

Synthesis and Crystal Structure of *p*-*tert*-Butylthiacalix[8]arene: A New Member of Thiacalixarenes

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Abstract

Even though it was obtained in poor yield, *p*-*tert*-butylthiacalix[8]arene (TC8A) has been synthesized as a new member of thiacalix[*n*]arenes by the terephthalate-induced cyclization of a mixture of acyclic oligomers, which was obtained by the reaction between *p*-*tert*-butylphenol and sulfur with CaO in ethylene glycol/diphenyl ether system. Slow evaporation of the chloroform solution of TC8A afforded guest-free crystals consisting of TC8A itself. The close-packed crystal structure of TC8A resembles that of *p*-*tert*-butylcalix[8]arene (C8A) closely, containing a plated loop molecular structure.

Introduction

The chemistry related to thiacalix[4]arene [1], a sulfur-bridged phenol cyclic tetramer, has grown remarkably in the past 5 years. Since the facile synthetic method of *p*-*tert*-butylthiacalix[4]arene (TC4A) by base-catalyzed condensation of *p*-*tert*-butylphenol and sulfur was developed [2], the sulfinyl [3], sulfonyl [4] and *de-tert*-butyl [5] counterparts as well as various kinds of modified molecules bearing such substituents as carboxyl [6], amide [7], ether [8], ester [9], phosphonyl [10], dansyl [11], and amino [12] groups have been synthesized, and their guest binding, molecular recognition, and metal complexation [13] properties have been demonstrated. Other thiacalixarenes consisting more than four phenol units [14], however, are still far less readily available while their methylene-bridged counterparts 'major' calixarenes [15] having four, six, and eight phenol units can be easily prepared in satisfactory yields. To our knowledge, particularly a thiacalixarene consisting eight aryl units has been only one reported by Iki and co-workers [16]. We report here that the another synthesis of *p*-*tert*-butylthiacalix[8]arene (TC8A), which can be obtained by the terephthalate-induced cyclization of a mixture of acyclic sulfide oligomers (precursor) was found, and TC8A forms guest-free crystals of which a structure closely resembles that of *p*-*tert*-butylcalix[8]arene (C8A) [17–19].

Experimental

Preparation of p-alkylphenolsulfid (precursor)

Under nitrogen a solution of *p*-*tert*-butylphenol (300 g, 2.0 mol), CaO (28.0 g, 0.5 mol), and sulfur (95.9 g, 3.0 mol) in the mixed solvent consisting of diphenyl ether and ethylene glycol was stirred at high temperatures (60–200 °C) totally for 6 h. After removal of CaSO₄ generated by acidification extraction with appropriate solvents followed by precipitation with acetic acid afforded the *p*-*tert*-butylphenolsulfio (precursor) (162 g, ca. 50 % yield based in the starting *p*-*tert*-butylphenol): ¹H NMR (300 MHz, CDCl₃, 25 °C, TMS): δ = 6.70–7.65 (br m, ca. 6H), 1.20–1.15 (br m, ca. 4H; C(CH₃)₃ on both terminal positions), 1.05–1.15 (br m, ca. 7H). Highly split broadening signals at 1.20–1.32 ppm and no OH signals at 6.28 ppm indicate that the precursor was presumed to be a complex mixture of the oligomers consisting of not less three *p*-*tert*-butylphenol units.

Preparation of p-*tert*-butylthiacalix[8]arene (TC8A)

Under nitrogen a mixture of the precursor (30 g), terephthalic acid (2.35 g, 14.1 mmol), and NaOH (3.99 g, 99.9 mmol) was stirred and heated to 100 °C at which sulfur (2.14 g, 66.6 mmol) was added. The temperature was raised to 230 °C in an hour and kept for 4 hrs. After cooling to 70 °C, 2N sulfuric acid (100 ml) was slowly added to the resulting dark-red viscous material. The organic layer on the acidic

