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Synthesis and crystal structure of a sulphur-bridged molecular hoop consisting of 5,7,12,14-tetrathiapentacene†

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A cyclic dimer consisting of 5,7,12,14-tetrathiapentacene (TC[2]TTP) forms a new extended series of thiacalix[*n*]arenes, and was successfully synthesized by an intramolecular Friedel–Crafts-type condensation of the macrocyclic precursor. TC[2]TTP was characterized using ¹H and ¹³C nuclear magnetic resonance and high-resolution mass spectrometry. Its hoop-shaped molecular structure was determined by X-ray crystallography. The two-tub-shaped TTP formed a hexagonal geometry via a sulphur linker, and TC[2]TTP adopted a honeycomb structure with columnar stacking in the crystal structure. Furthermore, TC[2]TTP exhibited crystal polymorphism, which incorporated appropriate organic solvents such as CHCl₃, benzene, and toluene into its internal cavity. This suggests that TC[2]TTP is a candidate for the components of cavity-assembled porous solids based on molecular tiling.

Introduction

Macrocycles bearing sulphur atoms as linkers, such as cyclo-*para*-phenylenesulphide,¹ thiacalixarenes,² and their analogues,³ which are categorized as flexible single-sulphur-bridged molecular nano-hoops, are important target molecules in electrochemistry and supramolecular chemistry. These molecules often show electrical conductivity caused by the generation of their stable radical cation.¹ Their unique internal cavity enables them to incorporate appropriate solvents,⁴ cationic molecules,⁵ and fullerene.^{3b} Furthermore, polygonal structures, which are formed by the carbon–sulphur–carbon (C–S–C) bond angle, are useful molecular tools to construct molecular arrangements based on molecular tiling.⁶ For the development and application of the solid materials based on molecular tiling, such as porous materials applying sulphur-embedded nano-hoops, a more durable and rigid framework is necessary. Therefore, we focused on double-sulphur-bridged macrocycles. The thianthrene-based macrocycles, thiacalix[2]thianthrene⁷ and thianthrenophane⁸ have been previously synthesized and demonstrated metal ion inclusion. Moreover, absolute double-sulphur-bridged belt-shaped compounds, [*n*]cyclothianthrene (*n* = 6–9), have recently been synthesized⁹ since they have been detected by MALDI-TOF-mass

spectroscopy.¹⁰ These belts showed unique redox properties and complexation due to their rigid polygonal geometry. Thus, thianthrene is expected to be a significant building block for double-sulphur-bridged macrocycles. However, there are few reports on double-sulphur-bridged macrocycles that provide insights into molecular assemblies and frameworks based on the sulphur bridge style. 5,7,12,14-tetrathiapentacene (TTP, Fig. 1) is a promising macrocyclic component. TTP possesses two 1,4-dithiin units and demonstrates reversible electron transfer with conformational change.¹¹ Furthermore, TTP can adopt both, tub and chair form, in solution. Although TTP usually exists in the chair form in the crystal structure,^{12a,b} the complex with 2,3-dichloro-5,6-dicyano-*p*-benzoquinone adopts the tub form.^{12c} Tub-shaped TTP plays a necessary role in constructing a polygonal macrocyclic framework, but a method to adopt a particular form has not yet been identified. If TTP units can be incorporated into the macrocyclic framework, the rigid polygonal structure due to its tub form might allow the control of minute molecular packing and introduce specific guest molecules into its cavity, indicating porosity in the assemblies. It is also fascinating to understand how the oxidation of TTP

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† Electronic supplementary information (ESI) available: Experimental procedures (general information and synthesis), crystal data for TC[2]TTP, 6', and 6'', ESI-MS spectra, theoretical calculation, ¹H and ¹³C NMR charts. CCDC 2141641 2141642 2141643 215327 2153528 2153529. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/d2ra00489e

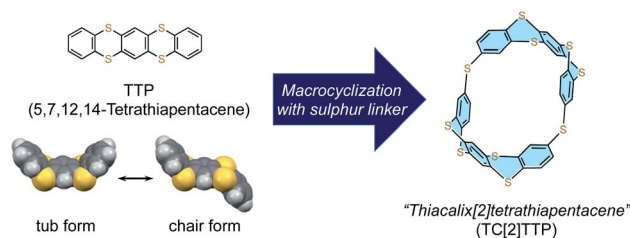


Fig. 1 Chemical structures of TTP and TC[2]TTP.



