ORIGINAL ARTICLE

Sulphur-enriched *thia*calix[4]arenes in the cone conformation: synthesis, crystal structures and cation binding properties

Saliha Bouhroum · Jong Seung Kim ·
Soon W. Lee · Pierre Thuéry · Glenn Yap ·
Françoise Arnaud-Neu · Jacques Vicens

Abstract The synthesis and crystal structure of *p-tert*-butyl*thia*- and *p-tert*-butylcalix[4]arene derivatives **1–7** substituted at the narrow rim by diethylthiophosphate ester groups, -PS(OEt)$_2$ are reported. In these compounds the phosphorus atoms are directly attached to the phenolic O atoms of the calix units and the S atoms of the *thio*phosphate may serve as a two-electron donor to a metal ion. Their crystal structures were solved, which revealed their cone conformation. Their cation-binding properties have been established by liquid-liquid extraction of metal picrates from water into dichloromethane and stability constant determination in acetonitrile using UV-absorption spectrophotometry. Quantitative extraction was achieved for Ag$^+$ (%E = 99) with the tetra-substituted *thia*calix[4]arene derivative. The complexes were found to be of 1:1 stoichiometry and the location of the metal cations was shown to be nearby the sulphur atoms by ^{1}H NMR.

S. Bouhroum · F. Arnaud-Neu (✉) · J. Vicens (✉)
Département des Sciences Analytiques, Institut Pluridisciplinaire
Hubert Curien, ULP, CNRS, ECPM, 25, rue Becquerel, 67087
Strasbourg, France
e-mail: farnaud@chimie.u-strasbg.fr

J. Vicens
e-mail: vicens@chimie.u-strasbg.fr

J. S. Kim
Department of Chemistry, Korea University, Seoul,
Republic of Korea

S. W. Lee
Department of Chemistry, Sungyunkwan University, Suwon
440-746, Republic of Korea

P. Thuéry
CEA Saclay, DSM/IRAMIS/SCM (CNRS URA 331), 91191
Gif-sur-Yvette, France

G. Yap
201 Brown Laboratory, Department of Chemistry &
Biochemistry, University of Delaware, Newark, DE 19716, USA

Introduction

The calixarenes are a class of cyclooligomers formed *via* phenol-formaldehyde condensation, which exist in a 'cup'-like shape with upper and lower rims and a central annulus [1]. Their rigid conformation enables them to act as host molecules, thanks to their preformed cavities. By chemical modification of either the upper and/or lower rims it is possible to prepare functionalised hosts differing in selectivities for various ions and small molecules. Considerable attention has been paid to the complexation properties of *O*-functionalized *p-tert*-butylcalix[4]arenes (cyclic tetramers) towards metal cations and their applications as extractants and sensors in analytical and separation chemistry [1]. *Thia*calixarenes are a new class of calixarene derivatives for which the replacement of CH$_2$ bridges by S atoms introduces potential coordination sites (in particular for soft metal cations) and modifies the dimension of the calix macrocycle [2]. As in the case of the 'classical' calixarenes, reactions of *thia*calix[4]arenes involve both lower and upper rim derivatizations, enabling shaping of the molecular skeleton [3]. Among these studies, an interesting work has been done on the synthesis and coordination properties of *thia*- and mercapto-derivatives, and more particularly of

Chart 1 Cone calixarene derivatives **1–7**
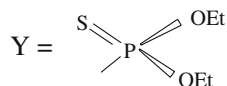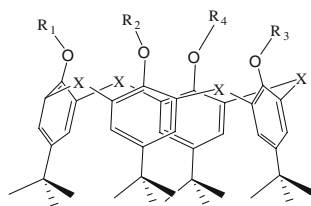
1. X = S $R_1 = R_3 = H$; $R_2 = R_4 = Y$
2. X = S $R_1 = H$; $R_2 = R_3 = R_4 = Y$
3. X = S $R_1 = R_2 = R_3 = R_4 = Y$
4. X = CH_2 $R_1 = R_3 = H$; $R_2 = R_4 = Y$
5. X = CH_2 $R_1 = H$; $R_2 = R_3 = R_4 = Y$
6. X = CH_2 $R_1 = R_3 = CH_2CO_2Et$; $R_2 = R_4 = Y$
7. X = CH_2 $R_1 = CH_2CO_2Et$; $R_2 = R_3 = R_4 = Y$

$Y =$

p-tert-butyl-tetrathiatetramercaptocalix[4]arene, which contains eight sulphur atoms and can be seen as *a sulphur-enriched receptor* [2c]. More recently, a *thia*calix[4]arene comprising cyclic or linear O, S, N ligating groups on the lower rim as selective ionophores for Ag^+ has been reported [3f].

As part of our ongoing research devoted to the complexation studies of calixarenes and *thia*calixarenes derivatives functionalised at the narrow rim [4], we report in the present paper the synthesis, crystal structure and cation-complexation studies of *p-tert*-butyl*thia*calix [4]arenes derivatives **1–3** (see Chart 1) in the cone conformation and substituted at the narrow rim by diethylthiophosphate ester groups, -PS(OEt)$_2$, in which the phosphorus atoms are directly attached to the phenolic O atoms of the calix units and the S atoms of the *thio*phosphate may serve as a two-electron donor to a metal ion. We also present cone calix[4]arenes counterparts **4–7** as to compare with the *thia* compounds series.

Experimental

Materials and syntheses

All reagents and solvents for synthesis were commercial and used without further purification. All the reactions were run under a nitrogen atmosphere. SiO$_2$ (Geduran 1.11567) was used for column chromatography. TLC plates for R_f's were from Merck (Silica 60, F$_{254}$-0.5 mm, Art 5744). Uncorrected melting points (Mps) were taken on a Buchi 500. ^{1}H NMR spectra (CDCl$_3$, 300 MHz, in ppm from tms) and ^{31}P{^{1}H}NMR spectra (CDCl$_3$, 400 MHz, δ phosphoric acid-water as standard) were recorded on a Bruker SY 200. FAB(+) MS spectra were measured on a Biflex Bruker. The elemental analyses were carried out at the Service de Microanalyse de l'ULP at Strasbourg. 5,11,17,23-tetra-*tert*-butylcalix[4]arene-25,26,27,28-tetraol or *p-tert*-butylcalix[4]arene [5] and 5,11,17,23-tetra-*tert*-butyl-25,26,27,28-tetraol-2,8,14,20-tetra*thia*calix[4]arene or *p-tert*-butyl*thia*calix[4]arene [2a,b] were prepared as described in the literature.

Preparation of 5,11,17,23-tetra-tert-butyl-25,27,28-didiethylthiophosphate-2,8,14,20-tetra-thiacalix[4]arene (1), 5,11,17,23-tetra-tert-butyl-25,26,27-tridiethylthiophosphate-2,8,14,20-tetrathiacalix[4]arene (2) and 5,11,17,23-tetra-tert-butyl-25,26,27,28-tetradiethylthio-phosphate-2,8,14,20-tetrathiacalix[4]arene (3)

p-tert-Butyl*thia*calix[4]arene (1.02 g; 1.39 mmol), K$_2$CO$_3$ (0.50 g; 3.62 mmol), ClPS(OEt)$_2$ (1.02 g; 5.67 mmol), acetonitrile (50 mL) were refluxed for 3 d. After evaporation of the solvents, the residue was dissolved in CH$_2$Cl$_2$ (500 mL) and aqueous 1 N HCl (500 mL). The organic layer was dried over sodium sulphate, filtered and concentrated under vacuum. The residue was chromatographed on silica column with a 1:1 mixture of CH$_2$Cl$_2$:hexane as eluent. **1–3** were isolated pure from the column eluted in this order:

1. white solid. Mp > 260 °C. $R_f = 0.75$ (1:1 mixture of CH$_2$Cl$_2$: hexane). ^{1}H NMR (CDCl$_3$): δ: 0.87 (s, 18H, C(CH_3)$_3$), 1.34 (s, 18H, C(CH_3)$_3$), 1.42 (t, 12H, $J = 7.0$ Hz, OCH$_2$CH_3), 4.40 (dq, 8H, $J_{P–H} = 9.1$ Hz, $J_{H–H} = 7.0$ Hz, OCH_2CH$_3$), 6.46 (s, 2H, ArOH), 7.70 (s, 4H, ArH). ^{31}P{^{1}H}NMR (CDCl$_3$): δ: 65.32. Calcd for C$_{48}$H$_{64}$O$_8$S$_6$P$_2$: MW = 1023.38. FAB(+)MS: m/z = 1029.42. Anal cald : C, 56.00; H, 6.85. Found C, 56.63; H, 7.02. Yield 1%.

