

Comparative study of novel sulfonylcalix[4]arene derivative compounds

A. Suwattanamala, A.L. Magalhães*, J.A.N.F. Gomes

REQUIMTE, Departamento de Química, Faculdade de Ciências, Universidade do Porto, Rua do Campo Alegre, 687, 4169-007 Porto, Portugal

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Abstract

Density functional theory (DFT) was applied to investigate the structure and conformational equilibrium of tetraaminosulfonylcalix[4]arene (**1**) and tetramercaptosulfonylcalix[4]arene (**2**) compounds, which are expected to contribute for the design of novel molecular receptors in supramolecular chemistry. All the calculations predict the *1,3-alternate* as the most stable conformer for both compounds, which contrasts with an earlier theoretical study on the corresponding thiacalix[4]arene derivatives where *cone* was shown to be the most stable. The strong intramolecular hydrogen bonding between the substituent groups at the lower rim and the oxygen atoms of sulfone groups seem to play an important role in the stabilization of the conformers. Besides, the influence of the solvent chloroform was taken into account in this study. The results show that chloroform does not modify the stability ordering of the conformers, but leads to a reduction in the energy gaps between them. The presence of additional coordination sites provided by sulfone groups may induce new binding properties of the host molecule towards a variety of metal ions.

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1. Introduction

Calix[*n*]arenes are one interesting class of macrocyclic molecules which play an important role in the broad field of supramolecular chemistry [1]. Their applications can be found in a wide variety of areas such as catalysis, host–guest chemistry, separation chemistry, selective ion transport and sensors [2–4]. The increasing interest in these molecules seems to be due to their versatility and utility as receptors, building blocks and molecular scaffolds, which have been obtained from the easy chemical functionalization at the phenolic oxygens (lower rim) and/or substitution at the *p*-position (upper rim) [3–5]. Replacement of the methylene linkages of the classical calix[*n*]arenes by hetero atoms [6–9], especially sulfur atoms as in thiacalix[*n*]arenes [7,8], have attracted considerable interest on new members of the calix[*n*]arene family. The presence of sulfur atoms in place of the usual methylene bridges implies some uncommon features such as different conformational behavior and

peculiar complexation properties with transition metal ions that have never been observed in the classical calix[*n*]arenes [10–15]. Very recently, the selective oxidation of the remarkable parent thiacalix[4]arene with controlled quantities of an oxidizing agent leads to new derivative compounds, namely sulfinylcalix[4]arenes and sulfonylcalix[4]arenes, based on the linking of four phenolic rings by sulfoxide (SO) and sulfone (–SO₂) groups, respectively [13,16–18]. A previous solvent extraction study of metal ion selectivities with these sulfur-containing ligands showed the important role of the bridging counterparts to bind the metal center [13,17]. Thiacalix[4]arene favors transition metal ions while sulfonylcalix[4]arene prefers alkaline earth metal ions and, interestingly, sulfinylcalix[4]arene can coordinate to both groups of metal ions.

In the past decades, theoretical investigation of these compounds revealed that they are a powerful tool for the design of new systems with improved properties, and for the interpretation of their chemical and physical properties [19]. Recently, density functional theory (DFT) methodologies have been successfully applied to study sulfur bridged derivative compounds [20–22]. In this work, we have carried out DFT calculations to investigate the structure and energetics of two novel sulfonylcalix[4]arene derivatives,

* Corresponding author. Tel.: +351 226 082804; fax: +351 226 082959.
E-mail address: almagalh@fc.up.pt (A.L. Magalhães).

namely tetraaminosulfonylcalix[4]arene (**1**) and tetramercaptosulfonylcalix[4]arene (**2**), in which the four hydroxyl groups at the lower rim of the parent sulfonylcalix[4]arene are replaced by amine and mercapto groups, respectively. The main goal of this study is to understand how the presence of different substituents at the lower rim of sulfone bridging compounds modifies their conformational flexibilities and binding abilities when compared with the corresponding sulfide bridging compounds [22]. Previous NMR spectroscopy study indicates that, in some cases, the dynamic equilibrium between the conformations especially the *cone* and *partial cone*, is influenced by the polarity of the solvent [3]. Chloroform is one of the most common solvents used in experimental studies [3,23], therefore its effect was also included in this theoretical study. We hope that the present study on two novel sulfonylcalix[4]arene derivatives will give some insights into the design and development of new receptors in supramolecular chemistry in the near future.

