Synthesis and Structural Studies on *p-tert*-Butyl-1,3-dihydroxy-2,4-disulfanylcalix[4]arene and its Mercury Complex

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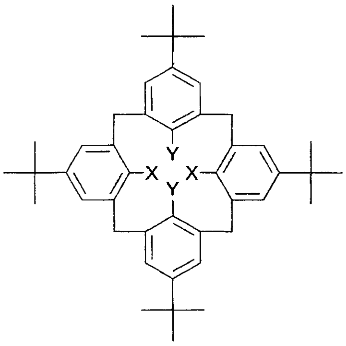
Reaction of mercury(II) acetate with *p-tert*-butyl-1,3-dihydroxy-2,4-disulfanylcalix[4]arene, obtained by a highly efficient synthesis starting from *p-tert*-butylcalix[4]arene, leads to a mononuclear complex in which the Hg ion is coordinated linearly to two arenethiolate groups.

The design and synthesis of binucleating ligands in which the coordination sites are oriented outwards (exoreceptors) are essential for the building of molecular wires composed of organic connectors and metal centres. This approach has been used successfully with tridentate ligands and transition metals.[1] Tetradentate exohomoditopic ligands have been reported.[2–5] In this vein, we investigated the substitution of two hydroxy groups in the 1,3-positions by two sulfanyl groups on *p-tert*-butylcalix[4]arene.[6] We report here the first synthesis of *p-tert*-butyl-1,3-dihydroxy-2,4-disulfanylcalix[4]arene **7** and of its monomercury complex.

The synthesis of **6** has been attempted previously.[7] For the synthesis of **7**, our approach was taken from the above-mentioned publication. The key step, the Newman–Kwart rearrangement[8] had already been used for the synthesis of **8**[7] and **9**[3,5] and of tetrasulfanylcyclophane.[4] Compound **1**[9] was first transformed (48% yield) into **2** by reaction with Me_2NCSCl (NaH, DMF, at 25 °C). Thermogravimetric analysis revealed that **2** decomposed above 260 °C; consequently, the thermal rearrangement of **2** into the di-*S*-phenyldimethylthiocarbamate derivative could not be achieved. In order to avoid the decomposition, the two hydroxy groups on **2** were protected by either methyl (**3**; 84%) or benzyl groups (**4**; 73%). The thermal rearrangement of **3** to **5** was achieved by heating the solid at 360 °C under argon for 20–30 min (46%). Under these conditions, in addition to **5**, 20% of the starting material **3** and 26% of the mono-rearranged compound were obtained. The reduction of **5** by $LiAlH_4$ in dry THF afforded **6** in 48% yield. Finally, the deprotection of **6** by BBr_3 in CH_2Cl_2 gave **7** in 72% yield.

All three intermediates **2**–**4** and the final compound **7** were structurally analysed in solution by two-dimensional ROESY–NMR experiments. In chloroform, **2** adopts a flattened cone conformation, whereas **3** was found to be in a flattened 1,3-alternate conformation, and the benzyl derivative **4** was isolated as the 1,3-alternate conformer. Dealing with the latter, its conformation was further confirmed by X-ray analysis.[10] For **6**, although it was isolated as a single product, its ^1H NMR spectrum (25 °C) was composed of broad signals, indicating considerable conformational mobility at room temperature. Variable ^1H NMR studies in $C_2D_2Cl_4$ revealed that the conformational mobility was still present at −30 °C, whereas above 100 °C singlets were obtained for all signals, implying a rapid interconversion between the different conformers.



1 X = Y = OH
2 X = OH, Y = $OCSN(Me)_2$
3 X = OMe, Y = $OCSN(Me)_2$
4 X = OBz, Y = $OCSN(Me)_2$
5 X = OMe, Y = $SCON(Me)_2$
6 X = OMe, Y = SH
7 X = OH, Y = SH
8 X = OMe, Y = SMe
9 X = Y = SH

For the final compound **7**, its ^1H NMR spectra in both $CDCl_3$ and in $C_2D_2Cl_4$ at 25 °C were composed of rather sharp signals, demonstrating the presence of a unique conformer and a slow rate of interconversion. NOESY–NMR experiments showed unambiguously that **7** exists in a cone conformation. For the parent compound **1**, it has been proposed that the cone conformation was stabilised by intramolecular hydrogen bonds.[6] In the case of **7**, the same explanation may also hold. In favour of this was the observation of a mixture of conformers at room temperature for **6**, in which the two hydroxy groups were replaced by two methoxy groups, thus preventing the possible formation of OH···S hydrogen bonds. The conformational mobility of **7** was studied over a range of 100 °C by variable ^1H NMR in $C_2D_2Cl_4$. Heating to 130 °C caused the coalescence of the signals corresponding to the H_A and H_B protons of the CH_2 groups to a singlet. The coalescence occurred at *ca.* 67 °C (at 200 MHz) with a rate constant of interconversion, k_c, of *ca.* 350 s^{-1}, and a free energy of activation, $\Delta G^\ddagger$, of *ca.* 16 kcal mol^{-1}. For comparison purposes, the following characteristics were reported for **1** in $CDCl_3$: T_c = 52 °C, $\Delta G^\ddagger$ = 15.7 kcal mol^{-1}, and k_c = 150 s^{-1}.[11] Although for **1** a unique process was postulated for the cone inversion process leading to equivalence of the two protons,[11] one cannot assume an exchange process involving only two states for **7**. Indeed, above the coalescence temperature, the δ value of 4.10 obtained for the singlet did not correspond to the average value of δ 3.99 [$(\delta H_A + \delta H_B)/2$] for H_A and H_B protons.

