Multibridged [3_n]Cyclophanes, 7[‡]

Improved Synthesis, Structure, and Cycloaddition Reaction of [3_4](1,2,4,5)Cyclophane

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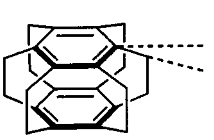
The modified synthetic route to [3_4](1,2,4,5)cyclophane (**3**) provides gram quantities of this compound in fewer steps than the conventional routes. The cycloaddition of **3** with dicyanoacetylene (**12**) gave barrelenophane **13**, which was transformed into semibullvalenophane **15** on photoirradiation. This transformation (**13** → **15**) is in sharp contrast to the case of Boekelheide's [2_4]barrelenophane, where cyclooctatetraenophane is obtained. The X-ray structural analyses of **3**, **13**, and **15** demonstrates their unique structures.

All members of both series of multibridged [2_n]- and [3_n]cyclophanes ($n = 2-6$) are known today. The synthetic efforts toward superphane, [2_6](1,2,3,4,5,6)cyclophane (**1**), by Boekelheide et al.[2] and Hopf et al.[3] provided a series of [2_n]cyclophanes ($n = 2-6$), and developed cyclophane chemistry with highly strained benzene rings.[4] Our efforts aimed at the synthesis of [3_6](1,2,3,4,5,6)cyclophane (**2**)[5] provided an alternative series of [3_n]cyclophanes ($n = 2-6$) with bridges longer by one carbon unit. Elongation of the bridge causes the cyclophane structure to be increasingly strain-free and more flexible as compared with the corresponding [2_n]series. As a result, [3_n]cyclophanes show much stronger π-electron-donating ability than the corresponding [2_n]cyclophanes because of effective hyperconjugation between the benzyl hydrogen atoms and the benzene ring, a phenomenon that is due to the existence of a conformation favorable for π−σ interaction.[5b]



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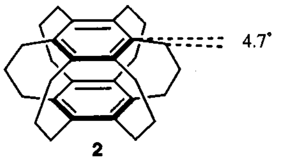

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The much stronger π-electron-donating ability of [3_n]cyclophane in comparison to the corresponding [2_n]cyclophane suggests that the former should serve as better monodentate or bidentate π ligands for transition metals than the latter. In our preliminary study[6] on the development of one-dimensional organometallic polymers[7], the electrochemical properties of Ru^{II} and Os^{II} complexes of [3_n]cyclophane ($n = 2-4$) showed that [3_4](1,2,4,5)cyclophane (**3**) was the most suitable π ligand for the subunits of the anticipated polymer.[6] As an extension of this work, we designed a synthetic route to ([3_n]cyclophane)lanthanide complexes. The 10π-aromatic cyclooctatetraene (COT) dianion ($C_8H_8^{2-}$) is one of the most important ligands and it is generated by a two-electron reduction of COT. Uranocene, $U(C_8H_8)_2$, is the parent of the (COT)lanthanide complexes and was synthesized by Streitwieser et al. in 1968.[8] Although a large number of transition-metal complexes of cyclophanes, mostly of [2_n]cyclophane, have been synthesized and characterized,[9] very few (cyclophane)lanthanide complexes have been reported. Boekelheide et al. reported the synthesis of the uranium complex of [2_2](1,6)cyclooctatetraenyl(1,4)cyclophane, a compound that is green in color, and confirmed the formation of this species by ^{1}H-NMR spectroscopy.[10]

In our study into the synthesis of COT-phane we found that [3_4](1,2,4,5)cyclophane (**3**) reacted smoothly with dicyanoacetylene (**12**) to give barrelenophane **13**, which was transformed not to the desired COT-phane **19** but to semibullvalenophane **15** upon photoirradiation. We describe here the results of this study as well as an improved synthetic route to **3** and the structural properties of **3**, **13**, and **15**.

Results and Discussion

Synthesis

[3_4](1,2,4,5)Cyclophane (**3**) was first synthesized by us using the TosMIC (**6**) [(*p*-tolylsulfonyl)methyl isocyanide] coupling of 5,7,14,16-tetrakis(bromomethyl)[3.3]metacyclophane (**5b**) followed by Wolf−Kishner reduction of the resultant diketone **8**.[11] However, this route was unsuitable to prepare **3** in large quantities because **5b**, the key precursor

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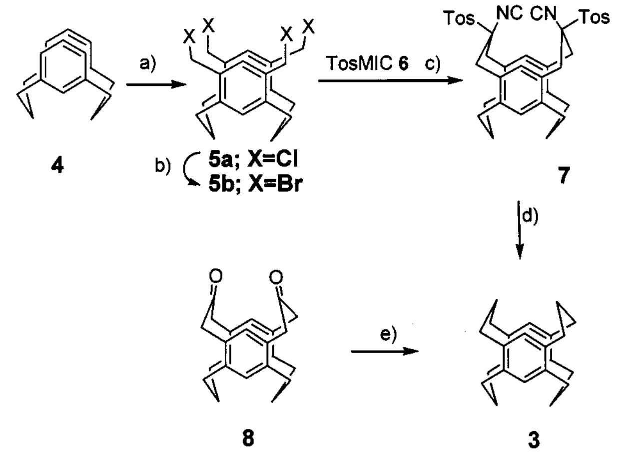


