), 3.45 (d, 8H, COCH_2PO), 3.50 (t, 4H, NCH_2), 3.05, 3.02 (2 × d, 4H, ArCH_2Ar), 1.86–1.78 (m, 8H, CH_2), 1.75–1.71(m, 2H, CH_2), 1.42–1.38 (m, 2H, CH_2), 0.94–0.87 (m, 9H, CH_3).

5,11,17,23-Tetra-CMPO-25-aminopentyloxy-26,27,28-tripropoxycalix[4]arene 1. Hydrazine hydrate (1.4 ml) was heated under reflux with **13** (0.3 g) in ethanol (15 ml) for 2 h. After evaporation the residue was dissolved in a mixture of CH_2Cl_2 and water. The aqueous layer was washed three times with CH_2Cl_2, the organic layers were combined, washed with brine, dried ($MgSO_4$) and evaporated to give **1** as a white solid. Yield: 0.25 g, 91%; mp 180–183 °C; (Found: C, 67.66; H, 6.14; N, 4.51; $C_{98}H_{101}N_5O_{12}P_4{\cdot}4H_2O$ requires C, 67.77; H, 6.33; N, 4.16%). ^{1}H NMR (400 MHz, $CDCl_3$, 55 °C): 8.87 (s, 4H, CON*H*), 7.79–7.72 (m, 16H, Ph_2P), 7.54–7.42 (m, 24H, Ph_2P), 6.61 (s, 2H, Ar*H*), 6.58 (s, 6H, Ar*H*), 4.36, 4.33 (2 × d, 4H, ArCH_2Ar), 3.85–3.77 (m, 8H, OCH_2), 3.45 (d, 8H, COCH_2PO), 3.07 (2 × d, 4H, ArCH_2Ar), 2.72 (m, 2H, NCH_2), 1.91–1.80 (m, 8H, CH_2), 1.53–1.49 (m, 2H, CH_2), 1.42–1.38 (m, 2H, CH_2), 0.97–0.93 (m, 9H, CH_3).

5,11,17,23-Tetranitro-25,26,27,28-tetraphthalimidopropoxycalix[4]arene 15. Tetraether **14** (1.6 g) was dissolved in dry CH_2Cl_2 (60 ml) at room temperature and mixed with 14 ml glacial acetic acid. Then 100% nitric acid (4.0 ml) was added dropwise with stirring. After 4 h, when the colour of the solution had changed from black-violet to orange-yellow, water was added and stirring continued for 1 h. The organic phase was separated, neutralized with sodium carbonate solution, washed with brine, dried ($MgSO_4$), and evaporated. The residue was dissolved in the smallest amount of $CHCl_3$, methanol was added to precipitate **15** as a nearly white powder. Yield: 0.51 g, 53%; mp > 330 °C; ^{1}H NMR (400 MHz, $CDCl_3$): 7.72 (m, 8H, Phth), 7.64 (m, 8H, Phth), 7.54 (s, 8H, Ar*H*), 4.62 (d, 4H, ArCH_2Ar), 4.18 (t, 8H, OCH_2), 3.92 (t, 8H, NCH_2), 3.45 (d, 4H, ArCH_2Ar), 2.36–2.31 (m, 8H, CH_2); FD-MS *m*/*z* = 1354.2 (MH^+, 100%, calc 1353.4).

5,11,17,23-Tetraamino-25,26,27,28-tetraphthalimidopropoxycalix[4]arene 16. A solution of **15** (0.50 g) in ethanol/dioxane (1 : 1, 20 ml) was heated under reflux with $SnCl_2{\cdot}H_2O$ (1.38 g) for 8 h. NaOH (10%) was added and the stirring continued for 1 h. The aqueous solution was extracted with CH_2Cl_2 (2 × 70 ml) and the organic phase was washed with water and brine, dried ($MgSO_4$) and evaporated. Precipitation from $CHCl_3$/hexane gave **16** as a pale yellow powder. Yield 0.36 g, 80%; mp 166–170 °C. ^{1}H NMR (400 MHz, $CDCl_3$): 7.70 (m, 8H, Phth), 7.59 (m, 8H, Phth), 6.03 (s, 8H, Ar*H*), 4.35 (d, 4H, ArCH_2Ar), 3.93 (t, 8H, OCH_2), 3.87 (t, 8H, NCH_2), 2.97 (d, 4H, ArCH_2Ar), 2.76 (broad s, 8H, NH_2), 2.30–2.23 (m, 8H, CH_2); FD-MS *m*/*z* = 1233.0 (MH^+, 100%, calc 1233.5).

