Medium-sized cyclophanes. Part 57.† Synthesis, conformations and stereodynamics of [2.*n*]metacyclophan-1-enes and their conversion to [2.*n*]metacyclophan-1-ynes

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anti- and *syn*-[2.8]Metacyclophan-1-enes **3a**, which are both conformationally rigid structures, were prepared in good yields by a McMurry cyclization of 1,8-bis(5-*tert*-butyl-3-formyl-2-methoxyphenyl)octane **2a**. Similarly, McMurry cyclization of 1,10-bis(5-*tert*-butyl-2-methoxy-3-formylphenyl)decane **2b** afforded (*E*)- and (*Z*)-[2.10]-metacyclophan-1-enes **3b** in good yields. The assignment of the *E* and *Z* structures was confirmed by ^{1}H-NMR analyses and single crystal X-ray diffraction studies. Bromination of (*E*)- and (*Z*)-**3b** with benzyltrimethyl-ammonium tribromide affords exclusively the *cis*-adduct **4b** to the bridged double bond. When treated with potassium *tert*-butoxide in refluxing HOBu^t at 80 °C for 3 h, bromine adduct *meso*-**4b** gave the dehydrobrominated product [2.10]metacyclophan-1-yne **6b** in 93% yield, along with 1-bromo[2.10]metacyclophan-1-ene **5b** in 7% yield; the same reaction with the bromine adduct *dl*-**4b** gave 29% **6b** along with **5b** in 71% yield. Similarly, *anti*- and *syn*-[2.8]metacyclophan-1-ynes **6a** were also prepared by bromination of *syn*-[2.*n*]metacyclophan-1-ene *syn*-**3a**, followed by the dehydrobromination of the bromine adduct. The characterization and the reaction pathway of these products are discussed. The dynamics of the ring inversion and UV spectra are also presented.

Cyclophanes belong to one of the remarkable compound classes that has attracted extensive studies.[2] In 1982, Psiorz and Hopf reported the identification of elusive strained paracyclophyne intermediates, which were indirectly confirmed by their giving Diels–Alder adducts with dienophiles or trimerizing to the hexaphenyl benzene derivatives.[3] Later, the groups of Meijere[4a,b] and Wong[4c,d] reported the existence of strained cyclophynes as intermediates, which was established by a trapping method. Ramming and Gleiter described the syntheses of [*n*]MCP-diynes (MCP = metacyclophane) and the transformation of the propargylic moieties into allenic groups, as well as reactions with strong bases.[5] Recently, Kawase and co-workers reported the synthesis of [2$_n$]MCP-*n*-ynes by bromination-dehydrobromination of the corresponding MCP-*n*-enes, which are considerably strained with bent triple bonds.[6] Although we have attempted to prepare [2.3]- and [2.4]MCP-1-ynes by dehydrobromination of the corresponding 1,2-dibromo[2.*n*]MCPs,[7] formation of the desired [2.*n*]MCP-ynes was not observed; instead, only 1-bromo[2.*n*]MCP-1-enes along with [2.*n*]MCP-1-ones were obtained. No reports of the synthesis of [2.*n*]MCP-ynes have yet been published. In this paper, we describe the first preparation of [2.*n*]MCP-1-enes using the low-valent titanium-induced McMurry reaction and their conversion to [2.*n*]MCP-1-ynes.

Results and discussion

Syntheses and structural determinations

In cyclophane chemistry, the reductive coupling of carbonyl compounds by low-valent titanium, the McMurry reaction,[8] has been used before by Mitchell and Weerawana[9] to synthesize cyclophanes with glycol units as bridges, by Tanner and Wennerström,[10] and recently by Hopf and Mlynek[11] and Grützmacher and Neumann,[12] for the cyclization of suitable dialdehydes to yield unsaturated cyclophanes.

The starting compounds, 1,8-bis(5-*tert*-butyl-2-methoxyphenyl)octane **1a** and 1,10-bis(5-*tert*-butyl-2-methoxyphenyl)-decane **1b**[13] are easily prepared in three steps from anisole by using the *tert*-butyl group as a positional protective group on the aromatic ring.[14] The cross-coupling reactions[15] of 5-*tert*-butyl-2-methoxyphenylmagnesium bromide with 1,8-dibromo-octane and 1,10-dibromodecane have been carried out in the presence of cuprous bromide as a catalyst in a mixture of hexamethylphosphoric triamide (HMPA) and tetrahydrofuran at reflux temperature to give the desired **1a** and **1b** in 87 and 81% yields, respectively.

Formylation of **1a** and **1b**[13] with dichloromethyl methyl ether in the presence of titanium tetrachloride in dichloromethane for 2 h yields the corresponding **2a** and **2b** in 73 and 70% yields, respectively (Scheme 1).

1,8-Bis(5-*tert*-butyl-3-formyl-2-methoxyphenyl)octane **2a** was subjected to reductive coupling by the McMurry reaction following Grützmacher's procedure (Scheme 2).[12,16] The desired [2.8]MCP-1-ene **3a** was obtained in 61% yield. The ^{1}H-NMR spectrum of **3a** shows two kinds of methoxy protons, each as a singlet. By careful column chromatography (silica gel, Wako C-300), two isomers, *anti*-**3a** and *syn*-**3a**, were separated in 13 and 48% yield, respectively. They are thermally stable and do not interconvert at 180 °C in DMSO solution and at 400 °C in the solid state.

The structures of products *anti*-**3a** and *syn*-**3a** were determined on the basis of their elemental analyses and spectral

† For part 56, see: ref. 1.

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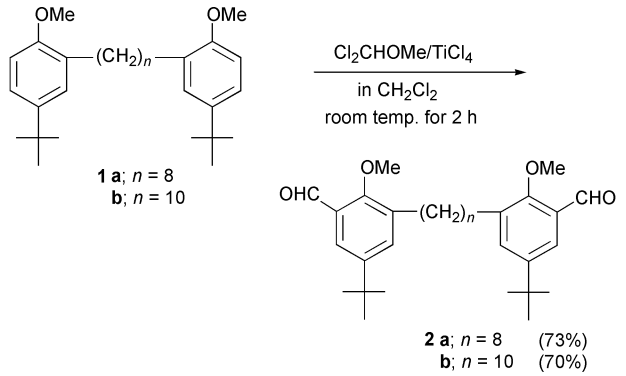
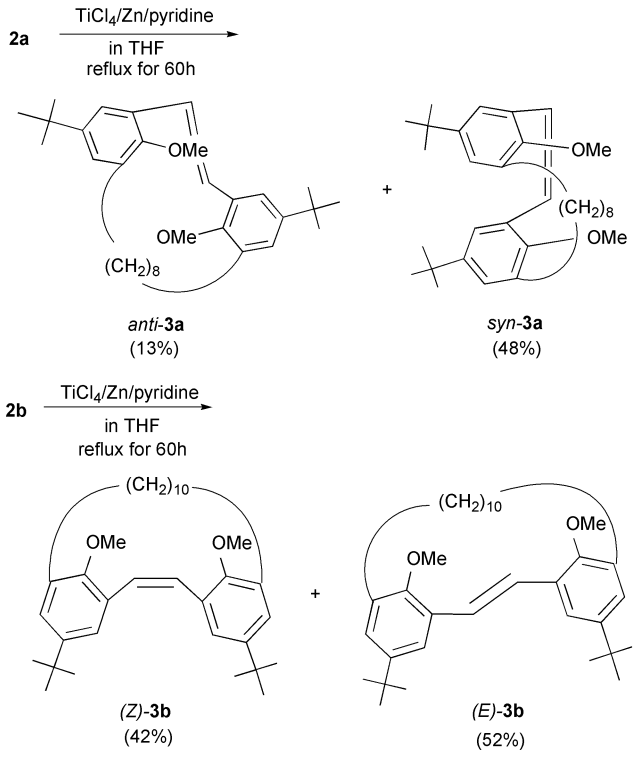


Scheme 1

data. The ^{1}H-NMR spectrum of *anti*-**3a** in $CDCl_3$ shows a singlet at δ 3.53 for methoxy protons, a singlet at δ 6.61 for olefinic protons and a pair of doublets (J 2.4 Hz) at δ 6.94, 7.29 for aromatic protons, which are in the deshielding region of the bridged double bond. Thus, the methoxy protons should show an upfield shift due to the ring current of the opposite aromatic ring.[2,17] The structure of the *syn* confomer is also readily assigned from the chemical shift of the methoxy protons at δ 3.69. Also, the *tert*-butyl proton of *syn*-**3a** is observed at higher field, δ 1.12, due to the shielding effect of the benzene ring. The aromatic protons of *syn*-**3a** are observed at much higher field (δ 6.79, 6.89) than those of *anti*-**3a**. These data confirm the assigned *anti* and *syn* structures of the two **3a** conformers.