2. Computational methodology

The structures of the four main conformers of compounds **1** and **2** were obtained by complete optimization without any constraints at DFT level using the Becke's three parameter hybrid exchange functional [24] combined with the Lee, Yang and Parr correlation functional [25] (B3LYP) with the 6-31G(d,p) basis set. Electronic energies were also obtained by additional single point calculations with the B3LYP and B3PW91 functionals (the latter one includes a correlation functional proposed by Perdew and Wang in 1991 [26,27]), with the 6-311G (d,p) basis set. In order to include the electrostatic influence of the solvent chloroform on the conformational isomerism, the integral equation formalism of the polarizable continuum model (IEF-PCM) of Tomasi and co-workers [28–30] has been employed at the B3LYP/6-31G(d,p) level. Each solute was inserted in a cavity with an appropriate shape based on interlocking atomic spheres centered on its non-hydrogen atoms, as defined by the united atom topology model (UATM) [31]. The cavity was inserted in a continuum medium characterized by a uniform dielectric constant for the chloroform. The population charge analysis was computed by Merz-Kollman-Singh (MK) scheme at the same DFT level [32]. All the calculations have been performed with the GAUSSIAN 03 program package [33].

3. Results and discussion

3.1. Structure and hydrogen bonding of sulfonylcalix[4]arene derivatives

The DFT optimized structures of the four conformers namely *cone*, *partial cone* (*paco*), *1,2-alternate* (*1,2-alt*) and

1,3-alternate (*1,3-alt*) of tetraaminosulfonylcalix[4]arene (**1**) and tetramercaptosulfonylcalix[4]arene (**2**) are shown in Figs. 1 and 2. Unfortunately, neither of them have been experimentally achieved yet. However, a similar compound with *tert*-butyl groups at the *para* position named tetraamino-*p-tert*-butylsulfonylcalix[4]arene [23] was synthesized.

Some relevant geometrical parameters of *cone* and *1,3-alt* conformers of **1** and **2** are gathered in Table 1 and Fig. 1, and they are compared with *cone* conformer of the corresponding thiacalix[4]arene derivatives [22]. The nature of the substituent groups at lower rim ($-\text{NH}_2$, $-\text{SH}$) has no effect on the majority of bond distances and bond angles except the C–X and X–X distances (X=N, S). In *cone* conformer, these distances increase from compound **1** to compound **2** because of the steric hindrance of the mercapto group, but in *1,3-alt* the steric effect leads to a decrease in the X–X distance and an increase in C–X distance. Clearly, when the conformer changes from *cone* to *1,3-alt* the X–X distances increase. The substitution of sulfide bridging by sulfone groups leads to a lengthening of the X–X distance ca. 0.3–0.4 Å in the amino compounds while this is not observed in the mercapto compound. The *cone* conformers of compounds **1** and **2** possess C_2 -like symmetry, which is in good agreement with previous studies on thiacalix[4]arene derivatives [22]. Accordingly, neither the X_1-X_3 and X_2-X_4 distances nor the two angles ϕ between opposite benzene rings are identical (see Table 1). The replacement of sulfide bridges by sulfone groups leads to a decrease in the angles ϕ without changing the circular skeleton of the calix. In fact, the distances between the two distal and the two proximal sulfur atoms of the sulfone bridging groups are 8.0 and 5.7 Å, respectively, for the compounds **1** and **2**, which are very close to the values obtained for the sulfur bridged derivative compounds (7.9 and 5.6 Å). Therefore, the replacement of sulfide bridging atoms by sulfone groups does not affect very much the size of the cavity, bond distances and bond angles when compared with the corresponding thiacalix[4]arene derivatives [22].

As expected, the optimized structures present hydrogen bonds arrays that contribute dominantly to the stabilization of the conformers (see Figs. 1 and 2). For instance, compound **1** presents $\text{NH}\cdots\text{O}=\text{S}'\text{O}$ interactions between the amino groups and the sulfone oxygen atoms which are obviously absent in the sulfur bridged derivative [22]. In *cone* conformer two different values of the $\text{NH}\cdots\text{O}$ distance (1.91, 2.13 Å) and one single value for the N–H–O angles (135.6°) are observed at B3LYP/6-31G(d,p) level, whereas in *1,3-alt* the values are 2.02 Å and 138.0°, respectively. Longer $\text{NH}\cdots\text{N}$ and $\text{NH}\cdots\text{S}'$ distances (2.77, 2.74 Å) are obtained when compared with the *cone* conformer of tetraaminothiacalix[4]arene [22], 2.28 and 2.50 Å, respectively. On the other hand, the angle N–H–N decreases from 167.0° in the sulfur bridged compound to 132.0° in the compound **1**.