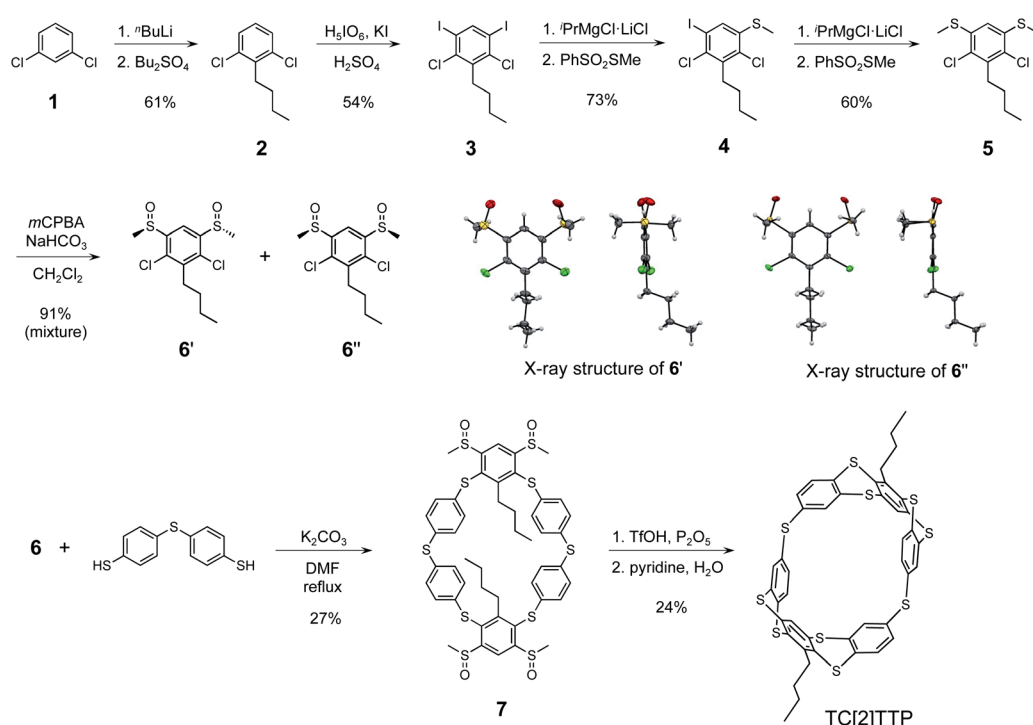
leads to conformational changes that affect the hoop-shaped geometry. However, the synthesis of organic macrocycles consisting of TTP remains a challenge. Therefore, we designed thiacalix[2]tetrathiapentacene (TC[2]TTP) as the smallest cyclic TTP dimer linked by sulphur. Herein, we report the successful synthesis and molecular structure characterization of the TC[2]TTP derivative. The host–guest chemistry in the crystal structure of TC[2]TTP was also described.

It is challenging to efficiently obtain the smallest target cyclic dimer by macrocyclization using the TTP derivative as the starting material because of its structural features. Instead, a flexible framework can be easily synthesized using thiacalix[6]arene analogues bearing methylsulphinyl groups *via* a bottom-up synthesis. Subsequently, intramolecular double-sulphur-bridging to form TTP units would be attained by an acid-induced Friedel–Crafts-type reaction.¹³ Furthermore, we introduced flexible butyl groups beforehand because of the potential low solubility of the target molecule due to their rigid framework.

Results and discussion

The synthetic route to the target compound TC[2]TTP is shown in Scheme 1. First, 1,3-dichlorobenzene (**1**) was treated with *n*-BuLi to generate a regioselective lithium salt, which was reacted with dibutyl sulphate to produce 2-butyl-1,3-dichlorobenzene (**2**) in 61% yield. Subsequently, the iodination of **2** using orthoperiodic acid and potassium iodide in sulphuric acid produced 3-butyl-2,4-dichloro-1,5-diiodobenzene (**3**) in 54% yield. Then, **3** was reacted with *i*PrMgCl·LiCl, generating the