The structure of **7** was studied by X-ray analysis (Fig. 1).[†] Compound **7** also adopts a cone conformation in the solid state, presenting the following features: (i) the O(1)–O(2) and S(1)–S(2) distances are 3.469 and 5.317 Å, respectively; (ii) the average distance between O and S atoms is *ca.* 3.29 Å; (iii) with respect to a mean plane defined by all four CH_2 groups, the average angles between planes containing the aromatic moieties bearing SH or OH groups are *ca.* 93 and 137°, respectively, showing that, whereas the thiophenol rings are almost perpendicular to the mean plane described above, the two phenol rings

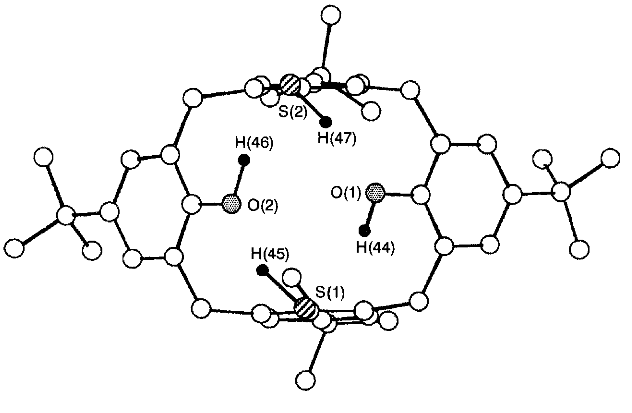


Fig. 1 Crystal structure of **7** (top view). Selected bond lengths (Å) and angles (°): O(1)–H(44) 0.980, S(1)–H(45) 1.353, O(2)–H(46) 1.083, S(2)–H(47) 1.234, O(1)–S(1) 3.311, S(1)–O(2) 3.266, O(2)–S(2) 3.281, S(2)–O(1) 3.294, O(1)–O(2) 3.469, S(1)–S(2) 5.317; O(1)–H(44)–S(1) 159.73, S(1)–H(45)–O(2) 132.04, O(2)–H(46)–S(2) 158.49, S(2)–H(47)–O(1) 145.87.

are tilted considerably towards the exterior of the calix; (iv) the average O–H and S–H distances, using isotropically refined hydrogen atoms, are *ca.* 1.03 and 1.29 Å, respectively; (v) The SH···O and OH···S distances (Å) and angles (°) are O(1)H(44)···S(1) 2.374, 159.73; S(1)H(45)···O(2) 2.203, 132.04; O(2)H(46)···S(2) 2.249, 158.49; S(2)H(47)···O(1) 2.200, 145.87. For **7**, although the OH and SH hydrogen atoms are properly oriented (Fig. 1), the average distance between O and S atoms of *ca.* 3.29 Å and the observed angles indicate that if hydrogen bonds do exist, they are rather weak.

Compound **7** possesses both 'hard' OH groups and 'soft' SH binding sites. Furthermore, as in the case of **9**,[3] for its 1,3-alternate conformation, within the side bearing the two SH groups which may act as 'soft' and strong binding sites, two aromatic phenolic rings are present as well and may also participate in the binding processes as 'soft', and probably weak, interaction sites.