5,11,17,23-Tetra-CMPO-25,26,27,28-tetraphthalimidopropoxycalix[4]arene 17. *p*-Nitrophenyl(diphenylphosphoryl)acetate (0.41 g) was stirred with **16** (0.3 g, 0.24 mmol) in chloroform (25 ml) containing 0.1 g of triethylamine for 18 h. Additional $CHCl_3$ (10 ml) was added, the solution was washed repeatedly with 10% aq. NaOH, dried ($MgSO_4$) and evaporated. After column chromatography ($CHCl_3$/methanol), and precipitation from $CHCl_3$ **17** was obtained as a pale yellow powder. Yield 0.35 g, 66%; mp 189–192 °C; ^{1}H NMR (400 MHz, $CDCl_3$): 8.94 (s, 2H, CON*H*), 7.74–7.71 (m, 16H, Ph_2P), 7.69 (m, 8H, Phth), 7.59 (m, 8H, Phth), 7.53–7.42 (m, 24H, Ph_2P), 6.55 (s, 4H, Ar*H*), 6.53 (s, 4H, Ar*H*), 4.35 (d, 4H, ArCH_2Ar), 3.96 (t, 8H, OCH_2), 3.86 (t, 8H, NCH_2), 3.44 (d, 8H, COCH_2PO), 3.50 (t, 4H, NCH_2), 3.07 (d, 4H, ArCH_2Ar), 2.28–2.25 (m, 8H, CH_2).

5,11,17,23-Tetra-CMPO-25,26,27,28-tetra(aminopropoxy)calix[4]arene 3. Hydrazine hydrate (1.4 ml) was heated under reflux with **17** (0.2 g) in ethanol (15 ml) for 2 h. The residue obtained after evaporation was dissolved in a mixture of CH_2Cl_2 and water. The aqueous layer was extracted three times with CH_2Cl_2, the combined organic layers were washed with brine, dried ($MgSO_4$) and evaporated to give **3** as a white powder. Yield: 84 mg, 55%; mp 145–147 °C; ^{1}H NMR (400 MHz, DMSO-d_6): 9.24 (s, 4H, CON*H*), 7.83–7.73 (m, 16H, Ph_2P), 7.52–7.46 (m, 24H, Ph_2P), 6.70 (s, 8H, Ar*H*), 4.33 (d, 4H, ArCH_2Ar), 3.90 (m, 8H, OCH_2), 3.86 (t, 8H, NCH_2), 3.62 (d, 16H, COCH_2PO), 3.28–2.76 (broad, 20H, ArCH_2Ar + NH_2 + NCH_2), 2.00–1.96 (m, 8H, CH_2).

***N*-3-(*p*-Nitrophenoxy)propylphthalimide 18a.** A solution of *N*-bromopropylphthalimide (9.5 g, 35 mmol) in acetonitrile (100 ml) was added dropwise to a stirred suspension of *p*-nitrophenol (5.0 g, 35 mmol) and K_2CO_3 (9.6 g, 70 mmol) in acetonitrile (100 ml). The resulting mixture was heated at reflux for 24 h. The solvent was evaporated and the residue taken up in CH_2Cl_2/water. The organic layer was washed repeatedly with an aqueous Na_2CO_3 solution, dried ($MgSO_4$) and evaporated. The crude material was purified by column chromatography (ethyl acetate) and precipitated from $CHCl_3$/hexane to give a white solid. Yield 9.76 g, 85%; mp 99–100 °C, ^{1}H NMR (200 MHz, $CDCl_3$) δ 8.21 (2H, d, J = 9.1 Hz, Ar*H*), 7.87–7.65 (4H, m, Phth), 6.87 (2H, d, J = 8.3 Hz, Ar*H*), 4.15 (2H, t, J = 6.6 Hz, ArOCH_2), 3.94 (2H, t, J = 7.2 Hz, NCH_2), 2.25 (3H, t, J = 6.8 Hz, CH_2).

