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

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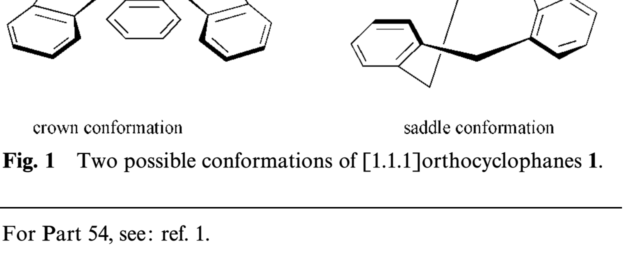
[2.1.1]Orthocyclophanes **2** are prepared by pyrolysis of the corresponding 2-thia[3.1.1]orthocyclophane 2,2-dioxides **9**, which are prepared by the reaction of 1,2-bis(2-bromomethylbenzyl)benzenes **7** with Na_2S in ethanol under high dilution conditions, followed by oxidation with *m*-chloroperbenzoic 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 ^{1}H-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 cyclotriveratrylenes, 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 cyclotriveratrylenes 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 group[5] or by the presence of bulky substituents[6] 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 [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.



crown conformation

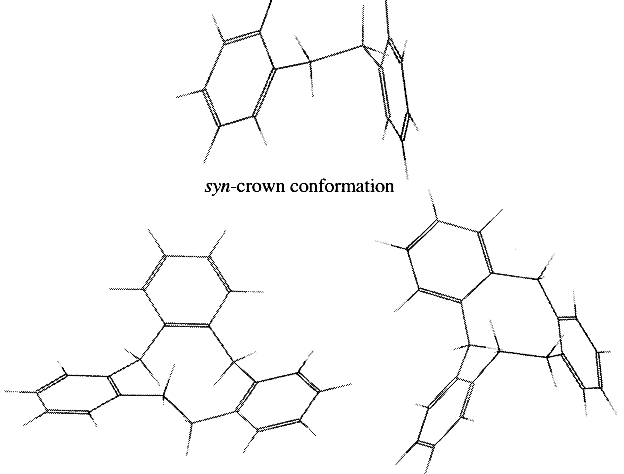
saddle conformation

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

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



syn-crown conformation

anti-saddle conformation

syn-saddle conformation

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

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mostly oligomers formed as by-products during the synthesis of smaller members.[11] We have previously described[12] the convenient and efficient method of Lewis acid or Nafion-H (a solid perfluorinated resin sulfonic acid) catalyzed Friedel–Crafts cyclibenzylation 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.

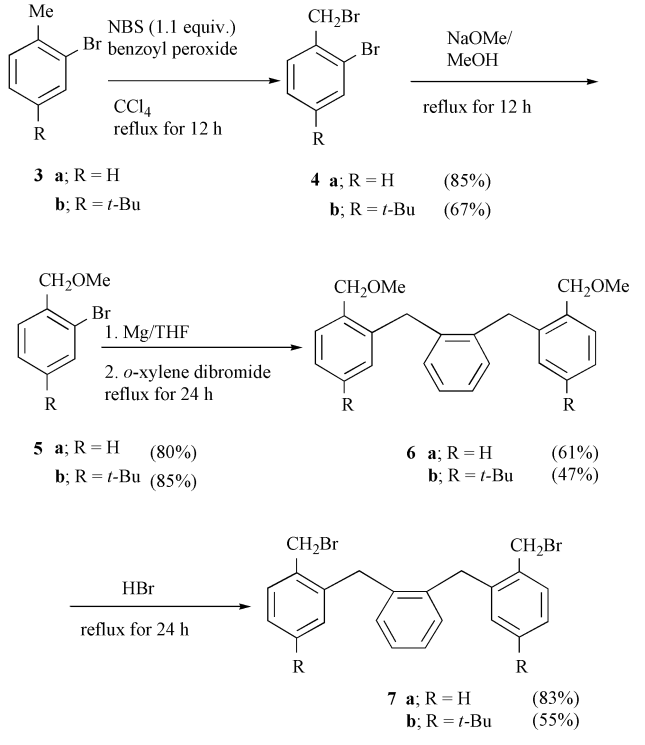
This strategy was expected to be applicable to the preparation of [2.1.1]orthocyclophanes **2**. However, Nafion-H catalyzed cyclibenzylation of 2,2′-bis(hydroxymethyl)-diphenylethanes with benzene did not afford the desired intermolecular cyclibenzylated products **2**; instead only a mixture of 10,11-dihydro-5*H*-dibenzo[*a*,*d*]cycloheptene and 1-benzyl-10,11-dihydro-5*H*-dibenzo[*a*,*d*]cycloheptene was obtained in quantitative yields *via* Friedel–Crafts intramolecular cyclibenzylation.[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 method[14] 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 reaction[15] 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.