Similarly, 1,10-bis(5-*tert*-butyl-2-methoxyphenyl)decane **2b** was subjected to reductive coupling by the McMurry reaction (Scheme 2). The novel [2.10]MCP-1-ene **3b** was obtained in almost quantitative yield. The ^{1}H-NMR spectrum of **3b** also shows two kinds of methoxy protons, each as a singlet. By careful column chromatography (silica gel, Wako C-300), two isomers, (*E*)-**3b** and (*Z*)-**3b**, were isolated in 52 and 42% yield, respectively.

The structures of products (*E*)-**3b** and (*Z*)-**3b** were also determined on the basis of their elemental analyses and spectral data. ^{1}H-NMR signals of the olefinic protons for *E*- and *Z*-olefins should be observed at $\delta > 7.4$ (*E*) and < 6.9 (*Z*).[18]



Scheme 2

The ^{1}H-NMR spectrum of (*E*)-**3b** in $CDCl_3$ shows a singlet at δ 7.44 for the olefinic protons and a doublet (J 2.4 Hz) at δ 7.30 for one aromatic proton, which is in the strongly deshielding region of the bridged double bond. In contrast, the ^{1}H-NMR spectrum of (*Z*)-**3b** in $CDCl_3$ shows a singlet at δ 6.67 for the olefinic protons and a set of doublets (J 2.4 Hz) at δ 6.77 and 6.87. Also, the *tert*-butyl protons of (*Z*)-**3b** are observed at higher field, δ 1.05, due to the strong shielding effect of the benzene ring. The *syn* conformation is also by the chemical shift of the methoxy proton peaks, at δ 3.71 for (*E*)-**3b** and 3.59 for (*Z*)-**3b**. These data strongly support the assigned *E* and *Z* configurations for **3b**, along with the *syn* conformation for both (*E*)-**3b** and (*Z*)-**3b**.

Single crystal X-ray diffraction structures of (*E*)-**3b** and (*Z*)-**3b**, recrystallized from hexane, are illustrated in Fig. 1 and 2, with the atom numbering system. Compound (*E*)-**3b** crystallized in the centrosymmetric triclinic space group $P\bar{1}$ (no. 2). In contrast, compound (*Z*)-**3b** crystallized in the centroasymmetric orthorhombic space group $P2_12_12_1$ (no. 19). Both compounds were located at general positions in the asymmetric unit of the crystal structure. The X-ray crystallographic analyses of (*E*)-**3b** and (*Z*)-**3b** clearly show that both compounds also adopt the *syn* conformation in the solid state. In addition, the two methoxy groups are obviously located on the same side of the 18-membered inner ring, which contains the long bridging C1–10 chain toward the outer direction, and the double bond adopts the *E* or *Z* configuration in the two compounds. These results seem to indicate that the double bond in (*E*)-**3b** and (*Z*)-**3b** plays an important role in fixing the conformation in the solid state.

In (*E*)-**3b** the bond distance C17–C18 is 1.33 Å, which is almost the same as that in ethylene. The bond distances C15–

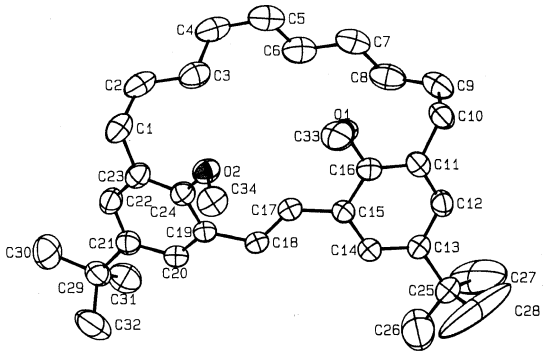


Fig. 1 X-Ray structure of (*E*)-5,21-di-*tert*-butyl-8,24-dimethoxy-[2.10]metacyclophan-1-ene (*E*)-**3b**. Thermal ellipsoids are drawn at the 50% probability level. For clarity, all hydrogen atoms are omitted.

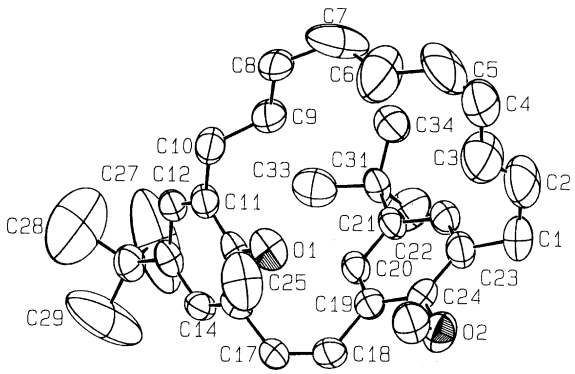


Fig. 2 X-Ray structure of (*Z*)-5,21-di-*tert*-butyl-8,24-dimethoxy-[2.10]metacyclophan-1-ene (*Z*)-**3b**. Thermal ellipsoids are drawn at the 50% probability level. For clarity, all hydrogen atoms are omitted.

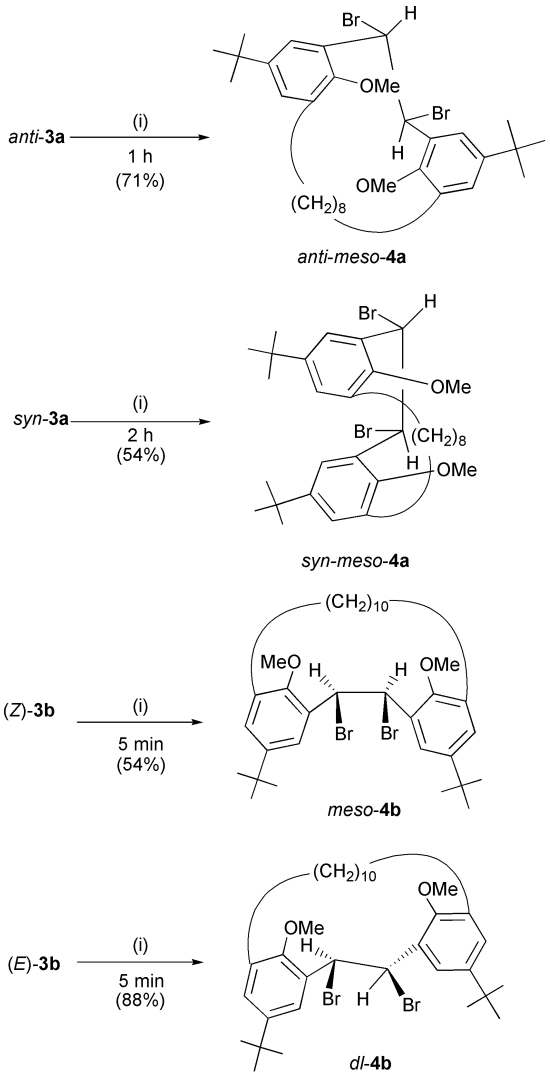
C17 and C18–C19 are 1.46 and 1.47 Å, respectively, which are slightly shorter than C1–C23 (1.51 Å) and C10–C11 (1.50 Å). This might be due to some conjugation effects through the ethylenic bond. The dihedral angles between the plane formed by the bridging alkyl chain and the bridging double bond (C1–C2–C3–C4–C5–C6–C7–C8–C9–C10–C17–C18) and the planes of the benzene rings (C11–C12–C13–C14–C15–C16 and C19–C20–C21–C22–C23–C24) have different values, 30.2 and 56.6°, respectively, showing that the aromatic rings adopt an asymmetrical conformation in the molecule. This reflects the bond angles in the ethylenic bridge chain; the bond angles C15–C17–C18 and C17–C18–C19 have different values, 129.7 and 122.7°.

In (*Z*)-**3b**, the bond distance C17–C18 is 1.28 Å, which is slightly shorter than that in ethylene. The bond distances C15–C17 and C18–C19 are 1.47 and 1.49 Å, respectively, almost equal to those of C1–C23 (1.50 Å) and C10–C11 (1.48 Å). The conjugation effects through the ethylenic bond are similar in (*Z*)-**3b** and (*E*)-**3b**. The dihedral angles between the planes C1–C2–C3–C4–C5–C6–C7–C8–C9–C10–C17–C18, C11–C12–C13–C14–C15–C16 and C19–C20–C21–C22–C23–C24 are 43.3 and 63.3°, respectively. These values are much larger than in the case of (*E*)-**3b**. This suggests that the aromatic rings of (*Z*)-**3b** adopt a tighter conformation than in (*E*)-**3b** to avoid steric repulsion. The bond angles C15–C17–C18 and C17–C18–C19 are also different, 125.5 and 129.1°, respectively. One of the two angles is much larger than in the case of (*E*)-**3b**, showing that (*Z*)-**3b** is a more strained compound than (*E*)-**3b**.