Scheme 1. Synthesis of [3_4](1,2,4,5)cyclophane (**3**); (a) $ClCH_2OCH_3$, $TiCl_4$, CS_2; (b) NaBr, EtBr, DMF; (c) NaH, DMF, room temp.; (d) Li, liq. NH_3, EtOH; (e) NH_2NH_2, $NH_2NH_2 \cdot HCl$, KOH, $(HOCH_2CH_2)_2O$

of **3**, was synthesized by a lengthy 12-step procedure from *meta*-xylene, and the yield of the TosMIC coupling was low.[11] Recently, Vögtle et al. reported an improved synthetic method for **5b** by the simultaneous introduction of four bromomethyl groups into [3.3]metacyclophane (**4**) (ca. 50%).[12] Although this method significantly decreased the number of synthetic steps, the yield was ca. 30% when we repeated this reaction both under similar and modified reaction conditions. As an alternative, we found that the chloromethylation of **4** with $ClCH_2OCH_3$ in the presence of $TiCl_4$ gave the tetrakis(chloromethyl) compound **5a** in high yield (92%). Halogen exchange of the chlorine atoms of **5a** with bromine atoms was effected by heating **5a** with NaBr and ethyl bromide in DMF to give **5b** (86%).[13] In the first synthesis of **3**, the coupling of **5b** with TosMIC (**6**) under conventional phase transfer conditions (NaOH, H_2O/CH_2Cl_2), followed by acid hydrolysis, gave diketone **8** in low yield (24%).[11] Since the major reason for this low yield seemed to be the base-catalyzed hydrolysis of the bromomethyl group of **5b** under the reaction conditions, we decided to employ anhydrous conditions;[14] a mixture of **5b** and TosMIC (**6**) in DMF was added to the suspension of NaH in DMF at room temperature to afford cyclic TosMIC adduct **7** in high yield (74%). The conversion of **7** to **3** was accomplished with Li in liquid NH_3 in the presence of EtOH (85%).[15] Thus, the series of reactions involving chloromethylation, halogen exchange, the TosMIC coupling reaction under anhydrous conditions, followed by reductive cleavage of the cyclic TosMIC adduct **7** constitutes a new practical synthetic route to **3** (Scheme 1).

Structure of [3_4](1,2,4,5)Cyclophane (3)

Both MM3 and AM1 calculations optimized the boat-boat conformation (D_{2h}) as the global minimum among the expected stable conformers (Figure 1)[16], and the D_{2h} structure was further optimized by ab initio MO calculations (RHF/6-31G*)[17]. The optimized geometry (Figure 2) is quite similar to that found in the crystals.

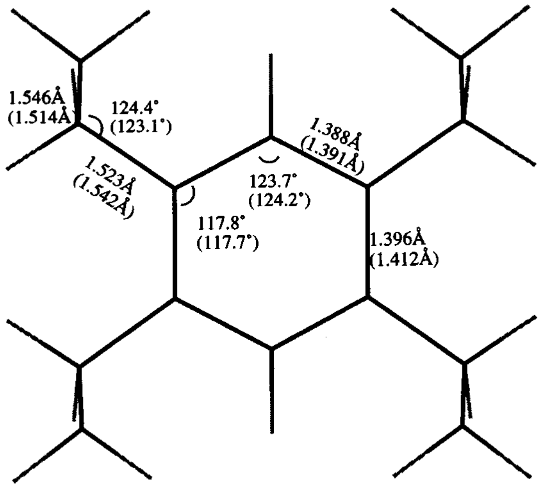


Figure 2. Calculated (X-ray) geometry of **3** at RHF/6-31G* level of theory

Figure 3 shows the ORTEP drawing of **3**, and the crystallographic data are listed in Table 3. Selected bond lengths and interatomic distances, and selected bond angles of **3** are listed in Tables 1 and 2, respectively. There are two crystallographically different molecules in the unit cell, but they have essentially the same geometry. The two molecules are faced in an orthogonal position, and this arrangement is generally observed in the crystal structures of [3_n]cyclophane.[18] In agreement with the theoretical calculations, the molecule assumes the most stable D_{2h} structure. Unlike the bridging bonds of [2_4](1,2,4,5)cyclophane (**9**) (1.591 Å),[19] all the bond lengths and bond angles of **3** are typical values. The geometry of the benzene ring of **3** is bent from planar to a boat-shaped form. The distortion angles as well as the interannular distances of **3**, [2_4](1,2,4,5)cyclophane (**9**),[19] [2.2]-[20] and [3.3]paracyclophanes[21] (**10** and **11**) are illustrated in Figure 4. The interannular distances of the two faced benzene rings of **3** are 3.03 Å for the shortest (b) and 3.20 Å for the longest positions (a), which are similar to corresponding distances in [3.3]paracyclophane (**11**).[21] The distortion angle α of **3** (7.4°) is smaller than that of [2_4]cyclophane **9**. Angle β of **3** (10.1°) is reduced due to the