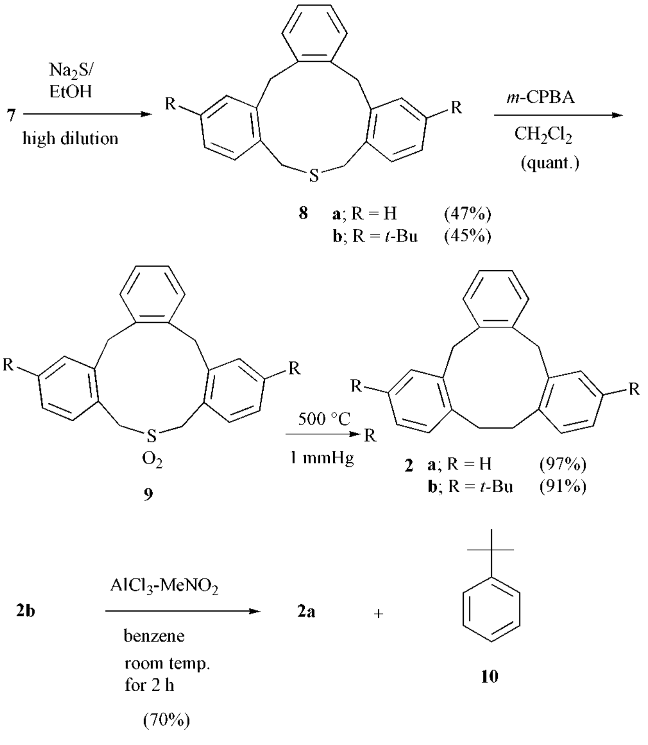
The cyclization of **7a**,**b** has been carried out under conditions of high dilution and in ethanolic Na_2S to afford the corresponding 2-thia[3.1.1]orthocyclophanes **8a**,**b** in 47% and 45% yield, respectively (Scheme 2). Oxidation of **8a**,**b** with *m*-chloroperbenzoic acid (*m*-CPBA) furnished 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 method[16] to afford **2a**,**b** in 97 and 91% yields, respectively. *Trans*-*tert*-butylation of **2b** using $AlCl_3$–$MeNO_2$[17] 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

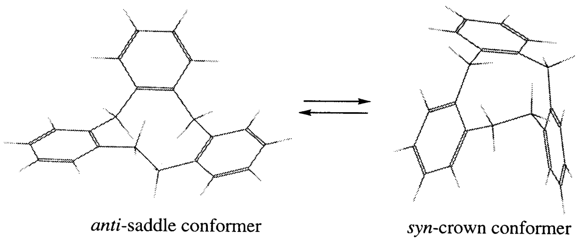
The ^{1}H-NMR spectrum (Fig. 3) of [2.1.1]orthocyclophane **2a** in CS_2–$CDCl_3$ (3 : 1) below −60 °C shows the methylene protons as two sets of doublets at δ 3.70, 3.83 and 4.63, 4.92 (each 1 H, $J = 13.8$ Hz) and as a set of doublets at δ 2.96, 3.16 (each 2 H, $J = 13.8$ Hz). It was also found that the CH_2CH_2 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 C_2 symmetrical structure of *syn*-crown-**2a** but not an unsymmetric *syn*-saddle conformation (C_1 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 (C_1 symmetry). However, as the temperature of the solution of **2a** in CS_2–$CDCl_3$ 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



