THE JOURNAL OF
PHYSICAL CHEMISTRY B

ARTICLE

pubs.acs.org/JPCB

Calixarene and Resorcarene Based Receptors: From Structural and Thermodynamic Studies to the Synthesis of a New Mercury(II) Selective Material

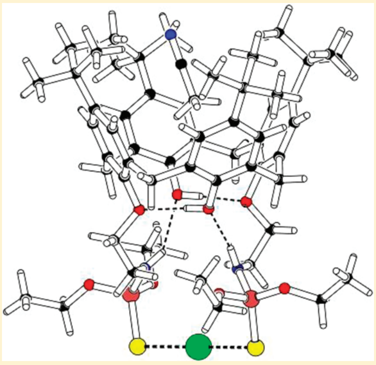
Angela F. Danil de Namor,*[†] Walther Aparicio-Aragon,[†] Nwanyinnaya Nwogu,[†] Abdelaziz El Gamouz,[†] Oscar E. Piro,[‡] and Eduardo E. Castellano[§]

[†]Thermochemistry Laboratory, Chemical Science Division, Faculty of Health and Medical Sciences, University of Surrey, Guildford, Surrey, GU2 7XH United Kigdom

[‡]Departamento de Fisica, Facultad de Ciencias Exactas, Universidad Nacional de La Plata, and Instituto IFLP (CONICET-UNLP), C.C. 67, 1900 La Plata, Argentina

[§]Instituto de Fisica de Sao Carlos, Universidade de Sao Paulo, C.P.369, 13560 Sao Carlos (SP), Brazil

Supporting Information



ABSTRACT: Materials used in current technological approaches for the removal of mercury lack selectivity. Given that this is one of the main features of supramolecular chemistry, receptors based on calix[4]arene and calix[4]resorcarene containing functional groups able to interact selectively with polluting ions while discriminating against biologically essential ones were designed. Thus two receptors, a partially functionalized calix[4]arene derivative, namely, 5,11,17,23-tetra-*tert*-butyl [25−27-bis(diethyl thiophosphate amino)dihydroxy] calix[4]arene (**1**) and a fully functionalized calix[4]resorcarene, 4,6,10,12,16,18,22,24-diethyl thiophosphate calix[4]resorcarene (**2**) are introduced. Mercury(II) was the identified target due to the environmental and health problems associated with its presence in water Thus following the synthesis and characterization of **1** and **2** in solution (^{1}HNMR) and in the solid state (X-ray crystallography) the sequence of experimental events leading to cation complexation studies in acetonitrile and methanol (^{1}H NMR, conductance, potentiometric, and calorimetric measurements) with the aim of assessing their behavior as mercury selective receptors are described. The cation selectivity pattern observed in acetonitrile follows the sequence Hg(II) > Cu(II) > Ag(I). In methanol **1** is also selective for Hg(II) relative to Ag(I) but no interaction takes place between this receptor and Cu(II) in this solvent. Based on previous results and experimental facts shown in this paper, it is concluded that the complexation observed with Cu(II) in acetonitrile occurs through the acetonitrile-receptor adduct rather than through the free ligand. Receptor **2** has an enhanced capacity for uptaking Hg(II) but forms metalate complexes with Cu(II). These studies in solution guided the inmobilization of receptor **1** into a silica support to produce a new and recyclable material for the removal of Hg(II) from water. An assessment on its capacity to extract this cation from water relative to Cu(II) and Ag (I) shows that the cation selectivity pattern of the inmobilized receptor is the same as that observed for the free receptor in methanol. These findings demonstrate that fundamental studies play a critical role in the selection of the receptor to be attached to silicates as well as in the reaction medium used for the synthesis of the new decontaminating agent.

INTRODUCTION

Calixarenes (products of condensation reaction between ρ-substituted phenol and aldehydes in alkaline medium) and calixresorcarenes (synthesized from resorcinol and formaldehyde in acid medium) and their derivatives have been the subject of numerous investigations, most of them included in several books and review articles.[1−6] Although the emphasis has been much more on calixarenes than resorcarenes, in the past few years the latter receptors have attracted considerable attention. Following the chapter on chemical modification of these receptors by Thonford et al.,[7] several contributions on the synthesis, characterization, and complexing properties of calixresorcarenes with ionic and neutral species as well as their applications have been reported in the literature.[8−25]

An interesting development is the inmobilisation of these receptors into solid supports for the generation of new materials for the removal of ions from contaminated sources. The attachment of calixarenes to solid supports has been reported by several workers. Representative contributions are those by Uysal Akkus and co-workers,[26] Harris,[27] and Shinkai et al.[28] In recent years we have been particularly interested in receptors based on calix[4]arene,[29−32] calix[4]pyrrole,[33−39] and calix[4]resorcarene derivatives[19,23] able to interact with polluting cations (heavy metals) and anions (fluoride, arsenates). The main aim of this

Received: October 25, 2010
Revised: April 18, 2011
Published: May 05, 2011

dx.doi.org/10.1021/jp110195f | *J. Phys. Chem. B* 2011, 115, 6922–6934

work is to anchor these receptors into solid supports in an attempt to explore the scope of supramolecular chemistry for the design of new decontaminating agents for water purification purposes.[40] In this paper the identified target is the mercury(II) cation. It is well established that the presence of mercury in the environment is a serious threat to human health.[41−43] Chemical technologies for the removal of mercury from water have limitations mainly due to the lack of selectivity of the materials used.[44,45] Here we introduce two new receptors, a partially functionalized calix[4]arene derivative, namely 5,11,17,23-tetra-*tert*-butyl [25−27-bis(diethyl thiophosphate amino) dihydroxy calix[4]arene, **1** and a fully functionalized calix[4]resorcarene, 4,6,10,12,16,18,22,24-diethyl thiophosphate calix[4]resorcarene, **2**. The design of these receptors is based on the following facts

(i) Receptor **1** differs from a previously reported receptor **3**[46] in that the carbonyl oxygens in the pendant arms have been replaced by sulfur donor atoms in an attempt to enhance its selectivity for mercury(II) and at the same time discriminate against the uptake of biologically essential cations.

(ii) Receptor **2** makes use of the possibility offered by calix[4]resorcarene of substantially increasing the number of donor atoms in the pendant arms through functionalization of the hydroxyl groups. The aim was to increase the hosting capacity of this receptor for the mercury(II) cation.

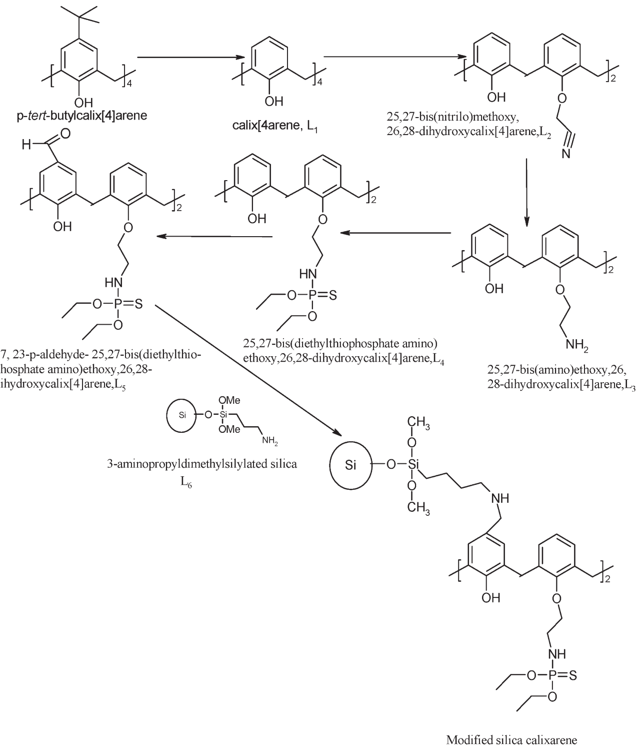
Thus the synthesis, the structural (^{1}H NMR and X-ray crystallography) and thermodynamic characterization of these receptors and their cation complexing properties through a detailed investigation which also includes the X-ray structure of the silver(I)−acetonitrile−**1** complex are reported. A comparative assessment with an analogous ligand is also carried out. In doing so only those systems for which thermodynamic data are available are considered. The experimentally determined structural and thermodynamic studies were used to guide the synthetic formulation of the obtained mercury selective calix[4]arene based material. Preliminary investigations on its ability for extracting mercury(II) from aqueous solution have been carried out and the cation extraction pattern of the inmobilised receptor is compared with that observed in solution. The role of cation hydration/solvation in the extraction/complexation processes is discussed.

■ EXPERIMENTAL SECTION

Synthesis of 5,11,17,23-Tetra-*tert*-butyl[25,27-bis(diethylthiophosphate amino) ethoxy-26,28-dihydroxycalix[4]arene, 1. In a three-necked round-bottomed flask (250 mL) equipped with an ice-bath, 5,11,17,23-tetra-*tert*-butyl-25,27-bis[amino]ethoxy-26,28-dihydroxycalix[4]arene,[46] (4.887 g, 6.65 mmol), potassium carbonate (1.369 g, 9.91 mmol), and potassium hydrogen carbonate (1.77 g, 17.73 mmol) were suspended in dry dichloromethane (CH_2Cl_2; 100 mL). The mixture was left under continuous stirring for 30 min. This was followed by dropwise addition of diethyl chlorothiophosphate (1 mL, 7.94 mmol). The reaction mixture was left at room temperature for 48 h under vigorous stirring. The course of the reaction was monitored by TLC using dichloromethane:methanol (9:1) mixture as the developing solvent system.

The solvent was removed under reduced pressure, and a white solid was afforded. The solid was recrystallized from methanol:chloroform (4:1). The mixture was left overnight at room temperature and the crystals furnished were left in a piston drier at 60 °C.

Scheme 1



The product obtained (70% yield) was characterized by ^{1}H spectroscopy, microanalysis, and X-ray crystallography. Melting point 169−170 °C. ^{1}H NMR (300 MHz, in $CDCl_3$); δ (ppm), J (Hz); 8.59 (s, 2H, Ar-**OH**), 7.03 (s, 8H, Ar-**H**), 5.60 (t, 2H, J = 11.10, $-CH_2-$**NH**-), 4.34 (d, 4H, J = 13.20, Ar−$\mathbf{CH_2ax}$-Ar), 4.13 (m, 12H, −O-$\mathbf{CH_2}$-CH_2, O−$\mathbf{CH_2}$-CH_3), 3.62 (m, 4H, $-CH_2-$$\mathbf{CH_2}$-NH), 3.38 (d, 4H, J = 12.91, Ar−$\mathbf{CH_2eq}$-Ar), 1.32 (t, 12H, O−CH_2-$\mathbf{CH_3}$), 1.24 (s, 18H, -C-$(\mathbf{CH_3})_3$), 1.15 (s, 18H, -C-$(\mathbf{CH_3})_3$).