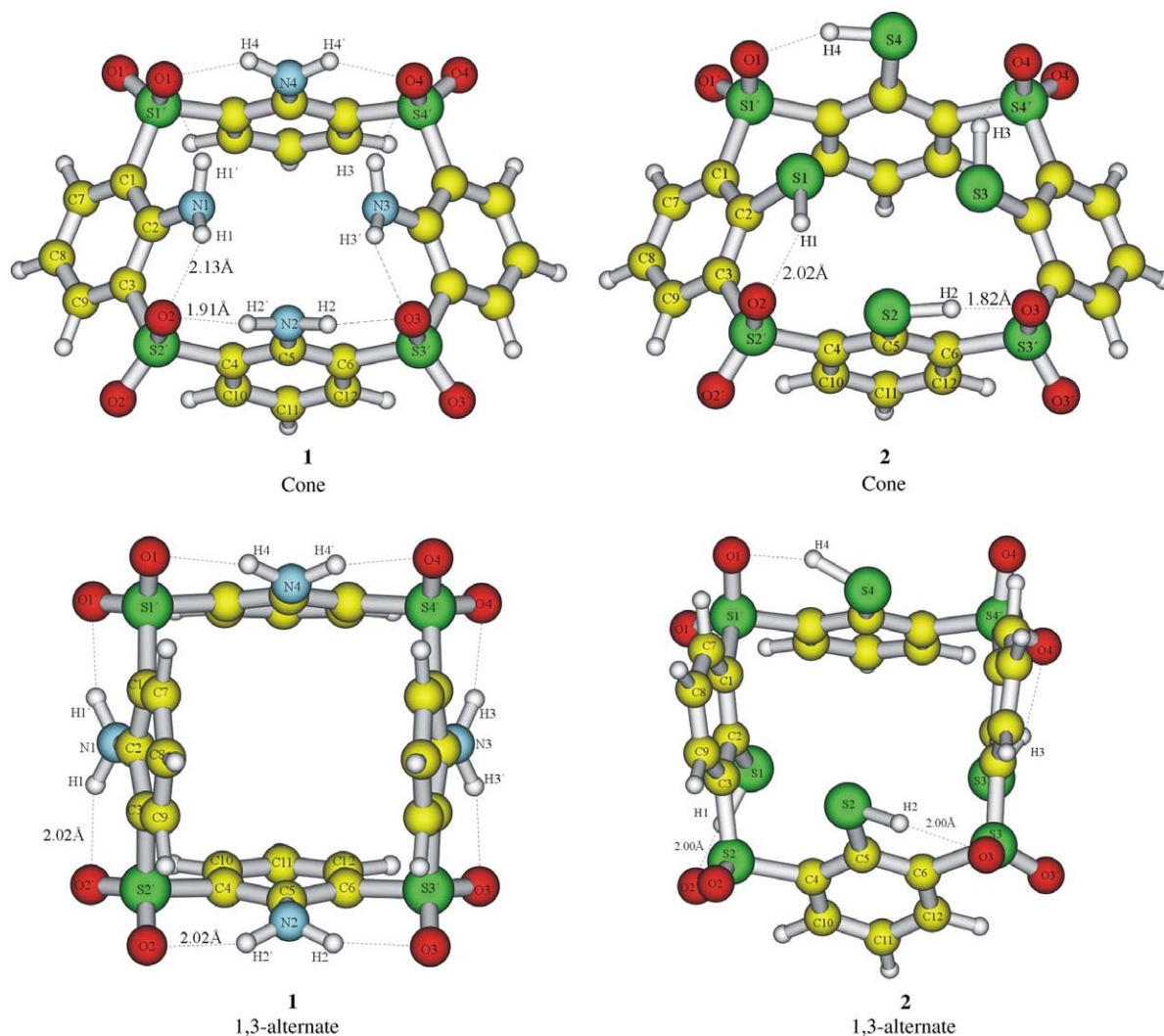


Fig. 1. Optimized *cone* and *1,3-alternate* structures for tetraaminosulfonylcax[4]arene (1) and tetramercaptosulfonylcax[4]arene (2) obtained at B3LYP/6-31G(d,p) level.

All these points suggest that the formation of hydrogen bonds of the type $\text{NH}\cdots\text{O}=\text{S}'\text{O}$ in **1** are energetically more favorable than the hydrogen bonds $\text{NH}\cdots\text{S}'$ or $\text{NH}\cdots\text{NH}$ observed at the lower rim of tetraaminothiacalix[4]arene. An occurrence of a hydrogen bond may be assumed when the $\text{XH}\cdots\text{O}$ distance is less than 2.5 Å and the $\text{X-H}\cdots\text{O}$ angle is between 135 and 225° [34]. Based on these criteria, the number of hydrogen bonds $\text{NH}\cdots\text{O}=\text{S}'\text{O}$ is found to be eight in all conformers of compound **1**. However, it is interesting to note that in the *1,3-alt* all the eight oxygen atoms interact with the NH hydrogen atoms, whereas in *cone* only the four axial oxygens establish hydrogen bonds. Consequently, each oxygen atom in *cone* participates simultaneously in two hydrogen bonds, but in *1,3-alt* conformer each oxygen is the acceptor of only one hydrogen atom. This is due to the relative positioning of the rings, which enables the formation of these two types of

hydrogen bonds. In *paco* and *1,2-alt* conformers there is an intermediate situation where two oxygen atoms establish a double hydrogen bond, and other four interact with a single hydrogen (see Figs. 1 and 2).