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aqueous layer was diluted with *n*-heptane (100 ml) at 50 °C and this bilayer solution was allowed to stand for 3 days. Obtained precipitates were filtered off from the mother liquor, washed with *n*-heptane (100 ml), distilled water (50 ml), acetone (50 ml) successively and dried in vacuo. Thus obtained crude product (16.26 g) consisted of 80% of *p*-*tert*-butylthiacalix[4]arene (13.98 g, 21% yield based on the starting *p*-*tert*-butylphenol), 11% of *p*-*tert*-butylthiacalix[6]arene (1.79 g, 2.7% yield), and 3.0% of *p*-*tert*-butylthiacalix[8]arene (0.49 g, 0.74% yield). Pure TC8A was favorably obtained by several recrystallization from the toluene solution of this crude product (0.25 g, 0.38% yield): IR (KBr): $\nu = 3360$ (O-H), 2962 (C-H), 1459 (C=C), 693 cm^{-1} (C-S); ^1H NMR (300 MHz, CDCl_3 , 25 °C, TMS): $\delta = 8.70$ (s, 8H; Ar-OH), 7.56 (s, 16H; Ar-H), 1.23 (s, 72H; $\text{C}(\text{CH}_3)_3$); ^{13}C NMR (75 MHz, CDCl_3 , 25 °C): $\delta = 31.3$ ($\text{C}(\text{CH}_3)_3$), 34.2 ($\text{C}(\text{CH}_3)_3$), and 120.4, 134.7, 144.4, 154.9 (Ar); FAB MS: Calcd 1440, Found: 1440; Elementary analysis for $\text{C}_{80}\text{H}_{96}\text{O}_8\text{S}_8$: Calcd: C 66.63, H 6.71; Found: C 66.82, H 6.80.

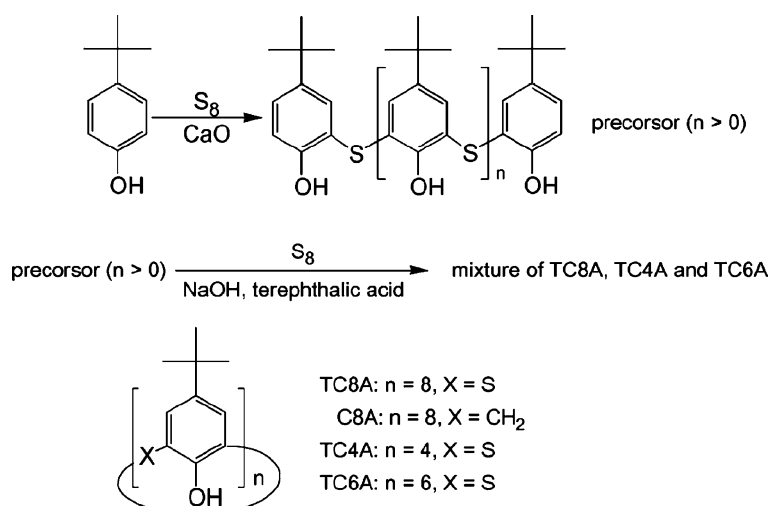
Results and discussion

The precursor, a mixture of sulfidically bridged oligonuclear *p*-*tert*-butylphenol [20], was obtained by the reaction between *p*-*tert*-butylphenol and sulfur with CaO in the mixture solvent of ethylene glycol and diphenyl ether at high temperature. The base-catalyzed cyclization of this precursor with sulfur and NaOH in the presence of terephthalic acid, followed by the acidification with H_2SO_4 and the precipitation with *n*-heptane, afforded the mixture of cyclic octomer (TC8A), tetramer (TC4A) and hexamer (TC6A) (Scheme 1). Pure TC8A was obtained by several recrystallization from the toluene solution of this crude product. On the other hand, TC8A was hardly obtained in a similar condition as above without terephthalic acid. In the case, a main product was

only TC4A. Whatever the details of the reaction mechanisms may be, it seems that the terephthalic acid plays an essential role for cyclization to TC8A as a template.

The TC8A is measurably soluble in chloroform at room temperature. Slow evaporation of the chloroform solution of TC8A affords guest-free single crystals consisting of only TC8A itself, nevertheless this single crystal is unstable when allowed to stand in contact with atmosphere at room temperature [21]. The structure of this crystal (monoclinic, $P2_1/a$) was determined by single-crystal X-ray diffraction [22]. To avoid loss of single crystallinity a moist crystal was mounted and cooled to 103 K for successful measurement. In the crystal, TC8A exists in a plated loop conformation which is closely similar to that of C8A reported by Gutsche *et al.* [18a] (Figure 1). The size of TC8A is slightly bigger, ca. 0.5 Å longer in diameter and ca. 0.5 Å thicker in thickness, and in molecule, the dihedral angles between the benzene rings and a least-squares plane determined by all the connected heavy atoms are in the range 37.7–53.2°, 4–5° tighter, in addition, the eight hydroxyl groups are set in OH...O hydrogen-bonded cyclic array whose hydrogen bond lengths (2.71–3.20 Å) are ca. 0.2 Å longer, respectively, than those C8A. A large central pore surrounded with eight hydroxyl groups is roughly 7 Å in a diameter, ca. 0.5 Å larger than a similar hole of C8A. It should be noted that most of these size differences between TC8A and C8A stem largely from the significant geometrical distinctions at the bridging moieties, where the bond lengths C–S (ca. 1.78 Å) and angles C–S–C (98.5–106°) of TC8A are ca. 0.2 Å longer and 7–8° narrower than C–C (ca. 1.55 Å) and C–C–C (107–112°) of C8A, respectively. These are why TC8A has tighter folded, but slightly larger and thicker plated loop conformation with lower planarity as compared to C8A.