Elemental analysis was carried out at the University of Surrey. Calculated %: C, 64.71; H 8.15; N 2.70; Found %: C, 64.62; H, 8.12; N, 2.67.

Synthesis of 4,6,8,10,12,16,18,22,24-Diethyl thiophosphate calix[4]resorcarene, 2. In a three-necked round-bottomed (250 mL) flask, resorcarene (2 g. 3.73 mmol), potassium carbonate (8.29 g, 60 mmol), and 18-crown-6 (0.8 g, 3.0 mmol) were suspended in dry acetonitrile and stirred for 1 h under a nitrogen atmosphere. Then diethyl chlorothiophosphate (9.2 mL, 59 mmol) was added dropwise with continuous stirring. The reaction was refluxed at 80 °C overnight and then rota-evaporated. The product was extracted with dichloromethane and rota-evaporated a second time to get a brown oil. The oil was triturated with methanol to obtain a white powder. Finally it was recrystallized in dichloromethane to give white crystals.

The product obtained (1.4 g, 0.90 mmol, 24.1% yield) was characterized by ^{1}H NMR spectroscopy, microanalysis, and X-ray crystallography.

^{1}H NMR in CD_3CN (300 MHz) δ (ppm) 7.530 (s, 2H Ar, H-1); 7.029 (s, 2H Ar, H-1^1); 5.991, (s, 2H, Ar H-2); 4.689 (q, 1H H-3); 1.553, (d, 3H, H-4);1.430 (t, 2H H-5), 1.360, (t, 2H H-5^1); 4.354, (q, 3H, H-6); 4.074, (q, 3H, H-6^1).

Microanalysis was carried out at the University of Surrey. Calculated % C, 43.63, H, 5.95; Found %, C, 43.51, H, 6.13.

Synthesis of the Silver-Acetonitrile Complex of 1. To a suspension of the ligand was added a 20% excess of solution of the metal-ion salt in acetonitrile. The mixture was stirred until a clear solution was obtained. This was filtered out and the filtrate was left to evaporate until colorless crystals were observed. These were separated from the solution and dried at 60 °C at reduced pressure for several days. The silver complex (perchlorate as counterion) was isolated from acetonitrile.

Synthesis of a Silicate-Based Material Containing 1 as an Anchor Group. The synthetic route used for the attachment of **1** to a silicate is shown in Scheme 1. L1 was obtained by the ditert-butylation of the parent calix[4]arene through a catalyzed retro-Friedel−Craft reaction described by Gutsche and co-workers[2,5] The product obtained (90% yield) was characterized by ^{1}H NMR spectroscopy.

^{1}H NMR (300 MHz, in $CDCl_3$); δ (ppm), J (Hz); 10.22 (s, 1H, Ar−OH), 7.07 (d, 2H, J = 7.50, Ar−H), 6.75 (t, 1H, J = 6.90, Ar−H), 4.26 (br, 1H, Ar−CH_2ax-Ar), 3.56 (br, 1H, Ar−CH_2eq-Ar). L_2, L_3, and L_4 were obtained using the same procedures shown above for the synthesis of **1**. These ligands were also characterized by ^{1}H NMR. The data are shown as follows.

L_2: ^{1}H NMR (300 MHz, in $CDCl_3$); δ (ppm), J (Hz); 7.07 (d, 2H, J = 4.50, Ar-**H**), 6.98 (d, 2H, J = 13.80, Ar-**H**), 6.81 (t, 1H, J = 5.10, Ar-**H**), 6.66 (t, 1H, J = 7.8, Ar-**H**), 4.35 (d, 2H, J = 12.60, Ar−$\mathbf{CH_2}$**ax**-Ar), 4.11 (t, 4H, J = 4.50, −O-$\mathbf{CH_2}$-CH_2−), 3.43 (d, 2H, J = 12.90, Ar−$\mathbf{CH_2}$**eq**-Ar), 3.35 (t, 4H, J = 4.50,-$\mathbf{CH_2}$-NH_2). L_2 was obtained in 75% yield.

L_3: ^{1}H NMR (300 MHz, in $CDCl_3$); δ (ppm), J (Hz); 8.60 (s, 1H, Ar-**OH**), 7.05 (d, 2H, J = 7.50, Ar-**H**), 7.01 (d, 2H, J = 7.50, Ar-**H**), 6.84 (t, 1H, J = 7.50, Ar-**H**), 6.67 (t, 1H, J = 7.20, Ar-**H**), 5.45 (t, 1H, J = 10.80, −CH_2−**NH**-), 4.36 (d, 2H, J = 12.90, Ar−$\mathbf{CH_2}$**ax**-Ar), 4.12 (m, 6H, −O-$\mathbf{CH_2}$-CH_2, O−$\mathbf{CH_2}$-CH_3), 3.74 (m, 2H, −CH_2−$\mathbf{CH_2}$-NH), 3.43 (d, 2H, J = 12.90, Ar−$\mathbf{CH_2}$**eq**-Ar), 1.30 (t, 6H, J = 7.50, O−CH_2-$\mathbf{CH_3}$). The product was obtained in 60% yield.

L_4: ^{1}H NMR (300 MHz, in $CDCl_3$); δ (ppm), J (Hz); 9.79 (s, 1H, Ar−CHO), 9.30 (s, 1H, Ar−OH), 7.64 (s, 2H, Ar−H), 7.64 (s, 2H, Ar−H), 7.05 (d, 2H, J = 6.90, Ar−H), 6.88 (t, 1H, J = 7.20, Ar−H), 5.02 (t, 1H, J = 6.00, −CH_2−NH-), 4.37 (d, 2H, J = 13.50, Ar−CH_2ax-Ar), 4.19 (t, 2H, J = 4.50, −O−CH_2-CH_2), 4.11 (m, 4H, O−CH_2-CH_3), 3.73 (m, 2H, −CH_2−CH_2−NH), 3.56 (d, 2H, J = 13.00, Ar−CH_2eq-Ar), 1.31 (t, 6H, J = 6.60, O−CH_2-CH_3). The product was obtained in 60% yield.

For the synthesis of 5,17-*p*-aldehyde-25,27-bis-(diethylthiophosphate amino) ethoxy-26,28-dihydroxycalix-[4]arene, L_5, in a dry 250 cm^3 three-necked round-bottomed equipped with a dry ice-bath, L_4 (1.00 g, 1.22 mmol) in dichloromethane (50 cm^3) was cooled to −10 °C. Then, dichoromethyl methyl ether (2.0 cm^3, 19.52 mmol) and tin(IV) chloride (20.0 cm^3, 20 mmol) were added. The resulting mixture was stirred for 30 min at −10 °C. The reaction was quenched by the addition of water (50 cm^3). The aqueous phase was separated, and NaOH (0.2M) was added (50 cm^3). The aqueous phase was extracted with dichloromethane, and the organic layer was dried over magnesium sulfate and concentrated in vacuo affording a yellow solid, which was recrystallized from methanol. The product was obtained in 60% yield.

^{1}H NMR (300 MHz, in $CDCl_3$); δ (ppm), J (Hz); 9.79 (s, 1H, Ar−**CHO**), 9.30 (s, 1H, Ar−**OH**), 7.64 (s, 2H, Ar-**H**), 7.64 (s, 2H, Ar-**H**), 7.05 (d, 2H, J = 6.90, Ar-**H**), 6.88 (t, 1H, J = 7.20, Ar-**H**), 5.02 (t, 1H, J = 6.00, −CH_2−**NH**-), 4.37 (d, 2H, J = 13.50, Ar−$\mathbf{CH_2}$**ax**-Ar), 4.19 (t, 2H, J = 4.50, −O-$\mathbf{CH_2}$-CH_2), 4.11 (m, 4H, O−$\mathbf{CH_2}$-CH_3), 3.73 (m, 2H, −CH_2−$\mathbf{CH_2}$-NH), 3.56 (d, 2H, J = 13.00, Ar−$\mathbf{CH_2}$**eq**-Ar.

Synthesis of 3-Aminopropyldimethylsilylated Silica, L_6. In a three-necked round-bottomed flask (250 mL) equipped with a condenser, dried silica (5 g) was dispersed in anhydrous toluene (100 cm^3). To the resulting slurry under a nitrogen atmosphere was added 3-aminopropyltrimethylsilane (2.5 g, 22.3 mmol). The resulting mixture was refluxed for 6 h and then cooled to 25 °C. It was then filtered and washed first with toluene and then with methanol.

Elemental analysis was carried out at the University of Surrey. Calculated %: C, 3.47; H, 0.81; N, 0.82; found %: C, 3.36; H, 0.75; N, 1.00.

Synthesis of Modified Silica. In a three-necked round-bottomed flask (250 mL) equipped with a condenser anhydrous, 3-aminopropyldimethylsilylated silica L_6 (1 g, 0.75 mmol) in absolute methanol (50 cm^3), (the pH of solution kept to 1 by the addition of a methanolic solution of HCl), L_5 (0.70 g, 0.96 mmol), and sodium cyanoboron hydride (0.07 g, 0.96 mmol) were added under a nitrogen atmosphere. The resulting slurry was stirred at 25 °C for 72 h. Then HCl (12 M) was added to the slurry until pH 1. The acidified slurry was filtered, and the resulting solid was washed (to remove impurities) with dichloromethane (50 cm^3), chloroform (50 cm^3), acetone (50 cm^3), ethanol (50 cm^3), methanol (50 cm^3), aqueous NaOH (50 cm^3), and water (50 cm^3) before being dried over $CaCl_2$ in vacuo for 12 h. Elemental analysis was carried out at the University of Surrey. Calculated %: C, 13.47; H, 2.01; N, 1.61; found %: C, 12.97; H, 1.94; N, 1.58.

X-ray Diffraction Data. The measurements on all compounds were performed at low temperature on an Enraf-Nonius Kappa-CCD diffractometer with graphite-monochromated Mo Kα (λ = 0.71073 Å) radiation. Diffraction data were collected (φ and ω scans with κ-offsets) with COLLECT.[47] Integration and scaling of the reflections was performed with the HKL DENZO-SCALEPACK[48] suite of programs. The unit cell parameters were obtained by least-squares refinement based on the angular settings for all collected reflections using HKL SCALEPACK.[48] Data of the silver complex were corrected numerically for absorption with PLATON[49] and also for extinction. The structures were solved by direct methods with SHELXS-97[50] and the molecular models refined by full-matrix least-squares procedure on F^2 with SHELXL-97.[51] The hydrogen atoms were positioned stereochemically and refined with the riding model. Further details on crystal data and refinement results are provided as Supporting Information.

Solubility Measurements. Saturated solutions were obtained by adding an excess amount of the appropriate receptor to various solvents. The mixtures were left for several days in a thermostat bath at 298.15 ± 0.02 K until equilibrium was attained. The solid was separated from the saturated solution. Accurate volumes of the saturated solution were taken and these were placed in different porcelain crucibles. The crucibles were initially washed, dried, weighed, and labeled. The solvents were evaporated until the weight of the crucible containing the solid became constant. Blank experiments were carried out to ensure the absence of impurities. The gravimetric analysis was done in triplicate on the same saturated solution.