In compound **2**, the orientation of the $-\text{SH}$ hydrogens toward oxygen atoms of sulfone bridges may dominantly contribute to stabilize all the conformations much more than the hydrogen bonds between the SH groups in the lower rim. This is supported by the shorter $\text{SH}\cdots\text{O}=\text{S}'\text{O}$ distances in *cone*, ranging from 1.82 to 2.02 Å, when compared with the $\text{SH}\cdots\text{S}$ distances in the range of 2.87–3.35 Å. Based on the same criteria referred above the number of hydrogen bonds $\text{SH}\cdots\text{O}=\text{S}'\text{O}$ is four for all the conformers. In the *cone*, only the four axial oxygen atoms play the role of hydrogen bond acceptor, while in *1,3-alt* conformer that role is played by two axial and two equatorial oxygen atoms.

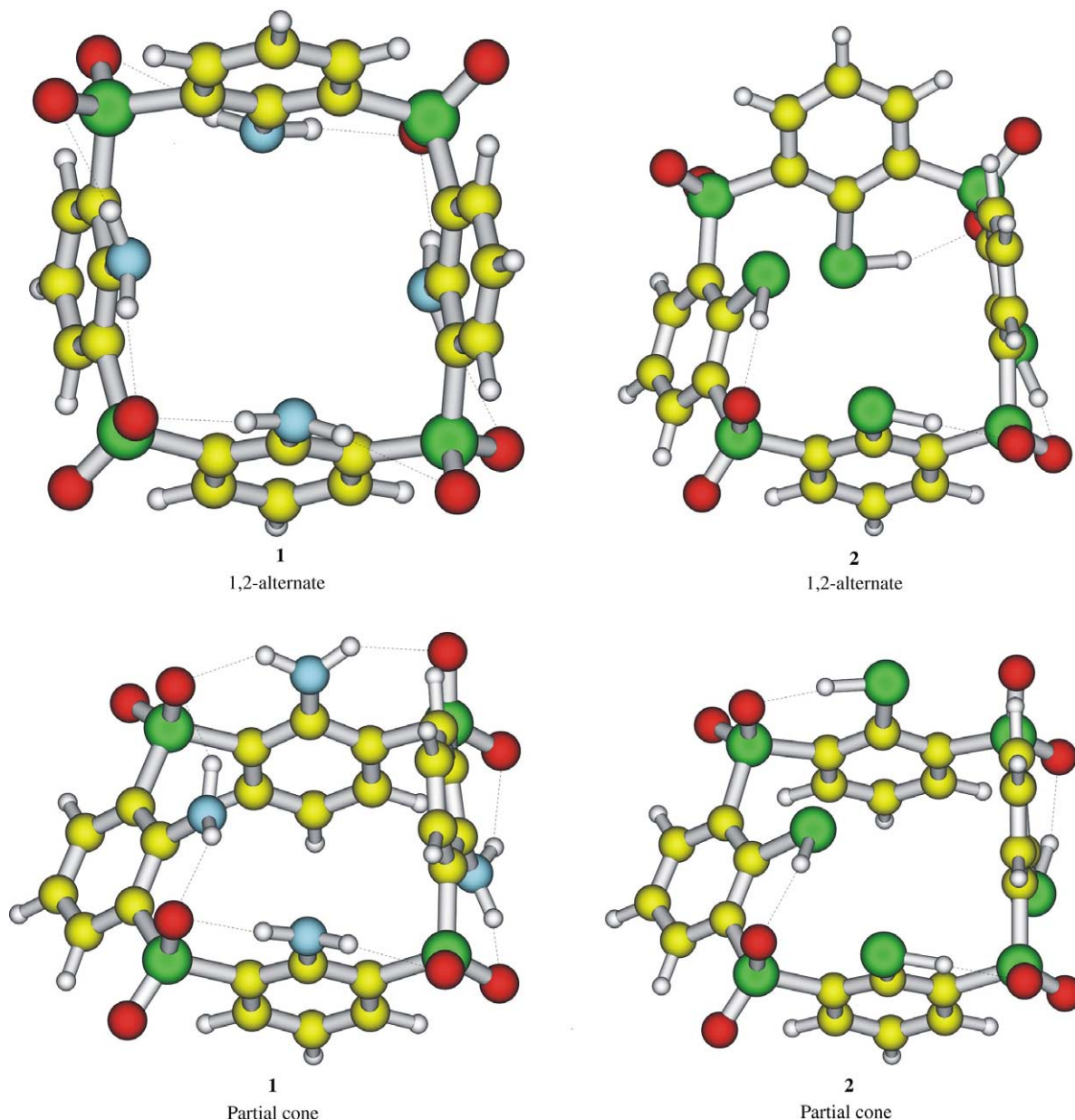


Fig. 2. Optimized *1,2-alternate* and *partial cone* structures for tetraaminosulfonylcalix[4]arene (**1**) and tetramercaptosulfonylcalix[4]arene (**2**) obtained at B3LYP/6-31G(d,p) level.

3.2. Energetics and conformational equilibrium of sulfonylcalix[4]arene derivatives

Taking the total energy of the most stable conformer as a reference, the conformational equilibrium data obtained at DFT level for both compounds are presented in Table 2. The energetic ordering of **1** is predicted to be $1,3\text{-alt} < \text{paco} < \text{cone} < 1,2\text{-alt}$, whereas this ordering is modified to $1,3\text{-alt} < \text{paco} < 1,2\text{-alt} < \text{cone}$ for **2**. The DFT calculations point out $1,3\text{-alt}$ as the most stable conformer for both compounds, which is in good agreement with previous X-ray crystallographic analysis on tetrahydroxy-*p-tert*-butylsulfonylcalix[4]arene [16]. Interestingly, this stability

orderings are different from those obtained on the corresponding thiacalix[4]arene derivatives which adopted *cone* as the most stable conformation. The geometrical characteristics of the hydrogen bonding established between the lower rim groups and the oxygen atoms seems to be a dominant factor to stabilize the conformation. At least, in the case of **1**, experimental data is available to compare with our calculations. In fact, these predictions are supported by NMR data in CDCl_3 solution of a similar compound namely tetraamino-*p-tert*-butylsulfonylcalix[4]arene [23]. On the other hand, individual hydrogen bonds might have a higher stabilization effect than the shared bonds referred in Section 3.1. In fact, no sharing is observed in $1,3\text{-alt}$, whereas *cone*

Table 1
Structural parameters for *cone* and *1,3-alt* conformers of sulfonylcalix[4]arene and thiacalix[4]arene derivatives at B3LYP/6-31G(d,p)