2. White solid. Mp > 260° C. $R_f = 0.63$ (1:1 mixture of CH$_2$Cl$_2$:hexane). ^{1}H NMR (CDCl$_3$): δ: 0.91 (s, 27H, C(CH_3)$_3$), 1.32 (s, 9H, C(CH_3)$_3$), 1.34 (t, 12H, $J = 6.6$ Hz, OCH$_2$CH_3), 1.41 (t, 6H, $J = 7.5$ Hz, OCH$_2$CH_3), 4.40–4.59 (m, 12H, OCH_2CH$_3$), 6.35 (s, H, ArOH), 6.92 (s, 2H, ArH), 7.00 (s, 6H, ArH). ^{31}P{^{1}H}NMR (CDCl$_3$): δ: 63.92 (1P), 66.05 (2P). calcd for C$_{52}$H$_{73}$O$_{10}$S$_7$P$_3$: MW = 1175.53. FAB(+)MS m/z = 1181.58. Anal calcd : C, 53.13; H, 6.25. Found C, 52.87; H, 6.83. Yield 9%.

3. White solid. Mp > 260° C. $R_f = 0.52$ (1:1 mixture of CH$_2$Cl$_2$:hexane). ^{1}H NMR (CDCl$_3$): δ : 1.14 (s, 36H, C(CH_3)$_3$), 1.39 (t, 24H, $J = 6.9$ Hz, OCH$_2$CH_3), 4.43 (dq, 16H, $J_{P–H} = 9.2$ Hz, $J_{H–H} = 7.2$ Hz, OCH_2CH$_3$),

7.45 (s, 8H, ArH). ^{31}P {^{1}H}NMR (CDCl$_3$): δ: 66.36. Calcd for C$_{56}$H$_{82}$O$_{12}$S$_8$P$_4$: MW = 1327.68. FAB(+)MS: m/z = 1333.74. Anal calcd: C, 50.66; H, 6.22. Found C, 50.51; H, 6.49. Yield 14%.

Preparation of 5,11,17,23-tetra-tert-butyl-25,27-didiethylthiophosphatecalix[4]arene (4)

p-tert-Butylcalix[4]arene (3.22 g; 4.96 mmol), K$_2$CO$_3$ (0.803 g; 5.78 mmol), ClPS(OEt)$_2$ (1.07 g; 5.67 mmol), acetonitrile (100 mL) were refluxed for 24 h. After evaporation of the solvents, the residue was dissolved in CH$_2$Cl$_2$ (500 mL) and aqueous 1 N HCl (500 mL). The organic layer was dried over sodium sulphate, filtered and concentrated under vacuum. Precipitation with methanol, afforded pure **4** as a white solid. Mp > 260 °C. ^{1}H NMR (CDCl$_3$): δ: 0.87(s, 18H, C(CH_3)$_3$), 1.34 (s, 18H, C(CH_3)$_3$, 1.37 (t, 12H, J = 7.1 Hz, OCH$_2$CH_3), 3.34 (d, 4H, J = 14.0 Hz, ArCH_2Ar), 4.29 (dq, 8H, $J_{P–H}$ = 9.1 Hz, $J_{H–H}$ = 7.1 Hz, OCH_2CH$_3$), 4.42 (d, 4H, J = 14.0 Hz, ArCH_2Ar), 5.13 (s, 2H, ArOH), 6.70 (s, 4H, ArH), 7.12 (s, 4H, ArH). ^{31}P {^{1}H}NMR (CDCl$_3$): δ: 65.13. Calcd for C$_{52}$H$_{72}$O$_8$P$_2$S$_2$: MW = 951.22. FAB(+)MS: m/z = 953.24. Anal calcd: C, 65.66; H, 7.62. Found C, 65.09; H, 7.83. Yield 47%.

Preparation of 5,11,17,23-tetra-tert-butyl-25,26,27-tridiethylthiophosphatecalix[4]arene (5)

4 (1.05 g; 1.05 mmol), Cs$_2$CO$_3$ (1.02 g; 3.10 mmol), ClPS(OEt)$_2$ (1.03 g; 5.67 mmol), acetonitrile (100 mL) were refluxed for 3 d. After evaporation of the solvents, the residue was dissolved in CH$_2$Cl$_2$ (500 mL) and aqueous 1 N HCl (500 mL). The organic layer was dried over sodium sulphate, filtered and concentrated under vacuum. Precipitation with methanol, afforded pure **5** as a white solid. Mp > 260° C. ^{1}H NMR (CDCl$_3$): δ = 1.05 (s, 18H, C(CH_3)$_3$), 1.22 (t, 12H, J = 7.0 Hz, OCH$_2$CH_3), 1.33 (s, 9H, C(CH_3)$_3$), 1.38 (t, 6H, J = 7.0 Hz, OCH$_2$CH_3), 1.45 (s, 9H, C(CH_3)$_3$), 3.24 (d, 4H, J = 14.0 Hz, ArCH_2Ar), 4.04–4.27 (m, 16H, OCH_2CH$_3$, ArCH_2Ar), 6.63 (s, 1H, ArOH), 7.07 (s, 4H, ArH), 7.69 (s, 4H, ArH). ^{31}P {^{1}H}NMR (CDCl$_3$): δ: 65.73 (2P), 65.80 (1P). Calcd for C$_{56}$H$_{81}$O$_{10}$P$_3$S$_3$: MW = 1103.37. FAB(+)MS: m/z = 1105.5. Anal calcd: C, 60.96; H, 7.39. Found C, 60.56; H, 7.97. Yield 26%.

Preparation of 5,11,17,23-tetra-tert-butyl-25,27-didiethylthiophosphate-26,28-diethoxy-carbonylcalix[4]arene (6)

4 (0.652 g; 0.68 mmol), Cs$_2$CO$_3$ (1.02 g; 3.10 mmol), BrCH$_2$CO$_2$Et (1.01 g; 6.02 mmol), acetonitrile (100 mL)

were refluxed for 24 h. After evaporation of the solvents, the residue was dissolved in CH$_2$Cl$_2$ (500 mL) and aqueous 1 N HCl (500 mL). The organic layer was dried over sodium sulphate, filtered and concentrated under vacuum. Precipitation with methanol, afforded pure **6** as a white solid. Mp > 260° C. ^{1}H NMR (CDCl$_3$): δ : 0.82 (s, 18H, C(CH_3)$_3$), 1.23 (t, 12H, J = 7.0 Hz, OCH$_2$CH_3), 1.30 (t, 6H, J = 7.0 Hz, CO$_2$CH$_2$CH_3), 1.34 (s, 18H, C (CH_3)$_3$), 3.22 (d, 4H, J = 13.5 Hz, ArCH_2Ar), 4.16–4.26 (m, 12H, OCH_2CH$_3$, CO$_2$CH_2CH$_3$), 4.75 (d, 4H, J = 13.5 Hz, ArCH_2Ar), 5.02 (s, 4H, OCH_2CO$_2$Et), 6.47 (s, 4H, ArH), 7.11 (s, 4H, Ar–H). ^{31}P {^{1}H}NMR (CDCl$_3$): δ: 65.38. Calcd for C$_{60}$H$_{86}$O$_{12}$P2S2: MW = 1125.42. FAB(+)MS: m/z = 1125.35. Anal calcd: C, 64.03; H, 7.70. Found C, 63.63; H, 7.65. Yield 48%.

Preparation of 5,11,17,23-tetra-tert-butyl-25,26,27-tridiethylthiophosphate-28-ethoxy-carbonylcalix[4] arene (7)

5 (0.350 g; 0.31 mmol), Cs$_2$CO$_3$ (1.04 g; 3.19 mmol), BrCH$_2$CO$_2$Et (0.200 g; 1.19 mmol), acetonitrile (50 mL) were refluxed for 5 h. After evaporation of the solvents, the residue was dissolved in CH$_2$Cl$_2$ (500 mL) and aqueous 1 N HCl (500 mL). The organic layer was dried over sodium sulphate, filtered and concentrated under vacuum. Precipitation with methanol, afforded pure **7** as a white solid. Mp > 260° C. ^{1}H NMR (CDCl$_3$): δ : 1.05 (s, 18H, C(CH_3)$_3$), 1.10 (t, 3H, J = 7.0 Hz, CO$_2$CH$_2$CH_3), 1.22 (t, 6H, J = 7.0 Hz, OCH$_2$CH_3), 1.27 (t, 12H, J = 7.0 Hz, OCH$_2$CH_3), 1.41 (s, 9H, C(CH_3)$_3$), 3.14 (d, 4H, J = 13.5 Hz, ArCH_2Ar), 3.98–4.21 (m, 14H, OCH_2CH$_3$, CO$_2$CH_2CH$_3$), 4.25 (s, 2H, OCH_2CO$_2$Et), 4.39 (s, 4H, J = 13.5 Hz, ArCH_2Ar), 6.50 (s, 2H, ArH), 7.06 (s, 2H, ArH), 7.65 (s, 4H, ArH). ^{31}P {^{1}H}NMR (CDCl$_3$): δ: 65.5 (2P), 65.8 (1P). Calcd for C$_{60}$H$_{87}$O$_{12}$P$_3$S$_3$: MW = 1189.46. FAB(+)MS: m/z = 1191.98. Anal calcd: C, 60.58; H, 7.37. Found C, 60.66; H, 7.24. Yield 50%.