corresponding Grignard reagent,¹⁴ which was reacted *in situ* with the prepared *S*-methylbenzenesulphonothioate as the electrophile. This reaction effectively converted the iodo groups to methylthio groups in a two-step reaction (first step (**4**): 73% yield; second step (**5**): 60% yield). Compound **7**, bearing methylsulphinyl groups, was obtained as a mixture of stereoisomers (**6'** and **6''**) in 91% yield by the oxidation of **5** with *m*-chloroperoxybenzoic acid. The absolute configuration of each isomer was determined by X-ray crystallography. The macrocyclization of a mixture of **6** with 4,4'-thiobisbenzenethiol in the presence of K₂CO₃ led to the production of thiacalix[6]arene analogue **7** including the structural isomers in 27% yield. This macrocyclization proceeded in both, the racemic mixture (**6'** and **6''**) and in each isolated compound. Under the conditions of macrocyclization, the molecular ion peaks of the linear polymer consisting of **6** and 4,4'-thiobisbenzenethiol at a ratio of 1 : 2 ($m/z = 831.0417$) and 2 : 3 ($m/z = 1335.0807$), and larger ring-sized thiacalix[8]arene analogue (cyclic timer: $m/z = 1513.1217$) were detected by electrospray ionization mass spectroscopy (ESI-MS, Fig. S1a and S1b†). However, these products could not be isolated. Owing to the presence of [1 + 2] and [3 + 2] adducts, we believe that the further optimization of macrocyclization is possible. The synthesis of the target molecule, TC[2]TTP, was achieved in 24% yield by Friedel–Crafts-type intramolecular condensation.¹⁵ TC[2]TTP was moderately soluble in CS₂ and sparingly soluble in CH₂Cl₂ and CHCl₃. The ¹H nuclear magnetic resonance (NMR) spectrum of the crude product indicated that the condensation did not completely progress the methylthio signal, and its cationic groups¹⁶ were observed (Fig. 2b). It is assumed that the ring strain arising



Scheme 1 Synthetic route of TC[2]TTP.

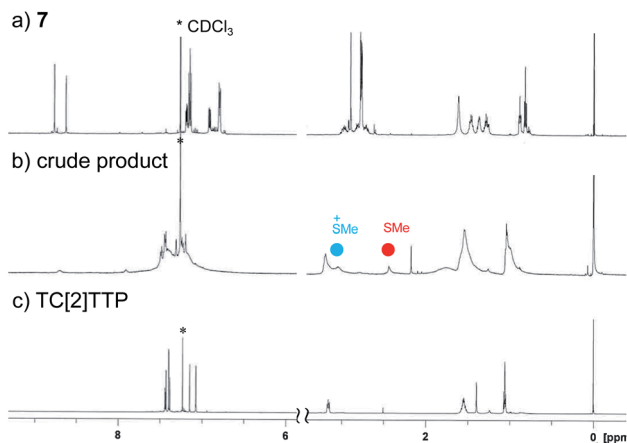


Fig. 2 ^1H NMR spectra (600 MHz): (a) 7 in CDCl_3 ; (b) crude product in macrocyclization in $\text{CDCl}_3/\text{CS}_2$; (c) TC[2]TTP in $\text{CDCl}_3/\text{CS}_2$.

from condensation toward the rigid cyclic dimer is higher than that in the case of the linear polymer. Finally, simple signals of TC[2]TTP were obtained owing to its high molecular symmetry (Fig. 2c). TC[2]TTP was fully characterized using ^1H and ^{13}C NMR spectroscopy, high-resolution mass spectroscopy ($m/z = 879.9709$, Fig. S2 †), and single-crystal X-ray diffraction analysis.

Single crystals of TC[2]TTP were grown by the slow evaporation of CS_2 and obtained as colourless hexagonal-shaped plate crystals. The crystal had a triclinic geometry with the $P\bar{1}$ space group. X-ray crystallography revealed that the two TTP units of TC[2]TTP adopted a tub form (Fig. 3a)¹⁴ with dihedral angles of $51.3(1)^\circ$ (S1-C6-C11-S2 and S1-C8-C9-S2) and