Interestingly, when (*E*)-**3b** was irradiated using a high pressure Hg lamp in cyclohexane at room temperature for 2 h, photo-induced isomerization occurred to afford (*Z*)-**3b** in quantitative yield. In contrast, irradiation of (*Z*)-**3b** under the same reaction conditions gave only recovery of the starting compound. Thus, one-way photoisomerization is observed in this system, as has been reported for normal cycloalkene systems.[19]

Attempted bromination of *anti*-5,19-di-*tert*-butyl-8,22-dimethoxy[2.8]MCP-1-ene (*anti*-**3a**) with 1.1 equiv. of bromine carried out in dichloromethane solution at room temperature for 1 h led to the expected *trans* adduct *anti*-**4a** (*endo*-*endo*-Br) in 60% yield, along with 40% of the starting compound. Bromination of *anti*-**3a** carried out with an equimolar amount of benzyltrimethylammonium tribromide ($BTMABr_3$) in dichloromethane, which was recently found to be a convenient solid brominating agent,[20] afforded the same bromine adduct *anti*-**4a** in 71% yield (Scheme 3). Interestingly reaction of *syn*-**3a** with 1.1 equiv. of $BTMABr_3$ in dichloromethane at room temperature for 2 h led to the *cis* adduct *syn*-**4a** (*endo*-*endo*-Br) in 54% yield. In contrast, bromination of (*Z*)- and (*E*)-5,21-di-*tert*-butyl-8,24-dimethoxy[2.10]MCP-1-ene (**3b**) with 1.1 equiv. of $BTMABr_3$ in dichloromethane at room temperature for 5 min afforded stereoselectively the *cis* adducts, *meso*-**4b** (*endo*-*endo*-Br) and *dl*-**4b** (*endo*-*exo*-Br) in 54 and 88% yields, respectively (Scheme 3).

The structures of the products obtained in the present work were determined from their elemental analyses and spectral data. We previously assigned[21] the ^{1}H-NMR signals of 1-*exo*-5,13-trichloro-8,16-dimethyl[2.2]MCP, and we have assigned the ^{1}H-NMR signals of *anti*-**4a** and *syn*-**4a** in a similar fashion. On the basis of the spectral data, *anti*-**4a** and *syn*-**4a** are assigned the structures, *anti*-15,16-dibromo- and *syn*-15,16-dibromo-11,19-di-*tert*-butyl-14,22-dimethoxy[8.2]MCP, respectively. The ^{1}H-NMR spectrum of *anti*-**4a** in $CDCl_3$ shows a singlet at δ 5.96 for the methine protons and a doublet (J 2.2 Hz) at δ 7.46 for the two aromatic protons which are in the strongly deshielding region of the *endo*-Br atom on the ethylene bridge. These data strongly support the *endo* arrangement for both Br atoms and therefore, *anti*-**4a** is found to be a *trans* adduct at the bridged double bond. Similarly, the ^{1}H-NMR spectrum of *syn*-**4a** in $CDCl_3$ shows a singlet at δ 6.07 for the methine protons and a doublet (J 2.0 Hz) at δ 7.46 for the two aromatic protons, which are in the strongly deshielding region of the *endo*-Br atom on the ethylene bridge. Thus, the two Br atoms are both *endo* and therefore, *syn*-**4a** is found to be the *cis* adduct at the bridged double bond.



(i) $BTMABr_3$ in CH_2Cl_2 at room temp.

Scheme 3

Previously, we reported that bromination of *anti*-[2.3]MCP-1-ene with bromine afforded exclusively the *cis* adduct and the *cis* addition of *anti*-[2.4]MCP-1-ene with bromine competed with *trans* addition due to the decrease of strain of the nonclassic bromonium ion intermediate **A**.[19] In the present system, in which the number of methylene units in the polymethylene bridge is increased from four to eight, bromine addition to the bridging double bond proceeds exclusively *via trans* addition, as has been reported for bromine addition in normal alkene systems.[19]

In contrast, the fact that the *cis* adduct *syn*-**4a** (*endo*-*endo*-Br) is exclusively obtained indicates the steric effect of the internal methoxy groups for the *exo*-Br addition, as well as the presence of a four-membered transition state **B**[22] rather than the nonclassic bromonium ion intermediate **A**[19] in the bromination process[7]. The absence of **A** might be a result of the strain in this intermediate.

When treated with potassium *tert*-butoxide in refluxing $HOBu^t$ at 50 °C for 1 h, bromine adduct *meso*-**4b** gave the monodehydrobrominated product 1-bromo[2.10]MCP-1-ene **5b** in 92% yield, along with 1% of [2.10]MCP-1-yne **6b**

Table 1 Dehydrobromination of 1,2-dibromo[2.10]MCPs **4b**

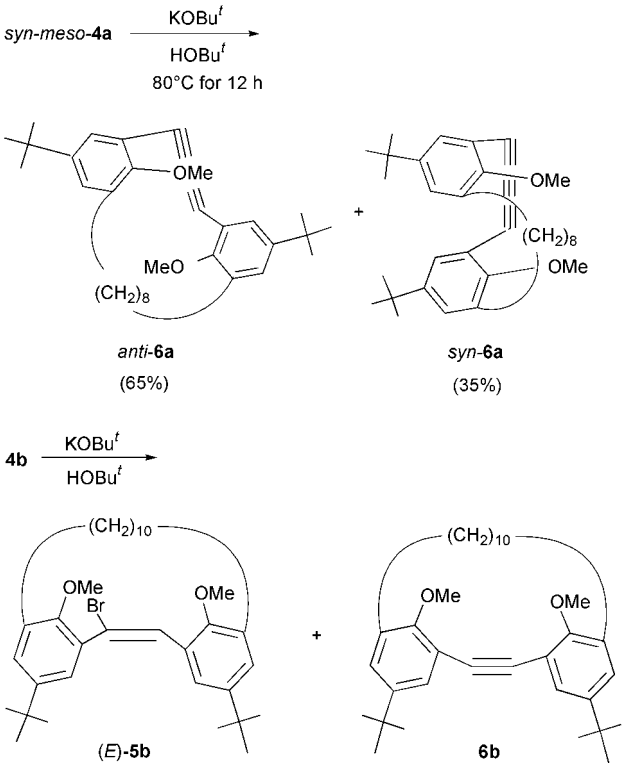
Substrate	T/°C	Time/h	Product yield[a] (%) (*E*)-**5b**	**6b**	Recovery
meso-**4b**	20	1	22	0	78
meso-**4b**	50	1	95(85)[b]	1	7
meso-**4b**	80	1	52	48	0
meso-**4b**	80	3	7	93(80)[b]	0
dl-**4b**	50	1	12	0	88
dl-**4b**	80	3	71	29	0

[a] Yields determined by ^{1}H-NMR spectrometry. [b] Isolated yields are shown in parentheses.

(Scheme 4). Prolonged reaction (to 3 h) and a higher reaction temperature (to 80 °C) furnished the doubly dehydrobrominated product **6b** in 93% yield, along with 7% of **5b** (Table 1). Similar treatment of the bromine adduct *dl*-**4b** under the same reaction conditions gave **6b** in 29% yield along with **5b** in 71% yield. Interestingly, similar dehydrobromination of the bromine adduct *syn*-**4a** carried out in HOBu^t at 80 °C for 12 h afforded [2.8]MCP-1-yne as a mixture of two isomers, *anti*-**6a** and *syn*-**6a**, in the ratio of 65 : 35 (Scheme 4). This finding strongly suggests that the ring inversion to the thermodynamically more stable *anti* conformation is possible in **6a**, as in [2.2]paracyclophan-ynes[23] and [*n*.2]MCPs.[24]

In contrast, attempts at dehydrobromination of the bromine adduct *anti*-**4a** with potassium *tert*-butoxide to afford *anti*-[2.8]MCP-1-yne under the various reaction conditions failed. Only the starting compound *anti*-**4a** could be recovered. Due to the fact that elimination of HBr should be antiperiplanar and that the rigid molecular frameworks restrict C–C bond rotation, *anti*-**4a** (*endo*-*endo*-Br) should react much more slowly than *syn*-**4a**, whose *exo*-H and *endo*-Br on the ethylene bridge can adopt a *trans*-arrangement.[4d]

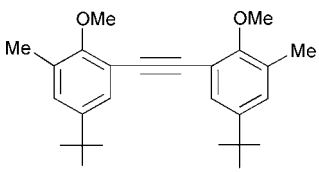
The structures of products **6a** and **6b** were determined on the basis of their elemental analyses and spectral data. From the ^{1}H-NMR spectrum of **6a** the products were found to be a mixture of two conformers, *anti*-**6a** and *syn*-**6a**. However, attempted separation of the mixture by careful column chromatography (silica gel, Wako C-300) or recrystallization



Scheme 4

failed. *anti*-**6a** and *syn*-**6a** are both thermally stable and do not interconvert at 180 °C in DMSO solution and at 400 °C in the solid state. The ^{1}H-NMR spectra of *anti*-**6a** and *syn*-**6a** show almost the same chemical shifts for the aromatic protons (δ 7.07, 7.18 for *anti*-**6a** and 7.02, 7.20 for *syn*-**6a**) and the *tert*-butyl protons (δ 1.31 for *anti*-**6a** and 1.28 for *syn*-**6a**); only the methoxy proton singlets are observed at significantly different chemical shifts, δ 3.58 and 3.85, respectively. Consequently, the ^{1}H-NMR spectrum of dimethoxy[2.8]MCP-1-yne **6a** shows that it is present as a mixture of two isomers, *anti*-**6a** and *syn*-**6a**, in the ratio 65 : 35 in $CDCl_3$.