Solvate formation was checked by placing a known amount of the ligand on a watch glass for several days over the appropriate solvent placed at the bottom of a closed desiccator to ensure a saturated atmosphere of the solvent.[52]

^1H NMR Measurements. ^1H NMR measurements were performed by using a Bruker AC-300E pulsed Fourier transform NMR spectrometer. The operating conditions for routine proton measurements involved a pulse or flip angle of 30°, spectral frequency (SF) of 300.137 MHz, delay time of 1.60 s, acquisition time (AQ) of 1.819 s, and line broadening of 0.55 Hz. The sample in the appropriate solvent ($\sim$0.5 cm^3) was placed in 5 mm NMR tubes using TMS (tetramethylsilane) as the internal reference, and the experimental temperature was 298 K.

The ligand (depending on its molecular weight) was dissolved in the deuterated solvent (3 mL) to give solutions within the concentration ranges from 9.0×10^{-4} to 1.2×10^{-3} mol dm^{-3} for **1** and from 3.0×10^{-4} to 2.5×10^{-3} mol dm^{-3} for **2**. The ^1H NMR spectrum was obtained and analyzed. Then a solution of the metal cation salt (from 7.0×10^{-3} to 2.0×10^{-2} mol dm^{-3}) for **1** and $\sim 1.0 \times 10^{-2}$ mol dm^{-3} for **2** in the appropriate solvent was added. For the titrations involving **1**, stepwise additions of varying amount of the metal—cation salt were made until chemical shift changes vanished. ^1H NMR measurements involving **2** were carried out by adding an excess of salt to a solution of the ligand. The chemical shift changes relative to those for the ligand were then calculated. TMS was used as the internal reference.

Conductometric Studies. Conductance measurements were used to determine (i) the composition of the metal ion complex and (ii) to establish the concentration range at which salts are predominantly in their ionic forms in solution.

(i) ConductImetric titrations were carried out in a conductivity cell filled with a weighed volume of the solution containing the cation salt of interest. The vessel was a glass cylinder wrapped in a thermostatic jacket and maintained at 298.15 K with a water bath. The vessel was mounted on a stand and equipped with a magnetic stirrer under a continuous flow of nitrogen. The solution of the ligand ($\sim 1.00 \times 10^{-3}$ mol dm^{-3}) was added to the vessel which contained the cation salt solution ($\sim 1.00 \times 10^{-4}$ mol dm^{-3}) in the same solvent in a step—wise titration using a glass syringe connected to a calibrated automatic buret. Readings as conductance values were recorded once equilibrium of the mixture was achieved ($\sim$3 min). This is indicative that the kinetics of the process is fast, an important requirement for the use of this receptor in extraction processes.

(ii) To determine the concentration range at which salts are predominantly in their ionic forms in solution, salts involving bivalent cations were used and their conductances at different concentrations were measured at 298.15 K. The molar conductance at different concentrations was measured and plotted against the square root of the concentration.

Potentiometric Measurements. A digital microprocessor pH/mV-meter HANNA model pH 213 Microprocessor pH-Meter was used to measure the potential changes during the course of the titration.

For the potentiometric titration, a reversible silver selective electrode was used with a silver/silver reference electrode. The indicator and the reference silver electrodes consisted of silver rods, immersed each in a separate jacket-thermostatted glass vessel, maintained at 298.15 ± 0.05 K. The reference silver electrode was immersed in a solution of silver perchlorate in acetonitrile or methanol and the indicator electrode in a solution of tetra-*n*-butyl ammonium perchlorate (TBAP), while the titration was performed and the activity of the free silver was measured. Constant ionic strength was maintained by using TBAP (0.05 mol dm^{-3}) in all solutions, including the filling solution of the salt bridge between the two glass vessels. The titrant was added with a micropipet.

Potentiometric Titration Using the Mercury Amalgam Electrode. The stability constant of **1** and the mercury(II) cation was measured by potentiometric titration using the Metrohm 716 DMS Titrino equipped with a calomel ($Hg/Hg_2Cl_2/KCl$) reference double junction electrode (Russell). Its internal electrolyte was a saturated solution of LiCl in ethanol, whereas the outer (salt bridge) electrolyte was a solution of TBAP (0.05 mol dm^{-3}) in acetonitrile or methanol. The concentration of the free cation was measured using a mercury amalgam indicator electrode. Both electrodes were connected to a compact automatic titrator- processor. All titrations were carried out under a nitrogen atmosphere. For the calibration experiments, the vessel was filled with a solution of TBAP in the appropriate solvent (20 mL, 0.05 mol dm^{-3}), whereas the buret was filled with a solution of $Hg(ClO_4)_2$ ($\sim 3 \times 10^{-3}$ mol dm^{-3}). After thermal equilibrium was reached, the automatic addition of titrant proceeded. Data were collected by a Hyperaccess data system. The Nernstian behavior of the electrode was evaluated from the slope of a plot of potential against $-\log[Hg(II)]$.

For the determination of the stability constant, the ligand solution ($\sim 1 \times 10^{-3}$ mol dm^{-3}) was prepared in a tetra-n-butyl ammonium perchlorate (TBAP) solution (0.05 mol dm^{-3}) and placed in the buret. The vessel solution containing a known concentration of Hg (II) was titrated with the ligand allowing the formation of the 1:1 mercury calixarenate complex. Data were collected by a Hyperaccess System and used for the calculation of the stability constant.

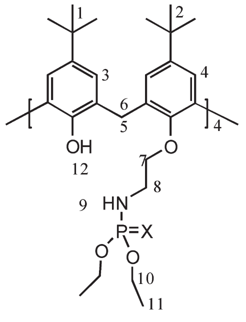
CALORIMETRIC STUDIES

Determination of the Enthalpy of Solution of 1 in Nonaqueous Solvents at 298.15 K. The accuracy of the TRONAC 450 equipment was checked by measuring the standard enthalpy of protonation of tris(hydroxymethyl)aminomethane, (THAM) with hydrochloric acid 0.1 mol dm^{-3} at 298.15 K.[53]

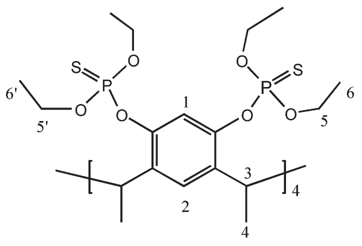
For measuring the enthalpies of solution, glass ampules containing accurately weighed amounts of the ligand in question were sealed and carefully placed in the stirring blade assembly. This was immersed in the calorimeter reaction vessel containing an accurate volume of the appropriate freshly distilled solvent (50 cm^3). The reaction vessel was then immersed in the thermostatted water bath and left for $\sim$20 min to reach thermal equilibrium. The reaction was subsequently initiated by breaking the ampule in the appropriate solvent and the resulting temperature change recorded. In all cases, electrical calibration experiments were carried out by introducing a known quantity of electrical heat approximately equal to the energy change of the main reaction.

Corrections for the heat associated with the breaking of empty ampules in the appropriate solvent were applied. The heat evolved in the reaction was calculated using the method of correction described by Dickinson.[54]

For the determination of the stability constant and the enthalpy of complexation of these ligands with metal cations the TRONAC 450 and the thermal activity monitor (TAM) microcalorimeter were used. The instruments were calibrated



1 (X = S)
3 (X = O)



2

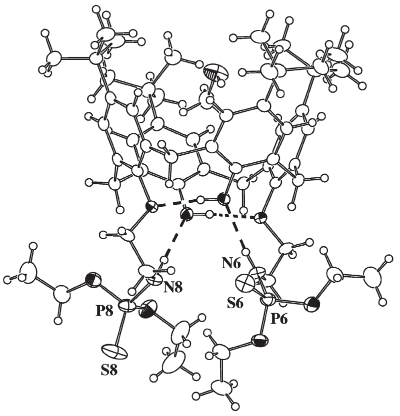


Figure 1. Side view of one molecular complex of **1** with methanol showing the non-H atoms displacement ellipsoids at the 50% probability level. Crossed ellipsoids denote nitrogen, sulfur, and phosphorus atoms, and the hatched ones, oxygen atoms. For clarity, only a few indicative atoms have been labeled. H-bonds are indicated by dashed lines.

electrically and chemically before the experiments were carried out as previously described.[38] For stability constants lower than 10^6 (log $K_s < 6$) direct calorimetric titrations were performed. Thus a solution of the metal−ion salt ($\sim 1.5 \times 10^{-2}$ mol dm^{-3}) was prepared in the appropriate solvent and placed in the buret. The metal−ion solution was titrated into the vessel containing a solution of the appropriate ligand (50 cm^3, $\sim 3.0 \times 10^{-4}$ mol dm^{-3}) prepared in the solvent of interest. To process the data, a CALLA.BAS and a KHNLR3 computer program written in basic language in the Thermochemistry Laboratory were employed when using the Tronac 450, while for the TAM microcalorimeter the computer program for TAM Digitam 4.1 for Windows from Thermometric AB was used to calculate log K_s and $\Delta_c H$ values.

Extraction Experiments. To determine the amount of mercury(II) extracted from water by the modified silica, column experiments were carried out. Thus a column (4.5 × 5.0 cm) was filled with the modified silicate (0.4 g) and an aqueous solution of mercury(II) picrate (1.56×10^{-3} mol dm^{-3}) was slowly pumped through the column. The effluent was collected and then analyzed by UV spectrophotometry.

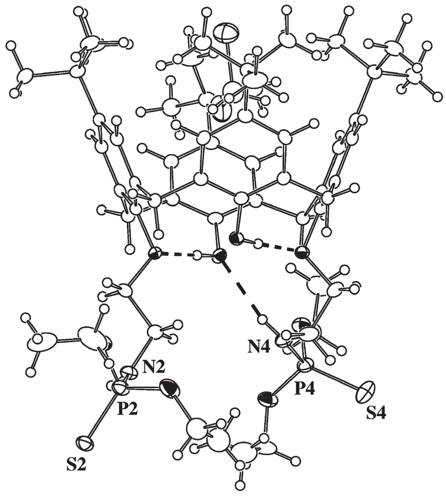


Figure 2. View of the molecular complex of **1** with dichloromethane.

■ RESULTS

Receptor 1. Under this heading the results obtained from solid state X-ray diffraction and solubility measurements of this receptor required for solution studies are presented together with results obtained from ^{1}H NMR, conductometry, calorimetry, and potentiometry which provide information regarding the cation complexing properties of this receptor in MeCN and MeOH.