	Tetraaminosulfonylcalix[4]arene		Tetramercapto sulfonylcalix[4]arene		Tetraamino thiacalix[4]arene ^a	Tetramercapto thiacalix[4]arene ^a
	<i>cone</i>	<i>1,3-alt</i>	<i>cone</i>	<i>1,3-alt</i>	<i>cone</i>	<i>cone</i>
<i>Bond distance</i> ^b (Å)						
S ₁ '–C ₁	1.80	1.80	1.82	1.82	1.80	1.80
C ₁ –C ₂	1.42	1.42	1.42	1.41	1.42	1.42
C ₂ –X ₁	1.36	1.37	1.77	1.78	1.36	1.77
C ₂ –C ₃	1.42	1.42	1.42	1.42	1.42	1.42
C ₃ –S ₂ '	1.80	1.80	1.82	1.82	1.80	1.80
S ₂ '–C ₄	1.81	1.80	1.83	1.82	1.81	1.81
C ₄ –C ₅	1.43	1.42	1.42	1.41	1.41	1.41
C ₅ –X ₂	1.36	1.37	1.78	1.78	1.40	1.78
C ₅ –C ₆	1.43	1.42	1.42	1.42	1.41	1.42
C ₆ –S ₃ '	1.81	1.80	1.84	1.82	1.81	1.81
S ₁ '–S ₂ '	5.62	5.60	5.71	5.73	5.64	5.63
S ₂ '–S ₃ '	5.72	5.60	5.82	5.73	5.58	5.64
S ₁ '–S ₃ '	8.01	7.92	8.18	8.08	7.93	7.98
S ₁ '–O ₁	1.49	1.48	1.47	1.48	–	–
S ₁ '–O ₁ '	1.47	1.48	1.47	1.47	–	–
X ₁ –X ₂	3.53	5.33	3.98	5.12	3.27	3.94
X ₂ –X ₃	3.53	5.33	3.83	5.12	3.27	3.82
X ₁ –X ₃	4.00	6.67	3.81	5.23	3.56	3.71
X ₂ –X ₄	5.76	6.67	6.78	5.23	5.41	6.81
X ₁ –O ₁	2.94	–	3.09	–	–	–
X ₁ –O ₁ '	–	2.85	–	3.34	–	–
X ₁ –O ₂	2.93	–	3.22	–	–	–
X ₁ –O ₂ '	–	2.85	–	3.20	–	–
X ₂ –O ₂	2.72	2.85	2.81	3.34	–	–
X ₂ –O ₃	2.72	2.85	3.08	3.20	–	–
<i>Angle</i> (°)						
S ₁ '–C ₁ –C ₂	121.2	120.9	123.3	124.2	121.5	121.3
C ₁ –C ₂ –X ₁	122.3	122.3	119.4	120.6	121.5	118.0
C ₂ –C ₃ –S ₂ '	121.2	120.9	123.7	124.0	121.5	122.5
C ₃ –S ₂ '–C ₄	104.7	104.0	102.9	106.8	102.8	100.0
S ₂ '–C ₄ –C ₅	123.7	120.9	125.5	124.2	119.8	120.9
C ₄ –C ₅ –X ₂	122.5	122.3	120.1	120.6	120.6	118.4
C ₅ –C ₆ –S ₃ '	123.7	120.9	127.6	124.0	119.8	122.1
X ₁ –H ₁ '–O ₁	135.5	–	–	–	–	–
X ₁ –H ₁ '–O ₁ '	–	138.0	–	–	–	–
X ₁ –H ₁ –O ₂	135.6	–	144.7	–	–	–
X ₁ –H ₁ –O ₂ '	–	138.1	–	144.3	–	–
X ₂ –H ₂ '–O ₂	135.5	138.0	–	–	–	–
X ₂ –H ₂ –O ₃	135.5	138.1	152.5	143.9	–	–
O ₁ –S ₁ '–O ₁ '	119.7	119.8	119.5	119.2	–	–
φ ^c (°)	92.8; 5.5	–	90.7; 15.1	–	109.1; 7.2	95.5; 26.4

^a Ref. [22].

^b X is denoted to the N atom for tetraaminosulfonylcalix[4]arene and tetraaminothiacalix[4]arene, and to the S atom for tetramercapto sulfonylcalix[4]arene and tetramercaptothiacalix[4]arene.

^c φ is the angle between two opposite benzene rings.

presents four pairs of hydrogen bonds sharing the same acceptor oxygen atom. Surprisingly, for all the conformers the energy differences (ΔE) are bigger than those obtained with the corresponding thiacalix[4]arene derivatives. This suggests that the stronger intramolecular hydrogen bonds (NH \cdots O=S'O) increase the relative stabilization of the conformers, and the breaking of such hydrogen bonds when the molecule changes to a less stable conformer is energetically more costly. The hydrogen bonds of the type SH \cdots O=S'O seem to have an important effect in

the stabilization of all the conformers of compound **2** (see Figs. 1 and 2). The steric hindrance of thiol groups and weaker SH \cdots S hydrogen bonds lead to favor the *1,3-alt* conformer.

Additional single point calculations were carried out with a different functional and basis set, which show the same energetic ordering of the conformers. Table 2 shows that triple zeta basis set does not modify the ΔE of both compounds when compared with the double zeta basis set at B3LYP level. The PW91 correlation functional seems to

Table 2

Relative energy difference (ΔE , in kcal mol⁻¹) of the main conformers of sulfonylcalix[4]arene derivatives at different DFT levels (the energy of the most stable conformer was taken as reference)