The ^{1}H-NMR spectrum of **6b** shows two internal methoxy protons as a singlet at δ 3.80, and two aromatic protons as a set of doublets at δ 7.08 and 7.27 (J 2.4 Hz). The presence of the signal due to the methoxy protons in the normal aromatic methoxy proton region strongly supports that the structure of **6b** is the *syn* conformer. A deshielded aromatic proton is observed in the NMR spectrum of **6b** at δ 7.27, which is in the strongly deshielding region due to the π-electrons of the triple bond. While the chemical shifts of the ^{1}H- and ^{13}C-NMR signals arising from the benzene rings of **6a** and **6b** are comparable to those of the acyclic compound **12**, which was prepared from 4-*tert*-butyl-2-formyl-6-methylanisole in 3 steps using the same procedure as for [2.*n*]MCP-1-ynes **6**, the signals of the acetylenic carbons (Table 2) are observed at considerably lower field than those of **12**. This reflects the appreciable strain in the triple bonds due to bending. In particular, the chemical shift of the sp carbon in *anti*-**6a** is to considerably lower field than that of **12** and has almost the same value as that of [2$_3$]MCP-1,9,17-triyne (δ 99.86),[6c] but is at lower field than that of [2$_4$]MCP-1,9,17,25-tetrayne (δ 92.20) or 1,5-cyclooctadiyne (δ 95.8).[25]



12

The single-crystal X-ray diffraction structure of the [2.10]MCP-1-yne **6b** recrystallized from methanol is shown in Fig. 3 with the atom numbering system. Compound **6b** crystallized in the centrosymmetric triclinic space group $P\bar{1}$ (no. 2)

Table 2 Spectral data of [2.*n*]MCP-1-ynes **6** and reference compound **12** at 270 MHz in $CDCl_3$

	^{1}H NMR, δ		^{13}C NMR, δ
	Aromatic	OMe	C≡C
anti-**6a**	7.07, 7.18	3.58	99.02
syn-**6a**	7.02, 7.20	3.85	97.52
6b	7.08, 7.27	3.80	92.86
12	7.21, 7.37	3.99	89.52

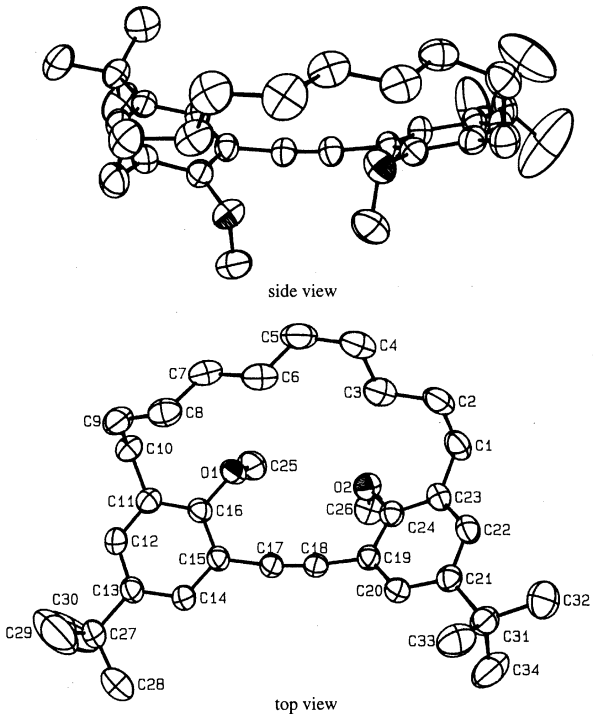


Fig. 3 X-Ray structure of 5,21-di-*tert*-butyl-8,24-dimethoxy[2.10]-metacyclophan-1-yne **6b**. Thermal ellipsoids are drawn at the 50% probability level. For clarity, all hydrogen atoms are omitted.

at the general position ($Z = 2$). The X-ray structure of **6b** clearly indicates that it is also the *syn* conformer in the solid state and that the two methoxy groups lie on the same side of the 18-membered inner ring, which contains the long bridging C1–10 chain toward the outer direction to avoid steric repulsion with the bridge chain as in (*E*)-**3b** and (*Z*)-**3b**. The bond distance C17–C18 is 1.19 Å, which is almost equal to that in acetylene. The bond distances C15–C17 and C18–C19 are both 1.44 Å, which is much shorter than C1–C23 and C10–C11 (1.51 Å). This might be attributed to conjugation effects through the acetylenic bond. Interestingly, the acetylene-containing bridge does not adopt the linear structure seen in reference compound **12**; the bond angles C15–C17–C18 and C17–C18–C19 have unusual values of 170.4 and 169.5°. This clearly shows that **6b** is significantly bent and explains the lower field shifts of the signals of the acetylenic carbons in its ^{13}C-NMR spectrum.

Ring inversion and transannular interaction

Recently, we have found[7,15b,c,24b] that the solution conformation of [*n*.2]MCPs is sensitive to the chain length of the bridges. The ring inversion barriers determined by variable temperature ^{1}H-NMR decrease with increasing length of the bridges. Thus, [*n*.2]MCPs are conformationally rigid for [7.2]- and [8.2]MCP below 140 °C, but [10.2]MCP exhibits conformational flipping above −20 °C ($\Delta G_c^{\neq} = 11.9$ kcal mol^{-1}).[7]

The conformations of dimethoxy[2.8]MCP-1-enes and -1-ynes, such as *anti*-**3a**, *syn*-**3a** and *anti*-**6a**, *syn*-**6a** that have been prepared in the present work, are rigid in solution and the signals of the methylene bridge do not coalesce below 150 °C. The energy barriers to flipping are greater than 25 kcal mol^{-1}. However, (*E*)- and (*Z*)-dimethoxy[2.10]MCP-1-enes **3b** and [2.10]MCP-1-yne **6b** seem to have sufficient space for conformational ring flipping, as demonstrated by molecular models. Therefore, we have studied the ring inversion of these systems by using variable temperature ^{1}H-NMR spectroscopy (Table 3). The ^{1}H-NMR spectrum of (*Z*)-**3b** and (*E*)-**3b** in $CDCl_3$ at room temperature exhibits a split pattern for the benzyl protons. For (*E*)-**3b**, as the temperature of a $CDBr_3$ solution is increased, the individual peaks of the benzyl protons merge and eventually a single peak is observed above 40 °C. The energy barrier to the conformational ring flipping estimated from the coalescence temperature (T_c) is 14.8 kcal mol^{-1}. Similarly, (*Z*)-**3b** exhibits conformational flipping with a coalescence temperature of 20 °C ($\Delta G_c^{\neq} = 13.8$ kcal mol^{-1}). This 1.0 kcal mol^{-1} difference indicates a more flexible structure for (*Z*)-**3b** than for (*E*)-**3b**, in spite of them both having the same ring size, which might be attributed to the different available space for conformational ring flipping. Interestingly, in the case of (*E*)-**5b** substitution of Br atoms at the double bond increases the energy barrier of the conformational ring flipping to 17.3 kcal mol^{-1} ($T_c = 90$ °C). Thus, the solution conformation of [2.*n*]MCP-1-enes is sensitive not only to the configuration of the double bond but also to the substituents at the double bond.