Crystallography

The crystal structures of compounds **2**, **3**, **4** and **6** were determined by single crystal X-ray diffraction. The data for compound **2** were collected on a Siemens P4 diffractometer, those for **3** and **4** on a Nonius κ-CCD area detector diffractometer and those for **6** on a Bruker-AXS APEX area detector diffractometer, all using graphite-monochromated Mo-Kα radiation (λ = 0.71073 Å). The data were processed with SHELXTL [6] or HKL2000 [7]. The structures were solved by direct methods with SHELXS-97 and subsequent Fourier-difference synthesis and refined by full-matrix least-squares on F^2 with SHELXL-97 [8]. Absorption effects were corrected empirically. One *tert*-butyl

group in compound **2** was found to be extremely disordered and was refined isotropically. Some restraints on bond lengths and/or displacement parameters were applied for some badly behaving atoms of the *tert*-butyl groups and ethyl chains in compound **4**. In **6**, one *tert*-butyl group was found to be rotationally disordered over two positions with refined occupancy factors of 0.53 and 0.47. All non-hydrogen atoms were refined with anisotropic displacement parameters, except those indicated above. Hydrogen atoms bound to oxygen atoms were found on Fourier-difference maps (they are disordered over two positions related by the symmetry plane in **4**) and all the other ones were introduced at calculated positions. All were treated as riding atoms with a displacement parameter equal to 1.2 (OH, CH, CH_2) or 1.5 (CH_3) times that of the parent atom. Crystal data and structure refinement parameters are given in Table 1. The molecular plots were drawn with SHELXTL [6].

Extraction studies

The extraction experiments of alkali, alkaline earth, transition and heavy metal picrates from water into dichloromethane were performed according to a procedure described in the literature [9]. 5 mL of a 2.5×10^{-4} M aqueous picrate solution and 5 mL of a 2.5×10^{-4} M solution of *thia*calix[4]arene in dichloromethane were shaken in a vortex for 3 min and then magnetically stirred in a stoppered glass tube immersed in a thermostated water bath at 20 ± 0.01 °C for 30 min. After the two phases separation, the absorbance A of the aqueous phase was measured at 355 nm. A blank experiment without calixarene was run under the same conditions which yielded the absorbance A° of the aqueous phase. The %E of extracted cation was calculated as the ratio $100 \times (A° - A)/A°$.

The metal picrates were prepared according to the methods previously reported [10, 11]. Their solutions were sheltered from moisture and light.

Stability constant determination

The stability constants β, defined as the concentration ratios $[M^{n+}L]/([M^{n+}][L]$ (where M^{n+} and L represent the cation and the ligand, respectively) were determined in acetonitrile (SDS, water content <0.05%) by UV

Table 1 Crystal data and structure refinement details

	2	**3**	**4**	**6**
Empirical formula	$C_{52}H_{75}O_{10}P_3S_7$	$C_{56}H_{84}O_{12}P_4S_8$	$C_{52}H_{74}O_8P_2S_2$	$C_{60}H_{86}O_{12}P_2S_2$
M/g mol^{-1}	1177.45	1329.59	953.17	1125.35
Crystal system	Monoclinic	Monoclinic	Orthorhombic	Monoclinic
Space group	$P2_1/c$	$P2_1/c$	$Pnma$	$P2_1/n$
a/Å	13.333(3)	22.6200(6)	19.1231(11)	14.259(2)
b/Å	34.173(6)	13.5391(2)	21.1379 (9)	21.044(3)
c/Å	15.387(4)	22.3215(6)	12.7985(6)	21.368(3)
β/°	113.829(16)	97.492(2)	90	93.161(3)
V/Å^3	6413(2)	6777.7(3)	5173.4(4)	6402.2(15)
Z	4	4	4	4
D_{calc}/g cm^{-3}	1.219	1.303	1.224	1.168
μ(MoKα)/mm^{-1}	0.369	0.412	0.216	0.189
T/K	293(2)	100(2)	100(2)	200(2)
Crystal size/mm	$0.28 \times 0.26 \times 0.24$	$0.17 \times 0.14 \times 0.11$	$0.14 \times 0.10 \times 0.08$	$0.32 \times 0.24 \times 0.08$
F (000)	2496	2816	2048	2416
θ range/°	2.1–25.0	2.2–25.7	3.3–25.7	1.68–20.82
Reflections collected	10341	44107	113979	38779
Independent reflections	10021	12686	4898	6711
Observed reflections [$I > 2\sigma(I)$]	4743	10173	3892	5057
R_{int}	0.100	0.049	0.063	0.100
Parameters refined	629	741	311	716
R_1	0.089	0.038	0.088	0.070
wR_2	0.257	0.099	0.254	0.184
S	0.993	1.017	1.073	1.054
$\Delta\rho_{min}$/e Å^{-3}	−0.43	−0.36	−0.42	−0.27
$\Delta\rho_{max}$/e Å^{-3}	0.76	0.74	1.29	0.30

absorption spectrophotometry according to the procedure already described [12]. The choice of acetonitrile was dictated by the sufficient solubility of all the ligands studied in this solvent. The ligand concentrations ranged between 10^{-5} M and 6×10^{-5} M for ligands **2** and **3** and between 10^{-4} M and 5×10^{-4} M for **4–7**. The spectra were treated by using the program Specfit [13]. The salts used were alkali and alkaline earth perchlorates and heavy and transition metal nitrates except in the case of Zn^{2+} which was used as perchlorate. They were all dried in small quantities for 24 h, while protected from light. The ionic strength was maintained at 0.01 M in all cases provided by Et_4NClO_4 (Fluka, purum), which was recrystallized twice from water after washing with acetone and dried at room temperature under vacuum during 24 h, or Et_4NNO_3 (ACAOS, 99%) without further purification.

Results and discussion

### Synthesis and characterisation of cone compounds 1–7

Starting from the seminal publication of Floriani et al. [5] describing the reaction of *p-tert*-butylcalix[4]arene with chlorodiphenylphosphinite to attach diphosphinite groups at the lower rim, several publications have described such formation of O–P bonding mainly to prepare new catalyzers [14, 15]. *p-tert*-Butyl*thia*calix[4]arene derivatives **1–3** have been isolated from the reaction of *p-tert*-butyl*thia*calix[4]-arene with ~ 4 equiv of chlorodiethylthiophosphate, ClPS(OEt)$_2$ and ~ 2.5 equiv of K_2CO_3 in refluxing acetonitrile for 3 days. They were separated by chromatography of the crude reaction mixture on silica with 1:1 mixture of CH_2Cl_2:hexane as eluent. **3** was readily characterised as the tetrasubstituted product on the view of the FAB(+)MS spectrum $m/z = 1333.74$ and elemental analysis. Its ^{1}H NMR in CDCl$_3$ displayed a very symmetrical pattern with two singlets at 1.14 ppm and 7.45 ppm for the protons of C(C**H$_3$**)$_3$ and Ar**H**, respectively, with a triplet at 1.39 ppm and a quartet at 4.43 ppm with $J = 7.2$ Hz for OCH$_2$C**H$_3$** and OC**H$_2$**CH$_3$, respectively. Its ^{31}P{^{1}H}NMR in the same solvent showed a singlet at 66.36 ppm. Trisubstitution into **2** was similarly deduced from the analytical data. Interestingly, the ^{31}P{^{1}H}NMR spectrum of **2** in CDCl$_3$ showed two singlets in 1:2 ratio at 63.92 ppm (central P) and 66.05 ppm (external P's). The external P's value matched the 66.36 ppm observed for **3**. Disubstitution into **1** was similarly deduced from mass spectrometry and elemental analysis. The ^{1}H NMR spectrum of a symmetrical compound was obtained and its ^{31}P{^{1}H}NMR in CDCl$_3$ showed a singlet at 65.32 ppm matching the δ values of external P's of **2** and P of **3**. We tentatively proposed a 1,3-disposition of the –PS(OEt)$_2$ groups on the *thia*calix[4]unit. **2** and **3** were shown

to be in the cone conformation by the determination of their crystal structure (see below). When *p-tert*-butylcalix [4]arene was reacted in similar conditions with ClPS(OEt)$_2$ we could isolate the 1,3-disubstituted derivative **4**. One AB system at 3.34 ppm and 4.42 ppm with $J = 14.0$ Hz was observed for the ArC**H$_2$**Ar proton leading to the conclusion that **4** is in the cone conformation, which was confirmed by the determination of its crystal structure (see below). Its ^{31}P{^{1}H}NMR in CDCl$_3$ presented a δ 65.13 ppm very similar to the δ 65.32 ppm of **1** leading us to assume that **1** is 1,3-disubstituted and in the cone conformation. Reaction of **4** with ClPS(OEt)$_2$ in the presence of Cs_2CO_3 gave trisubstituted **5**. We could not obtain the tetrasubstituted derivative probably because of steric hindrance of PS(OEt)$_2$ groups. This is not the case for *p-tert*-butyl*thia*calix[4]arene which is known to have a larger 'diameter' than the classical *p-tert*-butylcalix[4]arene [4c]. This was demonstrated by reacting **4** and **5** with BrCH$_2$CO$_2$Et in the presence of Cs_2CO_3 to give the mixed derivatives **6** and **7**. The crystal structure of **7** showed the [2 + 2'] disposition of the substituents and its cone conformation (see below).