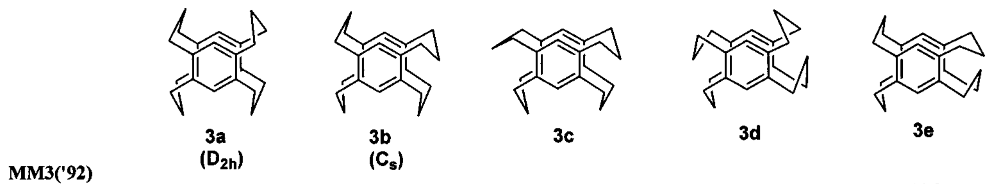


Figure 1. Relative free energies of conformers in **3** by molecular mechanics calculations [MM3('92)]

elongated methylene bridges. Smaller α and β values of **3** suggest higher π-electron-donating ability than the lower homolog **9**, as well as the lower reactivity of the benzene ring toward cycloaddition reactions.

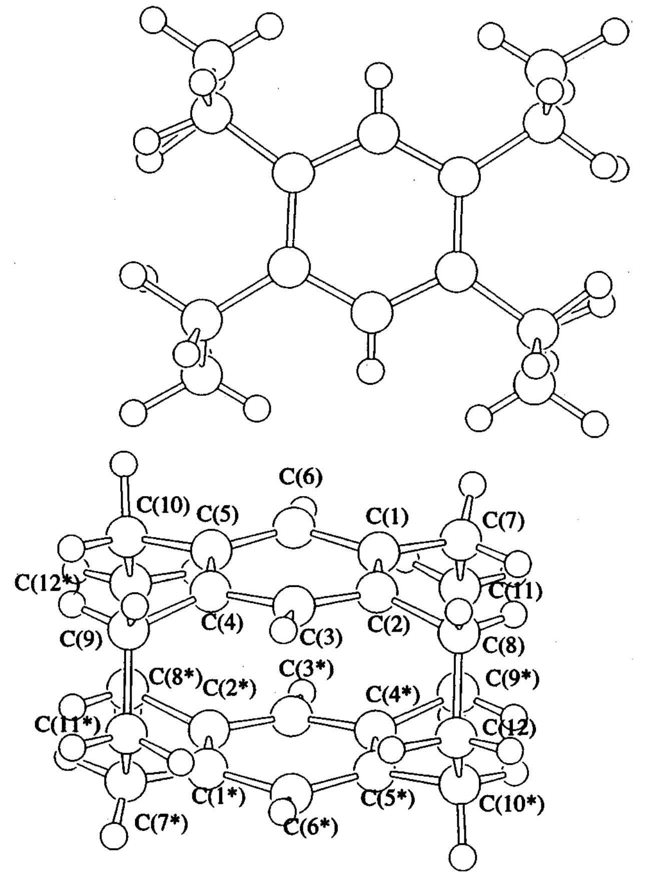


Figure 3. ORTEP drawings of **3**

Diels−Alder Reaction of 3 with Dicyanoacetylene (12)

The benzene rings in $[2_n]$cyclophane are quite reactive since participation of the benzene decks as a diene in the Diels−Alder reaction relieves strain, and the formation of barrelenophanes is a common phenomenon.[22,23a] $[2_4]$(1,2,4,5)Cyclophane (**9**) was reported to give barrelenophane as a 1:1 adduct (93%) on reaction with dicyanoacetylene (**12**) in refluxing $CHCl_3$ for 6 h,[10b] and the bis(adduct) was also formed on prolonged heating. The reaction of $[3_4]$cyclophane **3** with **12** (2.1 equiv.) in refluxing $CHCl_3$ for 6 h afforded barrelenophane **13** (29%) along with recovered **3** (43%), while increasing the reaction temperature by using refluxing toluene and the use of a large excess of **12** (5.1 equiv.) provided **13** in much higher yield (76%) (Scheme 2). The bis(adduct) was not formed under these reaction conditions. It is clear that a significant relief of strain occurs during the addition of the first mol of **12**, but the relief in strain on addition of the second mol of **12** is less marked. The result indicates that the reactivity of **3** in the Diels−Alder reaction is lower than that of the $[2_4]$homolog **9**, mainly because of lower molecular strain in the former in comparison to the latter.