Table 3 The coalescence temperatures and energy barriers of ring inversion in [10.2]MCP **13** and [2.10]MCPs **3b**–**6b**[a]

	T_c/°C	$\Delta\nu$/Hz	k_c	$\Delta G^{\neq}$/kcal mol^{-1}
13	−20	—	—	11.9
(*Z*)-**3b**	20	135.7	301.4	13.8
(*E*)-**3b**	40	140.7	312.3	14.8
(*E*)-**5b**	90	139.9	310.7	17.3
6b	−50	112.3	249.4	10.5

[a] T_c and $\Delta G_c^{\neq}$ were determined in 1 : 3 $CDCl_3$–CS_2 or $CDBr_3$ using $SiMe_4$ as reference.

The energy barrier to conformational ring flipping for [2.10]MCP-1-yne **6b**, estimated from the coalescence temperature, is 10.5 kcal mol^{-1}. A lower ring inversion barrier was observed for the [2.10]MCP-1-yne than that for the [2.10]MCP-1-ene, in spite of the smaller ring size due to the substitution of a triple bond for the alkene bridge. The barrier to ring inversion in the [2.10]MCP-1-yne corresponds to a decrease in the rigidity of the system by about 3.3–4.2 kcal mol^{-1} in $CDCl_3$. The decreased rigidity of **6b** may be due to the distorted bond angles of the bridged triple bond.

The UV spectra of the [2.*n*]MCP-1-ynes **6a** and **6b**, along with that of the reference compound 1,2-bis(5-*tert*-butyl-2-methoxy-3-methylphenyl)ethyne **12**, in cyclohexane are shown in Fig. 4. The UV spectra of the [2.*n*]MCP-1-ynes **6a** and **6b** show different absorption curves compared to that of the

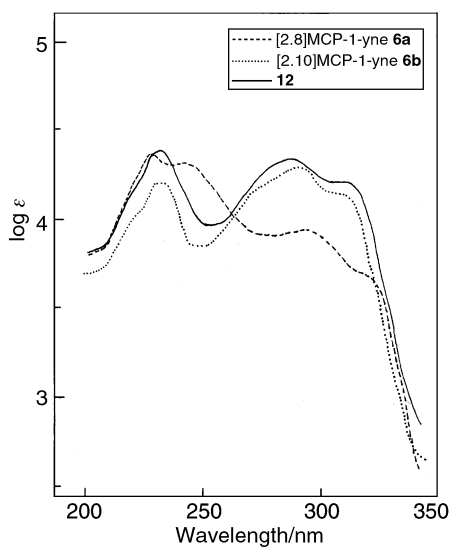


Fig. 4 UV absorption spectra of [2.8]MCP-1-yne **6a** and [2.10]MCP-1-yne **6b** in cyclohexane, along with that of the reference compound **12**.

model acyclic compound **12**. The lack of an acetylene-type chromophore in the UV spectra of the MCP-ynes confirms the non-planarity of the aromatic ring and triple bond.

Bathochromic shifts were observed for **6a** and **6b**, which are ascribed to a transannular interaction between the two benzene rings and an increase in the strain of these systems.[26] When the length of the methylene bridge is decreased by two carbons, a small red shift from 290 nm (log $\varepsilon = 4.29$) to 297 nm (log $\varepsilon = 3.92$) was observed. This finding seems to support the notion that the strain in the [2,*n*]MCP-1-ynes increases as the length of the methylene bridge decreases.

Conclusions

We have synthesized, for the first time, two conformers, *anti*-**6a** and *syn*-**6a**, of [2.8]MCP-1-yne in the MCP-1-yne systems. The dehydrobromination of bromine adducts of [2.*n*]MCP-1-enes with base will also open up new mechanistic aspects for cyclophane chemistry. Further studies on the chemical properties of [2.*n*]MCP-1-ynes **6** are now in progress.

Experimental

All melting points (Yanagimoto MP-S1) and boiling points are uncorrected. NMR spectra were determined at 270 MHz with a Nippon Denshi JEOL FT-270 NMR spectrometer with $SiMe_4$ as an internal reference: *J* values are given in Hz. IR spectra were measured for samples as KBr pellets or a liquid film on NaCl plates in a Nippon Denshi JIR-AQ2OM spectrophotometer. UV spectra were measured on a Shimadzu 240 spectrophotometer. Mass spectra were obtained on a Nippon Denshi JMS-01SA-2 spectrometer at 75 eV using a direct-inlet system through a GLC. Elemental analyses were performed on a Yanaco MT-5.

Syntheses

1,8-Bis(5-*tert*-butyl-2-methoxyphenyl)octane **1a** and 1,10-bis(5-*tert*-butyl-2-methoxyphenyl)decane **1b** were prepared from anisole according to the reported procedure.[13] The preparation of 4-*tert*-butyl-2-methylanisole **7** was previously described.[27]

1,10-Bis(5-*tert*-butyl-3-formyl-2-methoxyphenyl)decane, 2b. To a solution of **1b**[13] (12.57 g, 27 mmol) and Cl_2CHOCH_3 (6.84 mL, 75.6 mmol) in CH_2Cl_2 (60 mL) was added a solution of $TiCl_4$ (18.0 mL, 163.5 mmol) in CH_2Cl_2 (60 mL) at 0 °C. After stirring the reaction mixture at room temperature for 2 h, it was poured into a large volume of ice water (400 mL) and extracted with CH_2Cl_2 (200 mL × 2). The combined extracts were washed with water, dried with Na_2SO_4 and concentrated. The residue was chromatographed over silica gel (Wako C-300, 500 g) with benzene as eluent to give crude **2b**. Recrystallization from hexane gave 9.06 g (64%) of **2b** as pale yellow prisms, mp 82–84 °C; ν_{max}(KBr)/cm^{-1}: 1683 (C=O); δ_H($CDCl_3$): 1.31 (18 H, s), 1.20–1.40 (12 H, m), 1.50–1.70 (4 H, m), 2.66 (4 H, t, *J* 7.9), 3.87 (6 H, s), 7.48 (2 H, d, *J* 2.4), 7.69 (2 H, d, *J* 2.4), 10.36 (2 H, s); *m*/*z*: 522 (M^+). Anal. calc. for $C_{34}H_{50}O_4$ (522.8): C, 78.12; H, 9.64; found: C, 78.14; H, 9.72%.

*1,8-Bis(5-tert-butyl-3-formyl-2-methoxyphenyl)octane, **2a**.* Compound **2a** was synthesized in the same manner as described above for **2b** and obtained in 70% yield as a pale yellow oil; ν_{max} (NaCl)/cm^{-1}: 1692 (C=O); δ_H($CDCl_3$): 1.32 (18 H, s), 1.32–1.42 (8 H, m), 1.58–1.70 (4 H, m), 2.65–2.71 (4 H, m), 3.87 (6 H, s), 7.47 (2 H, d, *J* 2.4), 7.70 (2 H, d, *J* 2.4), 10.36 (2 H, s); *m*/*z*: 494 (M^+). Anal. calc. for $C_{32}H_{46}O_4$ (494.72): C, 77.69; H, 9.37. found: C, 77.37; H, 9.18%.

General procedure for the McMurry coupling reaction of 2. The McMurry reagent was prepared from $TiCl_4$ (13.75 mL, 125 mmol) and Zn powder (18 g, 275 mmol) in 500 mL of dry THF, under nitrogen. A solution of **2b** (4.72 g, 9 mmol) in dry THF (250 mL) was added over 60 h to the black McMurry reagent mixture by using a high-dilution technique with continuous refluxing and stirring. The reaction mixture was refluxed for an additional 8 h, cooled to room temperature, and hydrolyzed with aqueous 10% K_2CO_3 (500 mL) at 0 °C. The reaction mixture was extracted with CH_2Cl_2 (300 mL × 3). The combined extracts were washed with water, dried with Na_2SO_4 and concentrated. The residue was chromatographed over silica gel (Wako C-300, 500 g) with hexane–benzene (2 : 1) as eluent to give (*E*)-**3b** and (*Z*)-**3b** as colorless solids. Recrystallization from hexane afforded (*E*)-**3b** (2.30 g, 52%) and (*Z*)-**3b** (1.85 g, 42%), Compounds *anti*-**3a** and *syn*-**3a** were similarly prepared in 13 and 48% yields, respectively.

(E)-5,21-Di-tert-butyl-8,24-dimethoxy[2.10]metacyclophan-1-ene, (E)-3b. (*E*)-**3b** was obtained as colorless prisms (hexane), mp 160–162 °C; ν_{max} (KBr)/cm^{-1}: 2952, 2853, 1479, 1458, 1362, 1290, 1207, 1021, 870, 649; δ_H($CDCl_3$): 1.32 (18 H, s), 0.86–3.10 (20 H, m), 3.71 (6 H, s), 6.96 (2 H, d, *J* 2.4), 7.30 (2 H, d, *J* 2.4), 7.44 (2 H, br s); *m*/*z*: 490 (M^+). Anal. calc. for $C_{34}H_{50}O_2$ (490.8): C, 83.21; H, 10.27; found: C, 83.01; H, 10.67%.