As far as the X-ray crystallography is concerned, atomic fractional coordinates and equivalent isotropic displacement parameters for all compounds and corresponding full intramolecular bond distances and angles are available as Supporting Information in the format of a crystallographic information file (CIF). ORTEP[55] drawings of the adducts of **1** with methanol (**1a**) and dichloromethane (**1b**) are shown in Figures 1 and 2, respectively. Solubility data for **1** in acetonitrile (dipolar aprotic solvent), methanol, and ethanol (polar solvents) at 298.15 K are listed in Table 1. The solubility of **1** was enough as to determine calorimetrically the enthalpy of solution, $\Delta_s H$, also reported in Table 1. From solubility data, the standard solution Gibbs energy, $\Delta_s G°$, was calculated. These data are referred to the standard state of 1 mol dm^{-3}. Taking acetonitrile as the reference solvent, the standard transfer Gibbs energies to methanol and ethanol, $\Delta_t G°$, were evaluated. Combination of $\Delta_s H°$ and $\Delta_s G°$ for **1** in these solvents leads to the calculation of the entropy of solution, $\Delta_s S°$. Again transfer enthalpies, $\Delta_t H°$, and $\Delta_t S°$ from acetonitrile to methanol and ethanol were obtained

Results from ^{1}H NMR showed that the addition of alkali, alkaline-earth, and heavy metal cations to a solution of **1** in CD$_3$CN did not show chemical shift changes in any of the protons except for Hg(II) and Ag(I). Thus Figure 3 shows the ^{1}H NMR chemical shift changes relative to those for the free receptor ($\Delta\delta$) against the cation/receptor ratio in CD$_3$CN at 298 K for the titration of **1** with the mercury and silver cation salts respectively.

Conductance measurements revealed that the specific conductance,κ, was that of the solvent when different concentrations of **1** were measured in acetonitrile and methanol at the standard temperature. These findings are indicative that these ligands keep their neutrality (nonelectrolytes) in these solvents.

The conductometric titration data resulting from the addition of **1** to solutions of silver, mercury(II), and copper(II) salts (as perchlorates) in acetonitrile and methanol at 298.15 K are shown in Figure 4, where molar conductance, Λ_m (S cm^{-1} mol^{-1}) values are plotted against ligand/metal cation ratios.

Based on the complexation of **1** with soft metal cations in solution, attempts were made to isolate the complexes for X-ray diffraction studies. Suitable crystals were only obtained with silver.

Table 1. Solution Thermodynamics of 1 and 2 in Nonaqueous Solvents[a]

solvent[b]	MeCN	MeOH	EtOH
		1	
solubility/mol dm^{-3}	(1.34 ± 0.05) × 10^{-3}	(1.13 ± 0.02) × 10^{-3}	(1.23 ± 0.05) × 10^{-3}
$\Delta_s G°$/kJ mol^{-1}	16.4 ± 0.2	16.8 ± 0.3	16.6 ± 0.2
$\Delta_s H°$/kJ mol^{-1}	20.1 ± 0.7[c]	32.9 ± 0.1	~0
$\Delta_s S°$/J K^{-1} mol^{-1}	12	54	−56
$\Delta_t G°$ (MeCN→s)/kJ mol^{-1}	0	0.4	0.2
$\Delta_t H°$ (MeCN→s)/kJ mol^{-1}	0	12.8	−20.1
$\Delta_t S°$ (MeCN→s)/J K^{-1} mol^{-1}	0	42	−68
		2	
solubility/mol dm^{-3}	(1.1 ± 0.2) × 10^{-1}	(5.4 ± 0.9) × 10^{-4}	(3.8 ± 0.3) × 10^{-4}
$\Delta_s G°$/kJ mol^{-1}	5.5	18.65	19.52
$\Delta_t G°$ (MeCN→s)/kJ mol^{-1}	0	13.15	14.02

[a] Derived transfer data from acetonitrile at 298.15 K. [b] Abbreviations for solvents; acetonitrile, MeCN; methanol, MeOH; ethanol, EtOH. [c] Calorimetric data.

Thus Figure 5 displays a plot of the complex of **1** with silver and acetonitrile, **1c**, in the Ag**1**(MeCN)Na.(ClO_4)$_2$ solid.

Thermodynamic data such as stability constants (expressed as log K_s) and derived standard Gibbs energies, $\Delta_c G°$, enthalpies, $\Delta_c H°$, and entropies, $\Delta_c S°$ of complexation are reported in Table 2. The standard deviation of the data is also included in this Table. Representative calorimetric titration curves for the complexation of **1** with silver and mercury in acetonitrile respectively are shown in Figure 6. For stability constants derived from potentiometry, typical titration curves for Ag(I) and Hg(II) with **1** in methanol are shown in Figure 7. Based on these results, attachment of **1** to a silicate (see the Experimental Section) was carried out using the calixarene upper rim to ensure that the active sites of the inmobilised receptor are free to uptake the cation from aqueous solution. The efficiency of the silicate calix[4]arene amino thiophosphorus polymer is shown in Figure 8 which is a plot of the percentage of mercury(II) extracted as picrate vs the volume of solution circulating through the column. Given that no uptake of this metal cation was observed with the 3-aminopropyldimethylsilylated silica, L_6, it follows that these preliminary experiments demonstrate the potential offered by this material for the removal of mercury(II) from aqueous solution. Extraction studies using aqueous solutions containing Cu(II) showed that this cation is not extracted by this material. Similar experiments carried out with silver(I) have shown that the material is more selective for Hg(II) relative to Ag(I) by a factor of 4. The recycling of the material was easily achieved by washing the column with an aqueous solution of EDTA.

Receptor 2. A drawing of the solid state diethyl thiophosphate calix[4]resorcarene molecule (from X-ray diffraction) is displayed in Figure 8.Solubility data and derived standard Gibbs energies of solution in MeCN, MeOH, and EtOH for **2** are listed in Table 1. The solubility of this receptor in the alcohols is relatively low and therefore we were unable to determine the enthalpy associated to these processes. ^{1}H NMR results showed that among the monovalent cations (alkali and silver cations) chemical shift changes were observed in H-5^1 (0.10 ppm downfield shift) by the addition of silver to the ligand) .The only bivalent cation which led to chemical shift changes relative to the free ligand was Hg(II). No signals were observed for H-1, H-1^1, and H-5′ while measurable chemical shift changes were found for H-4 (0.20 ppm), H-5 (0.16 ppm), H-6 (0.30 ppm), and H-7 (0.47 ppm). In summary changes are observed for all protons except H-3. Conductometric titration curves involving these cations and **2** in acetonitrile are shown in Figure 4. Thermodynamic data for the formation of the 2:1 (Hg 2 (II)) complex referred to the processes described in Table 2 (first colum) are listed in this table.

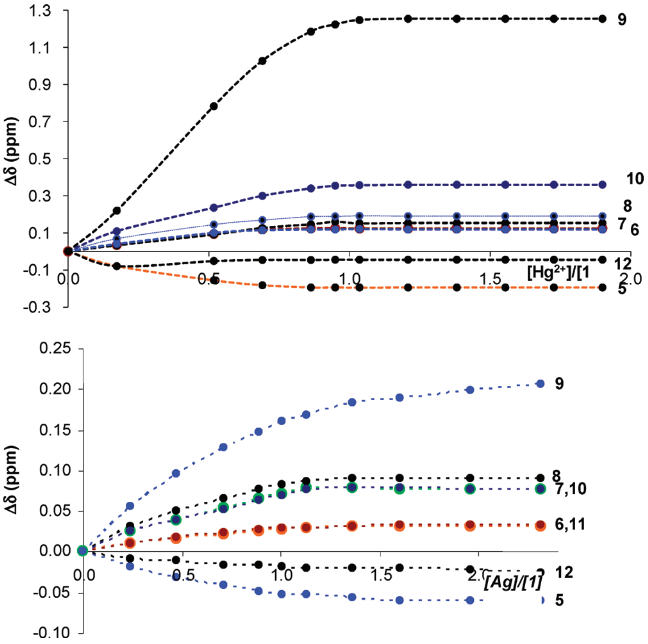


Figure 3. ^{1}H NMR titration of **1** with Ag(I) and Hg(II) in deuterated acetonitrile at 298 K.

■ DISCUSSION

Structural Studies of 1 in the Solid State and in Solution. **1a**. The X-ray structure of **1a** (Figure.1) shows that both independent macrocycles in the cell asymmetric unit adopt a distorted "cone" conformation with the larger cone aperture bonded by the opposite underivatized phenyl rings. A pair of

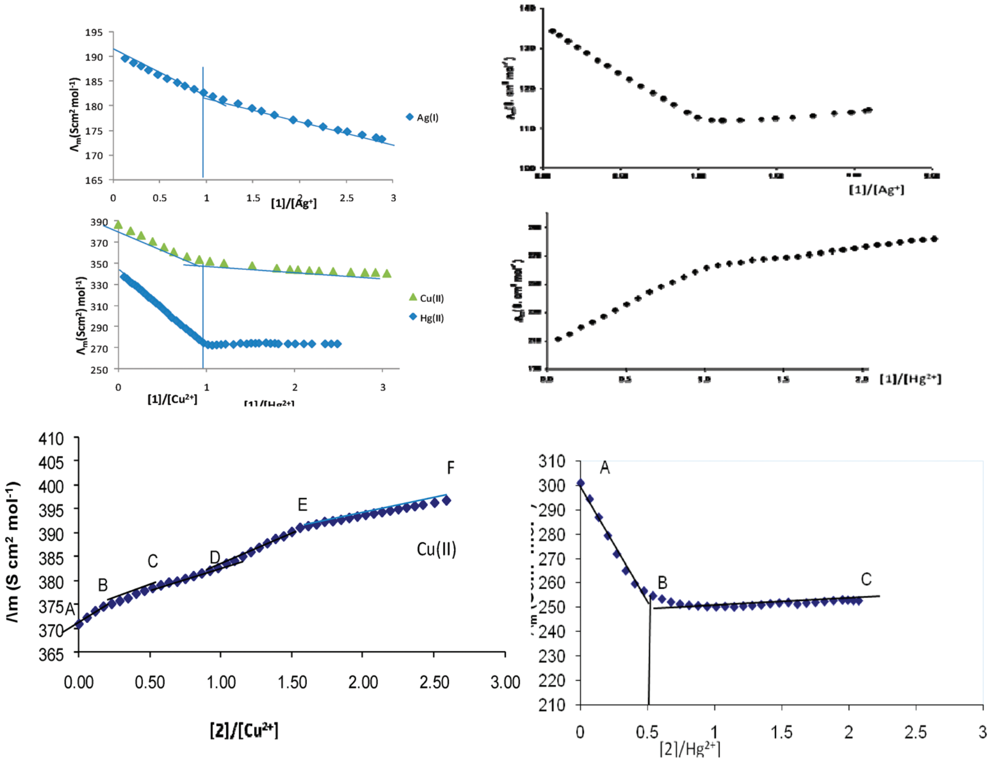


Figure 4. Conductometric titrations curves (a) Ag(I), Cu(II), and Hg(II) with **1** in acetonitrile, (b) Ag(I) and Hg(II) with **1** in methanol, and (c) Cu(II) and Hg(II) with **2** in acetonitrile at 298.15 K.