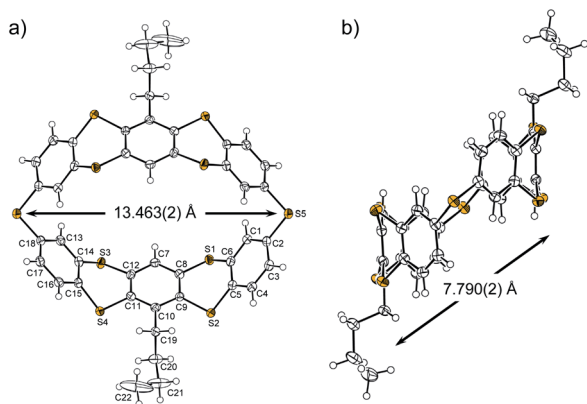


Fig. 3 ORTEP drawing of the molecular structure of TC[2]TTP: top view (a) and side view (b). Ellipsoids have a 50% probability. Selected bond lengths [Å]: C1–C2 = 1.397(3); C1–C6 = 1.391(3); C2–C3 = 1.391(3); C3–C4 = 1.392(3); C4–C5 = 1.387(3); C5–C6 = 1.396(3); C7–C8 = 1.388(3); C7–C12 = 1.383(3); C8–C9 = 1.404(3); C9–C10 = 1.405(3); C10–C11 = 1.409(3); C11–C12 = 1.401(3); C13–C14 = 1.392(3); C13–C18 = 1.397(3); C14–C15 = 1.394(3); C15–C16 = 1.394(3); C16–C17 = 1.393(3); C17–C18 = 1.393(3); C10–C19 = 1.508(3); C19–C20 = 1.534(3); C20–C21 = 1.521(3); C21–C22 = 1.491(6); S1–C6 = 1.769(2); S1–C8 = 1.765(2); S2–C5 = 1.769(2); S2–C9 = 1.778(2); S3–C12 = 1.761(2); S3–C14 = 1.760(2); S4–C11 = 1.776(2); S4–C15 = 1.771(2); S5–C2 = 1.778(2); S5–C18 = 1.781(2).

$49.8(1)^\circ$ (S3-C12-C11-S4 and S3-C14-C15-S4), respectively. These values were almost the same as those of TTP in the crystal structure. Two TTP units were bridged through S5 between C2 and C18 and were horizontal and vertical inverted. The difference in the bridge mode is considered to contribute to formation of the structural isomer, bridged at the C2–C2' and C18–C18' of each TTP. However, a theoretical calculation using the B3LYP/6-31G level of theory indicated that the isomer was $2.1 \text{ kcal mol}^{-1}$ more unstable compared to the molecular structure of TC[2]TTP (Fig. S3 †). The atomic distance of S5–S5' was $13.463(2) \text{ \AA}$, and the face-to-face distance of the central benzene ring of the TTP unit was $7.790(2) \text{ \AA}$. Thus, TC[2]TTP has an elongated and deflated hexagonal geometry arising from a tight cyclic framework with a tub-shaped TTP unit. The resulting hexagonal cavity is expected to demonstrate the unusual shape selectivity of small molecules based on host-guest chemistry. Furthermore, this hexagonal geometry is helpful in controlling the molecular rearrangement and self-assembly toward molecular tiling.^{6b}

TC[2]TTP formed a honeycomb structure based on the hexagonal geometry (Fig. 4a). Atomic contacts, such as $\text{S}\cdots\text{S}$ ($3.503(2) \text{ \AA}$) and $\text{C-H}\cdots\pi$ ($3.790(2) \text{ \AA}$), were constructed between adjacent molecules. Thus, TC[2]TTP demonstrated close molecular tiling owing to the control of rearrangement in the robust intramolecular network. TC[2]TTP formed a channel-type packing structure with columnar stacking (Fig. 4b). There were intermolecular interactions of $\text{C-H}\cdots\text{S}$ ($3.577(2)$ and $3.590(2) \text{ \AA}$) contacts. This is therefore a candidate for a cavity-assembled porous solid,¹⁷ which can incorporate several guest molecules into its cavity.

Next, we investigated the host-guest chemistry of TC[2]TTP in various organic solvents to uncover the applicability of its internal cavity. In a solution containing TC[2]TTP in CS_2 with some tested solvents, colourless block crystals were obtained from the liquid–liquid diffusion of CHCl_3 , benzene, and toluene. X-ray crystallography revealed crystal polymorphisms, in which TC[2]TTP incorporated the corresponding solvents into its cavity (Fig. 5). These belong to the triclinic with $P\bar{1}$ (CHCl_3 and benzene) and monoclinic with $P2_1/c$ space group (toluene), respectively. The crystals of TC[2]TTP containing

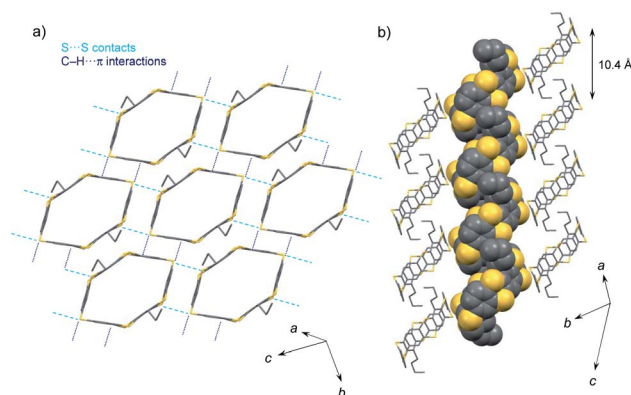


Fig. 4 Crystal structure of TC[2]TTP: (a) honeycomb structure; and (b) columnar stacking. Hydrogen are omitted for clarity.