X-ray studies

The calixarene macrocycle is in a much distorted *cone* conformation in compounds **2**, **3**, **4** and **6** (Fig. 1). The molecule in **4** sits on a symmetry plane containing atoms O1 and O5, whereas it has no crystallographic symmetry in the other compounds. In all cases, two non-adjacent aromatic rings are nearly perpendicular to the mean plane defined by the four bridging sulfur or methylene carbon atoms. The dihedral angles between this mean plane and the aromatic rings are 38.9(2), 100.8(2), 53.3(1) and 84.2(2)° in **2**, 56.49(6), 89.86(5), 54.40(4) and 96.54(5)° in **3**, 24.44(17) and 90.95(9)° in **4** and 38.03(16), 93.20(11), 39.42(12) and 85.90(11)° in **6** (a dihedral angle larger than 90° indicates that the aromatic ring has its *para* carbon atom pointing towards the inside of the cavity). Further distortion is present in the *thia*calixarenes **2** and **3**, due to the large deviations of the bridging sulfur atoms from the mean plane they define (r.m.s. deviation 0.17 Å in **2**, 0.20 Å in **3**). As a result of this geometry, the *O*-substituents linked to aromatic rings closer to the mean plane have one of their ethyl chains pointing towards the calixarene cone axis, whereas those bound to the nearly perpendicular rings are pointing outwards so as to minimize steric interactions. By contrast, the mono-substituted PS(OEt)$_2$ derivative of *p-tert*-butylcalix[4]arene has a much more regular cone conformation, being free of inter-substituent interactions [16]. Intramolecular hydrogen bonds are present in compounds **2** and **4**. In **2**, the proton linked to O1 is involved in a bifurcated hydrogen bond with the phenolic oxygen atom O8 and the bridging atom S4 [O1···O8 3.166(7) Å, O1–H1···O8 158°; O1···S4 3.034(6) Å,

Fig. 1 Molecular structures of (**a**) **2** Displacement ellipsoids are drawn at the 10% probability level. (**b**) **3** Displacement ellipsoids are drawn at the 30% probability level. (**c**) **4** Only one position of the disordered hydrogen atoms is represented. Displacement ellipsoids are drawn at the 20% probability level. Symmetry code: $' = x, 1.5 − y, z$. (**d**) **6** Only one position of the disordered *tert*-butyl group is represented. Displacement ellipsoids are drawn at the 10% probability level. Hydrogen atoms are omitted, except when involved in hydrogen bonds (dashed lines)
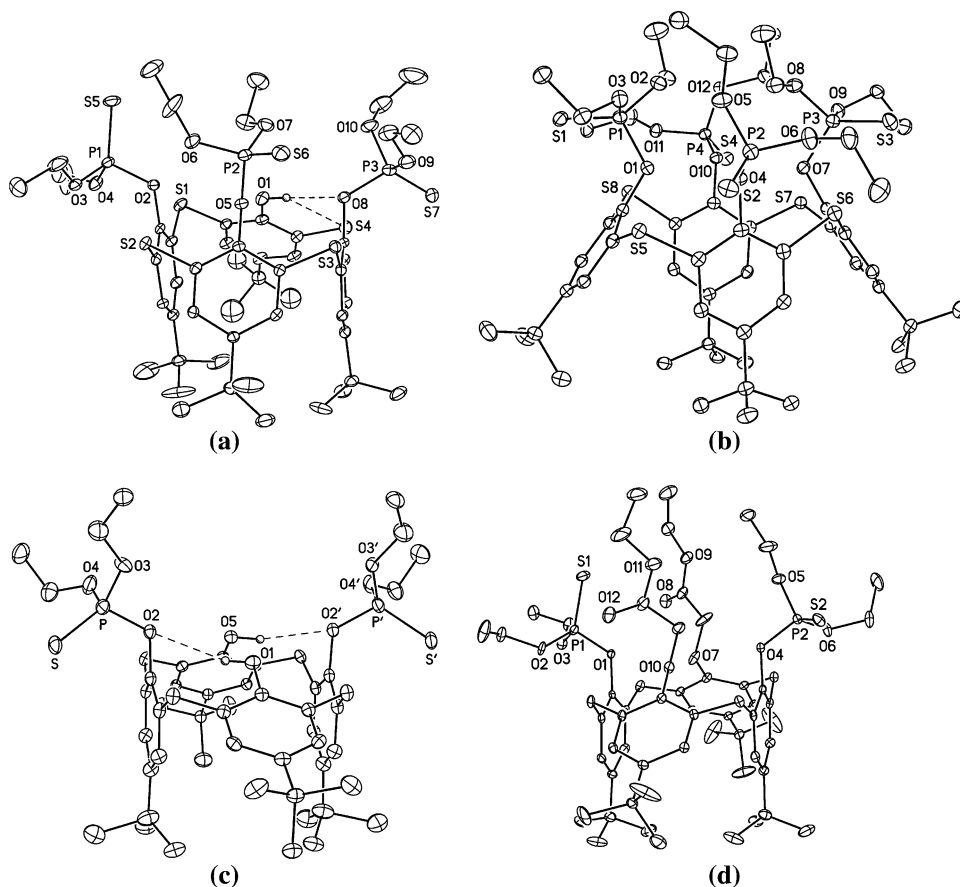
O1–H1···S4 123°]. In **4**, due to the presence of a symmetry plane containing the two protonated oxygen atoms O1 and O5, the hydrogen atoms are disordered over two positions; they are involved in hydrogen bonds with the phenolic oxygen atom O2 or its symmetry equivalent [O1···O2 3.206(3) Å, O1–H1···O2 158°; O5···O2 3.242(3) Å, O5–H5···O2 168°].

Binding of alkali and alkaline earth metal ions

The results of the extraction of alkali and alkaline earth metal picrates are given in Table 2. They show that both series of cations are poorly extracted either by the *thia*calix[4]arenes **2** and **3** or the calix[4]arenes **4** and **5**, the percentage of cation extracted (%E) not exceeding a value of 3.1 with the former (case of K$^+$ with **3**) and a value of 7.3 with the latter (case of Ba^{2+} with **4**). This observation is consistent with the low affinity of thiophosphate functions for 'hard' cations. However, the fact that calixarenes **4** and **5** are slightly better extractants than the *thia*calixarene **2** may indicate that their size is best adapted than the size of *thia*calixarenes. Such a trend has already been observed for *thia*- and calix[4]*bis*crowns and attributed to the larger diameter of the *thia*calix[4]arene framework making these ligands less receptive for these cations

[4c, e]. The introduction of one or two ester groups in thiophosphate calix[4]arene derivatives, as in compounds **6** and **7**, is not sufficient to improve significantly the extraction levels in both series of cations. The percentage of cation extracted remains very low, the highest %E values being close to 8 and 9 for Na$^+$ and Sr^{2+}, respectively, with compound **7** bearing one ester group.

Although a first estimation of the binding ability of ligands can be provided by extraction experiments, their affinity for a given cation is more clearly described by the stability constants of the complexes formed in a single solvent as the liphilicity of the system has not to be considered. These parameters have been determined in acetonitrile, a solvent in which all the ligands studied are soluble, using absorption spectrophotometry. With both series of cations the spectral changes upon complexation in this solvent are weak, but significant enough to be interpreted with the program Specfit [13]. The results show the formation of 1:1 complexes. With the alkali metal ions, the values of the stability constants (log β) are ranging from 2.5 and 3.9 log units with **2** and from 2.2 to 3.6 with **3**. The highest values are obtained for the Li$^+$ complex with **2** and for the Li$^+$, K$^+$ and Rb$^+$ complexes with **3**. The high stability of Li$^+$ complexes in acetonitrile has already been observed with calix[4]arene derivatives [12] and cryptands

Table 2 Percentage (%E)[a] of alkali and alkaline earth picrates extracted from water into dichloromethane by ligands **2–7** and stability constants (log $\beta \pm \sigma$)[b] of the complexes in acetonitrile

