

Medium-sized cyclophanes. Part 55.† Synthesis and conformational studies of [2.1.1]orthocyclophanes

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Received (in Montpellier, France) 9th October 2000, Accepted 4th December 2000

First published as an Advance Article on the web 22nd February 2001

[2.1.1]Orthocyclophanes **2** are prepared by pyrolysis of the corresponding 2-thia[3.1.1]orthocyclophane 2,2-dioxides **9**, which are prepared by the reaction of 1,2-bis(2-bromomethylbenzyl)benzenes **7** with Na₂S in ethanol under high dilution conditions, followed by oxidation with *m*-chloroperbenzoic acid. The conformational studies on [2.1.1]orthocyclophanes **2**, which adopt flexible saddle and crown structures in comparison with the corresponding 10,15-dihydro-5*H*-tribenzo[*a,d,g*]cyclononene ([1.1.1]orthocyclophane) **1**, are discussed.

One of the most interesting properties of [1.1.1]orthocyclophane **1** (10,15-dihydro-5*H*-tribenzo[*a,d,g*]cyclononene) and its congeners is their stable crown conformation, evidenced, in ¹H-NMR spectra, by the characteristic AX quartet of the methylene bridges.² Thus, the pseudo-axial protons (H_{ax}) resonate 1.2 ppm downfield with respect to their pseudo-equatorial counterparts (H_{eq}), a consequence of the steric compression. From the X-ray crystallographic studies of cyclotrimeratrylenes, that is 10,15-dihydro-2,3,7,8,12,13-hexamethoxy-5*H*-tribenzo[*a,d,g*]cyclononenes,³ the aromatic hydrogen atoms of two adjacent rings [*e.g.* H(1) and H(14)] are almost within contact distance (2.5 ± 0.1 Å between their centers) and thus there is not much room in these positions for a substituent, unless it is small. The activation barrier for the crown-to-crown interconversion in cyclotrimeratrylenes has been found to be 26.5 kcal mol⁻¹.⁴ Destabilization of the crown may arise from steric hindrance created either by geminal substitution of one methylene group⁵ or by the presence of bulky substituents⁶ such as a bromine atom or an allyl group in the aromatic positions *ortho* to the 9-membered ring, an exception being the methoxy group.⁷

Although there are two possible conformational isomers for **1**: crown and saddle conformation (Fig. 1), three different conformational isomers: crown, *anti*-saddle and *syn*-saddle conformers are possible for **2**, with the *syn*-saddle conformer now being included, due to the ethylene bridge in

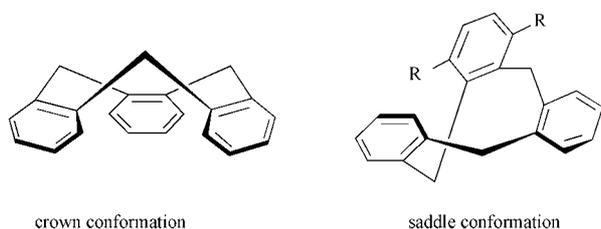


Fig. 1 Two possible conformations of [1.1.1]orthocyclophanes **1**.

[2.1.1]orthocyclophane **2** (Fig. 2). Thus, in contrast to [1.1.1]orthocyclophanes,² the conformational isomerism in the present system is slightly more complicated. Furthermore, the conformations of **2** are undetermined so far. Thus, there is substantial interest in investigating the effects of the ethylene bridge on their conformations. We report here the preparation of [2.1.1]orthocyclophanes **2** using the sulfur method and studies on their conformations in solution and the solid state.

Results and discussion

Synthesis of [2.1.1]orthocyclophanes

The chemistry of medium- and large-sized bridged aromatics with one or two aromatic rings has been extensively studied.⁸ Recently, many examples of compounds containing three or more aromatic rings have been reported^{9,10} and these are

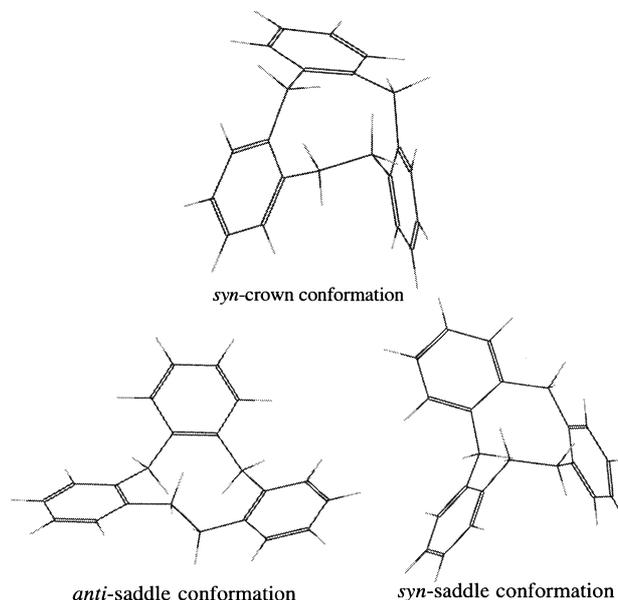


Fig. 2 Conformations of [2.1.1]orthocyclophanes **2**.