The aromatic and bridgehead proton signals in the ^1H-NMR spectrum of **13** appear as singlets at $\delta = 6.75$ (Hb) and 3.95 (Ha), respectively, and the values are comparable to the corresponding protons of $[2_4]$(1,2,4,5)barrelenophane (**9**) ($\delta = 6.71$ and 3.89).[10b] In the ^{13}C-NMR spectrum, the carbon signals of the cyano groups and the bridgehead carbon atoms appear at $\delta = 114.8$ and 61.8, respectively. The infrared band due to the stretching frequency of the CN group of **13** appears at 2207 cm^{-1}, and this value is lower than the corresponding frequency of **9** (2310 cm^{-1}).[10b] The absorption spectrum of **13** shows maxima at 292 ($\varepsilon = 1609$) and 408 nm ($\varepsilon = 347$) in CH_2Cl_2, and the λ_{max} shows a strong bathochromic shift as compared with the corresponding band of **9** [$(CD_3)_2C(OH)_2$ 370 nm ($\varepsilon = 242$)] and other barrelenophanes (Figure 5).[10b]

Photochemical Conversion of the Barrelenophane 13 to Semibullvalenophane 15

Zimmerman et al. reported the rearrangement of barrelene to semibullvalene (25−40%) and COT (1−2%) by acetone photosensitization.[24a] The direct irradiation of barrelene afforded COT, whereas the sensitized irradiation of barrelene led to semibullvalene. COT was reconverted to semibullvalene at low temperatures by photosensitization.

Table 1. Selected bond lengths [Å] and interatomic distances [Å] of compound **3**

	Molecule A	Molecule B		Molecule A	Molecule B
C(1)−C(2)	1.407(8)	1.418(8)	C(7)−C(11)	1.534(9)	1.542(9)
C(4)−C(5)	1.403(8)	1.421(8)	C(8)−C(12)	1.558(9)	1.532(9)
Mean	1.412		Mean	1.542	
C(2)−C(3)	1.384(8)	1.384(8)	C(7)···C(9′)	2.62(1)	2.617(9)
C(3)−C(4)	1.402(8)	1.383(8)	C(8)···C(10′)	2.61(1)	2.63(1)
C(5)−C(6)	1.382(8)	1.392(8)	Mean	2.62	
C(6)−C(1)	1.413(8)	1.391(9)	C(1)···C(4′)	3.032(7)	3.066(8)
Mean	1.391		C(2)···C(5′)	3.059(8)	3.057(8)
C(1)−C(7)	1.492(8)	1.522(8)	Mean	3.054	
C(2)−C(8)	1.518(9)	1.514(9)	C(3)···C(6′)	3.205(8)	3.238(9)
C(4)−C(9)	1.508(8)	1.514(8)	Mean	3.222	
C(5)−C(10)	1.537(8)	1.510(8)			
Mean	1.514				

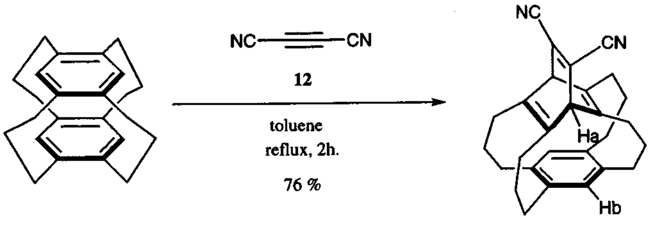
Table 2. Selected bond angles [°] of compound **3**

	Molecule A	Molecule B		Molecule A	Molecule B
C(6)−C(1)−C(2)	116.5(6)	116.5(6)	C(2)−C(1)−C(7)	125.6(6)	123.7(6)
C(1)−C(2)−C(3)	119.5(6)	117.9(6)	C(1)−C(2)−C(8)	123.2(6)	123.3(6)
C(3)−C(4)−C(5)	117.9(6)	117.4(6)	C(5)−C(4)−C(9)	124.9(6)	123.3(6)
C(4)−C(5)−C(6)	118.6(6)	116.9(6)	C(4)−C(5)−C(10)	123.3(6)	123.6(6)
Mean	117.7		Mean	123.9	
C(2)−C(3)−C(4)	122.9(6)	124.9(6)	C(7)−C(11)−C(9′)	116.3(5)	116.7(6)
C(5)−C(6)−C(1)	123.7(6)	125.4(6)	C(8)−C(12)−C(10′)	115.0(6)	116.8(6)
Mean	124.2		Mean	116.2	
C(6)−C(1)−C(7)	117.8(6)	119.6(6)			
C(3)−C(2)−C(8)	116.7(6)	118.5(6)			
C(3)−C(4)−C(9)	116.9(6)	118.9(6)			
C(6)−C(5)−C(10)	117.9(6)	119.4(6)			
Mean	118.2				

	a(Å)	b(Å)	α(deg)	β(deg)
[2_4](1,2,4,5)cyclophane 9[19)]	2.95	2.69	12.2	-
[3_4](1,2,4,5)cyclophane 3	3.20	3.03	7.4	10.1

	a(Å)	b(Å)	α(deg)
[2.2]paracyclophane 10[20)]	3.09	2.78	12.6
[3.3]paracyclophane 11[21)]	3.30	3.14	6.4