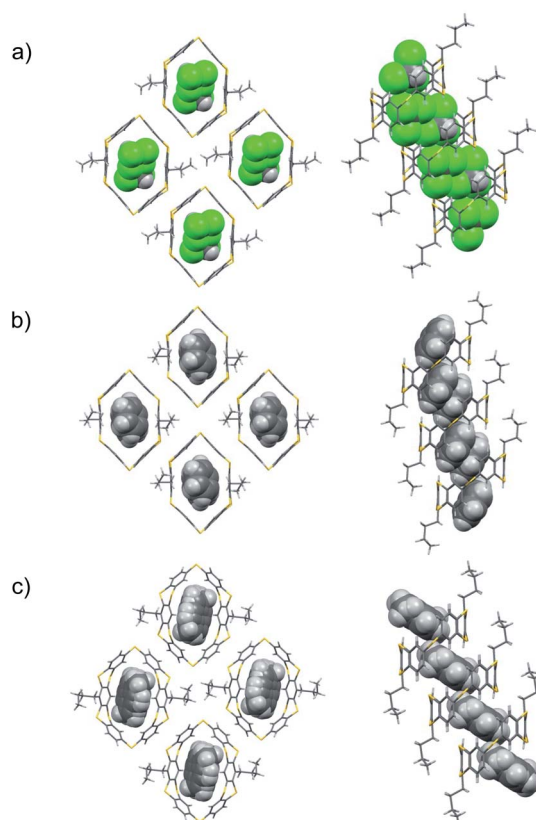


Fig. 5 Packing diagrams of TC[2]TTP with organic solvents. Solvent molecules are drawn by a space filling model. (a) TC[2]TTP with CHCl_3 , (b) with benzene, and (c) with toluene. Toluene molecules are depicted as a disordered state.

chloroform and benzene were similar to those of naked TC[2]TTP. These guests captured two molecules in a hoop-shaped framework. The driving forces were mainly $\text{C-H}\cdots\pi$, halogen $\cdots\pi$ interactions, and $\text{Cl}\cdots\text{S}$ contacts. Conversely, the crystals obtained from toluene exhibited a different crystal system. Although toluene was intensely disordered, the guest was fitted into the cavity by $\text{C-H}\cdots\pi$ interactions. Moreover, these guest molecules were allowed to align along with the lamination structure because these crystals formed channel-type columnar stacking, similar to non-solvent crystals. Thus, TC[2]TTP exhibited effective porosity in solid-state materials.

Although we attempted to reveal the redox behaviour of TC[2]TTP by using cyclic voltammetry, unfortunately, clean redox waves were not observed in the potential windows (from 0.0 V to 1.5 V) in CH_2Cl_2 and benzonitrile. This suggests that the conformational change from the tub form to the planar structure of TTP might be inhibited by the large ring or macrocyclic strain arising from the rigid framework. This larger and more rigid bending destabilizes the radical cation state, in which the potential can be increased as with distorted tetrathiafulvalene-based macrocycle.¹⁸

Conclusions

We have successfully synthesized a novel family of thiacalix[*n*]arenes consisting of 5,7,12,14-tetrathiapentacene, thiacalix[2]tetrathiapentacene (TC[2]TTP), via intramolecular Friedel–Crafts-type condensation. We should further consider optimizing this macrocyclization, such as by lengthening the reaction time, modifying the temperature, and applying transition metal catalysts (e.g., copper). X-ray crystallography revealed that the TTP unit of TC[2]TTP adopts a tub form, and TC[2]TTP constructs a hexagonal-shaped macrocycle. This unique geometry generated a honeycomb structure with columnar stacking. Furthermore, TC[2]TTP constructed a crystal polymorphism that incorporated appropriate organic solvents, such as CHCl_3 , benzene, and toluene into its internal cavity. Therefore, TC[2]TTP is a candidate for molecular tiling and cavity-assembled porous solids. The synthesis of other derivatives with larger ring sizes is currently underway.

Conflicts of interest

There are no conflicts to declare.

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