Ligands		Li^+	Na^+	K^+	Rb^+	Cs^+	Mg^{2+}	Ca^{2+}	Sr^{2+}	Ba^{2+}
2	%E	2.5	1.7	0.9	1.5	1.2	1.2	1.8	1.1	1.3
	log β	3.9 ± 0.1	2.5 ± 0.1	2.5 ± 0.2	3.3 ± 0.2	3.4 ± 0.3	2.5 ± 0.1	3.0 ± 0.1	3.7 ± 0.1	3.4 ± 0.1
3	%E	2.3	1.5	3.1	1.8	1.0	<1	<1	1.5	1.9
	log β	3.6 ± 0.2	2.51 ± 0.02	3.6 ± 0.4	3.6 ± 0.1	2.18 ± 0.02	3.1 ± 0.2	3.6 ± 0.1	2.2 ± 0.1	3.0 ± 0.1
4	%E	5.4	3.2	2.8	2.9	1.2	1.5	2.1	3.1	7.3
	log β	4.2 ± 0.1	3.4 ± 0.2	3.3 ± 0.2	5.3 ± 0.1	2.8 ± 0.8	2.7 ± 0.2	3.0 ± 0.1	3.7 ± 0.3	5.3 ± 0.1
5	%E	6.1	5.1	5.5	2.7	2.1	2.3	2.5	1.9	6.8
	log β	4.7 ± 0.2	4.0 ± 0.1	5.0 ± 0.1	3.31 ± 0.04	3.12 ± 0.03	3.08 ± 0.02	3.3 ± 0.1	3.4 ± 0.1	4.89 ± 0.04
6	%E	2.8	4.3	3.8	2.1	1.8	3.9	2.7	3.4	6.2
	log β	4.08 ± 0.01	3.5 ± 0.4	2.12 ± 0.08	4.0 ± 0.1	4.36 ± 0.03	3.83 ± 0.07	3.96 ± 0.07	3.51 ± 0.05	4.3 ± 0.1
7	%E	2.8	7.9	3.2	2.3	3.1	4.0	2.5	8.4	8.8
	log β	4.11 ± 0.04	4.12 ± 0.07	3.52 ± 0.04	3.14 ± 0.07	4.4 ± 0.3	3.2 ± 0.1	2.50 ± 0.07	4.13 ± 0.04	4.3 ± 0.1

[a] Values with uncertainties less than 5%

[b] σ, standard deviation on the mean of several experiments, T = 25 °C, I = 10^{-2} M (Et$_4$NClO$_4$)

[17] despite unfavourable size effects and it has been explained by the particular solvation of this cation in this solvent as compared to the other alkali cations. The difference in the complex stability between these two ligands does not exceed 1.1 log units and is not systematically in favor of the same ligand, so that it is very difficult to clearly assess the influence of the fourth diethylthiophosphate arm on the complex stability. The corresponding complexes with calixarenes **4** and **5** are generally more stable, their stability constants varying between 2.8 and 5.3 log units with **4** and between 3.5 and 5.0 with **5**. Derivative **5**, bearing three thiophosphate arms is a better binder of the smaller cations Li^+, Na^+ and K^+ while **4**, with only two thiophosphate arms, has a higher affinity for the larger Rb^+ and Cs^+ cations. The comparison between *thia*calixarene **2** with its calixarene counterpart **5** shows that the replacement of the bridging CH$_2$ with sulphur atoms decreases the complex stability. This difference is ranging from 0.2 for Cs^+ to 2.5 for K^+. Such results could be ascribed to an unfavourable size effect in the case of *thia*calixarenes, these ligands being probably less adapted to smaller cations. It appears that the complexing power and the selectivity of the calixarene derivatives depend strongly on the number of chelating arms, whereas this is not the case with *thia*calixarenes.

The stability of the complexes with alkaline earth cations is more or less of the same order of magnitude as that with alkali cations. A decrease in the complex stability is also observed on going from the calixarene **5** to the *thia*calixarene **2**, in particular for Ba^{2+} whose complex is clearly less stable with **2**. This result is consistent with the trend observed in extraction. It can also be noted that the presence of sulphur atoms in the macrocyclic framework has a great influence on the stability profiles along the series. Calixarenes **4** and **5** have an increasing affinity from Mg^{2+} to Ba^{2+} (the Ba^{2+} over Mg^{2+} selectivity expressed as the ratio of the stability constants is 398 for **4**), whereas the *thia*calixarenes **2** and **3** are selective for Sr^{2+} and Ca^{2+}, respectively.

With regard to the mixed ester/thiophosphate derivatives **6** and **7**, the introduction of one or two ester groups leads to changes in the complex stability and selectivity profiles but there is no systematic increase of the complex stability on going from **4** to **6** and from **5** to **7**, contrary to what could be expected from the presence of "hard" carbonyl donor groups. For instance, the results show a similar stability of the Li^+ and Na^+ complexes with **4** and **6**, a significant decrease of the stability of the K^+ and Rb^+ complexes (Δlog β = 1.2–1.3) from **4** to **6** and on the opposite an increase of the stability of the Cs^+ complex (Δlog β = 1.6), resulting in a shift of the selectivity from Cs^+ for **4** to Rb^+ for **6**.

Binding of heavy and transition metal ions

The percentages of %E of heavy and transition metal ions extracted are given in Table 3 and in Fig. 2. The high values obtained show clearly the stronger efficiency of ligands **2–5** for heavy metal ions, in particular for Ag^+, which is quantitatively extracted by the tetrasubstituted *thia*calixarene **3** [18]. This is explained by the strong affinity of these cations for the sulphur atoms present in the binding groups. It can be noted also that Ag^+ is better extracted by ligand **2** (%E = 67) than by its calixarene homologue **5** (%E = 17.7). A similar observation can be made for Zn^{2+}. This indicates also a strong influence of the presence of the bridging sulphur atoms in *thia*calixarenes
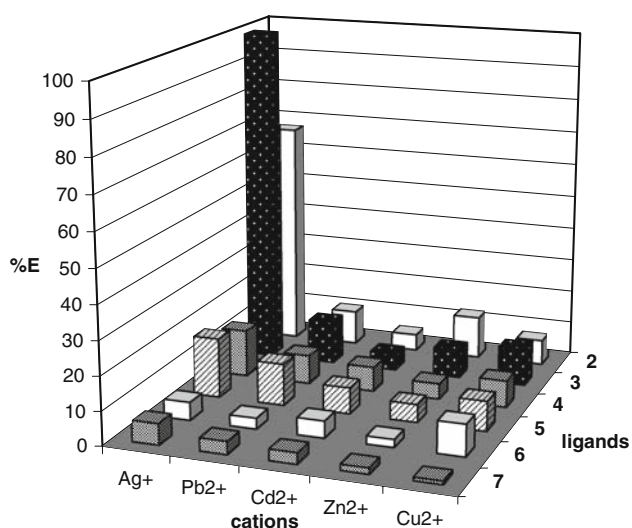
Table 3 Percentage extraction (%E)[a] of transition and heavy metal picrates extracted from water into dichloromethane by **2–7** and stability constants (log $\beta \pm \sigma$)[b] of the complexes in acetonitrile

Ligands		Ag^+	Pb^{2+}	Cd^{2+}	Hg^{2+}	Zn^{2+}	Cu^{2+}
2	%E	67.1	10.2	4.9	nd	12.6	7.5
	log β	3.91 ± 0.06	2.7 ± 0.3	4.3 ± 0.2	3.4 ± 0.2	2.6 ± 0.1	nd
3	%E	99.9	12.8	4.9	nd	8.5	11.1
	log β	4.09 ± 0.06	4.3 ± 0.1	3.5 ± 0.2	2.6 ± 0.2	2.3 ± 0.3	nd
4	%E	13.9	8.51	7.32	nd	4.7	7.96
	log β	3.26 ± 0.03	4.4 ± 0.4	3.7 ± 0.1	7.4 ± 0.5	3.6 ± 0.2	nd
5	%E	17.7	12.39	7.73	nd	5.3	8.8
	log β	5.5 ± 0.3	2.84 ± 0.01	3.4 ± 0.2	3.87 ± 0.07	4.3 ± 0.3	nd
6	%E	5.3	3.2	5.0	nd	2.3	9.3
	log β	4.7 ± 0.4	2.77 ± 0.07	3.7 ± 0.4	4.3 ± 0.3	4.8 ± 0.4	nd
7	%E	6.2	3.8	3.3	nd	1.8	1.0
	log β	2.3 ± 0.1	2.92 ± 0.07	2.88 ± 0.04	2.89 ± 0.09	2.41 ± 0.07	nd

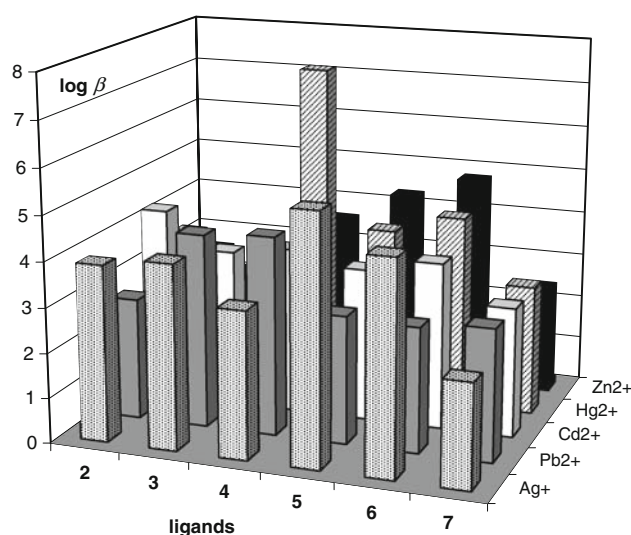[a] Values with uncertainties less than 5%

[b] σ, Standard deviation on the mean of several experiments, T = 25 °C, I = 10^{-2} M (Et_4NClO_4) or Et_4NNO_3)

nd, Not determined

Fig. 2 Percentage extraction (%E) of heavy and transition metal picrates from water into dichloromethane containing *thia*calixarenes and calixarenes **2–7**

Fig. 3 Comparison of the stability (log β) of complexes of heavy and transition metal ions with *thia*calixarenes and calixarenes **2–7**

which, apparently, contribute also to the higher efficiency of these compounds towards these cations. However, with Pb^{2+}, Cd^{2+} and Cu^{2+}, the extraction is slightly lower with the *thia*calixarene than with the calixarene. These extraction data show the high selectivity of the *thia*calixarenes for Ag^+: for instance the Ag^+/Cd^{2+} selectivities of **2** and **3**, expressed as the ratio of the percentages of cation extracted, are 13.7 and 20, respectively, instead of only 2.3 for **5**.