(Z)-5,21-Di-tert-butyl-8,24-dimethoxy[2.10]metacyclophan-1-ene, (Z)-3b. (*Z*)-**3b** was obtained as colorless prisms (hexane), mp 95–96 °C; ν_{max} (KBr)/cm^{-1}: 2912, 1474, 1362, 1217, 1018, 881, 744; δ_H($CDCl_3$): 1.05 (18 H, s), 0.99–1.21 (4 H, m), 1.31–1.36 (4 H, m), 1.95–3.12 (2 H, br s), 3.59 (6 H, s), 6.67 (2 H, br s), 6.77 (2 H, d, *J* 2.4), 6.87 (2 H, d, *J* 2.4); *m*/*z*: 490 (M^+). Anal. calc. for $C_{34}H_{50}O_2$ (490.8): C, 83.21; H, 10.27; found: C, 83.34; H, 10.56%.

anti-5,19-Di-tert-butyl-8,22-dimethoxy[2.8]metacyclophan-1-ene, anti-3a. *anti*-**3a** was obtained as colorless prisms (MeOH), mp 200–202 °C; ν_{max} (KBr)/cm^{-1}: 2917, 1474, 1255, 1097, 1010, 881, 871; δ_H($CDCl_3$): 0.80–1.19 (4 H, m), 1.20–1.60 (8 H, m), 1.35 (18 H, s), 2.32–2.44 (2 H, m), 2.69–2.82 (2 H, m), 3.53 (6 H, s), 6.61 (2 H, s), 6.94 (2 H, d, *J* 2.4), 7.29 (2 H, *J* 2.4); *m*/*z*: 462 (M^+). Anal. calc. for $C_{32}H_{46}O_2$ (462.72): C, 83.06; H, 10.02; found: C, 82.98; H, 9.71%.

syn-5,19-Di-tert-butyl-8,22-dimethoxy[2.8]metacyclophan-1-ene, syn-3a. *syn*-**3a** was obtained as a colorless oil; ν_{max} (NaCl)/cm^{-1}: 2962, 1479, 1327, 1215, 1019, 883, 810; δ_H ($CDCl_3$): 0.88–1.20 (8 H, m), 1.12 (18 H, s), 1.22–1.36 (2 H, m), 1.38–1.45 (2 H, m), 2.15–2.25 (2 H, m), 2.72–2.82 (2 H, m), 3.69 (6 H, s), 6.79 (2 H, d, *J* 2.4), 6.89 (2 H, d, *J* 2.4), 6.88 (2 H, s); *m*/*z*: 462 (M^+). Anal. calc. for $C_{32}H_{46}O_2$ (462.72): C, 83.06; H, 10.02; found: C, 82.81; H, 10.04%.

General procedure for the bromination of 3 with $BTMABr_3$. To a solution of (*Z*)-**3b** (253 mg, 0.52 mmol) in CH_2Cl_2 (50 mL) was added $BTMABr_3$ (223 mg, 0.57 mmol) at room temperature. After stirring the reaction mixture at room temperature for 5 min, it was poured into a large volume of ice water (50 mL) and extracted with CH_2Cl_2 (50 mL × 2). The combined extracts were washed with water, dried with Na_2SO_4 and concentrated. The residue was recrystallized from hexane gave 182 mg (54%) of 17,18-di-*endo*-bromo-13,21-di-*tert*-butyl-16,24-dimethoxy[10.2]metacyclophane, *meso*-**4b** as colorless prisms, mp 134–135 °C; ν_{max}(KBr)/cm^{-1}: 2928, 1858, 2824, 1458, 1427, 1363, 1204, 1115, 1008, 810, 449; δ_H($CDCl_3$): 1.16 (18 H, s), 0.75–1.78 (16 H, m), 2.19–2.35 (2 H, m), 2.62–2.80 (2 H, m), 3.65 (6 H, s), 5.95 (2 H, s), 7.00 (2 H, d, *J* 2.4), 7.23–7.60 (2 H, br d); *m*/*z*: 648, 650, 652 (M^+). Anal. calc. for $C_{34}H_{50}O_2Br_2$ (650.6): C, 62.77; H, 7.75; found: C, 63.05; H, 8.01%.

17-endo,18-exo-Dibromo-13,21-di-tert-butyl-16,24-dimethoxy[10.2]metacyclophane, dl-4b. Compound *dl*-**4b** was synthesized in the same manner as described above for *meso*-**4b** and

obtained in 88% yield as colorless prisms (hexane), mp 199 °C; ν_{max}(KBr)/cm^{-1}: 2900, 2863, 1484, 1477, 1463, 1363 1247, 1231, 1212, 1013, 1003; δ_H($CDCl_3$): 0.43–0.62 (2 H, br m), 0.73–1.59 (14 H, m), 1.20 (18 H, s), 2.15–2.28 (2 H, m), 2.64–2.80 (2 H, br m), 3.71 (6 H, s), 5.99 (2 H, s), 6.84 (2 H, d, *J* 1.95), 7.24 (2 H, br d); *m*/*z*: 648, 650, 652 (M^+). Anal. calc. for $C_{34}H_{50}O_2Br_2$ (650.6): C, 62.77 ; H, 7.75; found: C, 63.32; H, 7.88%.

- *anti-15,16-Di-endo-bromo-11,19-di-tert-butyl-14,22-dimethoxy*[*8.2*]*metacyclophane*, *anti-meso-**4a***. Compound *anti-meso-***4a** was synthesized in the same manner as described above for *meso-***4b** and obtained in 71% yield as colorless prisms (hexane), mp 134–135 °C; ν_{max}(KBr)/cm^{-1}: 2928, 1858, 2824, 1458, 1427, 1363, 1204, 1115, 1008, 810, 449; δ_H($CDCl_3$): 0.70–1.02 (6 H, m), 1.07–1.43 (6 H, m), 1.27 (18 H, s), 2.16–2.38 (2 H, m), 2.58–2.72 (2 H, m), 3.64 (6 H, s), 5.96 (2 H, s, CHBr), 6.95 (2 H, d, *J* 2.2), 7.46 (2 H, d, *J* 2.2); *m*/*z*: 620, 622, 624 (M^+). Anal. calc. for $C_{32}H_{46}O_2Br_2$ (622.52): C, 61.74; H, 7.45; found: C, 61.91; H, 7.12%.

syn-15,16-Di-endo-bromo-11,19-di-tert-butyl-14,22-dimethoxy[*8.2*]*metacyclophane*, *syn-meso-**4a***. Compound *syn-meso-***4a** was synthesized in the same manner as described above for *meso-***4b** and obtained in 54% yield as a colorless oil; ν_{max}(NaCl)/cm^{-1}: 2923, 1463, 1169, 1037, 809, 667; δ_H($CDCl_3$): 0.78–0.94 (2 H, m), 0.97–1.39 (8 H, m), 1.17 (18 H, s), 1.48–1.67 (2 H, m), 2.19–2.35 (2 H, br m), 2.62–2.79 (2 H, br m), 3.68 (6 H, s), 6.07 (2 H, s, CHBr), 6.94 (2 H, d, *J* 2.0), 7.55 (2 H, d, *J* 2.0); *m*/*z*: 620, 622, 624 (M^+). Anal. calc. for $C_{32}H_{46}O_2Br_2$ (622.53): C, 61.74; H, 7.45; found: C, 62.01; H, 7.25%.

Dehydrobromination of 4b with KOBu^t. To a solution of *meso-***4b** (180 mg, 0.28 mmol) in HOBu^t (24 mL) was added KOBu^t (1.18 g, 10.5 mmol) at room temperature. After stirring the reaction mixture at 50 °C for 1 h, it was poured into a large amount of ice water (50 mL) and extracted with CH_2Cl_2 (100 mL × 2). The combined extracts were washed with water, dried with Na_2SO_4 and concentrated. The residue was recrystallized from methanol gave 136 mg (85%) of (*E*)-1-bromo-5,21-di-*tert*-butyl-8,24-dimethoxy[2.10]metacyclophan-1-ene, (*E*)-**5b** as colorless prisms, mp 89–90°C; ν_{max}(KBr)/cm^{-1}: 2899, 2866, 2830, 1469, 1427, 1363, 1295, 1235, 1210, 1114, 1008; δ_H($CDCl_3$): 0.92 (9 H, s), 1.27 (9 H, s), 1.10–1.65 (16 H, br m), 1.95–3.06 (4 H, br m), 3.63 (3 H, s), 3.88 (3 H, s), 6.42 (1 H, d, *J* 2.4), 6.92 (1 H, d, *J* 2.4), 7.06 (1 H, d, *J* 2.4), 7.31 (1 H, s), 7.38 (1 H, d, *J* 2.4); *m*/*z*: 568, 570 (M^+). Anal. calc. for $C_{34}H_{49}O_2Br$ (569.7): C, 71.69; H, 8.67; found: C, 71.62; H, 8.39%.