***N*-5-(*p*-Nitrophenoxy)pentylphthalimide 18b.** Prepared as described for **18a**; yield 85%, mp 110–115 °C. ^{1}H NMR (200 MHz, $CDCl_3$) δ 8.17 (2H, d, J = 8.2 Hz, Ar*H*), 7.24–7.14 (4H, m, Phth), 6.91 (2H, d, J = 8.3 Hz, Ar*H*), 4.02 (2H, t, J = 7.2 Hz, ArOCH_2), 1.95–1.75 (2H, m, CH_2), 1.52–1.31 (4H, m, CH_2), 0.93 (3H, t, J = 7.2 Hz, CH_2).

***N*-3-(*p*-Aminophenoxy)propylphthalimide 19a.** A catalytic amount of Pd/C was added to a solution of **18a** (4 g, 12.2 mmol) in toluene. H_2 gas was admitted under normal pressure and the mixture stirred for 48 h. Filtration through a celite® bed and evaporation gave the amine as a colourless oil in nearly quantitative yield.

***N*-5-(*p*-Aminophenoxy)pentylphthalimide 19b.** Prepared analogously from **18b** and both amines were used for the acylation without further characterisation.

***p*-(Diphenylphosphorylacetamino)phenoxypropylphthalimide 20a.** *p*-Nitrophenyl(diphenylphosphoryl)acetate (2.66 g, 7 mmol) and monoamine **19a** (2.0 g, 6.75 mmol) were dissolved in toluene (30 ml) and kept at 50 °C for 24 h. The solvent was evaporated and the residue dissolved in CH_2Cl_2. The solution was washed repeatedly with 10% aqueous Na_2CO_3, dried ($MgSO_4$) and the solvent removed *in vacuo*. Precipitation from CH_2Cl_2/hexane gave a white solid. Yield 2.5 g, 69%; mp 210–211 °C. ^{1}H NMR (200 MHz, $CDCl_3$) δ_H 9.45 (1H, s, ArN*H*), 7.76–7.65 (8H, m, Phth and Ph_2P), 7.51–7.40 (6H, m, Ph_2P), 7.29 (2H, d, J = 8.3 Hz, Ar*H*), 6.63 (2H, d, J = 8.3 Hz, Ar*H*), 3.98–3.81 (4H, CH_2), 3.45 (2H, d, J = 13.5 Hz, PCH_2), 2.11 (3H, t, J = 6.3 Hz, CH_2).

***p*-(Diphenylphosphorylacetamino)phenoxypentylphthalimide 20b.** Prepared as described for **20a** using monoamine **19b**. Yield 75%; mp 256–257 °C; ^{1}H NMR (200 MHz, $CDCl_3$) δ 9.45 (1H, s, ArN*H*), 7.76–7.65 (8H, m, NPht*H* and Ph_2P), 7.51–7.40 (6H, m, Ph_2P), 7.29 (2H, d, J = 8.3 Hz, Ar*H*), 6.63 (2H, d, J = 8.3 Hz, Ar*H*), 3.98–3.81 (4H, m, CH_2), 3.45 (2H, d, J = 13.5 Hz, PCH_2), 2.11 (3H, t, J = 6.3 Hz, CH_2).

***p*-(Diphenylphosphorylacetamino)phenoxypropylamine 4a.** Hydrazine hydrate (5.7 ml) was added to a suspension of **20a** (2.0 g, 3.71 mmol) in ethanol (40 ml). The mixture was heated to reflux upon which the solid dissolves to give a pale yellow solution. After 1 h, the ethanol was partially removed by evaporation and the residue dissolved in a mixture of CH_2Cl_2/water. The aqueous layer was extracted four times with CH_2Cl_2, the combined organic phase was washed with aqueous Na_2CO_3 and brine, dried ($MgSO_4$) and evaporated to afford a white solid powder which was recrystallised from hexane. Yield: 1.3 g, 86%; mp 243–245 °C; (Found: C, 67.83; H, 6.41; N, 6.65; $C_{23}H_{25}N_2O_3P$ requires C, 67.64; H, 6.17; N. 6.86%). ^{1}H NMR (200 MHz, $CDCl_3$) δ 9.56 (1H, s, ArN*H*), 7.77–7.66 (4H, m, Ph_2P), 7.53–7.42 (6H, m, Ph_2P), 7.32 (2H, d, J = 7.8 Hz, Ar*H*), 6.71 (2H, d, J = 8.1 Hz, Ar*H*), 3.93 (2H, t, J = 6.5 Hz, CH_2), 3.47 (2H, d, J = 13.8 Hz, PCH_2), 2.83 (2H, t, J = 7.5 Hz, CH_2), 2.70 (2H, b s, NH_2), 1.83 (3H, t, J = 6.8 Hz, CH_2).