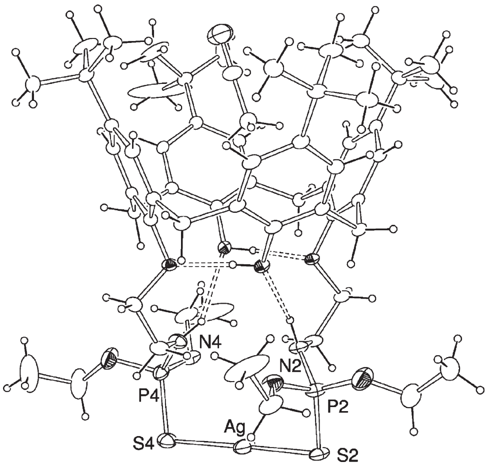


Figure 5. View of the complex of **1** with silver(I) showing the non-H atoms displacement ellipsoids at the 30% probability level.

strong and relatively linear O−H···O(pend) bonds in the lower rim [O(oxy)···O(pend) distances of 2.672 and 2.693 Å and O−H···O(pend) angles of 167.4 and 167.0°, respectively, for one macrocycle and O(oxy)···O(pend) distances of 2.649 and 2.743 Å and O−H···O(pend) angles of 162.8 and 174.2°, respectively, for the other one] produce relatively open chalices. These hydrophobic slots interact with the methanol solvent molecules found included in the baskets giving rise to molecular complexes. The upper half of the pendant arms enclosing the hydrophilic cavity of both independent ligands are anchored by a pair of medium strength and linear N−H···O(ox) intramolecular bonds where now the hydroxyl oxygens of the underivatized phenol groups act as H-bond acceptors along their electron lone pair directions [N−H···O(oxy) distances of 3.029 and 2.949 Å and N−H···O(oxy) angles of 173.4 and 172.0°, respectively, for one molecular complex and N−H···O(oxy) distances of 2.975 and 3.085 Å and N−H···O(oxy) angles of 174.3 and 175.8°, respectively, for the other one]. Despite this relative rigidity of the upper half of the hydrophilic cavity, the lower half shows appreciable flexibility. In particular, it is preorganized toward metal cation complexation at the sulfur binding sites by rotation mainly around the N−P σ-bond. As shown by the similar torsion angles along the opposite pendant arms (with the exception of a disordered terminal methyl group), one of the macrocycles shows an approximate 2-fold molecular symmetry around the calix axis while in the other one this local symmetry extends down to the anchoring nitrogen atom.

1b. As in the **1a** molecular complex, the **1** molecule (Figure 2) shows a similar, slightly more symmetric, 'cone' conformation but now a dichloromethane solvent molecule fills the calix. Again, O−H···O(pend) bonds in the lower bore stabilizes the cone conformation [O(oxy)···O(pend) distances of 2.736 and 2.710 Å and O−H···O(pend) angles of 173.3 and 176.0°, respectively]. At variance with the **1a** complex, the upper half of only one pendant arm is anchored by a N−H···O(ox) bond [N−H···O(oxy) distance of 3.102 Å and N−H···O(oxy) angle of 165.8°] while the N−H group of the other arm points away from the hydrophilic cavity.

The X-ray diffraction studies demonstrate the "cone" conformation of **1a** and **1b** and the ability of this receptor to form adducts with the solvent in the solid state hence showing the versatile behavior of calix[4]arene based receptors. As far as the behavior of **1** in solution is concerned, the pair of doublets observed for the methylene protons in the ^{1}H NMR spectrum (see the Experimental Section) is indicative that receptor **1** also

Table 2. Thermodynamic Parameters of Complexation of 1 and 2 with Metal Cations in Acetonitrile (MeCN) and Methanol (MeOH) at 298.15 K

general equations and thermodynamic parameters	s = MeCN			s = MeOH	
$M^{n+}(s) + 1(s) \leftrightarrow M^{n+}1(s)$	M^{n+} = Ag(I)	M^{n+} = Hg(II)	M^{n+} = Cu(II)	M^{n+} = Ag(I)	M^{n+} = Hg(II)
$\log K_s$	4.07 ± 0.07^a 3.94 ± 0.03^b 3.98 ± 0.05^c	10.02 ± 0.08^b	4.46 ± 0.04^a	7.47 ± 0.04^b	8.49 ± 0.09^b
$\Delta_cG°$/kJ mol^{-1}	22.7 ± 0.5	-57.5 ± 0.5	-25.5 ± 0.2	-42.6 ± 0.2	-48.40 ± 0.59
$\Delta_cH°$/kJ mol^{-1}	9.9 ± 0.2^a	-69.5 ± 0.7^a	3.2 ± 0.5^a	-42.8 ± 0.4^a	-42.4 ± 0.4^a
$\Delta_cS°$/J K^{-1} mol^{-1}	43	-40	96	-1	22
$M^{n+}(s) + 2(s) \leftrightarrow M^{n+}2(s)$					
$M^{n+}2(s) + M^{n+}(s) \leftrightarrow M^{2n+}2(s)$					
$\log K_{s1}$ (1:1)		5.4 ± 0.1^a			
$\log K_s$ (2:1)		3.3 ± 0.1^a			
$\Delta_cG°$/kJ mol^{-1} (1:1)		-30.9 ± 0.1			
$\Delta_cG°$/kJ mol^{-1} (2:1)		-19 ± 0.1			
$\Delta_cH°$/kJ mol^{-1} (1:1)		18.5 ± 0.1^a			
$\Delta_cH°$/kJ mol^{-1} (2:1)		-21.2 ± 0.2^a			
$\Delta_cS°$/J K^{-1} mol^{-1} (1:1)		166			
$\Delta_cS°$/J K^{-1} mol^{-1} (2:1)		-1			

[a] Calorimetric data. [b] Potentiometric data. [c] Average value.

adopts a "cone" conformation in solution. Gutsche[56] stated that a difference of 0.90 ppm between the chemical shifts of the axial and equatorial protons ($\Delta_{ax\text{-}eq}$) of the methylene bridge is found when the receptor adopts a perfect "cone" conformation in solution. Values lower or higher than 0.90 ppm correspond respectively to calix[4]arenes in a "flattened" or "distorted" cone conformation respectively. The $\Delta_{ax\text{-}eq}$ values for **1** in $CDCl_3$ (1.06 ppm) and CD_3CN (0.823 ppm) show that this receptor is in an almost perfect "cone" conformation in both solvents. It is generally observed that fully functionalized calix[4]arenes are found in solution in a distorted "cone" conformation with $\Delta_{ax\text{-}eq}$ values exceeding 1.50 ppm. The difference in patterns observed for the fully relative to the partially substituted calix[4]arenes must be attributed to the possibility of hydrogen bond formation OH···O of the latter relative to the former. This is certainly observed in the solid state as shown in the X-ray structure of this receptor (Figure 1, panels a and b), and it seems to be the case in solution. Another point to stress is the significant downfield chemical shift changes observed in the aromatic protons in moving from $CDCl_3$ to CD_3CN as commonly observed for other calix[4]arene derivatives in CD_3CN. This has been attributed to the hosting ability of the hydrophobic cavity of calix[4]arenes for this solvent as previously shown.[29] In fact the X-ray structure of an analogue of **1** containing carbonyl oxygens in their pendant arms rather than sulfur donor atoms have shown the presence of acetonitrile in this cavity when this solvent was used in the recrystallization process.[4,31]

Cation Complexation Studies of 1. The composition of the complexes formed between **1** and the Hg (II) and Ag (I) cations in acetonitrile and methanol is confirmed by the various experimental techniques used as reflected in Figures 3−7.

It can be seen from the ^{1}H NMR titration that, as far as mercury(II) is concerned (upper part of Figure 3), the most significant chemical change is found in NH(9) proton next to the sulfur donor atoms. These changes occur gradually until the metal cation: receptor ratio reaches a value of 1, and then no further changes are observed hence suggesting the formation of a 1:1 (metal cation:ligand) complex. Deshielding effects are also observed, although to a lesser extent in H-10, H-8, and H-11. A further point of interest arises from the observation that the addition of increasing amounts of mercury salt exert a larger influence on H-10 relative to the effect caused in the methylene protons adjacent to nitrogen (H-7). This fact may be associated with the restricted rotation resulting from complexation. The $\Delta\delta_{ax\text{-}eq}$ value of the bridging methylene protons is reduced from 0.87 ppm for the free to 0.50 ppm therefore suggesting that the receptor adopts a flattened conformation upon complexation. No significant changes were observed in the remaining protons relative to the ligand upon complexation. The ^{1}H NMR titration of **1** with the silver cation in CD_3CN at 298 K (Figure 3) shows that again the most significant chemical shift is that for the NH proton, but to a much lesser extent than Hg(II) to the point that the chemical shift changes for H-10, H-7, and H-8 are relatively small (~0.08 ppm) . No changes are observed in the remaining protons including the bridging methylene ones. The outcome of the ^{1}H NMR studies is that the sulfur donor atoms are responsible for the interaction of **1** with these cations in these solvents. In fact this is the case for the silver cation and **1** in the solid state as shown by the X-ray crystallography of the silver(I)**1** acetonitrile adduct **1c** (Figure 5). Here, the bifunctional **1** ligand shows the most symmetric cone conformation in the series and hosts a silver(I) ion in the hydrophilic cavity and an acetonitrile molecule in the hydrophobic basket, to conform an Ag **1**(MeCN) complex. As for the **1a** and **1b** adducts, the complex is stabilized by O−H···O(pend) bonds in the lower rim [O(oxy)···O(pend) distances of 2.692 and 2.657 Å and O−H···O(pend) angles of 177.4 and 168.3°, respectively] and the upper half of the pendant arms is hold by a pair of N−H···O(ox) bonds [N−H···O(oxy) distances of 2.991 and 3.114 Å and N−H···O(oxy) angles of 163.3 and 146.6°, respectively]. This macrocycle displays an approximate 2-fold symmetry around the calix axis. The silver(I) ion, on the calixarene axis, is linearly coordinated to the sulfur atoms of the opposite