† For Part 54, see: ref. 1.

mostly oligomers formed as by-products during the synthesis of smaller members.¹¹ We have previously described¹² the convenient and efficient method of Lewis acid or Nafion-H (a solid perfluorinated resin sulfonic acid) catalyzed Friedel–Crafts cyclization of 2,2'-bis(hydroxymethyl)diphenylmethanes with arenes to afford 10,15-dihydro-5*H*-tribenzo[*a*,*d*,*g*]cyclononenes **1** under relatively mild reaction conditions, in which an arene molecule is directly incorporated into the cyclic system as a phenylene unit.

This strategy was expected to be applicable to the preparation of [2.1.1]orthocyclophanes **2**. However, Nafion-H catalyzed cyclization of 2,2'-bis(hydroxymethyl)diphenylethanes with benzene did not afford the desired intermolecular cyclized products **2**; instead only a mixture of 10,11-dihydro-5*H*-dibenzo[*a*,*d*]cycloheptene and 1-benzyl-10,11-dihydro-5*H*-dibenzo[*a*,*d*]cycloheptene was obtained in quantitative yields *via* Friedel–Crafts intramolecular cyclization.¹³ Consequently, the benzene molecule must not have been directly incorporated in the cyclic system as an *ortho*-phenylene unit in the case of diphenylethane derivatives.

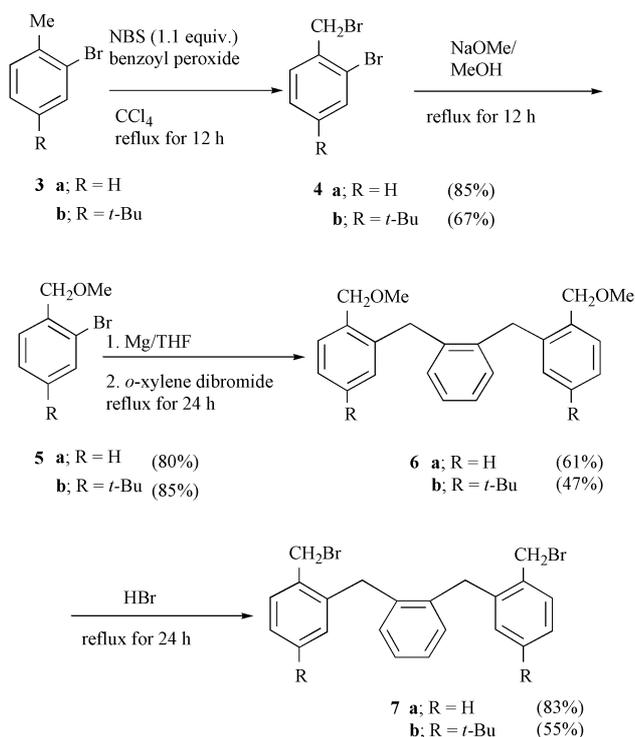
Therefore, we have prepared [2.1.1]orthocyclophanes **2** from 2-bromotoluene **3a** and 2-bromo-4-*tert*-butyltoluene **3b** by using the desulfurization method¹⁴ as shown in Schemes 1 and 2. 2-Methoxymethylbromobenzene **5a** was prepared by reaction of 2-bromotoluene **3a** with *N*-bromosuccinimide (NBS) in the presence of benzoyl peroxide, followed by treatment of the resulting product, 2-bromobenzyl bromide **4a**, with sodium methoxide in refluxing methanol for 12 h. The cross coupling reaction¹⁵ of 2-methoxymethylphenylmagnesium bromide with *o*-xylene dibromide was carried out in the presence of cuprous bromide as catalyst in a mixture of hexamethylphosphoric triamide (HMPA) and tetrahydrofuran at reflux temperature, to give the desired 1,2-bis(2-methoxymethylbenzyl)benzene **6a** in 61% yield. 1,2-Bis(2-bromomethylbenzyl)benzene **7a** was prepared in 83% yield by bromination of **6a** with 48% HBr under reflux. Similarly, 1,2-bis(2-bromomethyl-5-*tert*-butylbenzyl)benzene **7b** was prepared from 2-bromo-4-*tert*-butyltoluene, as shown in Scheme 1.