Similary, compound *meso-***4b** was treated with KOBu^t in HOBu^t at 80 °C for 3 h to afford 5,21-di-*tert*-butyl-8,24-dimethoxy[2.10]metacyclophan-1-yne, **6b** (80%) as colorless prisms (methanol), mp 137 °C; ν_{max}(KBr)/cm^{-1}: 2949, 2853, 2822, 2210, 1479, 1459, 1363, 1237, 1200, 1023, 873; δ_H($CDCl_3$): 1.30 (18 H, s), 0.82–1.58 (16 H, br m), 2.61–2.68 (4 H, t, *J* 6.1), 3.80 (6 H, s), 7.08 (2 H, d, *J* 2.4), 7.27 (2 H, d, *J* 2.4); *m*/*z*: 488 (M^+). Anal. calc. for $C_{34}H_{48}O_2$ (488.8): C, 83.55; H, 9.90; found: C, 83.60; H, 10.14%.

Dehydrobromination of *syn*-4a with KOBu^t. To a solution of *syn-***4a** (285 mg, 0.458 mmol) in THF (20 mL) was added KOBu^t (513 mg, 4.58 mmol) at room temperature. After stirring the reaction mixture under reflux for 12 h, it was poured into a large volume of ice water (50 mL) and extracted with CH_2Cl_2 (100 mL × 2). The combined extracts were washed with water, dried with Na_2SO_4 and concentrated. The residue was chromatographed over silica gel (Wako C-300, 500 g) with hexane as eluent to give crude **6a** as a colorless solid. The solid was recrystallized from methanol to afford a mixture of *anti*- (*anti-***6a**) and *syn*-5,19-di-*tert*-butyl-8,22-dimethoxy[2.8]metacyclophane-1-yne, *syn-***6a** in a ratio of 65 : 35 determined from the ^{1}H-NMR spectrum.

5,19-Di-tert-butyl-8,22-dimethoxy[*2.8*]*metacyclophane-1-yne*, ***6a***. **6a** was obtained as colorless prisms (MeOH), mp 117–119 °C; ν_{max}(KBr)/cm^{-1}: 2916, 1471, 1363, 1261, 1221, 1104, 1008, 875; (*anti-***6a**) δ_H($CDCl_3$): 0.75–1.68 (12 H, m), 1.31 (18 H, s), 2.29–2.43 (2 H, br m), 2.77–2.98 (2 H, br m), 3.58 (6 H, s), 7.07 (2 H, d, *J* 2.4), 7.18 (2 H, d, *J* 2.4); δ_C($CDCl_3$): 26.14, 29.13, 29.41, 30.04, 30.20, 31.10, 31.57, 32.77, 34.29, 59.95, 99.02 (acetylenic C), 116.43, 123.76, 127.36, 134.23, 145.96, 160.64; (*syn-***6a**) δ_H($CDCl_3$): 0.75–1.68 (12 H, m), 1.28 (18 H, s), 2.29–2.43 (2 H, br m), 2.77–2.98 (2 H, br m), 3.85 (6 H, s), 7.02 (2 H, d, *J* 2.4), 7.20 (2 H, d, *J* 2.4); δ_C($CDCl_3$): 26.55, 29.13, 29.41, 29.75, 30.57, 31.10, 31.49, 32.77, 33.15, 61.47, 97.52 (acetylenic C), 117.22, 124.67, 127.27, 134.81, 145.96, 158.70; *m*/*z*: 460 (M^+). Anal. calc. for $C_{32}H_{44}O_2$ (460.71): C, 83.43; H, 9.63; found: C, 83.68; H, 9.51%.

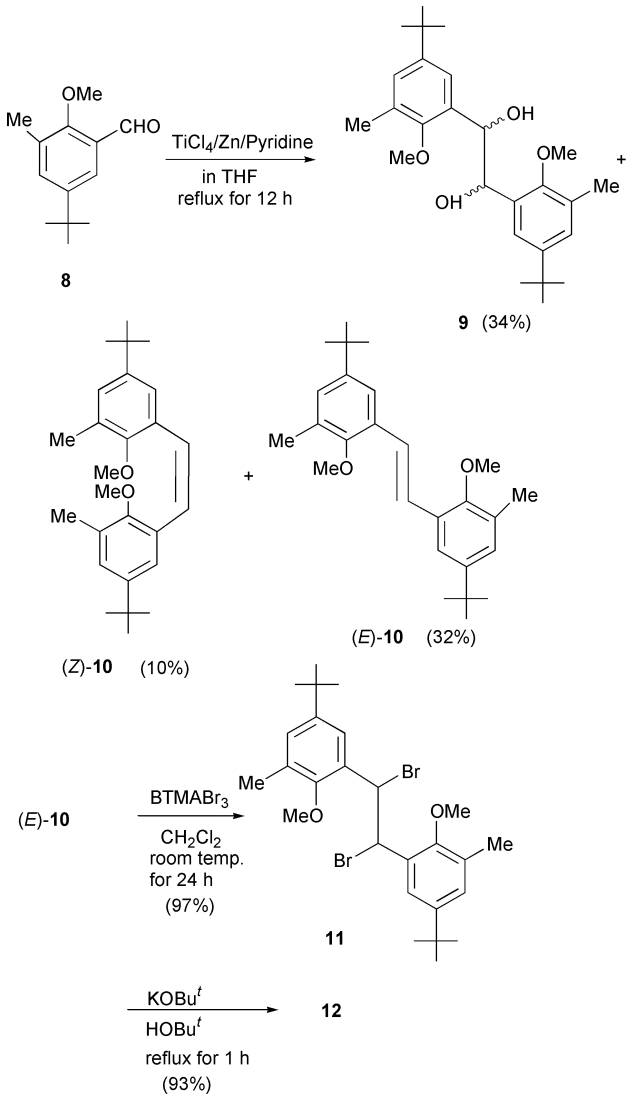
4-*tert*-Butyl-2-formyl-6-methylanisole, 8. To a solution of 4-*tert*-butyl-2-methylanisole **7**[27] (6.38 g, 35.76 mmol) and Cl_2CHOCH_3 (4.52 mL, 150 mmol) in CH_2Cl_2 (40 mL) was added a solution of $TiCl_4$ (12.0 mL, 108.4 mmol) in CH_2Cl_2 (40 mL) at 0 °C. After stirring the reaction mixture at room temperature for 2 h, it was poured into a large volume of ice water (400 mL) and extracted with CH_2Cl_2 (200 mL × 2). The combined extracts were washed with water, dried with Na_2SO_4 and concentrated. The residue was chromatographed over silica gel (Wako C-300, 500 g) with hexane as eluent to give **8** (5.93 g, 80%) as a yellow oil; ν_{max}(NaCl)/cm^{-1}: 1683 (C=O); δ_H($CDCl_3$): 1.31 (9 H, s), 2.34 (3 H, s), 3.86 (3 H, s), 7.47 (1 H, d, *J* 2.1), 7.70 (1 H, d, *J* 2.1), 10.37 (1 H, s); *m*/*z*: 206 (M^+). Anal. calc. for $C_{13}H_{18}O_2$ (206.29): C, 75.69; H, 8.8; found: C, 75.52; H, 8.72%.

McMurry coupling reaction of 8 (Scheme 5). The McMurry reagent was prepared from $TiCl_4$ (13.75 mL, 125 mmol) and Zn powder (18 g, 275 mmol) in 300 mL of dry THF, under nitrogen. A solution of **8** (5.37 g, 25.95 mmol) and pyridine (22.8 mL, 200 mmol) in dry THF (100 mL) was added over 1 h to the black McMurry reagent mixture by using a high-dilution technique with continuous refluxing and stirring. The reaction mixture was refluxed for an additional 12 h, cooled to room temperature, and hydrolyzed with aqueous 10% K_2CO_3 (500 mL) at 0 °C. The reaction mixture was extracted with CH_2Cl_2 (300 mL × 3). The combined extracts were washed with water, dried with Na_2SO_4 and concentrated. The residue was chromatographed over silica gel (Wako C-300, 500 g) with hexane, 3 : 1 hexane–benzene and 4 : 1 benzene–EtOAc as eluents to give (*E*)-**10** (1.58 g, 32%), (*Z*)-**10** (507 mg, 10%) and **9** (1.82 g, 34%), respectively.