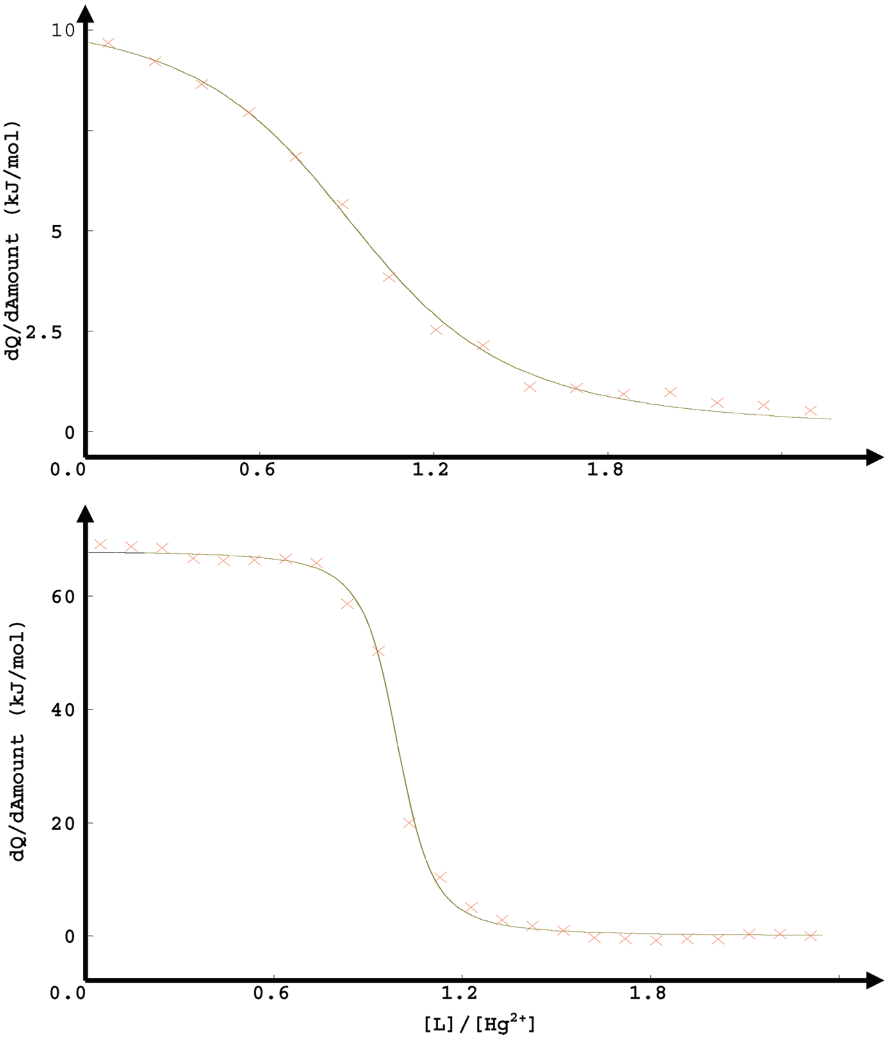


Figure 6. Calorimetric titration curves for Ag (I) (upper curve) and Hg(II) and **1** in acetonitrile at 298.15 K.

pendant groups [Ag−S distances of 2.413(2) and 2.423(2) Å, ∠(S−Ag−S) = 172.01(9)°]. It is to be noted that this linear S-M-S coordination has also been found in the complex of another soft metal ion, Hg(II), with a related *tert*-butyl calix[4]arene, also partially derivatized with sulfur-containing pendant groups.[57]

In accord with the ^{1}H NMR results discussed above for Ag(I) and Hg(II) and **1**, the most pronounced curvature of the titration of these systems in acetonitrile is that for mercury(II) (Figure 4), revealing that in this solvent **1** is selective for this cation relative to Ag(I) and Cu(II). While a weak interaction is shown for Ag(I) and **1** in MeCN, a dramatic effect is observed when this experiment was carried out in MeOH, hence demonstrating the medium effect on the complexation process (Figure 4). In fact the end point of the titration of silver(I) in methanol is as sharp as that for mercury(II) in this solvent. These results show that **1** strongly binds (high stability constants) these cations in MeOH. However the Cu(II) complex appears to be relatively weak. The unusual behavior observed in the titration curve of Hg(II) in methanol in that there is an increase in conductance upon addition of **1** is mainly due to the fact that, at the investigated concentration, the free mercury(II) salt is slightly associated (ion pair formation) in this solvent. Upon formation of the metal ion complex by the addition of **1**, likely to be fully dissociated (the cation size of the metal ion complex is much larger than that for the free cation), an increase in conductance occurs. Thus Λ_m values increase as the **1**/Hg(II) ratio increases until the ligand:cation ratio is 1.

Regarding the complexation thermodynamics of these systems (Table 2), an interesting feature of the data in acetonitrile is that the complexation of Ag(I) and Cu(II) is entropically controlled, whereas for Hg(II) and this receptor it is enthalpically controlled. The data for silver(I) and Cu(II) are representative of systems which undergo strong desolvation upon complexation resulting in a gain in entropy and a loss of enthalpic stability (slightly negative for Ag(I) and positive for Cu(II)). It is known that the silver cation is strongly solvated in acetonitrile. The preferential solvation of this cation in this solvent has been discussed by Otzusumi et al.[58] In fact X-ray diffraction studies have shown that the Ag(I)−N bond in [Ag(CH_3CN)$_4$] is even shorter than that found in [Ag(I)(Py)$_4$] and [Ag(I) (NH_3)$_4$]. This was attributed to the interaction of Ag(I) with the π electron and the C≡N bond of the solvent molecule. The results clearly show that the solvation of Ag(I) has a predominant effect on the complexation of this cation and **1** in this solvent. In moving from acetonitrile to methanol, the complex stability increases substantially. In an attempt to gain further insight into the factors contributing to the

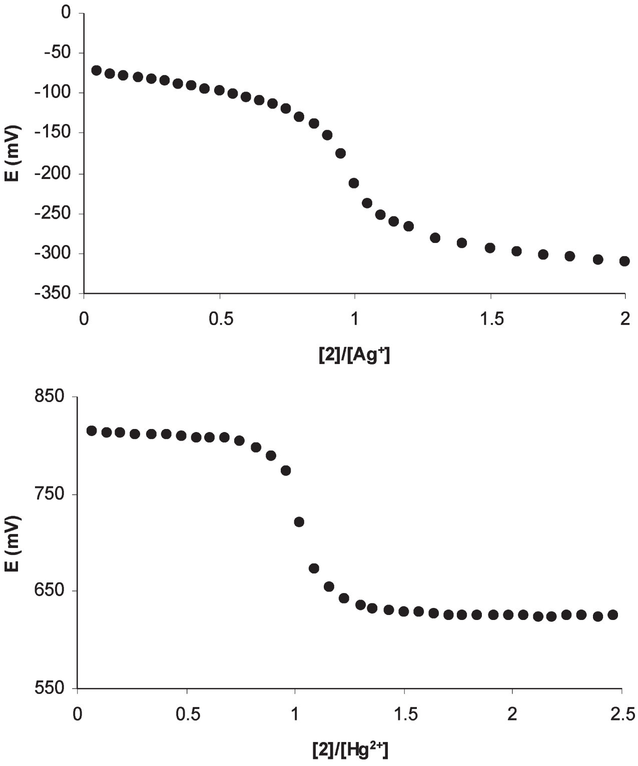


Figure 7. Potentiometric titration curves for Ag (I) in MeOH (upper curve) and Hg(II) and **1** in acetonitrile (lower curve).

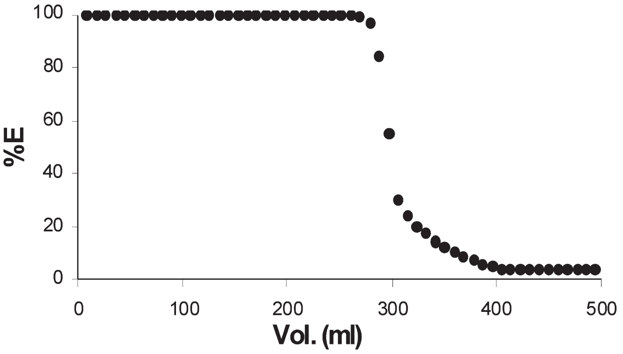


Figure 8. Percentage of extraction of Hg(II) (picrate as counterion) vs volume of solution.

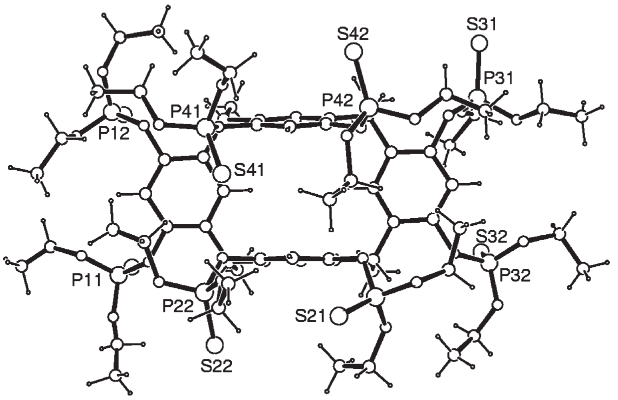


Figure 9. Side (upper) and top views of **2**. For clarity, only some phosphorus and sulfur atoms of the upper rim $-O-(P{=}O)(O-CH_2-CH_3)_2$ pendant arms have been identified to show the numbering scheme. The smallest disks indicate oxygen atom.

higher stability of Ag(I) and **1** in MeOH relative to MeCN, the solvation changes of reactants and product from one solvent to another are considered taking into account the following relationship[29]

$$\Delta_c P^\circ(s_2) - \Delta_c P^\circ(s_1) = \Delta_t P^\circ(ML^{n+})(s_1 \rightarrow {}_s s_2) - \Delta_t P^\circ(M^{n+})(s_1 \rightarrow {}_s s_2) - \Delta_t P^\circ(L^+)(s_1 \rightarrow {}_s s_2) \quad (2)$$

In eq 2, P = G.H.S and $\Delta_c P$ and $\Delta_t P$ denote the thermodynamic parameters of complexation and transfer respectively from a reference solvent, s_1, to another solvent, s_2. By inserting in eq 2 the relevant single-ion transfer values for Ag(I) based on the Ph_4 $AsPh_4$ B convention[59] ($\Delta_t G^\circ = -30.12$ kJ mol^{-1}, $\Delta_t H^{\circ\circ} = -32.30$ kJ mol^{-1}, $\Delta_t S^\circ = -7$ J K^{-1} mol^{-1}), transfer data for **1** (Table 1) from MeOH to MeCN and complexation data in MeCN and MeOH (Table 2) transfer values for the metal–ion complex from MeOH to MeCN are calculated (($\Delta_t G^\circ = -10.62$ kJ mol^{-1}, $\Delta_t H^{\circ\circ} = -12.2$ kJ mol^{-1}, $\Delta_t S^\circ = -5$ J K^{-1} mol^{-1}). Interpretation of these parameters shows that the higher stability of the complex in MeOH relative to MeCN is entirely due to the lower solvation of the free cation in the former solvent. This statement is based on the fact that the $\Delta_t G^\circ$ of the metal ion complex favors complexation in MeCN. In terms of enthalpy, both the metal ion and the ligand contribute favorably to the enthalpic stability in MeOH overcoming the unfavorable contribution of the cation complex in this solvent. An analysis in terms of entropy leads to the conclusion that the $\Delta_c S^\circ$ in MeOH results from a compensation between (i) the loss of entropy of the free metal cation in its transfer to MeCN and the gain in entropy of the complex from MeCN to MeOH and (ii) the favorable $\Delta_c S^\circ$ in MeCN which is compensated by the destabilizing effect of the transfer entropy of the ligand in moving from MeOH to MeCN.