The packing mode of molecules of TC8A in the crystalline state is also essentially identical with that of C8A, both crystal are isomorphous crystallographically.



Scheme 1. Synthetic route for cyclic octomer TC8A and structural formulas of related compounds.

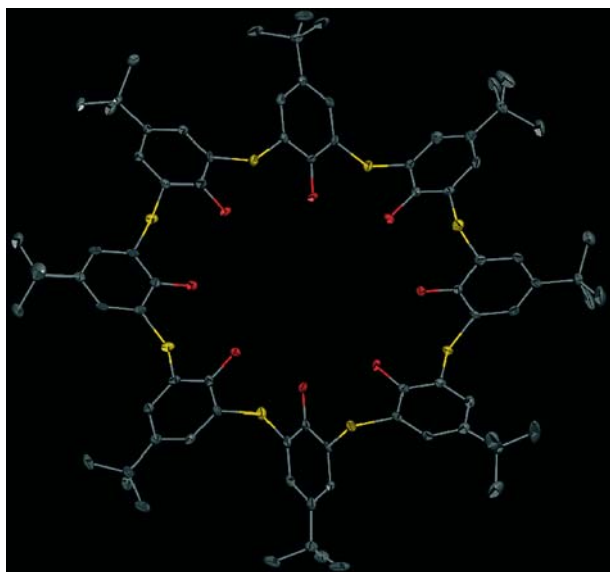


Figure 1. Plated loop conformation of TC8A in the crystalline state. The carbons, oxygens, sulfurs, and hydrogens are in gray, red, yellow, and white, respectively. All the hydrogen atoms are omitted for clarity.

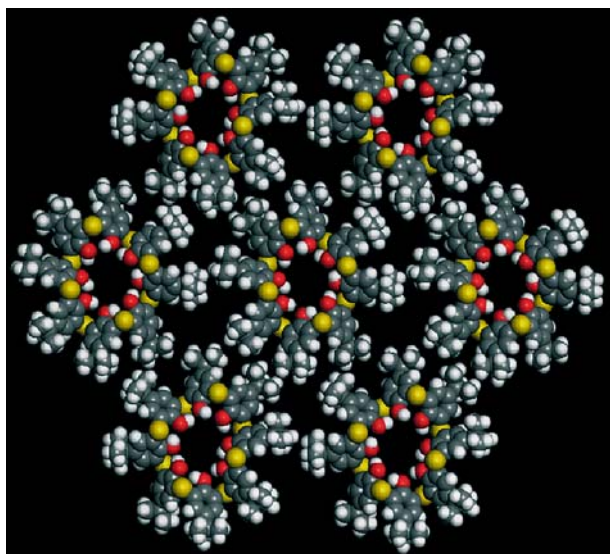


Figure 2. Hexagometry-arranged molecular sheet of TC8A in the lattice plane (2 0 -1). The colors have the same meaning as in Figure 1.

In the lattice plane (2 0 -1), a molecule is surrounded with six neighboring molecules to give a hexagonally arranged molecular sheet with large number of intramolecular and intermolecular cavities (Figure 2). Three neighboring sheets (A, B, and C) are stacked in an $\cdots ABCABC \cdots$ manner so as to give a pseudo face-centered-cubic (fcc) type close-packed molecular arrangement in which a molecule is covered by a total of twelve neighboring molecules (Figure 3). Figure 4a and b show the self-assembled three octomers along a lattice direction [1 0 1] in the crystal. Each intramolecular central cavity surrounded with eight hydroxyl groups and eight sulfur atoms is sandwiched with two bulky *tert*-butyl