Figure 4. Geometries of benzene rings of cyclophanes **3**, **9**, **10**, and **11**



3 **13**

Scheme 2. Diels−Alder reaction of [3_4](1,2,4,5)cyclophane (**3**) with dicyanoacetylene (**12**)

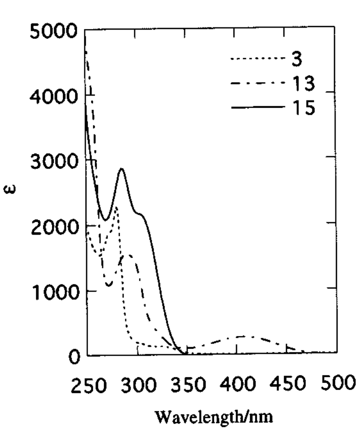
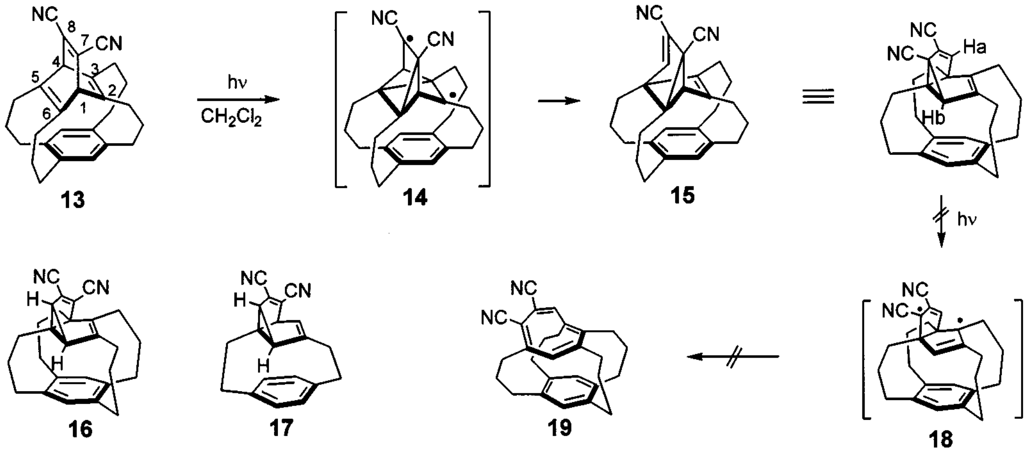


Figure 5. Electronic absorption spectra of [3_4](1,2,4,5)cyclophane (**3**), barrelenophane **13**, and semibullvalenophane **15** in CH_2Cl_2

The mechanism of the conversion of barrelene to semibullvalene and then COT was studied.[24b] Boekelheide et al. reported that the irradiation of a THF solution of [2_4](1,2,4,5)barrelenophane with a medium-pressure Hg lamp provided 13,16-dicyano[2_4](1,2,5,6)cyclooctatetraenyl-(1,2,4,5)cyclophane (71%),[10a] but this primary product was thermally unstable and underwent electrocyclic ring closure to give the bicyclo[4.2.0]octatriene derivative on standing in solution at room temperature. Hopf et al. reported that [2.2]barrelenophane transformed into semibullvalenophane **17** (56%) on irradiation in toluene with a high-pressure Hg lamp for 1 h.[23]

A CH_2Cl_2 solution ($0.4 \cdot 10^{-3}$ mol L^{-1}) of **13** in a Pyrex apparatus was irradiated with a 400-W high-pressure Hg lamp for 45 min at room temperature. The initial yellow solution was colorless after irradiation. This reaction proceeded quantitatively to give semibullvalenophane **15** as pale yellow crystals, but no COT-phane **19** was detected (Scheme 3).