With both kinds of ligands the percentage of cation extracted generally increases with the number of thiophosphate arms. For instance in the case of *thia*calixarenes,

the extraction percentage of Ag^+ extracted is higher (%E = 99.9) with **3** which contains four diethylthiophosphates than with **2** which contains only three such arms (%E = 67.1). The only exception concerns Cd^{2+} whose extraction level is similar, whatever the calixarenes **4** or **5**, or the *thia*calixarenes **2** or **3**.

Complexation results were obtained for all the cations studied in extraction except for Cu^{2+} for which equilibria were found to be very sluggish. They include also data for Hg^{2+} which was not studied in extraction (Table 3, Fig. 3). The results show that the stability constants are ranging between 2.3 and 4.3 log units with the *thia*calixarenes **2**

and **3**, and between 2.8 and 7.4 with the calixarenes **4** and **5**. Whereas all these ligands were selective for Ag$^+$ in extraction, complexation selectivities are different from one ligand to another. Where **2** and **5** remain selective for Ag$^+$, Cd^{2+} is the cation best complexed by **2** and Hg^{2+} by **4**. The comparison between **2** and **5** shows that the introduction of sulphur atoms in the macrocyclic framework modifies completely the selectivity profile. **5** complexes remakably Ag$^+$ and Zn^{2+} (log β = 5.5 and 4.3, respectively), while **2** presents a high affinity for Ag$^+$ and Cd^{2+} (log β = 3.9 and 4.3, respectively). As a consequence the complexation selectivity for Ag$^+$ over Pb^{2+} decreases from 457 for **5** to 15.8 for **2**.

The extraction data concerning the mixed thiophosphate/ester derivatives (Fig. 2) show that the presence of the ester groups reduces considerably the extraction level of these cations. For instance, the percentage of Ag$^+$ extracted decreases from 13.9 and 17.7 with ligands **4** and **5** to 5.3 and 6.2 with ligands **6** and **7**, respectively. This can be due to the presence of the ester groups possessing a 'hard' character and having a lower affinity for this kind of cations. As regard the complexation data (Fig. 3), the comparison between **4** and **6** shows that the introduction of two esters functions slightly increases the stability of Ag$^+$ and Zn^{2+} complexes (Δlog β = 1.45 and 1.2, respectively) but decreases considerably that of the Pb^{2+} and Hg^{2+} complexes (Δlog β = 1.63 and 3.1, respectively), while keeping the stability of the Cd^{2+} complex unchanged.

These variations result in interesting selectivities, as those of Zn^{2+} over Pb^{2+} and of Ag$^+$ over Pb^{2+}, which amount to 107 and 76, respectively (expressed as the ratio of the stability constants). With the ligand **7** there is generally a decrease of the stability of the complexes with respect to **5**, with a levelling of the stability constants and the disappearence of any selectivity.

^{1}H-NMR of the Ag, Zn and Pb complexes

We used proton nuclear magnetic resonance (^{1}H NMR) to get information on the structures of the free macrocyclic ligands and their complexes. The highest values of complexation being observed for Ag$^+$, Zn^{2+} and Pb^{2+}, we undertook ^{1}H-NMR studies by extraction of the corresponding solid metal picrates by **1–7** in deuterated chloroform. CDCl$_3$ solutions of **1–7** ($\sim 10^{-2}$ M) were reacted with the different metal picrates Ag$^+$Pic$^-$, Pb^{2+}(Pic$^-$)$_2$ and Zn^{2+}(Pic$^-$)$_2$. ^{1}H-NMR spectra were registered until remaining unchanged. The formation of a complex induced changes (probably due to the presence of a metal) in the ^{1}H NMR patterns with the appearance of a singlet corresponding to the extracted picrate. The complexation of Ag$^+$ by ligands **2** and **3** and of Zn^{2+} by ligand **2** are given in Fig. 4 and 5 as examples.

The ratio of the extracted cation to ligand in solution was estimated by calculating the integration ratio of the picrate protons resonances vs those of the aromatic protons

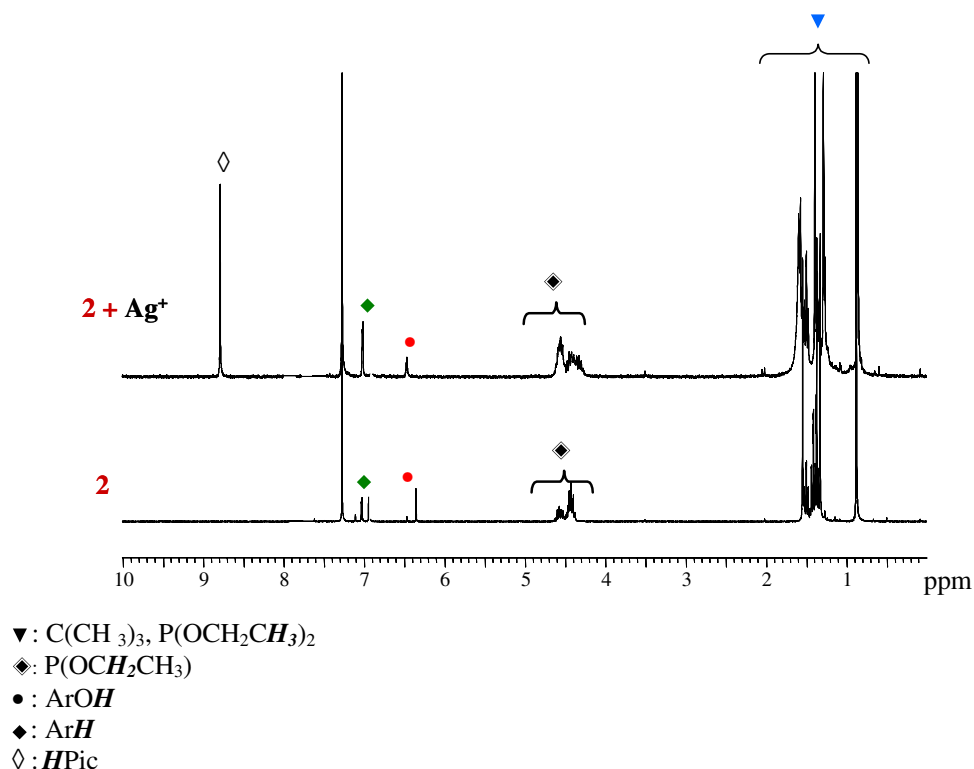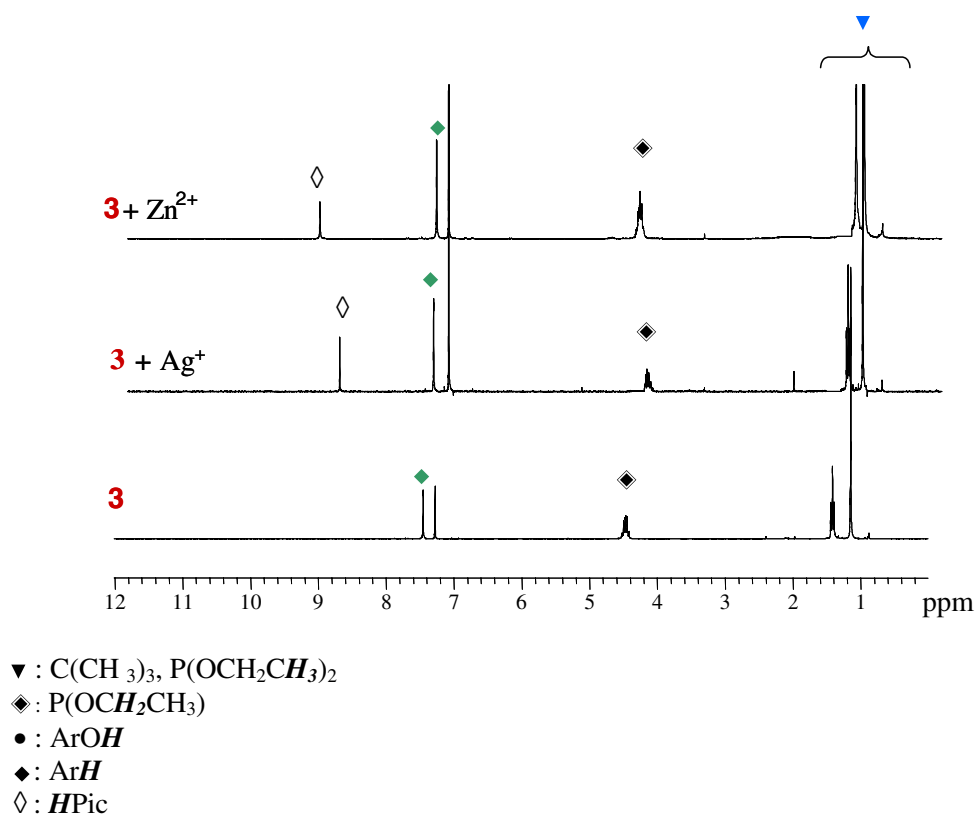**Fig. 4** ^{1}H-NMR spectra of **2** and **2**•Ag$^+$ in CDCl$_3$