The cyclization of **7a,b** has been carried out under conditions of high dilution and in ethanolic Na₂S to afford the corresponding 2-thia[3.1.1]orthocyclophanes **8a,b** in 47% and

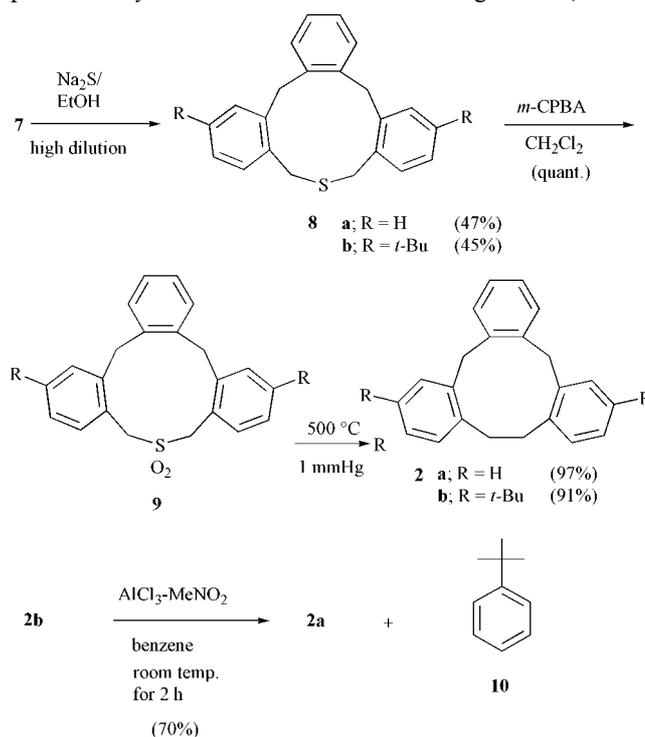
45% yield, respectively (Scheme 2). Oxidation of **8a,b** with *m*-chloroperbenzoic acid (*m*-CPBA) furnished the corresponding sulfones **9a,b** in almost quantitative yields. Pyrolysis of **9a,b** under reduced pressure (1 mmHg) was carried out according to the reported method¹⁶ to afford **2a,b** in 97 and 91% yields, respectively. *Trans-tert*-butylation of **2b** using AlCl₃–MeNO₂¹⁷ as catalyst in benzene succeeded in providing *de-tert*-butylated product **2a** in 70% yield along with *tert*-butylbenzene. No concomitant ring cleavage such as *trans*benzylation was observed under the reaction conditions. The structures of **2a** and **2b** were elucidated based on their elemental analyses and spectral data. In particular, the mass spectral data for **2a** and **2b** (*M*⁺ = 284 and 396) strongly suggest that the desired [2.1.1]orthocyclophane structures have been obtained.

Conformational studies in solution

The ¹H-NMR spectrum (Fig. 3) of [2.1.1]orthocyclophane **2a** in CS₂–CDCl₃ (3 : 1) below –60 °C shows the methylene protons as two sets of doublets at δ 3.70, 3.83 and 4.63, 4.92 (each 1 H, *J* = 13.8 Hz) and as a set of doublets at δ 2.96, 3.16 (each 2 H, *J* = 13.8 Hz). It was also found that the CH₂CH₂ methylene protons were observed as four multiplet peaks at δ 1.97–3.15 and as a set of doublets at δ 3.36, 3.58 (each 2 H, *J* = 13.0 Hz). On the basis of these data it may be inferred that **2a** at this temperature exists as a mixture of *syn*-crown and *anti*-saddle conformers in a ratio of 35 : 65. Thus, the signals for the bridged methylene protons of the *syn*-crown conformer correspond to the set of doublets at δ 2.96, 3.16 and those at δ 3.36, 3.58, which strongly suggests the C₂ symmetrical structure of *syn*-crown-**2a** but not an unsymmetric *syn*-saddle conformation (C₁ symmetry). In contrast, the remaining signals for the bridged methylene protons are assigned as due to the *anti*-saddle conformer, *anti*-saddle-**2a**, which adopts an unsymmetric structure (C₁ symmetry). However, as the temperature of the solution of **2a** in CS₂–CDCl₃ is increased, the individual peaks of the benzyl protons merge and eventually a pair of single peaks is observed above –20 °C. A similar phenomenon was observed for the *tert*-butyl derivative **2b**, with the ratio of *syn*-crown to *anti*-saddle conformer being 20 : 80. Also, the *tert*-butyl protons of *syn*-crown-**2b** were observed at higher field, δ 1.10,