Concerning Cu(II), such analysis is handicapped due to the lack of data on the single ion parameters of transfer of this cation between these solvents. Availability of transfer thermodynamic data for Hg(II) based on the Ph_4As Ph_4B convention[60] ($\Delta_t G^\circ = -9.8$ kJ mol^{-1}, $\Delta_t H^\circ = 33.5$ kJ mol^{-1}, $\Delta_t S^\circ = -123$ J K^{-1} mol^{-1}), transfer data for **1** (Table 1), complexation data in MeCN and MeOH (Table 2) and calculated transfer values from MeOH to MeCN for the metal–ion complex ($\Delta_t G^\circ = -19.3$ kJ mol^{-1}, $\Delta_t H^{\circ\circ} = -6.8$ kJ mol^{-1}, $\Delta_t S^\circ = -227$ J K^{-1} mol^{-1}) allows us to proceed with an assessment of the medium effect on this system. Unlike silver(I) the higher stability of Hg(II) and **1** in acetonitrile relative to MeOH is entirely attributed to the higher solvation of the complex in the former relative to the latter solvent. Indeed the cation is better solvated in acetonitrile than in methanol and therefore does not contribute favorably to the stability of the complex in acetonitrile. However, the higher enthalpic stability of the free cation in MeOH and that of the complex in MeCN lead to the higher enthalpic stability of the complexation process in MeCN. However it is the free metal cation which mainly contributes to the entropic destabilization observed in the binding of Hg(II) and **1** in moving from methanol to acetonitrile.

Overall, the thermodynamics provides quantitative information regarding the strength of interaction between cation and receptor and allows us to calculate the selectivity factor ($S = K_s$(Hg(II)/K_s (M(II)). Thus in MeCN, **1** is more selective for

Hg(II) relative to Ag(I) and Cu(II) by factors of 1.2×10^6 and 3.6×10^5, respectively, whereas in MeOH the selectivity factor for Hg(II) relative to Ag(I) is 10.5.

However the fact that complexation between **1** and Cu(II) takes place in acetonitrile but not in MeOH provides a strong indication that in this solvent it is the **1**−MeCN adduct rather than the free ligand which interacts with the metal cation in this solvent. Given the affinity of N donor atoms for Cu(II), it is most likely that, unlike in the Ag−**1**−MeCN complex, the CN end of the acetonitrile molecule sitting in the hydrophobic cavity of **1** points inward to provide a coordination site for the metal cation as previously found for a calix[4]arene derivative and Cd(II).[31] Since the main aim of this paper is to produce a Hg(II)-selective decontaminating agent, the above finding is most relevant in the selection of solvents used in the attachment of the receptor to the silicate. To eliminate the possible uptake of Cu(II), acetonitrile was not used in the synthetic route leading to the production of the new material. Another advantage of **1** is that it is soluble in MeOH which is a protic solvent like water. The discussion below assesses whether or not the selective pattern of the inmobilised receptor resembles, at least in qualitatively terms, the one found for the free receptor in methanol.

Extraction of Hg(II) from Aqueous Solution by a Calix[4]arene Modified Silica. As in MeOH the inmobilised receptor is unable to remove Cu(II) from aqueous solutions. The observation that the cation extraction pattern observed for the material mirrors the selectivity trend of Hg(II) relative to Ag(I) in MeOH strongly suggest that the uptake of these cations by the inmobilised receptor results from the interactions taking place between these cations and the sulfur donor atoms of the anchored receptor. Indeed the most striking feature of these results is that while the extraction of Hg(II) from water is four times higher than that of Ag(I) the selectivity factor of **1** for Hg(II) relative to Ag(I) in methanol is 10.5. This outcome is justified given that water is a better solvator for the cations than methanol as reflected in the single-ion $\Delta_t G°$ values (based on the Ph_4AsPh_4B convention) of Ag(I) (47.9 kJ mol^{-1}) and Hg(II) (57.7 kJ mol^{-1}) from water to methanol Therefore the competition between the solvent and the inmobilised receptor for the cation would be greater in water than in methanol and consequently the cation would be better extracted from methanot than from water.

Structural Studies of 2 in the Solid State and in Solution. The X-ray diffraction structure of **2** (Figure 3) shows that this macrocycle has a strongly distorted cone conformation in the solid state. This can be described by the dihedral angles (δ) that the phenol rings subtend with the best least-squares plane through the tertiary carbon atoms of the four $>CH-CH_3$ groups linking adjacent rings.The corresponding dihedral δ-values are $\delta_1 = 172.1(2)$, $\delta_2 = 84.2(1)$, $\delta_3 = 179.0(2)$, and $\delta_4 = 83.6(1)°$. An opposite pair of phenyl rings are unfolded from each other to near antiparallelism [$\delta_{1-3} = 167.8(1)°$], whereas the other ones are folded onto each other to near parallelism [$\delta_{2-4} = 7.2(2)°$]. The corresponding cross-distances between apical carbon atoms at the calix upper bore are 10.821(8) and 4.448(7) Å, respectively.

The ^{1}H NMR signals for H-1, H-1′, H-5, H-5′, H-6, and H-6′ shown in the Results are related to the 1,3 alternate conformation found in the solid state (Figure 9). As previously stated this receptor is not soluble enough in MeOH as to proceed with solution studies in this solvent.

Cation Complexation Studies of 2. Concerning the **2**-Ag(I) binding, the relatively small chemical shift change observed for H-5^1 in the ^{1}H NMR in CD_3CN suggests the formation of a weak complex . For Hg(II) the significant changes observed particularly for the protons close to the S donor atoms provide a strong indication that these donor atoms act as complexation sites in the formation of a strong complex..Conductometric studies involving **2** and these cations in acetonitrile (Figure 4) contrast sharply with those for **1** in acetonitrile in that

(i) Hardly any changes are found in the Λ_m values upon addition of **2** to the solution of the silver salt in this solvent. It is therefore concluded that very weak complexation takes place between this ligand and this cation in this solvent. This result is concomitant with the relatively small chemical shift changes observed for this system in the ^{1}H NMR studies.

(ii) In the case of Hg(II), a clear break in the curvature of the titration curve is found at a ligand:metal cation concentration ratio of 0.5. This result is indicative of an enhancement in the hosting ability of this receptor for mercury(II) relative to **1**. Thus two metal cations are taken up per unit of ligand.

(iii) The conductometric titration curve for Cu(II) and **2** is striking. It reveals the formation of weak complexes of various compositions. Thus upon excess of Cu(II) in solution, metallates complexes are formed. This is reflected in the breaks observed in the titration curve at 0.25 and 0.50 ligand:metal cation ratios. These may indicate that four and two cations, repectively, are taken up per unit of ligand. It seems that successive transfers of cations from the complex to the free ligand may take place until the formation of a 1:1 complex. The tendency of resorcarenes to form metalate complexes with different cations has been previously reported by several authors ourselves included.[19,61−63]

As the metal cation is consumed during the course of the titration by addition of the ligand, the composition of the complex is altered. As a result the number of ligands per unit of metal cation increases. The presence of various species in solution may lead to the increase observed in conductance.

Thermodynamic data for **2** and Hg(II) in MeCN are also shown in Table 2. Unlike **1** which is partially functionalized and therefore able to take one metal cation per unit of ligand, receptor **2** is fully functionalized having four times more binding sites than **1**. Thus this receptor is able to host two mercury ions per unit of ligand in this solvent according to the processes listed in Table 2 (first column). The composition of the complex established by conductance measurements is in accord with that found from titration calorimetry.

At this stage it is relevant to emphasize that the pendent arms in **1** have more flexibility than those in **2** due to the presence of the methylene group between the ethereal oxygen and the NH functionality. This is also likely to contribute to the higher stability observed in the 1:1 complex involving **1** relative to **2**. Such functional group is absent in **2**. Data for this ligand and Hg(II) (Table 2) show that the formation of the 1:1 complex is enthalpically destabilized and entropically controlled. This may be attributed to a strong desolvation of the reactants or a considerable conformational change upon complexation. This statement is based on the fact that a strong solvation of the 1:1 complex is expected to lead to the opposite trend in enthalpy and entropy. It is interesting to note that the overall process which involves one ligand and two metal cations to give a unit of the complex is entropy driven.

Although the hosting capacity of **2** for Hg(II) is higher than that of **1**, the fact that this receptor interacts with Cu(II) forming metallates may certainly interfere with the main objective of this paper which is to produce a Hg(II) selective material. Therefore we did not pursue further work attempting to immobilize this receptor.

CONCLUSIONS

From the above discussion, the following main conclusions can be drawn:

(i) Two new cation receptors have been synthesized and structurally and thermodynamically characterized.

(ii) The crystallographic structural results disclosed here on the binding of **1** to silver(I) through S−Ag−S linear coordination, along with similar bonding conformations found for the environmentally relevant Hg(II) in a related *tert*-butyl calix[4]arene partial derivative, suggest that a similar S−Hg(II)−S coordination may be operative in the mercury(II) complex with **1** detected in solution.

(iii) Substitution of the lower rim carbonyl oxygen atoms in **3** by sulfur donor atoms led to **1**. As a result the complexing abilities of the former relative to the latter are dramatically altered. While **3** interacts with alkaline-earth metal cations (1:2 metal cation:ligand stoichiometry) as well as with other bivalent cations [Cd(II), Hg(II), Cu(II), and Zn(II)] forming 1:1 complexes of moderate stability, receptor **1** interacts selectively with Hg(II) and Ag(I) and its selectivity for Hg(II) is significantly enhanced. Its discriminating behavior against other metal cations including the essential ones makes this receptor suitable for its incorporation into a silica support leading to a new recyclable material with potential use in the removal of the polluting mercury cation from water.

(iv) One main point of interest is that fundamental studies guided the selection of the receptor to be attached to the silica support. Furthermore complexation studies in MeCN indicated that this solvent should be excluded from the synthetic route leading to the Hg(II)-selective to avoid the possible interference of the Cu(II) ions commonly found in water. In addition the selective extraction of the immobilize receptor for Hg(II) relative to Ag(I) matches the cation selectivity trend observed for the free receptor in the methanol solvent.

ASSOCIATED CONTENT

Supporting Information. Tables of crystal data and structure solution methods and refinement results (Tables S1 and S2), atomic coordinates and equivalent isotropic displacement parameters (Tables S3−S6), full intramolecular bond distances and angles (Tables S7−S10), atomic anisotropic displacement parameters (Tables S11−S14), and hydrogen atoms positions (Tables S15−S18). Crystallographic data are also provided in the format of a crystallographic information file (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

ACKNOWLEDGMENT

The authors acknowledge the financial support provided by the European Commission under Contract 509159 This work was supported in part by FAPESP of Brazil and by CONICET of Argentina. O.E.P. is a Research Fellow of CONICET.