***p*-(Diphenylphosphorylacetamino)phenoxypentylamine 4b.** Prepared from **20b** as described for **4a**. Yield: 78%; mp 140–141 °C; (Found: C, 68.43; H, 6.98; N, 6.28; $C_{25}H_{29}N_2O_3P$ requires C, 68.79; H 6.70; N, 6.42%). ^{1}H NMR (200 MHz, $CDCl_3$) δ 9.50 (1H, s, ArN*H*), 7.78–6.67 (4H, m, Ph_2P), 7.51–7.42 (6H, m, Ph_2P), 7.32 (2H, d, J = 8.1 Hz, Ar*H*), 6.72 (2H, d, J = 8.4 Hz, Ar*H*), 3.86 (2H, t, J = 7.2 Hz, CH_2), 3.46 (2H, d, J = 14.2 Hz, PCH_2), 2.67 (2H, t, J = 6.7 Hz, CH_2), 1.72 (2H, t, J = 7.1 Hz, CH_2), 1.50–1.38 (4H, m, CH_2).

Preparation of CMPO-coated magnetic particles

Covalent attachment of calix[4]arenes 1–3. 50 µmol of each of the calix[4]arenes **1**–**3** and 50, 100 or 200 µmol triethylamine (1 mole per mole –NH_2) were dissolved in 20 ml chloroform (solution A). 1.5 g of dry 4,6-dichloro-1,3,5-triazin-2-yl functionalized magnetic silica particles (micromod, product-code: 58-39-105) were added and the particle suspensions were shaken at room temperature for 24 h. Then the particles were separated with a permanent magnet. The supernatant (solution B) was removed and the particles were washed with chloroform by three successive resuspension/magnetic separation cycles using 20 ml chloroform per washing step. After the last magnetic separation the supernatant was removed and the particles were dried in vacuum for 8 h.

For the UV-spectroscopic determination of the calix[4]arene concentration 20 µl of solution A were diluted to 2 ml with chloroform to reach c(calix) = 25 µmol l^{-1}. Further dilutions with chloroform (c = 12.5, 6.25, 3.13, and 1.56 µmol l^{-1}) were used to measure the absorption at 242 nm and to establish a calibration curve A(242 nm) = f[c(calix)] by linear regression. 20 µl of solution B were diluted analogously to 2 ml with chloroform, the absorption at 242 nm was measured to determine c(calix) and to calculate the amount of calix[4]arene bound to the particles. It was checked that the amount of calixarene in the chloroform of the first washing step was negligible.

Covalent attachment of model compounds 4. The procedure for the immobilization of model compounds **4** was similar using a solution of 200 µmol of **4a**,**b** and 200 µmol triethylamine in 20 ml chloroform for the reaction with 1.5 g of DCT functional-

ized magnetic silica particles. The UV-spectroscopic analysis was carried out analogously at 266 nm.

Extraction experiments

10 ml of the Eu/Am solution in 3 M HNO_3 were added to 300 mg magnetic particles. This suspension was shaken for one hour at room temperature and afterwards separated with the help of a magnetic field. The activity of the radionuclide in the starting solution and in the supernatant after shaking was determined by γ-spectrometry. In a typical experiment the initial activity of ^{241}Am (1381 kBq l^{-1}) and ^{152}Eu (1511 kBq l^{-1}) was reduced to 134 kBq l^{-1} and 309 kBq l^{-1} respectively, by shaking with 300 mg of **2b**, leading to K_D values of 310 ml g^{-1} and 130 ml g^{-1}, respectively.

These conditions, leading to a low final activity of 10% or less for particles **1**–**3**, were chosen to study particles with the model compounds **4a**,**b**, where the final activity is 90% or more, under identical conditions.

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