Scheme 1



Scheme 2

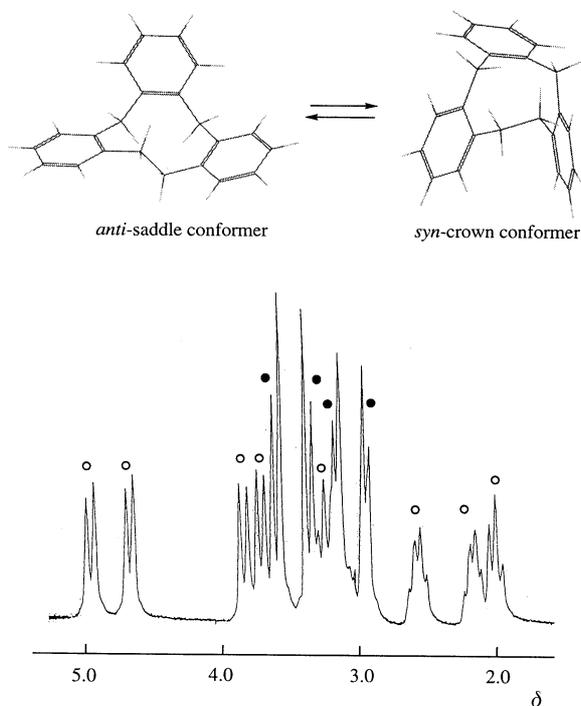


Fig. 3 Partial $^1\text{H-NMR}$ spectrum of **2a** at -60°C ($\text{CDCl}_3\text{-CS}_2 = 1:3$). The open circles indicate the methylene protons for the *anti*-saddle conformer and filled circles indicate the methylene protons for the *syn*-crown conformer.

in comparison with those of *anti*-saddle-**2b** (δ 1.31) due to the strong shielding effect of the benzene ring.^{14,18} These results seem to indicate that the bulky *tert*-butyl groups in **2b** play an important role in fixing the conformation. Thus, the bulkiness of the *tert*-butyl groups might inhibit the population of the *syn*-conformer. Accordingly, the amount of *anti*-conformer is found to increase on introduction of *tert*-butyl groups at the 6 and 19 positions on the benzene ring.

PM3 calculations show that the *syn*-saddle conformer has the highest energy, $H_f = 68.41 \text{ kcal mol}^{-1}$, then the *syn*-crown conformer, $H_f = 62.26 \text{ kcal mol}^{-1}$, with the *anti*-saddle conformer being lowest in energy $H_f = 58.35 \text{ kcal mol}^{-1}$. The higher energy of the *syn* conformers could be attributable to the fact that the 1,2-diarylethane moiety in the *syn*-saddle and *syn*-crown conformers is eclipsed, whereas that of the *anti*-saddle conformer is staggered. These findings are consistent with the $^1\text{H NMR}$ data showing that the *anti*-saddle and *syn*-crown conformers equilibrate.

In the case of calix[4]arenes ([1₄]metacyclophanes),¹⁹ $\Delta\delta$ between H_{exo} and H_{endo} in the ArCH_2Ar methylene moiety serves as a measure of the “flattening” of each phenyl unit: $\Delta\delta$ is generally 0.9 ppm for a system in the regular cone conformation and in the “flattened” conformation $\Delta\delta$ is significantly decreased. Therefore, $\Delta\delta$ of the ArCH_2Ar methylene protons in *syn*-crown-**2** might have almost the same value as that for 10,15-dihydro-5*H*-tribenzo[*a,d,g*]cyclononene, $\Delta\delta = 1.15$, whereas that for the *syn*-crown conformer has quite a different value: 0.22 ppm for *syn*-crown-**2a** and 0.30 ppm for *syn*-crown-**2b**. The large decrease of $\Delta\delta$ for the ArCH_2Ar methylene protons in **2** implies that one phenyl ring of **2** becomes flattened to reduce the steric crowding between the two adjacent aromatic protons in the 14 and 18 positions.

X-Ray crystallography

Single colorless crystals of the [2.1.1]orthocyclophane **2a** suitable for X-ray crystallography were obtained by recrystallization from 1:1 methanol–chloroform. A perspective ORTEP drawing of **2a** is illustrated in Fig. 4, with the atom

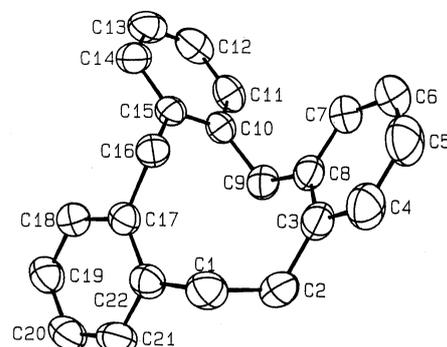


Fig. 4 X-Ray crystal structure of [2.1.1]orthocyclophane **2a** with thermal vibration ellipsoids shown at the 50% probability level. Hydrogen atoms are omitted for clarity.

numbering. Compound **2a** crystallizes in the triclinic space group $P\bar{1}$ (No. 2) and has one independent molecule ($Z = 2$) in the equivalent position. The bond angles $\text{C}(8)\text{-C}(9)\text{-C}(10)$ and $\text{C}(15)\text{-C}(16)\text{-C}(17)$ over one methylene group are $112.8(1)$ and $113.8(1)^\circ$, respectively. Although these values are slightly smaller than the angles $\text{C}(1)\text{-C}(2)\text{-C}(3)$ and $\text{C}(2)\text{-C}(1)\text{-C}(22)$ [$115.2(1)$ and $115.6(1)^\circ$] over two methylene groups, the carbon–carbon bond distances have reasonable values, $1.504(2)\text{-}1.519(2) \text{ \AA}$, and there is no significant distortion in the three aromatic rings of the molecule.