When $Hg(OAc)_2$ and **7** are mixed in a 1 : 1 ratio at room temperature in THF, exclusive formation of the 1 : 1 mercury(II) complex occurs. Even in the presence of a large excess of $Hg(OAc)_2$ (4 : 1 or 10 : 1) at room temperature or in refluxing THF, the only complex isolated was the mononuclear species. The preferential binding of mercury at sulfur in **7** may be expected, owing to the thiophilicity of Hg^{II}.[12] The structure of the **7**–Hg complex was investigated by X-ray crystallography.‡ This study revealed the following features (Fig. 2): (i) **7** adopts a 1,3-alternate conformation in the solid state in which the mercury ion is coordinated to two sulfur atoms [linear two-coordination at Hg in $Hg(SR)_2$ compounds[12] has been established]; (ii) in the mononuclear **7**–Hg complex, the average Hg–S distance of *ca.* 2.35 Å and S–Hg–S angle of *ca.* 176.0° are close to the values observed for the binuclear **9**–Hg_2 complex previously obtained;[3] (iii) the distance between two S atoms in the S–Hg–S unit (4.710 Å) is shorter than that in the free ligand (5.317 Å), showing that the ligand must bend by *ca.* 0.60 Å in order to accommodate the metal ion. Consequently, with respect to a mean plane defined by all four CH_2 groups, the average angles between planes containing the aromatic moieties bearing SH or OH groups are *ca.* 99.3 and 101.2°, respectively. This shows that both thiophenol and phenol rings are almost perpendicular to this mean plane.

Although strong two-coordination at Hg in $Hg(SR)_2$ compounds is common, weaker additional interactions are not excluded and the coordination chemistry of Hg^{II} shows many aspects which may be rationalised in terms of a '2 + 4' model.[13] For the **7**–Hg complex the mercury cation is located, in an almost symmetrical fashion, between the two phenolic rings with distances from Hg to the centroids of the two rings of 3.07 and 3.11 Å. The same observation was made for the **9**–Hg_2 complex in which the average distance between Hg ions and the centroids of the aromatic rings located on the same side was found to be *ca.* 3.1 Å. Although in the latter case one could argue that this was structurally imposed by the ligand,[3] for the **7**–Hg complex the fact that the ligand undergoes a conformational change in the complex is a clear-cut argument in favour of the '2 + 4' model. In other terms, due to its flexibility, the ligand offers to mercury(II) the possibility of having its secondary coordination requirements satisfied by polyhapto (π)-interactions with two of the phenyl rings.

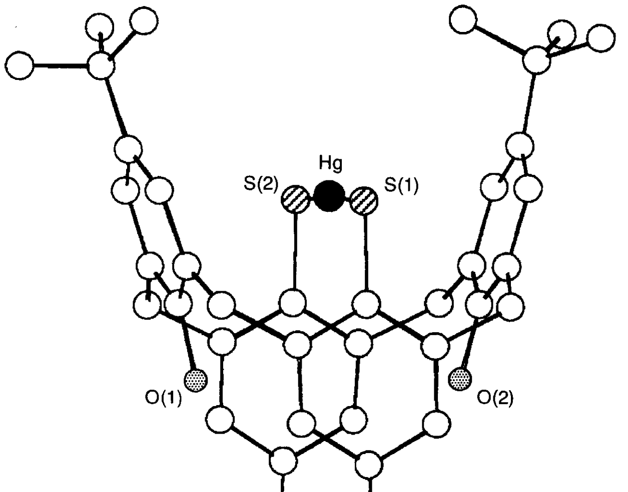


Fig. 2 Crystal structure of the **7**–Hg complex (lateral view). Selected bond lengths (Å) and angles (°): S(1)–Hg 2.358, S(2)–Hg 2.355, O(1)–O(2) 4.626; S(1)–Hg–S(1) 176.0.

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Footnotes

† *Crystal data* for **7**: $C_{44}H_{56}O_2S_2$, M = 681.1, triclinic, a = 12.316(3), b = 16.058(4), c = 11.261(3) Å, α = 104.60(2), β = 108.15(2), γ = 94.51(2)°, U = 2017.9 Å^3, space group $P\bar{1}$, Z = 2, D_c = 1.121 g cm^{-3}, μ(Cu-Kα) = 14.053 cm^{-1}, T = 173 K; $R(F)$ = 0.054, [$R_w(F)$ = 0.075] using 3292 reflections with $I > 3\sigma(I)$. A disorder was found for one of the four *tert*-butyl groups and the relative occupancy factors were refined by least-squares analysis to a final ratio of 50 : 50.

‡ *Crystal data* for **7**–Hg: $C_{44}H_{54}HgO_2S_2$, M = 879.6, monoclinic, a = 14.239(4), b = 15.919(4), c = 18.578(5) Å, β = 101.11(2)°, U = 4131.8 Å^3, space group $P2_1/n$, Z = 4, D_c = 1.414 g cm^{-3}, μ(Mo-Kα) = 38.529 cm^{-1}, T = 293 K; $R(F)$ = 0.039, [$R_w(F)$ = 0.052] using 4673 reflections with $I > 3\sigma(I)$. For the **7**–Hg complex, an orientational disorder was observed. Whereas for 90% of molecular units the S–Hg–S moiety was located above the basic plane defined by the calix core, for the other 10% this moiety was located below the above-mentioned plane.

For both structures, atomic coordinates, bond lengths and angles, and thermal parameters have been deposited at the Cambridge Crystallographic Data Centre. See Information for Authors, Issue No. 1.

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