The ^{1}H-NMR spectrum shows two signals due to aromatic protons at δ = 6.98 (s, 1 H) and 7.00 (s, 1 H), a signal of an olefinic proton Ha at δ = 5.73 (s, 1 H), one of a methyne proton Hb at δ = 3.26 (s, 1 H), and signals of the trimethylene bridge protons at δ = 3.13−1.72 (m, 24 H). In the ^{13}C-NMR spectrum, the cyano group carbon signals appear at δ = 114.3 and 117.0, and the sp^3-carbon signals of the semibullvalene skeleton appear at δ = 45.2, 57.0, 64.1, and 72.6. The infrared bands show the stretching frequencies of the CN groups at 2220 and 2230 cm^{-1}. The UV absorption bands appear at 286 (ε = 3550) and 305 nm (ε = 2920) in CH_2Cl_2 (Figure 5), and λ_{max} showed a blue shift as compared with that of **17** [343 nm (ε = 4070) in CH_3CN].[24] Since the possibility of an alternative structure **16**, which was found in **17** by Hopf et al.,[23] could not be



Scheme 3. Photochemical conversion of barrelenophane **13** to semibullvalenophane **15**

ruled out based on the spectroscopic data, the structure was finally confirmed by an X-ray structural analysis. The formation of **15** is ascribed to the 3,5- and 6,7-bonding in barrelene **13**, followed by 3,4-bond fission of an intermediate **14**[24b] (Scheme 3). The semibullvalene skeleton of **17** has the Cope-rearranged structure of that of **15**. No Cope rearrangement was observed in **15** up to 150°C in [D_6]DMSO.

In contrast to the case of [2_4](1,2,4,5)barrelenophane,[10a] the irradiation of a THF solution of **13** resulted in the formation of the semibullvalenophane **15**. Paquette et al. reported that semibullvalene was converted to COT by flash vacuum pyrolysis,[25a] and this method was successfully applied to the synthesis of [*n*](1,5)cyclooctatetraenophanes (n = 5, 6, 8, 10)[25b] and doubly decked [8]annulene from bridged semibullvalenes and bis(semibullvalene),[25c] respectively. Flash vacuum pyrolysis of **15** in a quartz tube at 530°C for a few minutes, however, gave the [3_4]cyclophane **3** (70%) along with dicyanoacetylene (**12**). This retro Diels−Alder reaction may occur via the once generated barrelenophanes **13**.

X-ray Structural Analyses of Barrelenophane 13 and Semibullvalenophane 15

The structures of **13** and **15** were finally confirmed by X-ray structural analyses. These X-ray structures are the first examples of four-bridged cyclophanes. In the ORTEP drawings and packing diagram of barrelenophane **13** (Figures 6−8), four trimethylene bridges assume the boat-boat conformation, as was observed in the parent [3_4]cyclophane **3**. A similar boat-shaped deformation of the benzene ring was also found and the distortion angle α is 7.33° [C(1)−C(2)−C(4)−C(5) and C(1)−C(6)−C(5)] and 6.35° [C(1)−C(2)−C(4)−C(5) and C(2)−C(3)−C(4)]. The nonbonding distances between the decks in **13** are 3.81−3.84 Å for the bridgehead carbon atoms [C(12)−C(6), C(9)−C(3)] and 3.10−3.12 Å for the other aromatic carbon atoms [C(7)−C(1), C(8)−C(2), C(10)−C(4), C(11)−C(5)]. The bridgehead angles of the barrelene skeleton C(7)−C(12)−C(11) and C(7)−C(12)−C(13) are 111.7° and 104.1°, respectively. These values are very similar to formally sp^3-hybridized angles and suggest the low strain and rigid structure of **13**. The angles at the formally sp^2-hybridized atoms C(7), C(8), C(10), and C(11) are also ideal.

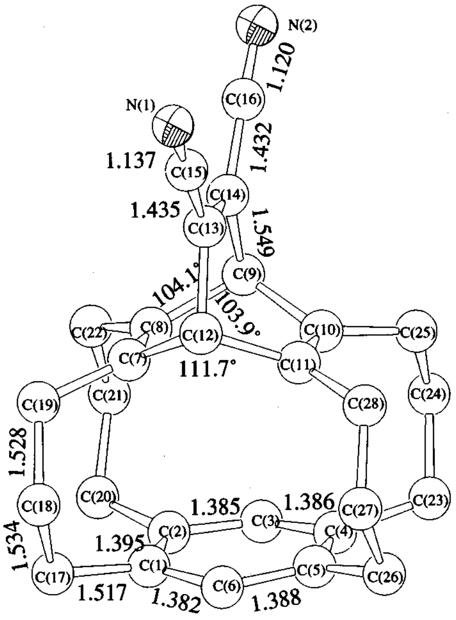


Figure 6. ORTEP drawing (side view) of **13** with bond angles and bond lengths [Å]

Figures 9 and 10 show the ORTEP drawing and packing diagram of the semibullvalenophane **15**. Hopf et al. reported the crystal structure of [2.2]semibullvalenophane **17**,[23] but they could not discuss the structure quantitatively because of a disorder problem. Our study confirmed the structure of the semibullvalenophane to be **15** rather than **16**, which was expected from the result by Hopf et al. The benzene ring of **15** is slightly deformed into the boat form and the distortion angle α is 9.89° [C(1)−C(2)−C(4)−C(5) and C(1)−C(6)−C(5)] and 5.83° [C(1)−C(2)−C(4)−C(5) and C(2)−C(3)−C(4)]. The bond lengths and angles of the semibullvalene moiety of **15** are