The dihedral angles between the internal ten-membered ring, defined by $\text{C}(1)\text{-C}(2)\text{-C}(3)\text{-C}(8)\text{-C}(9)\text{-C}(10)\text{-C}(15)\text{-C}(16)\text{-C}(17)\text{-C}(22)$, and the three aromatic rings, $\text{C}(3)\text{-C}(4)\text{-C}(5)\text{-C}(6)\text{-C}(7)\text{-C}(8)$, $\text{C}(10)\text{-C}(11)\text{-C}(12)\text{-C}(13)\text{-C}(14)\text{-C}(15)$ and $\text{C}(17)\text{-C}(18)\text{-C}(19)\text{-C}(20)\text{-C}(21)\text{-C}(22)$, are $54.97(4)$, $37.02(6)$ and $50.03(4)^\circ$, respectively. This X-ray crystallography clearly reveals that compound **2a** adopts the *anti*-saddle conformation in which one benzene is present between two aromatic rings that are forced towards each other (as predicted from the $^1\text{H NMR}$ data).

Conclusions

We have prepared the [2.1.1]orthocyclophane **2a** from 4-*tert*-butyltoluene by using the desulfurization method. An interesting result was obtained concerning the conformation of the [2.1.1]orthocyclophanes **2**, which exist as a mixture of *anti*-saddle and *syn*-crown conformers due to the effects of the ethylene bridge, the difference between these compounds and the [1.1.1]orthocyclophanes. Further studies on the chemical properties of [2.1.1]orthocyclophanes **2** are now in progress.

Experimental

All melting points (Yanagimoto MP-S1) are uncorrected. Proton nuclear magnetic resonance ($^1\text{H NMR}$) spectra were recorded on a Nippon Denshi JEOL FT-270 spectrometer. Chemical shifts are reported as δ values relative to internal Me_4Si . Mass spectra were obtained on a Nippon Denshi JMS-01SA-2 mass spectrometer at an ionization energy of 70 eV; m/z values reported include the parent ion peak. Infrared (IR) spectra were obtained on a Nippon Denshi JIR-AQ2OM spectrophotometer as KBr disks. Elemental analyses were performed with a Yanaco MT-5. GLC analyses were performed on a Shimadzu GC-14A gas chromatograph, silicone OV-1 2 m column; programmed temperature rise of $12^\circ\text{C min}^{-1}$; nitrogen carrier gas at 25 mL min^{-1} .

Syntheses

The preparation of 2-bromo-4-*tert*-butyltoluene (**3b**) has been previously described.¹⁵

2-Bromo-4-tert-butylbenzyl bromide, 4b. A mixture of 4-tert-butyl-2-bromotoluene **3b**¹⁵ (8 g, 35.2 mmol), *N*-bromosuccinimide (6.65 g, 37.4 mmol), benzoyl peroxide (100 mg, 0.376 mmol) and carbon tetrachloride (300 mL) was refluxed for 12 h and the cooled reaction mixture was washed with aqueous NaOH and water, dried over Na₂SO₄, and concentrated. The residue was distilled under reduced pressure to give **4b** (7.27 g, 67.4%) as a colorless liquid, bp 119–121 °C (3 mmHg). δ_{H} (CDCl₃): 1.27 (9 H, s), 4.56 (2 H, s), 7.28 (1 H, dd, *J* 1.8, 7.9), 7.35 (1 H, d, *J* 7.9), 7.96 (1 H, d, *J* 1.8 Hz); *m/z*: 304, 306, 308 (M⁺). Anal. calc. for C₁₁H₁₄Br₂: C, 43.17; H, 4.61%. Found: C, 42.96; H, 4.50%.

2-Bromo-4-tert-butylmethoxymethylbenzene, 5b. To a solution of sodium (1.53 g) in absolute methyl alcohol (60 mL) was added a solution of **4b** (16.0 g, 52.3 mmol) in methyl alcohol (25 mL), and the mixture was refluxed for 12 h. Upon cooling, it was diluted with water, acidified with acetic acid, and product was extracted with CH₂Cl₂. The CH₂Cl₂ solution was washed with water, dried over Na₂SO₄, and concentrated. The residue was distilled under reduced pressure to give 11.4 g (85%) of **5b** as a colorless liquid, bp 124–125 °C (4 mmHg). ν_{max} (NaCl)/cm⁻¹: 2965, 2870, 2820, 1479, 1463, 1375, 1364, 1274, 1199, 1167, 1112, 1096, 875; δ_{H} (CDCl₃): 1.29 (9 H, s), 3.39 (3 H, s), 4.42 (2 H, s), 7.28 (1 H, dd, *J* 2.0, 7.9), 7.35 (1 H, d, *J* 7.9), 7.96 (1 H, d, *J* 2.0 Hz); *m/z*: 256, 258 (M⁺). Anal. calc. for C₁₂H₁₇BrO: C, 56.05; H, 6.66%. Found: C, 56.26; H, 6.76%.