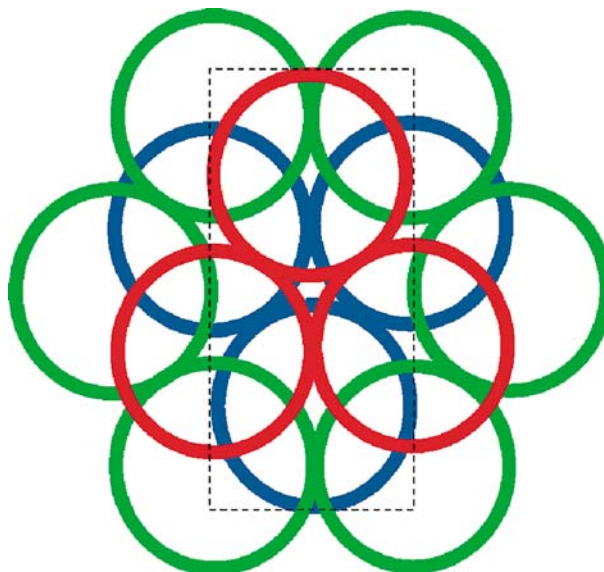


Figure 3. Schematic representation of pseudo fcc type close-packed molecular arrangement. Each circle indicates a molecule of TC8A, colored in red, green, and blue for A, B, and C layer, respectively. Three neighboring molecules being shown in (a) and (b) are inside the rectangle with dotted line.

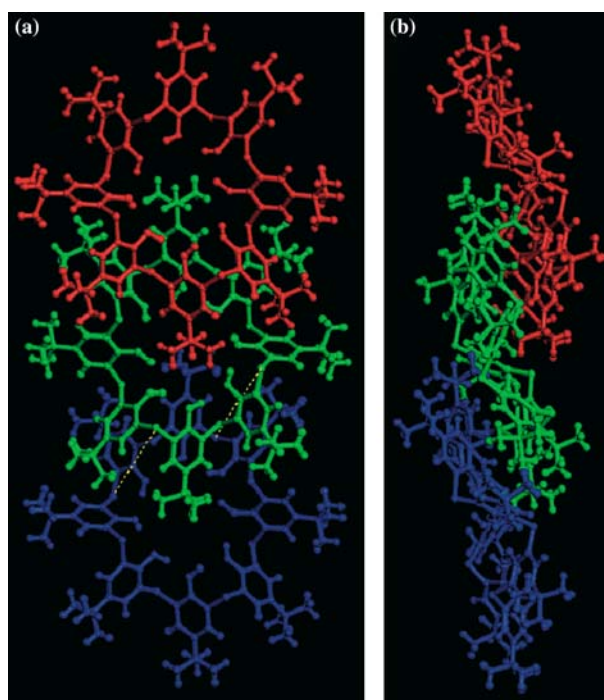


Figure 4. (a) Three neighboring octomers TC8A along [1 0 1] direction in the crystal. The colors have the same meaning as in Figure 3 and white dotted lines indicated the S...S distance of ca. 3.86 Å. (b) Side view of (a).

moieties from above and underneath the plane. Thus, the intramolecular cavities in a sheet are filled up efficiently with the side chains of octomers being in the adjacent sheets. In marked contrast to this efficient packing, the intermolecular cavities which cannot be covered so efficiently leave the asymmetrical void spaces which will probably be unsuitable for guest inclusion. As

a consequence, it can be assumed that the unstable nature [21] of the guest-free crystal of TC8A at room temperature would be due to the remaining void spaces which may allow the drastic movement of molecules, i.e., disorder of crystal structure.

It is also interesting to note that there are soft S...S interactions (3.86 Å) between S(2) and S(8) as shown in Figure 3. This distance is ca. 0.2 Å shorter than methylene-to-methylene distance at a similar position in the crystal of C8A, while being ca. 0.16 Å longer than twofold van der Waals radius of sulfur atom. This may allow the unexpectedly closer packing of TC8A than that C8A. In fact, despite the larger molecule size of TC8A, its lattice volume (ca. 8501 Å³) is remarkably smaller, by ca. 200 Å³, than that of C8A being smaller in size (ca. 8707 Å³). In addition, on closer inspection for the lattice parameters for TC8A, *a* and *c*, both of which would mainly be affected by S...S distances, are shorter by ca. 0.5 Å and ca. 0.6 Å, respectively, while *b*, which would be affected only the diameter of molecule, is predictably longer by ca. 0.3 Å in comparison with crystal of C8A.

The present work may provide a synthetic method for TC8A as a new larger member of thiacalixarenes. The TC8A can be obtained terephthalate-induced cyclization of a precursor and forms the guest-free crystal. In the crystalline state of TC8A is slightly larger, but can be packed closely, than a methylene-bridged counterpart C8A, while both a plated loop conformation and a molecular arrangement are essentially same each other. The targets in further work which is now under way in our laboratory include increase of the yields of TC8A by exploring more effective templates, and revealing their functions such as guest binding, molecular recognition as well as self-assembling properties both in solution and in solid states.

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