		<i>cone</i>	<i>paco</i>	<i>1,2-alt</i>	<i>1,3-alt</i>
Tetraaminosulfonylcalix[4]arene: compound 1					
B3LYP/6-31G(d,p) ^a	Vacuum	5.58	2.94	13.65	0.00
B3PW91/6-31G(d,p) ^b	Vacuum	5.65	2.80	13.47	0.00
B3LYP/6-311G(d,p) ^b	Vacuum	5.61	3.04	13.62	0.00
B3PW91/6-311G(d,p) ^b	Vacuum	5.59	2.83	13.27	0.00
B3LYP/6-31G(d,p) ^c	Chloroform	6.03	2.15	13.02	0.00
Tetramercaptosulfonylcalix[4]arene: compound 2					
B3LYP/6-31G(d,p) ^a	Vacuum	9.58	4.24	7.89	0.00
B3PW91/6-31G(d,p) ^b	Vacuum	9.13	4.06	8.17	0.00
B3LYP/6-311G(d,p) ^b	Vacuum	9.22	4.40	7.76	0.00
B3PW91/6-311G(d,p) ^b	Vacuum	9.03	4.42	8.18	0.00
B3LYP/6-31G(d,p) ^c	Chloroform	9.33	3.86	8.28	0.00
Tetraaminothiacalix[4]arene ^d					
B3LYP/6-31G(d,p) ^a	Vacuum	0.00	1.41	6.83	4.11
B3PW91/6-31G(d,p) ^b	Vacuum	0.00	1.09	6.81	3.24
B3LYP/6-311G(d,p) ^b	Vacuum	0.00	1.37	6.70	4.38
B3PW91/6-311G(d,p) ^b	Vacuum	0.00	0.89	6.48	2.97
Tetramercaptothiacalix[4]arene ^d					
B3LYP/6-31G(d,p) ^a	Vacuum	0.00	1.81	4.97	2.04
B3PW91/6-31G(d,p) ^b	Vacuum	0.00	2.42	5.84	2.89
B3LYP/6-311G(d,p) ^b	Vacuum	0.00	2.16	5.15	2.10
B3PW91/6-311G(d,p) ^b	Vacuum	0.00	2.68	5.85	2.75

^a Geometry was optimized at this level of the theory.

^b Geometry was optimized at B3LYP/6-31G(d,p).

^c Free energies of conformational isomerism in chloroform solvent ($\Delta\Delta G_{\text{sol}}$, in kcal mol⁻¹).

^d Ref.[22].

reduce slightly ΔE for compound **1** when compared with LYP correlation functional. In case of compound **2** this is not observed for *1,2-alt* conformation. Table 2 reports also the same approach for the previous corresponding thiacalix[4]arene derivative compounds namely tetraaminothiacalix[4]arene and tetramercaptothiacalix [4]arene [22]. In the former compound, the PW91 functional presents the same tendency to reduce ΔE , but the latter one shows an opposite effect. All these results point out that PW91 predictions may be sensitive to the number of sulfur atoms of the molecule under study.

3.3. Solvent effect

The total free energy of solvation (ΔG_{sol}) for each conformer in chloroform was computed with a combination of B3LYP/6-31G(d,p) level and IEF-PCM methodology [28–30]. This took into account the electrostatic potential effect of the bulk solvent. The ΔG_{sol} is the sum of the electronic energy and all the non-electrostatic terms such as cavitation, dispersion and repulsion energy. The large size of the molecular systems does not allow a geometry optimization or the inclusion of explicit solvent molecules in the first solvation shell within the PCM model. However, it is expected that solvent molecules do not establish local interactions with the atoms of the solute that could eventually induce a change in their structures. Therefore, the study of the solvent effect was carried out through

single-point calculations on the previously optimized structures in vacuum. Results of the free energy on conformational isomerism between the most stable conformer and the other conformers in chloroform ($\Delta\Delta G_{\text{sol}}$) are presented in Table 2, which also indicate that solvation does not modify the vacuum energetic ordering of both **1** and **2**. However, the electrostatic influence of chloroform can reduce the energy gap between different conformers.

3.4. Charge distribution

Partial charges for *cone* and *1,3-alt* conformers of both compounds and the corresponding thiacalix[4]arene derivatives are presented in Table 3. The charge analysis has been carried out using the Merz-Kollman-Singh (MK) scheme [32] at the same DFT level, which fits a set of atomic point charges to the calculated electrostatic potential. Due to the C_2 -like symmetry, only information for two units of adjacent benzene ring and sulfone bridging group are reported. The increasing negative charge of substituent groups at the lower rim is predicted to be: $\text{NH}_2 > \text{SH}$, which is the same ordering obtained previously with the thiacalix[4]arene derivatives. Interestingly, the presence of four sulfone groups in **1** increases the negative charge of the N donor atoms when compared with the tetraaminothiacalix[4]arene. Surprisingly, the sulfur atoms in sulfone groups of both compounds show higher positive charges, which completely contrast with the negative charges on the

Table 3
MK atomic charges (in e) for the *cone* and *1,3-alt* conformer of sulfonylcalix[4]arene and thiacalix[4]arene derivatives at B3LYP/6-31G(d,p) level