1,2-Bis(5-tert-butyl-2-methoxymethylbenzyl)benzene, 6b. To a mixture of Mg (1.7 g), tetrahydrofuran (5 mL), and a small amount of iodine was added a solution of **5b** (9.0 g, 35 mmol) in tetrahydrofuran (25 mL) and the mixture refluxed for 12 h. This Grignard reagent was added to a solution of *o*-xylene dibromide (3.96 g, 15 mmol) and CuBr (0.5 g) in HMPA (4 mL) and refluxed for 24 h. After the reaction mixture was cooled to room temperature, it was poured into cold NH₄Cl solution and extracted with CH₂Cl₂. The CH₂Cl₂ solution was washed with water, dried over Na₂SO₄, and concentrated. The residue was chromatographed over silica gel (Wako C-300) using hexane–benzene, 1 : 1, as eluents to give 3.23 g (47%) of **6b** as a colorless oil. δ_{H} (CDCl₃): 1.25 (18 H, s), 3.27 (6 H, s), 4.02 (4 H, s), 4.29 (4 H, s), 6.86–6.89 (2 H, m), 7.03–7.14 (4 H, m), 7.25–7.29 (4 H, m); *m/z*: 458 (M⁺). Anal. calc. for C₃₂H₄₂O₂: C, 83.79; H, 9.23%. Found: C, 83.36; H, 9.15%.

1,2-Bis(2-methoxymethylbenzyl)benzene, 6a. Compound **6a** was synthesized in the same manner as described above for **6b** and obtained in 61% yield as a colorless oil. δ_{H} (CDCl₃): 3.27 (6 H, s), 3.98 (4 H, s), 4.32 (4 H, s), 6.91–7.37 (12 H, m); *m/z*: 346 (M⁺). Anal. calc. for C₂₄H₂₆O₂: C, 83.28; H, 7.56%. Found: C, 83.06; H, 7.35%.

1,2-Bis(2-bromomethyl-5-tert-butylbenzyl)benzene, 7b. A mixture of **6b** (566 mg, 1.23 mmol) and 48% HBr (20 mL) was refluxed for 24 h and the reaction mixture was cooled to room temperature. This mixture was poured into a large amount of ice water, and extracted with CH₂Cl₂ (30 mL × 2). The CH₂Cl₂ solution was washed with water, dried over Na₂SO₄, and concentrated. The residue was chromatographed over silica gel (Wako C-300) with hexane–benzene, 1 : 1, as eluents to give a colorless solid. Recrystallization from hexane afforded 376 mg (55%) of **7b** as colorless prisms, mp 114 °C. ν_{max} (KBr)/cm⁻¹: 2965, 1604, 1474, 1450, 1362, 1231, 1202, 1186, 827, 753, 631, 618; δ_{H} (CDCl₃): 1.25 (18 H, s), 4.15 (4 H, s), 4.39 (4 H, s), 6.88–6.92 (2 H, m), 7.03 (4 H, m), 7.23–7.30 (4 H, m); *m/z*: 554, 556, 558 (M⁺). Anal. calc. for C₃₀H₃₆Br₂O: C, 64.76; H, 6.52%. Found: C, 64.81; H, 6.48%.

1,2-Bis(2-bromomethylbenzyl)benzene, 7a. Compound **7a** was synthesized in the same manner as described above for **7b** and obtained in 83% yield as colorless prisms (hexane), mp 110–112 °C. ν_{max} (KBr)/cm⁻¹: 2965, 2870, 1491, 1453, 1218, 757, 742, 722, 607; δ_{H} (CDCl₃): 4.10 (4 H, s), 4.39 (4 H, s), 6.92–7.00 (4 H, m), 7.16–7.22 (6 H, m), 7.31–7.35 (2 H, m); *m/z*: 442 (M⁺), 444, 446. Anal. calc. for C₂₂H₂₀Br₂: C 59.49, H 4.54%. Found: C 59.55, H 4.69%.

7,20-Di-tert-butyl-2-thia[3.1.1]orthocyclophane, 8b. A solution of **7b** (900 mg, 1.62 mmol) in ethanol (40 mL) and benzene (10 mL) and a solution of Na₂S · 9H₂O (2.0 g, 8.33 mmol) in ethanol (40 mL) and water (8 mL) were added separately, but simultaneously, from two Hershberg funnels to boiling ethanol (4 L). When addition was complete (21 h), the mixture was refluxed for 16 h with stirring. Then the reaction mixture was concentrated and the residue extracted with CH₂Cl₂. The CH₂Cl₂ extract was washed with water, dried over Na₂SO₄, and concentrated. The residue was chromatographed over silica gel (Wako C-300) with hexane–benzene, 1 : 1, as eluents to give a colorless solid. Recrystallization from hexane afforded 312 mg (45%) of **8b** as colorless prisms, mp 251–253 °C. ν_{max} (KBr)/cm⁻¹: 2962, 2904, 2865, 1498, 1487, 1453, 1431, 1400, 838, 749; δ_{H} (CDCl₃): 1.14 (18 H, s), 3.55 (4 H, s), 3.57 (4 H, s), 6.80 (2 H, d, *J* 8.1), 7.22–7.29 (6 H, m), 7.59 (2 H, d, *J* 8.1 Hz); *m/z*: 428 (M⁺). Anal. calc. for C₃₀H₃₆S: C, 84.06; H, 8.46%. Found: C, 83.99; H, 8.53%.