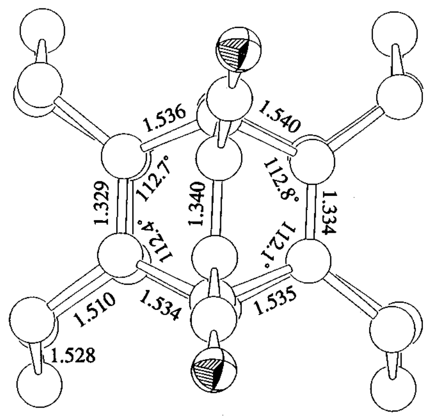


Figure 7. ORTEP drawing (top view) of **13** with bond angles and bond lengths [Å]

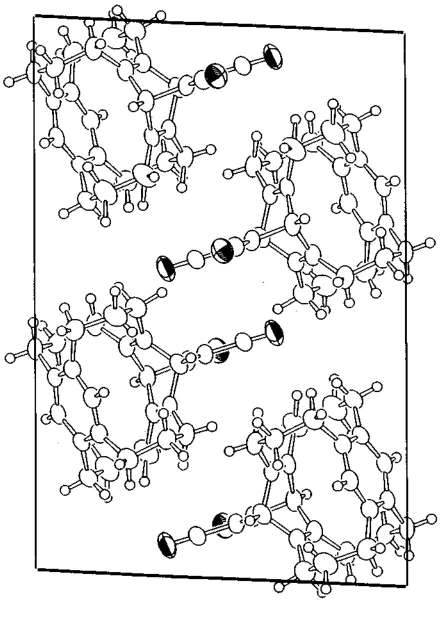


Figure 8. Packing diagram of **13**

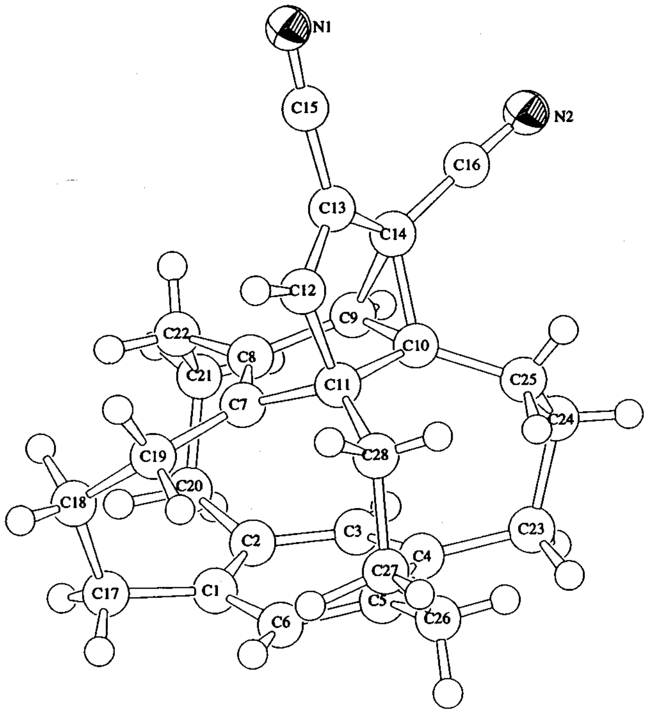


Figure 9. ORTEP drawing of **15**

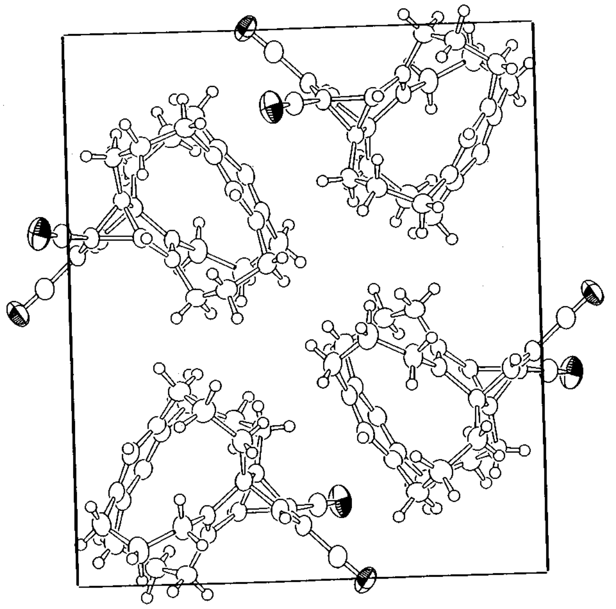


Figure 10. Packing diagram of **15**

shown in Figure 11. The cyclopropane ring is significantly distorted from a regular triangle. The angle C(10)−C(9)−C(14) is normal (59.9°), whereas that of C(10)−C(14)−C(9) is significantly narrowed (56.0°) and, corresponding to this, the angle C(9)−C(10)−C(14) spreads out to 64.1°. Corresponding to the deformation of the angles, the bond length C(9)−C(14) of the cyclopropane moiety is unusually long (1.601 Å), whereas the C(9)−C(10) bond becomes significantly shorter (1.475 Å). Similar abnormal bond lengths are also observed in C(10)−C(11) (1.575 Å) and C(8)−C(9) (1.481 Å) of the semibullvalene moiety.