Atoms ^a	Tetraaminosulfonylcalix[4]arene		Tetramercapto sulfonylcalix[4]arene		Tetraamino thiacalix[4]arene ^b	Tetramercapto thiacalix[4]arene ^b
	<i>cone</i>	<i>1,3-alt</i>	<i>cone</i>	<i>1,3-alt</i>	<i>cone</i>	<i>cone</i>
C1	-0.19	-0.16	0.20	0.12	0.13	0.41
C2	0.45	0.37	-0.23	-0.11	0.10	-0.33
C3	-0.19	-0.15	0.08	0.04	0.13	0.36
X1	-0.96	-0.89	-0.22	-0.26	-0.55	-0.19
H1	0.44	0.42	0.28	0.28	0.23	0.19
H1'	0.44	0.42	-	-	0.23	-
S1'	0.82	0.82	0.62	0.73	-0.24	-0.27
O1	-0.50	-0.48	-0.41	-0.48	-	-
O1'	-0.44	-0.48	-0.41	-0.44	-	-
C7	-0.04	-0.03	-0.13	-0.16	-0.09	-0.21
C8	-0.24	-0.24	-0.16	-0.13	-0.30	-0.15
C9	-0.04	-0.04	-0.10	-0.08	-0.09	-0.20
C4	-0.23	-0.19	0.07	0.08	-0.01	0.25
C5	0.52	0.41	-0.04	-0.09	0.31	-0.03
C6	-0.24	-0.20	-0.03	0.06	0.01	0.17
X2	-0.89	-0.91	-0.15	-0.27	-0.51	-0.20
H2	0.42	0.42	0.26	0.27	0.26	0.21
H2'	0.42	0.43	-	-	0.26	-
S2'	0.82	0.83	0.72	0.78	-0.24	-0.24
O2	-0.50	-0.48	-0.43	-0.45	-	-
O2'	-0.44	-0.48	-0.43	-0.48	-	-
C10	-0.07	-0.02	-0.19	-0.17	-0.18	-0.33
C11	-0.17	-0.25	-0.07	-0.10	-0.09	0.03
C12	-0.06	-0.01	-0.11	-0.10	-0.19	-0.27

^a X is denoted to the N atom for tetraaminosulfonylcalix[4]arene and tetraaminothiacalix[4]arene, and to the S atom for tetramercaptosulfonylcalix[4]arene and tetramercaptothiacalix[4]arene.

^b Ref. [22].

sulfur bridging atoms in thiacalix[4]arene derivatives [22]. This same behavior was also found in the *1,3-alt* conformer. The sulfone bridging groups carry one oxygen in axial position and another in equatorial, and both atoms exhibit higher negative charges when compared with the sulfur atoms. The oxygen orientation has a slight influence in its charge in *cone* conformer of compound **1**, but this is not observed in *1,3-alt*. The contrary happens for compound **2**. This suggests that oxygen atoms introduce stronger binding sites than sulfur atoms for complexation with metals. Unfortunately, no experimental results have been reported yet for these two new compounds. However, experimental data [35] obtained with a Zn(II) complex with the deprotonated form of tetrahydroxy-*p-tert*-butylsulfonyl calix[4]arene and 1,4,7 triazacyclononane (TACN) show an octahedral coordination environment with two deprotonated phenoxy oxygens and one sulfone oxygen of calix[4]arene and three N donor atoms from TACN, and these observations suggest also that oxygen atoms are preferred over sulfur atoms to coordinate metal ions.

The atomic charge distribution of carbon atoms in the benzene ring is different in both compounds. In addition, carbon atoms linked to the sulfone bridging group (C₁, C₃, C₄, C₆) in **1** exhibit more negative charge in comparison with the same atoms in the corresponding sulfur bridged compounds. This suggests also the possibility of the ring

carbon atoms to participate in the complexation of metal ions through cation- π electron interaction.

4. Conclusion

Structure and energetics of the four main conformers of two novel sulfone bridged compounds named tetraaminosulfonylcalix[4]arene (**1**) and tetramercaptosulfonylcalix[4]arene (**2**) have been investigated by a DFT methodology. The stronger intramolecular bonding between amino or thiol groups and sulfone oxygen atoms seems to be a dominant contribution for the stabilization of all the conformers rather than hydrogen bonds between the substituent groups at the lower rim. Our results found the *1,3-alternate* to be the most stable conformer for both compounds, which contrasts with a previous theoretical investigation on the corresponding sulfur bridged derivatives pointing out *cone* as the most stable conformer. Two different reasons can explain the favorable *1,3-alt* conformation. In the case of compound **1**, the number of individual hydrogen bonds as opposed to the weaker shared hydrogen bonds is an important stabilization factor. However, in compound **2** the steric hindrance effect of thiol groups seems to play the major role. The free energies on conformational isomerism of both compounds in chloroform were also obtained with a combination of the

IEF-PCM and DFT methodologies. The solvent does not modify the energy ordering of the conformers but leads to a reduction of the energy gap between conformers. The two new compounds studied here show sulfone oxygen atoms as additional coordination sites. They can bring a new and diverse range of host–guest complex properties toward metal ions.

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