2-Thia[3.1.1]orthocyclophane, 8a. Compound **8a** was synthesized in the same manner as described above for **8b** and obtained in 47% yield as colorless prisms (hexane–benzene, 1 : 1); mp 263–267 °C. ν_{max} (KBr)/cm⁻¹: 2962, 1485, 1450, 1430, 1081, 1043, 747, 733, 704, 621; δ_{H} (CDCl₃): 3.58 (4 H, s), 3.59 (4 H, s), 6.78 (2 H, d, *J* 7.8), 7.03–7.31 (8 H, m), 7.69 (2 H, d, *J* 7.8 Hz); *m/z*: 316 (M⁺). Anal. calc. for C₂₂H₂₀S: C, 83.50; H, 6.37%. Found: C, 83.31; H, 6.22%.

7,20-Di-tert-butyl-2-thia[3.1.1]orthocyclophane 2,2-dioxide, 9b. To a solution of **8b** (196 mg, 0.457 mmol) in CH₂Cl₂ (20 mL) was added *m*-chloroperbenzoic acid (240 mg, 1.39 mmol). After the reaction mixture had been stirred at room temperature for 24 h, it was washed with 10% NaHCO₃ aqueous solution and brine, dried over Na₂SO₄, and concentrated. The residue was chromatographed over silica gel (Wako C-300) with hexane–benzene, 1 : 1, as an eluent to give a colorless solid. Recrystallization from hexane afforded 212 mg (100%) of **9b** as colorless prisms, mp >300 °C. ν_{max} (KBr)/cm⁻¹: 2962, 2915, 1318, 1308, 1122, 1113, 870, 584; δ_{H} (CDCl₃): 1.13 (18 H, s), 3.52 (4 H, br s), 3.85–4.50 (4 H, br s), 6.85 (2 H, d, *J* 8.3 Hz), 7.26–7.38 (6 H, m), 7.75 (2 H, d, *J* 8.3 Hz); *m/z*: 460 (M⁺). Anal. calc. for C₃₀H₃₆O₂S: C, 78.22; H, 7.88%. Found: C, 78.13; H, 7.78%.

2-Thia[3.1.1]orthocyclophane 2,2-dioxide, 9a. Compound **9a** was synthesized in the same manner as described above for **9b** and obtained in quantitative yield as colorless prisms, mp >300 °C. ν_{max} (KBr)/cm⁻¹: 2962, 1490, 1450, 1410, 1317, 1308, 1297, 1247, 1119, 855, 841; δ_{H} (CDCl₃): 3.56 (4 H, br s), 3.82–4.60 (4 H, br s), 6.84 (2 H, d, *J* 7.8), 7.18–7.40 (8 H, m), 7.85 (2 H, d, *J* 7.8 Hz); *m/z*: 348 (M⁺). Anal. calc. for C₂₂H₂₀O₂S: C, 75.83; H, 5.79%. Found: C, 75.70; H, 5.64%.

6,19-Di-tert-butyl[2.1.1]orthocyclophane, 2b. The sulfone **9b** (150 mg, 0.326 mmol) was pyrolyzed at 500 °C under reduced pressure at 1 mmHg as reported previously.¹⁶ The sublimed product was collected and chromatographed on silica gel with hexane as an eluent to give a colorless solid. Recrystallization from hexane afforded 118 mg (91%) of **2b** as colorless prisms, mp 166–168 °C. δ_{H} (CDCl₃; 27 °C): 1.33 (18 H, s, 'Bu), 2.67 (4 H, br s, CH₂CH₂), 4.14 (4 H, br s, CH₂), 7.03–7.18 (4 H, m, ArH), 7.20–7.36 (6 H, m); δ_{H} (CS₂–CDCl₃, 3 : 1; –80 °C):

(*anti-2b*) 1.31 (18 H, s, ^tBu), 1.86–1.96 (1 H, m, CH₂CH₂), 2.08–2.22 (1 H, m, CH₂CH₂), 2.48–2.60 (1 H, m, CH₂CH₂), 3.12–3.22 (1 H, m, CH₂CH₂), 3.68 (1 H, d, *J* 13.8, CH₂), 3.83 (1 H, d, *J* 13.8, CH₂), 4.63 (1 H, d, *J* 13.8, CH₂), 3.92 (1 H, d, *J* 13.8, CH₂), 6.8–7.4 (10 H, m, ArH); (*syn-2b*) 1.10 (18 H, s, ^tBu), 2.88 (2 H, d, *J* 13.0, CH₂CH₂), 3.10 (2 H, d, *J* 13.0, CH₂CH₂), 3.34 (2 H, d, *J* 13.8, CH₂), 3.64 (2 H, d, *J* 13.8 Hz, CH₂), 6.8–7.4 (10 H, m, ArH); *m/z*: 396 (M⁺). Anal. calc. for C₃₀H₃₆: C, 90.85; H, 9.15%. Found: C, 90.66; H, 9.08%.