▼ : C(CH$_3$)$_3$, P(OCH$_2$C**H**$_3$)$_2$
◈ : P(OC**H**$_2$CH$_3$)
● : ArO**H**
◆ : Ar**H**
◊ : **H**Pic

Fig. 5 ^{1}H-NMR spectra of **3**, **3•Ag$^+$** and **3•Zn^{2+}** in CDCl$_3$

▼ : C(C**H**$_3$)$_3$, P(OCH$_2$C**H$_3$**)$_2$
◈ : P(OC**H$_2$**CH$_3$)
● : ArO**H**
◆ : Ar**H**
◊ : **H**Pic

of the calix unit. All the data were in agreement with the formation of 1:1 complexes.

Tables 1S–7S (supplementary data) report the variations of the chemical shifts of the various complexes compared to the free ligands ($\Delta\delta = \delta_{complex} - \delta_{ligand}$) which gives information on the location of the metal in the ligand. We assumed the $\Delta\delta$ values ≥ 0.05 to be an indication of the presence of the metal.

All ligands **1**–**7** extracted Ag$^+$. For ligands **1**–**5** bearing only –PS(OCH$_2$CH$_3$)$_2$ functions the largest $\Delta\delta$'s were observed for the methyl, OCH$_2$C**H$_3$** and methylene OC**H$_2$**CH$_3$ protons. The triplets at 1.42, 1.34 and 1.41, 1.39, 1.37 and 1.22 ppm corresponding to the OCH$_2$C**H$_3$** of **1**–**5** are shifted to 1.62, 1.47 and 1.54, 1.35, 1.30 and 1.13 ppm, respectively. Similarly, the quadruplets of the methylene OC**H$_2$**CH$_3$ of **1**, **3** and **4** are shifted from 4.39, 4.43, and 4.29 ppm to 4.61, 4.30, and 4.42 ppm while the related multiplets 4.39–4.59 ppm (for **2**) and 4.31–4.59 ppm (for **5**) shifted to 4.04–4.27 ppm and 3.89–4.36 ppm, respectively. We propose that the silver cation is located nearby the sulphur atoms of the thiophosphates. The similarity of the general patterns of the free ligands and their complexes seems to indicate that the cone conformation is maintained during the complexation. $\Delta\delta$'s values for ArC**H$_2$**Ar (for **4** and **5**) were also observed to be higher than 0.5 ppm and we also conclude the silver cation to be located close to the methylene ring of the calix unit in

these ligands. When comparing ligands **6** and **7** containing both PS(OCH$_2$CH$_3$)$_2$ and CO$_2$CH$_2$CH$_3$ functions one can rationalize the data by a complexation of the silver cation in the cavity delineated by these functions and the methylene ring of the calixarene.

Pb^{2+} was complexed by ligands **2**, **3**, **5** and **6**. When compared with Ag$^+$ extraction, it appears that ligands **3** and **7**, which are fully functionalized by four PS(OCH$_2$CH$_3$)$_2$ (for **3**) and three PS(OCH$_2$CH$_3$)$_2$ and one CO$_2$CH$_2$CH$_3$ (for **7**), present steric hindrance preventing complexation of the larger Pb^{2+}. The fact that **6** also extracts Pb^{2+} in spite of bearing four substituents indicates that CO$_2$CH$_2$CH$_3$ is less bulky a substituant than PS(OCH$_2$CH$_3$)$_2$. For ligand **4**, which bears only two PS(OCH$_2$CH$_3$)$_2$ groups, it seems that the necessary number of chelating atoms for complexation is not fulfilled. However, comparison with **3** shows that the sulphur atoms present are able to chelate Pb^{2+}. As for silver, the $\Delta\delta$'s values are the largest when all OCH$_2$CH$_3$ (belonging to both PS(OCH$_2$CH$_3$)$_2$ and CO$_2$CH$_2$CH$_3$ functions) are involved in the complexation. One can assume Pb^{2+} to be located in the same site than Ag$^+$.

Zn^{2+} was extracted by **3**, **6** and **7** which are the ligands fully functionalized in the series, which shows that this metal needs more coordinating atoms than Pb^{2+}. When comparing the data for Zn^{2+} complexation by **6** with those for Ag$^+$ and Pb^{2+}, it appears that the spectral modifications

are larger for the thiophosphate diethyl ester region. This allows to postulate that Ag^+ and Pb^{2+} are more deeply engaged in the calixarene molecule and closer to the oxygen atoms of the calixarene unit. Similar findings were made when studying the complexation of Zn^{2+} by ligand **7**.

Conclusions

The present work reports the synthesis and characterisation of novel *thia*calix[4]arenes and calix[4]arenes bearing two to four thiophosphate substituents except for the tetrasubstituted calix[4]arene probably because of steric hindrance. As expected for these sulphur-enriched *thia*calixarenes, evidence was made of their affinity for heavy metal ions. Extraction and complexation levels increase with the number of thiophosphates groups. In particular Ag^+ is quantitatively extracted by the tetrasubstituted derivative. Of interest is also the formation of the most stable complex of the tris-substituted derivative with Cd^{2+} which is noticeable because receptors of cadmium are scarcely found in the literature [19]. The best extracted metals were located nearby the sulphur atoms. The results show that the introduction of sulphur atoms in the macrocyclic framework modifies completely the selectivity profiles. Whilst *thia*calixarenes are in general better extractants than calixarenes suggesting the contribution of the bridging sulphur to the coordination, the selectivity remains in favour of calixarenes.

References

1. (a) Gutsche, C.D.: Calixarenes. The Royal Society of Chemistry, Cambridge (1989); (b) Gutsche, C.D.: Calixarenes revisited. The Royal Society of Chemistry, Cambridge (1998); (c) Böhmer, V., Vicens, J. (eds.): Calixarenes: a versatile class of macrocyclic compounds. Kluwer Academic Publishers, Dordrecht, The Netherlands (1991); (d) Asfari, Z., Böhmer, V., Harrowfield, J., Vicens, J. (eds.): Calixarenes 2001. Kluwer Academic Publishers, Dordrecht (2001); (e) Asfari, Z., Harrowfield, J., Vicens, J. (eds.): Calixarenes 50th Anniversary: Commemorative Volume. Kluwer Academic Publishers, Dordrecht, The Netherlands (1994); (f) Harrowfield, J., Vicens, J. (eds.): Calixarenes in the Nanoworld Springer, Dordrecht, The Netherlands (2007)

2. (a) Kumagai, J., Hasegawa, M., Miyanari, S., Sugawa, Y., Sato, Y., Hori, T., Ueda, S., Kamiyama, H., Miyano, S.: Facile synthesis of *p-tert*-butylthiacalix[4]arene by reaction of *p-tert*-butylphenol with elemental sulphur in the presence of a base. Tetrahedron Lett. **38**, 3971–3972 (1997); (b) Iki, N., Kabuto, C., Fukushima, T., Kumagai, H., Takeya, H., Miyanari, S., Miyashi, T., Miyano, S.: Synthesis of *p-tert*-butylthiacalix[4]arene and its inclusion properties. Tetrahedron. **56**, 1437–1443 (2000); (c) Hosseini, M.W.: Thia-, mercapto-, and thiamercaptocalix[4]arenes. In: Asfari, Z., Böhmer, V., Harrowfield, J., Vicens, J. (eds.) Calixarenes 2001, pp. 110–129. Kluwer Academic Publishers, Dordrecht, The Netherlands (2001); (d) Iki N., Miyano, S.: Can thiacalixarenes surpass calixarenes? J. Incl. Phenom. Macroc. Chem. **41**, 99–105 (2001); (e) Shokova, E.A., Kovalev, V.: Thiacalixarenes—a new class of synthetic receptors. Russian J. Org. Chem. **39**, 13–40 (2003); (f) Lhotak, P.: Chemistry of Thiacalixarenes. Eur. J. Org. Chem. 1675–1692 (2004); (g) Morohashi, N., Narumi, F., Iki, N., Hattori, N.T., Miyano, S.: Thiacalixarenes. Chem. Rev. **106**, 5291–5316 (2006)