1,2-Bis(*5-tert-butyl-2-methoxy-3-methylphenyl*)*ethane-1,2-diol*, ***9***. **9** was obtained as a yellow oil; ν_{max}(NaCl)/cm^{-1}: 3407 (OH); δ_H($CDCl_3$): 1.29 (18 H, s), 2.27 (2 H, s), 2.30 (6 H, s), 3.78 (6 H, s), 4.70 (2 H, s), 7.14 (2 H, d, *J* 2.4), 7.18 (2 H, d, *J* 2.4); *m*/*z*: 414 (M^+). Anal. calc. for $C_{26}H_{38}O_4$ (414.59): C, 75.32; H, 9.24; found: C, 75.05; H, 9.34%.

(*Z*)-*1,2-Bis*(*5-tert-butyl-2-methoxy-3-methylphenyl*)*ethene*, (*Z*)-***10***. (*Z*)-**10** was obtained as a colorless oil; ν_{max}(NaCl)/cm^{-1}: 2928, 1478, 1362, 1210, 1118, 1015, 810; δ_H($CDCl_3$): 1.05 (18 H, s), 2.28 (6 H, s), 3.78 (6 H, s), 6.81 (2 H, s), 6.92 (2 H, d, *J* 2.4), 7.01 (2 H, d, *J* 2.4); *m*/*z*: 380 (M^+). Anal. calc. for $C_{26}H_{36}O_2$ (380.58): C, 82.06; H, 9.53; found: C, 81.86; H, 9.52%.

(*E*)-*1,2-Bis*(*5-tert-butyl-2-methoxy-3-methylphenyl*)*ethene*, (*E*)-***10***. (*E*)-**10** was obtained as colorless prisms (MeOH), mp 148–150 °C; ν_{max}(KBr)/cm^{-1}: 2958, 1483, 1428, 1368, 1248, 1205, 1111, 1003, 870; δ_H($CDCl_3$): 1.34 (18 H, s), 2.32 (6 H, s), 3.76 (6 H, s), 7.25 (2 H, br s), 7.40 (2 H, s), 7.48 (2 H, br s); *m*/*z*: 380 (M^+). Anal. calc. for $C_{26}H_{36}O_2$ (380.58): C, 82.06; H, 9.53; found: C, 82.22; H, 9.30%.



Scheme 5

Bromination of (*E*)-10 with $BTMABr_3$. To a solution of (*E*)-**10** (380 mg, 1 mmol) in CH_2Cl_2 (40 mL) was added $BTMABr_3$ (440 mg, 1.1 mmol) at room temp. After stirring the reaction mixture at room temperature for 24 h, it was poured into a large volume of ice water (100 mL) and extracted with CH_2Cl_2 (50 mL × 2). The combined extracts were washed with water, dried with Na_2SO_4 and concentrated. The residue was recrystallized from hexane to give 526 mg (97%) of 1,2-dibromo-1,2-bis(5-*tert*-butyl-2-methoxy-3-methylphenyl)ethane, **11** as colorless prisms, mp 193–195 °C; ν_{max}(KBr)/cm^{-1}: 2955, 1482, 1361, 1249, 993, 605; δ_H($CDCl_3$): 1.13 (9 H, s), 1.34 (9 H, s), 2.10 (3 H, s), 2.33 (3 H, s), 3.82 (3 H, s), 3.93 (3 H, s), 5.30 (1 H, s), 6.15 (1 H, s), 6.84 (1 H, br d), 7.10 (1 H, br d), 7.20 (1 H, br d), 7.45 (1 H, br d); *m*/*z*: 538, 540, 542 (M^+). Anal. calc. for $C_{26}H_{36}O_2Br_2$ (540.38): C, 57.79; H, 6.72; found: C, 57.78; H, 6.46%.

Dehydrobromination of 11 with KOBu^t in THF. To a solution of **11** (376 mg, 0.696 mmol) in THF (62 mL) was added KOBu^t (2.98 g, 26.59 mmol) at room temperature. After stirring the reaction mixture at 50 °C for 1 h, it was poured into a large volume of ice water (100 mL) and extracted with CH_2Cl_2 (100 mL × 2). The combined extracts were washed with water, dried with Na_2SO_4 and concentrated. The residue was recrystallized from methanol to give 245 mg (93%) of 1,2-bis(5-*tert*-butyl-2-methoxy-3-methylphenyl)ethyne, **12**, as colorless prisms, mp 126–127 °C; ν_{max}(KBr)/cm^{-1}: 2358, 1227, 1116, 1002, 878, 651; δ_H($CDCl_3$): 1.31 (18 H, s), 2.29 (6 H, s), 3.99 (6 H, s), 7.16 (2 H, d, *J* 2.4), 7.37 (2 H, d, *J* 2.4); δ_C($CDCl_3$): 15.91, 30.89, 33.72, 60.09, 89.52, 115.77, 127.59, 128.15, 129.94, 145.67, 156.64; *m*/*z*: 378 (M^+). Anal. calc. for $C_{26}H_{34}O_2$ (378.56): C, 82.49; H, 9.05; found: C, 82.30; H, 9.02%.

Estimation of the activation energy of the ring flipping

The rate constant (k_c) of the observed conformational interconversion at the coalescence temperature (T_c) can be calculated by using eqn. (1).[28] The free energy of activation ($\Delta G_c^{\neq}$) at coalescence can then be estimated by using the Eyring equation [eqn. (2)].[28]

$$k_c = \pi\Delta\nu/2^{1/2} \quad (1)$$

$$\Delta G_c^{\neq} = 2.303RT_c(10.32 + \log T_c - \log k_c) \quad (2)$$

X-Ray crystallography

Crystallographic data and data collection details for (*E*)-**3b**, (*Z*)-**3b** and **6b** are given in Table 4. In a typical procedure, a single crystal was mounted on a quartz fiber and the unit cell constants for (*E*)-**3b** were derived from a least-squares analysis

Table 4 Crystallographic data and data collection details for (*E*)-5,21-di-*tert*-butyl-8,24-dimethoxy[2.10]metacyclophan-1-ene (*E*)-**3b**, (*Z*)-5,21-di-*tert*-butyl-8,24-dimethoxy[2.10]metacyclophan-1-ene (*Z*)-**3b** and 5,21-di-*tert*-butyl-8,24-dimethoxy[2.10]metacyclophan-1-yne **6b**

	(*E*)-**3b**	(*Z*)-**3b**	**6b**
Formula	$C_{34}H_{50}O_2$	$C_{34}H_{50}O_2$	$C_{34}H_{48}O_2$
FW	490.78	490.78	488.76
Crystal system	Triclinic	Orthorhombic	Triclinic
Space group	$P\bar{1}$ (no. 2)	$P2_12_12_1$ (no. 19)	$P\bar{1}$ (no. 2)
a/Å	12.554(1)	14.4498(14)	12.1080(8)
b/Å	13.707(2)	21.115(2)	13.949(2)
c/Å	10.288(1)	9.6625(7)	10.2097(11)
α/°	108.20(1)		105.5138(99)
β/°	113.805(8)		113.595(7)
γ/°	83.10(1)		84.019(8)
U/Å^3	1538.5(3)	3152.0(4)	1522.7(3)
Z	2	4	2
T/K	295	295	298
μ/cm^{-1}	4.52	4.42	4.57
No. of reflections	6366	3203	6198
Unique reflections	5694	3176	5872
R_{int}	0.04	—	0.03
R	0.107	0.090	0.066
R_w [a]	0.150	0.116	0.096

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

of the settings of a CAD4 FR 586 diffractometer for 25 reflections, in the range $29.92° < \theta < 31.43°$. The intensities of all independent reflections with $8° < 2\theta < 144°$ were measured with $\omega - 2\theta$ scan width $(0.80 + 0.14 \tan \theta)$ using Ni-filtered Cu-Kα radiation ($\lambda = 1.541\,84$ Å). The X-ray analysis was performed with the MolEN program package[29] and the structure was determined uneventfully by direct methods (SIR 88).[30] The structure of **6b** was determined by direct methods using MULTAN 80.[31] No corrections were made for absorption effects. The 36 independent non-hydrogen atoms were refined anisotropically. The 41 independent hydrogen atoms, except for those on C26, C27 and C28, were put in calculated positions, thermally fixed (B_{iso} 5.0 Å^{-2}) and included in the refinement, but restrained to ride on the atoms to which they are bonded. The refinement was performed by full-matrix least-squares methods using 326 parameters in which the scale factor and secondary extinction coefficient were included.

CCDC reference number 156035–156037. See http://www.rsc.org/suppdata/nj/b0/b010205i/ for crystallographic data in CIF or other electronic format.

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