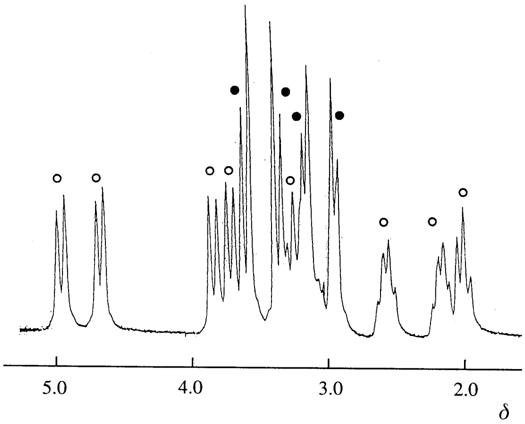


Fig. 3 Partial ^{1}H-NMR spectrum of **2a** at −60 °C ($CDCl_3$–CS_2 = 1 : 3). The open circles indicate the methylene protons for the *anti*-saddle conformer and filled circles indicate the methylene protons for the *syn*-crown conformer.

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 confomer has the highest energy, $H_f = 68.41$ kcal mol^{-1}, then the *syn*-crown conformer, $H_f = 62.26$ kcal mol^{-1}, with the *anti*-saddle conformer being lowest in energy $H_f = 58.35$ 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}H NMR data showing that the *anti*-saddle and *syn*-crown conformers equilibrate.

In the case of calix[4]arenes ([1_4]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 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 C(8)–C(9)–C(10) and C(15)–C(16)–C(17) over one methylene group are 112.8(1) and 113.8(1)°, respectively. Although these values are slightly smaller than the angles C(1)–C(2)–C(3) and C(2)–C(1)–C(22) [115.2(1) and 115.6(1)°] over two methylene groups, the carbon–carbon bond distances have reasonable values, 1.504(2)–1.519(2) Å, and there is no significant distortion in the three aromatic rings of the molecule.

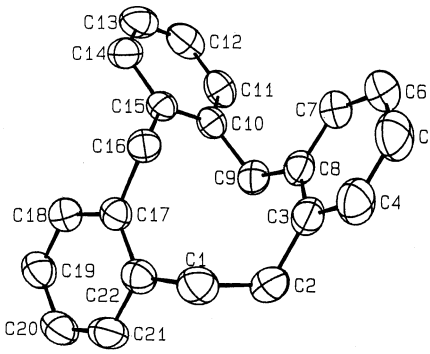


Fig. 4 X-Ray crystal structure of [2.1.1]orthocyclophane **2a** with thermal vibration ellipsoids shown at the 50% probability level. Hydrogen atoms are omitted for clarity.

The dihedral angles between the internal ten-membered ring, defined by C(1)–C(2)–C(3)–C(8)–C(9)–C(10)–C(15)–C(16)–C(17)–C(22), and the three aromatic rings, C(3)–C(4)–C(5)–C(6)–C(7)–C(8), C(10)–C(11)–C(12)–C(13)–C(14)–C(15) and C(17)–C(18)–C(19)–C(20)–C(21)–C(22), are 54.97(4), 37.02(6) and 50.03(4)°, 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}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}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 °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 Na_2SO_4, 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 ($CDCl_3$): 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 $C_{11}H_{14}Br_2$: 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 CH_2Cl_2. The CH_2Cl_2 solution was washed with water, dried over Na_2SO_4, 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 ($CDCl_3$): 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 $C_{12}H_{17}BrO$: 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 NH_4Cl solution and extracted with CH_2Cl_2. The CH_2Cl_2 solution was washed with water, dried over Na_2SO_4, 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 ($CDCl_3$): 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 $C_{32}H_{42}O_2$: 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 ($CDCl_3$): 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 $C_{24}H_{26}O_2$: 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 CH_2Cl_2 (30 mL × 2). The CH_2Cl_2 solution was washed with water, dried over Na_2SO_4, 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 ($CDCl_3$): 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 $C_{30}H_{36}Br_2O$: 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 ($CDCl_3$): 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 $C_{22}H_{20}Br_2$: 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 $Na_2S \cdot 9H_2O$ (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 CH_2Cl_2. The CH_2Cl_2 extract was washed with water, dried over Na_2SO_4, 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 ($CDCl_3$): 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 $C_{30}H_{36}S$: 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 ($CDCl_3$): 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 $C_{22}H_{20}S$: 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 CH_2Cl_2 (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% $NaHCO_3$ aqueous solution and brine, dried over Na_2SO_4, 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 ($CDCl_3$): 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 $C_{30}H_{36}O_2S$: 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 ($CDCl_3$): 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 $C_{22}H_{20}O_2S$: 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 ($CDCl_3$; 27 °C): 1.33 (18 H, s, ^{t}Bu), 2.67 (4 H, br s, CH_2CH_2), 4.14 (4 H, br s, CH_2), 7.03–7.18 (4 H, m, ArH), 7.20–7.36 (6 H, m); δ_H (CS_2–$CDCl_3$, 3 : 1; −80 °C):