3. See for recent examples: (a) Dvorakova, H., Lang, J., Vlach, J., Sykora, J., Cajan, M., Himl, M., Pojarova, M., Stibor, I., Lhotak, P.: Partially O-alkylated Thiacalix[4]arenes: synthesis, molecular and crystal structures, Conformational Behavior. J. Org. Chem. **72**, 7157–7166 (2007); (b) Cao, S., Yuan, D., Lü, J., Li, T., Cao, R.: Multilayer films of single-component and charged tetraaminocalix[4]arenes based on hydrogen bonding. Chem. Commun. 1813–1815 (2007); (c) Sykora, J., Himl, M., Stibor, I., Cisarova, I. Lhotak, P.: Unique self-assembly patterns based on thiacalix[4]arene–silver interactions. Tetrahedron, **63**, 2244–2248 (2007); (d) Tran, H.-A., Georghiou, P.E.: Synthesis and complexation study of (1,4-linked)-homothiaisocalixnaphthalenes. New J. Chem. **31**, 921–926 (2007); (e) Chakrabarti, A., Chawla, H.M., Pant, N., Singh, S.P., Upreti, S.: Synthesis of conformationally diverse tetrathiacalix[4]arene(amido)crowns and tetrathiacalix[4]arene amides with pendant amine functions. Tetrahedron. **62**, 8974–8981 (2006); (f) Csokai, V., Grün, A., Balazs, B., Simon, A., Toth, G., Bitter, I.: Functionalized thiacalix- and calix[4]arene-based Ag^+ ionophores: synthesis and comparative NMR study. Tetrahedron. **62**, 10215–10222 (2006)

4. (a) Arnaud-Neu, F., McKervey, M.A., Schwing-Weill, M.J.: Metal-Ion complexation by narrow rim carbonyl derivatives. In: Asfari, Z., Böhmer, V., Harrowfield, J., Vicens, J. (eds.) Calixarenes 2001, pp. 385–406. Kluwer Acadamic Publishers, Dordrecht, The Netherlands (2001); (b) Casnati, A., Ungaro, R., Asfari, Z., Vicens, J.: Crown ethers derived from calix[4]arenes. In: Asfari, Z., Böhmer, V., Harrowfield, J., Vicens, J. (eds.) Calixarenes 2001, pp. 365–384. Kluwer Acadamic Publishers, Dordrecht, The Netherlands (2001); (c) Lamare, V., Dozol, J.F., Thuéry, P., Nierlich, M., Asfari, Z., Vicens, J.: Experimental and theoretical study of the first thiacalixcrowns and their alkali metal ion complexes. J. Chem. Soc. Perkin Trans. **2**, 1920–1925 (2001); (d) Bouhroum, S., Arnaud-Neu, F., Asfari, Z., Vicens, J.: Tetra(diethyl)amide *p-tert*-butyl-thiacalix[4]arene in cone conformation: synthesis and binding properties with alkali, alkaline earth, heavy and transition metal ions. Supramol. Chem. **17**, 629–635 (2005); (e) Bouhroum, S., Arnaud-Neu, F., Asfari, Z., Vicens, J.: Ionic recognition by thiacalixarenes: binding of alkali and heavy metal ions by thiacalix[4]arene-bis-crowns. Russian Chem. Bull. Int. Ed. **53**, 1544–1548 (2004)

5. Floriani, C., Jacoby, D., Chiesi-Villa, A., Guastini, C.: Aggregation of metal ions with functionalized calixarenes: synthesis and structure of an octanuclear copper(I) chloride complex. Angew. Chem. Int. Ed. Engl. **28**, 1376–1381 (1989)

6. Sheldrick, G.M.: SHELXTL, Version 5.1. Bruker AXS Inc, Madison, WI, USA (1999)

7. Otwinowski, Z., Minor, W.: Processing of X-ray diffraction data collected in oscillation mode. Methods Enzymol. **276**, 307–326 (1997)

8. Sheldrick, G.M.: SHELXS–97 and SHELXL–97. University of Göttingen, Germany (1997)

9. (a) Pedersen, C.J.: New macrocyclic polyethers. J. Amer. Chem. Soc. **92**, 391–394 (1970); (b) Frensdorff, H.K.: Salt complexes of cyclic polyethers. Distribution equilibriums. J. Am. Chem. Soc. **93**, 4684–4688 (1971)

10. Arnaud-Neu, F., Schwing-Weill, M.J., Ziat, K., Cremin, S., Harris, S.J., McKervey, M.A.: Selective alkali and alkaline-earth cation complexation by calixarene amides. New J. Chem. **15**, 33–37 (1991)

11. Aggarwal, R.C., Singh, N.K.: Synthesis and characterization of some first row transition metal picrates. Def. Sci. J. **25**, 153–158 (1975)

12. Arnaud-Neu, F., Collins, E.M., Deasy, M., Ferguson, G., Harris, S.J., Kaitner, B., Lough, A.J., McKervey, M.A., Marques, E., Rhul, B.L., Schwing-Weill, M.J., Seward, E.M.: Synthesis, X-ray crystal structures and cation-binding properties of alkyl calixaryl esters and ketones, a new family of macrocyclic molecular receptors. J. Am. Chem. Soc. **111**, 8681–8691 (1989)

13. Gampp, H., Maeder, M., Meyer, C.J., Zuberbuehler, A.D.: Calculation of equilibrium constants from multiwavelength spectroscopic data II Specfit: two user-friendly programs in basic and standard fortran 77. Talanta **32**, 257–264 (1985)

14. Steyer, S., Jeunesse, C., Armspach, D., Matt D., Harrowfield, J.: Coordination chemistry and catalysis. In: Asfari, Z., Böhmer, V., Harrowfield, J., Vicens, J. (eds.) Calixarenes 2001, pp. 513–535. Kluwer Acadamic Publishers, Dordrecht, The Netherlands (2001)

15. (a) Roundhill, D.M., Georgiev E., Yordanov, A.: Calixarenes with nitrogen or phosphorus substituents on the lower rim. J. Incl. Phenom. **19**, 101–109 (1994); (b) Lukin, O., Vysotsky, M.O., Kalchenko, V.I.: O-Phosphorylated calix[4]arenes as Li$^+$-selective receptors. J. Phys. Org. Chem. **14**, 468–473 (2001)

16. Selkti, M., Coleman, A. W., Routaboul, J.; Kalchenko, V.I., Tomas, A., Villain, F., de Rango, C.: Crystal structure of [mono-O-(diethoxy)thiophosphonato]tetra-tert-butyl-calix[4]arene, C$_{48}$H$_{66}$O$_6$PS. Z. Kristallogr. New Cryst. Struct. **214**, 224–226 (1999)

17. Cox, B.G., Garcia-Rosas, J., Schneider, H.: Solvent dependence of the stability of cryptate complexes. J. Am. Chem. Soc. **103**, 1384–1389 (1981)

18. Several Ag$^+$-selective ionophores based on *thia*calix- and calix[4]arenes have been described, see for example: (a) Bhalla, V., Babu, J.N., Kumar, M., Hattori, T., Miyano, S.: Synthesis and binding studies of novel thiacalixpodands and bisthiacalixarenes having O,O″-dialkylated thiacalix[4]arene unit(s) of 1,3-alternate conformation. Tetrahedron Lett. **48**, 1581–1585 (2007); (b) van Leeuwen, F.W.B., Beijleveld, H., Kooijman, H., Spek, A.L., Verboom, W., Reinhoudt, D.N.: Cation control on the synthesis of p-t-butylthiacalix[4](bis)crown ethers. Tetrahedron Lett. **43**, 9675–9678 (2002); (c) Zeng, X., Weng, L., Chen, L., Leng, X., Ju, H., He, X., Zhang, Z.Z.: The synthesis of some pyridyl functionalized calix[4]arenes as the sensor molecule for silver ion-selective electrodes. J. Chem. Soc. Perkin Trans. **2**, 545–549 (2001); (d) Lee, J.Y., Kwon, J., Park, C. S., Lee, J.E., Sim, W., Kim, J.S., Seo, J., Yoon, I., Jung J.H., Lee, S.S.: Calix[4]thiacrowns as ditopic hosts for homo- and heterobinuclear accommodation: First report of a chopsticks-type -coordination. Org. Lett. **9**, 493–496 (2007)

19. Esteban, D., Banobre, D., de Blas, A., Rodriguez-Blas, T., Bastida, R., Macias, A., Rodriguez, A., Fenton, D.E., Adams, H., Mahia, J.: Cadmium(II) and Lead(II) Complexes with novel macrocyclic receptors derived from 1,10-Diaza–15-crown-5. Eur. J. Inorg. Chem. 1445–1456 (2000)