[2.1.1]Orthocyclophane, 2a. Compound **2a** was synthesized in the same manner as described above for **2b** and obtained in 97% yield as colorless prisms (hexane), mp 174–176 °C. ν_{\max} (KBr)/cm⁻¹: 2962, 1490, 1453, 1434, 1086, 771, 757, 740, 726, 621; δ_{H} (CDCl₃): 2.85 (4 H, br s, CH₂CH₂), 4.00 (4 H, br s, CH₂), 7.15–7.25 (12 H, m, ArH); δ_{H} (CS₂-CDCl₃, 3 : 1 –80 °C): (*anti-2a*) 1.97–2.06 (1 H, m, CH₂CH₂), 2.12–2.24 (1 H, m, CH₂CH₂), 2.51–2.63 (1 H, m, CH₂CH₂), 3.03–3.15 (1 H, m, CH₂CH₂), 3.70 (1 H, d, *J* 13.8, CH₂), 3.83 (1 H, d, *J* 13.8, CH₂), 4.63 (1 H, d, *J* 13.8, CH₂), 4.92 (1 H, d, *J* 13.8, CH₂), 6.8–7.43 (12 H, m, ArH); (*syn-2a*) 2.96 (2 H, d, *J* 12.0, CH₂CH₂), 3.16 (2 H, d, *J* 12.0, CH₂CH₂), 3.36 (2 H, d, *J* 13.8, CH₂), 3.58 (2 H, d, *J* 13.8 Hz, CH₂), 6.8–7.43 (12 H, m, ArH); *m/z*: 284 (M⁺). Anal. calc. for C₂₂H₂₀: C, 92.91; H, 7.09%. Found: C, 93.00; H, 7.24%.

AlCl₃-MeNO₂ catalyzed *trans-tert*-butylation of **2b** in benzene

To a solution of **2b** (100 mg, 0.25 mmol) in benzene (5 mL) was added a solution of AlCl₃ (80 mg, 0.6 mmol) in MeNO₂ (0.15 mL) at room temperature. After stirring the reaction mixture at room temperature for 2 h, it was poured into ice water (30 mL) and extracted with benzene (10 mL × 2). The combined extracts were washed with water (10 mL × 2), dried (Na₂SO₄) and concentrated. The residue was chromatographed over silica gel using hexane as eluent to give 50 mg (70%) of **2a** as colorless prisms. The formation of *tert*-butylbenzene **10** was confirmed by GLC.

PM3 calculations

PM3 calculations and energy minimizations were carried out with the Wavefunction MacSpartan Plus (V 1.2.2) package software using an Apple Macintosh G4/400.

X-Ray crystallography

Crystallographic data for **2a** are given in Table 1. The unit cell constants were derived from least-squares analysis of the settings, on an Enraf-Nonius CAD4 FR 586 diffractometer, for 25 reflections in the range 34.96° < θ < 36.83°. The intensities of all independent reflections with 6.02° < 2 θ < 149.76° were

Table 1 Crystallographic data and data collection details for [2.1.1]orthocyclophane **2a**

| | |
|------------------------------------|---------------------------------|
| Formula | C ₂₂ H ₂₀ |
| FW | 284.40 |
| Crystal system | Triclinic |
| Space group | P $\bar{1}$ (no. 2) |
| <i>a</i> /Å | 10.2590(5) |
| <i>b</i> /Å | 14.7368(7) |
| <i>c</i> /Å | 5.1617(4) |
| α /° | 93.601(5) |
| β /° | 111.643(5) |
| γ /° | 85.992(4) |
| <i>U</i> /Å ³ | 772.88(8) |
| <i>Z</i> | 2 |
| <i>T</i> /K | 298 |
| μ /cm ⁻¹ | 4.82 |
| <i>R</i> | 0.046 |
| <i>R</i> _w ^a | 0.081 |
| No. of reflections | 3556 |
| Unique reflections | 3187 |

$$^a \omega = 4(F_o)^2 / [(\sigma I_o)^2 + 0.0016(F_o)^4].$$

measured with ω -2 θ scans (ω scan width = 0.8 + 0.14 tan θ); Ni-filtered Cu-K α radiation (λ = 1.54184 Å) was used. The X-ray analysis was performed with the MolEN program package²⁰ and the structure was solved uneventfully by direct methods (SIR88).²¹ The refinement was by full-matrix least-squares.

CCDC reference number 440/248. See <http://www.rsc.org/suppdata/nj/b0/b008258i/> for crystallographic files in .cif format.

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