(*anti*-**2b**) 1.31 (18 H, s, ^{t}Bu), 1.86–1.96 (1 H, m, CH_2CH_2), 2.08–2.22 (1 H, m, CH_2CH_2), 2.48–2.60 (1 H, m, CH_2CH_2), 3.12–3.22 (1 H, m, CH_2CH_2), 3.68 (1 H, d, J 13.8, CH_2), 3.83 (1 H, d, J 13.8, CH_2), 4.63 (1 H, d, J 13.8, CH_2), 3.92 (1 H, d, J 13.8, CH_2), 6.8–7.4 (10 H, m, ArH); (*syn*-**2b**) 1.10 (18 H, s, ^{t}Bu), 2.88 (2 H, d, J 13.0, CH_2CH_2), 3.10 (2 H, d, J 13.0, CH_2CH_2), 3.34 (2 H, d, J 13.8, CH_2), 3.64 (2 H, d, J 13.8 Hz, CH_2), 6.8–7.4 (10 H, m, ArH); m/z: 396 (M^+). Anal. calc. for $C_{30}H_{36}$: 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. υ_{max} (KBr)/cm^{-1}: 2962, 1490, 1453, 1434, 1086, 771, 757, 740, 726, 621; δ_H ($CDCl_3$): 2.85 (4 H, br s, CH_2CH_2), 4.00 (4 H, br s, CH_2), 7.15–7.25 (12 H, m, ArH); δ_H (CS_2–$CDCl_3$, 3 : 1 −80 °C): (*anti*-**2a**) 1.97–2.06 (1 H, m, CH_2CH_2), 2.12–2.24 (1 H, m, CH_2CH_2), 2.51–2.63 (1 H, m, CH_2CH_2), 3.03–3.15 (1 H, m, CH_2CH_2), 3.70 (1 H, d, J 13.8, CH_2), 3.83 (1 H, d, J 13.8, CH_2), 4.63 (1 H, d, J 13.8, CH_2), 4.92 (1 H, d, J 13.8, CH_2), 6.8–7.43 (12 H, m, ArH); (*syn*-**2a**) 2.96 (2 H, d, J 12.0, CH_2CH_2), 3.16 (2 H, d, J 12.0, CH_2CH_2), 3.36 (2 H, d, J 13.8, CH_2), 3.58 (2 H, d, J 13.8 Hz, CH_2), 6.8–7.43 (12 H, m, ArH); m/z: 284 (M^+). Anal. calc. for $C_{22}H_{20}$: C, 92.91; H, 7.09%. Found: C, 93.00; H, 7.24%.

$AlCl_3$–$MeNO_2$ 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 $AlCl_3$ (80 mg, 0.6 mmol) in $MeNO_2$ (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 (Na_2SO_4) 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° < 2θ < 149.76° were measured with ω–2θ scans (ω scan width = 0.8 + 0.14 tan θ); Ni-filtered Cu-Kα radiation (λ = 1.541 84 Å) was used. The X-ray analysis was performed with the MolEN program package[20] and the structure was solved uneventfully by direct methods (SIR88).[21] The refinement was by full-matrix least-squares.

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)
a/Å	10.2590(5)
b/Å	14.7368(7)
c/Å	5.1617(4)
α/°	93.601(5)
β/°	111.643(5)
γ/°	85.992(4)
U/Å^3	772.88(8)
Z	2
T/K	298
μ/cm^{-1}	4.82
R	0.046
R_w [a]	0.081
No. of reflections	3556
Unique reflections	3187

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

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

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