REFERENCES

(1) Gutsche, C. D. Calixarenes. *Monographs in Supramolecular Chemistry*; Stoddart, F. J., Ed.; The Royal Society of Chemistry: Cambridge, 1989.

(2) Gutsche, C. D. Calixarenes Revisited. *Monographs in Supramolecular Chemistry*; Stoddart, F. J., Ed.; The Royal Society of Chemistry: Cambridge, 1988.

(3) *Calixarenes, A Versatile Class of Macrocyclic Compounds*; Vicens, J., Böhmer, V., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1991.

(4) *Calixarenes 50th Anniversary*; Vicens, J., Asfari, Z., Harrowfield, J. M., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1994.

(5) *Calixarences*; Asfari, Z., Böhmer, V., Harrowfield, J. M,, Vicens, J., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2001.

(6) *Calixarenes in the Nanoworld*; Vicens, J., Harrowfield, J. M., Eds.; Springer Publishers: Dordrecht, The Netherlands, 2007.

(7) Thondorf, I.; Shivanyuk, A.; Böhmer, V. In *Calixarences 2001*; Asfari, Z., Böhmer, V., Harrowfield, J. M., Vicens, J., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2001; Chapter 2.

(8) Wright, A. J.; Mathews, S. E.; Fischer, W. B.; Beer, P. D. *Chem.—Eur. J.* **2001**, *7*, 3474–81.

(9) Iwanek, W.; Urbaniak, M. *Tetrahedron* **2001**, *57*, 10377–82.

(10) Makinen, M.; Vainiotalo, P.; Rissanen, K. *J. Am. Soc. Mass Spectrom.* **2002**, *13*, 851–61.

(11) Smith, K. J.; Wilcox, J. D.; Mirick, G. E.; Wacker, L. S.; Ryan, N. S.; Vensel, D. A.; Redling, R.; Domush, H. L.; Amonoo, E. P.; Shariff, S. S.; Wenzel, T. J. *Chirality* **2002**, *15*, S150–58.

(12) Botta, B.; Botta, M.; Filippi, A.; Tafi, A.; Delle Monache, G.; Speranza, M. *J. Am. Chem. Soc.* **2002**, *124*, 7658–59.

(13) Falabu, D.; Shivanyuk, A.; Nissinen, M.; Rissanen, K. *Org. Lett.* **2002**, *4*, 3019–22.

(14) Makinen, M.; Vainiotalo, P.; Nissinen, M.; Rissanen, K. *J. Am. Soc. Mass Spectrom.* **2003**, *14*, 143–51.

(15) Botta, B.; Subissati, D.; Tafi, A.; Delle Monache, G.; Filippi, A.; Speranza, M. *Angew. Chem., Int. Ed.* **2004**, *43*, 4767–70.

(16) Urbaniak, M.; Iwanek, W. *Tetrahedron* **2004**, *60*, 8265–73.

(17) Dignam, C. F.; Richards, C. J.; Zopf, J. J.; Wacker, L. S.; Wenzel, T. J. *Org. Lett.* **2005**, *7*, 1773–76.

(18) Botta, B.; Caporuscio, F.; Subissati, D.; Tafi, A.; Botta, M.; Filippi, A.; Speranza, M. *Angew. Chem., Int. Ed.* **2006**, *45*, 2717–20.

(19) Danil de Namor, A. F.; Chaaban, J. K.; Piro, O. E.; Castellano, E. E. *J. Phys. Chem. B* **2006**, *110*, 2442–50.

(20) Botta, B.; Caporuscio, F.; D'Acquarica, I.; Delle Monache, G.; Subissati, D.; Tafi, A.; Botta, M.; Filippi, A.; Speranza, M. *Chem.—Eur. J.* **2006**, *12*, 8096–8105.

(21) Schiel, C.; Hembury, G. A.; Borovkov, V. V.; Klaes, M.; Agena, C.; Woda, T.; Grimme; Inoue, Y.; Mattay, J. *J. Org. Chem.* **2006**, *71*, 976–82.

(22) Botta, B.; D'Acquarica, I.; Delle Monache, G.; Subissati, D.; Uccello-Barretta, G.; Mastrini, M.; Nazzi, S.; Speranza, M. *J. Org. Chem.* **2007**, *72*, 9283–90.

(23) Danil de Namor, A. F.; Chaaban, J. K. *J. Phys Chem. B* **2008**, *112*, 2070–77.

(24) Botta, B.; Fraschetti, C.; Novara, F. R.; Tafi, A.; Sacco, F.; Mannina, L.; Sobolev, A. P.; Mattay, J.; Letzel, M. C.; Speranza, M. *Org. Biomol. Chem* **2009**, *7*, 1798–1806.

(25) Moore, D.; Matthews, S. E. *J. Incl. Phenom. Macrocycl. Chem.* **2009**, *65* (1−2), 137.

(26) Uysal Akkus, I.; Aslan, S.; Taktak, F. F.; Memon, S. *Turk. J. Chem* **2008**, *32*, 635–43and references therein.

(27) Perrin, R.; Harris, S. In *Calixarenes A Versatile Class of Macrocyclic Compounds*; Eds.; Vicens, J., Böhmer, V., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1991; Part 4.

(28) Shinkai, S.; Mori, S.; Koreishi, H.; Tsubaki, T.; Manabe, O. *J. Am. Chem. Soc.* **1986**, *108*, 2409–16.

(29) Danil de Namor, A. F.; Cleverley, R. M.; Zapata-Ormachea, M. L. *Chem. Rev.* **1998**, *98*, 2495–2526.

(30) Danil de Namor, A. F. In *Calixarenes 2001*; Asfari, Z., Böhmer, V., Harrowfield, J. M., Vicens, J., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2001; Chapter 19.

(31) Danil de Namor, A. F.; Chahine, S.; Kowalska, D.; Castellano, E. E.; Piro, O. E. *J. Am. Chem. Soc.* **2002**, *124*, 12824–36.

(32) Danil de Namor, A. F.; Zegarra Fernandez, K. *J. Phys. Chem.* **2007**, *111*, 7321–30.

(33) Danil de Namor, A. F.; Shehab, M. *J. Phy. Chem. B* **2003**, *107*, 6462–68.

(34) Danil de Namor, A. F.; Shehab, M. *J. Phys. Chem. B* **2004**, *108*, 7324–30.

(35) Danil de Namor, A. F.; Shehab, M.; Abbas, I.; Withams, M. V.; Zvietcovich, J. *J. Phys. Chem.* **2006**, *110*, 12653–59.

(36) Danil de Namor, A. F.; Abbas, I.; Hammud, H. *J. Phys. Chem.* **2007**, *111*, 5803–10.

(37) Danil de Namor, A. F. *J. Therm. Anal. Calorim.* **2007**, *87*, 7–14.

(38) Danil de Namor, A. F.; Shehab, M.; Khalife, R.; Abbas, I. *J. Phys. Chem.* **2007**, *111*, 12177–84.

(39) Danil de Namor, A. F.; Khalife, R. *J. Phys. Chem. B* **2008**, *112*, 15766–74.

(40) Danil de Namor, A. F.; Abbas, I. *Anal. Meth.* **2010**, *2* (1), 63–71.

(41) Lee, Y. K.; Ryu, R. K.; Ryu, J. W.; Kim, B. E.; Park, J. H. *Chromatography* **1997**, *46* (9), 507–10.

(42) Diener, L. *J. Chem. Educ.* **2009**, *86* (10), 1139.

(43) Sayadi, M. H.; Sayyed, M. R. G.; Saptarshi, P. G. *Pollution Res.* **2008**, *27*, 627–34.

(44) Pudasainee, D.; Lee, S. J.; Lee, S.-H.; Kim, J.-H.; Jang, H.-N.; Cho, S. J.; Seo, Y.-C. *Fuel* **2010**, *89* (4), 804–9.

(45) Kagaya, S.; Miyazaki, H.; Ito, M.; Tohda, K.; Kanbara, T. *J. Hazardous Mater.* **2010**, *175* (1−3), 1113–15.

(46) Danil de Namor, A. F.; Aparicio-Aragon, W.; Goitia, M. T.; Casal, A. R. *Supramol. Chem.* **2004**, *16*, 423.

(47) Enraf-Noniu; COLLECT; Nonius BV: Delft, The Netherlands, 1997−2000.

(48) Otwinowski, Z.; Minor, W. In *Methods in Enzymology*; Carter, C. W., Jr., Sweet, R. M., Eds.; Academic Press: New York, 1997; pp 307−326.

(49) Spek, A. L. *PLATON, A Multipurpose Crystallographic Tool*; Utrecht University: Utrecht, The Netherlands, 1998.

(50) Sheldrick, G. M. *SHELXS-97. Program for Crystal Structure Resolution*; University of Göttingen: Göttingen, Germany, 1997.

(51) Sheldrick, G. M. *SHELXL-97. Program for Crystal Structures Analysis*; University of Göttingen: Göttingen, Germany, 1997.

(52) Bax, D.; de Ligny, C.; Remijnse, G. *Recl. Trav. Chim. Pays-Bas* **1972**, *91*, 965.

(53) Irving, R.; Wadsö, I. *Acta Chem. Scand.* **1964**, *18*, 195–201.

(54) Dickinson, C. *Bull. Natl. Bur., Std* **1914**, *11*, 189.

(55) Johnson, C. K. ORTEP. Report ORNL-3794, Oak Ridge, TN, 1965.

(56) Gutsche, C. D. *Aldrichim. Acta* **1995**, *28*, 3–9.

(57) Bibal, B.; Declercq, J.-P.; Dutasta, J.-P.; Tinant, B.; Valade, A. G. *Tetrahedron* **2003**, *59*, 5849–54.

(58) Ozutsumi, K.; Kitakaze, K.; Inomi; Ohtaki, H. *J. Mol. Liq.* **1997**, *73−74*, 385–96.

(59) Cox, B. G.; Hedwig, G. R.; Parker; Watts, D. W. *Aust. J. Chem.* **1974**, *27*, 477.

(60) Chaudhry, M.; Dash, K. C.; Dash, E.; Kamienska-Piotrowicz, E.; Kinjog, Y.; Persson, I. *J. Chem. Soc. Faraday Trans.* **1994**, *90*, 2235–42.

(61) Eisler, D.; Hong, J. W.; Jennings, R. J.; Puddephatt, M. C. *Organometallics* **2002**, *21*, 3955.

(62) Eisler, D. J.; Kirby, C. W.; Puddephatt, C. W. *Inorg. Chem.* **2003**, *42*, 7626–34.

(63) Danil de Namor, A. F.; Chahine, S.; Castellano, E. E.; Piro, O. E. *J. Phys. Chem. B* **2005**, *A109*, 6743–51.