Conclusion

An improved synthetic route to **3** provides gram quantities of this compound in fewer steps than the conventional route. The cycloaddition reaction of **3** with dicyanoacetylene (**12**) gave barrelenophane **13**, which was then transformed into semibullvalenophane **15** on photoirradiation. Neither photoirradiation nor flash vacuum pyrolysis of **15** afforded COT-phane **19**. This is in sharp contrast to the reactivity of [2_4]barrelenophane.[10] Although we cannot fully explain the different photochemical reactivity of [3_4]- and [2_4]barrelenophanes at this stage, it is clear that the former compound favors the formation of the semibullvalene skeleton, whereas the latter favors the COT skeleton under similar reaction conditions. The unique structures of the barrelenophane **13** and semibullvalenophane **15** were re-

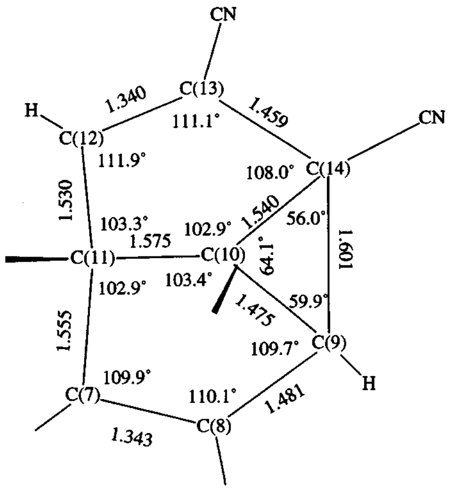


Figure 11. Selected bond lengths [Å] and bond angles [°] of **15**

vealed by X-ray structural analyses. The synthetic study of COT-phanes with a [3.3]cyclophane structure is in progress.

Experimental Section

General: Melting points: Yanaco micro melting point apparatus MP-S3. – NMR: JEOL JNM-EX 270 (270 MHz and 68 MHz for ^{1}H and ^{13}C, respectively). For ^{1}H and ^{13}C NMR, $CDCl_3$ as solvent unless otherwise stated, TMS as internal standard. – FABMS: JEOL JMS-SX/SX 102A (*m*-nitrobenzyl alcohol). – UV/Vis: Hitachi U-3500. – IR: Hitachi Nicolet I-5040 FT-IR. – Elemental analysis: the Service Center of the Elementary Analysis of Organic Compounds affiliated with the Faculty of Science, Kyushu University. – Analytical thin layer chromatography (TLC) and column chromatography were performed on silica gel 60 F_{254} (Merck) and silica gel 60 (Merck, 40–63 μm or 60–200 μm), respectively. DMF was dried using molecular sieves 4 Å. Dicyanoacetylene (**12**) was prepared according to the literature procedures.[26]

X-ray Crystallographic Study: All measurements were made with a Rigaku AFC7R diffractometer with graphite-monochromated Mo-K_α (**3**, **13**) or Cu-K_α radiation (**15**) and a rotating anode generator. The crystal structure was solved by direct methods [SHELXS86[27] (**3**, **13**), SAPI91[28] (**15**)] and refined by full-matrix least-squares methods. The non-hydrogen atoms were refined anisotropically, and hydrogen atoms isotopically. All the computations were performed using the teXsan package.[29] Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-102847 (**3**), -102834 (**13**), and -102835 (**15**). Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [Fax: int. code + 44-1223/336-033; E-mail: deposit@ccdc.cam.ac.uk].

[3.3]Metacyclophane (4): Coupling between 1,3-bis(bromomethyl)benzene and 1,3-bis[2-isocyano-2-(tolylsulfonyl)ethyl]benzene is described here since this procedure provides [3.3]metacyclophane-2,11-dione in much higher yield than the reported coupling between 1,3-bis(bromomethyl)benzene and TosMIC itself.[30a] To a stirred mixture of nBu$_4$NI (5.0 g, 13.5 mmol), NaOH (40 g), water (120 mL), and CH_2Cl_2 (1.5 L), was added a mixture of 1,3-bis(bromomethyl)benzene (7.18 g, 27.2 mmol) and 1,3-bis[2-isocyano-2-(tolylsulfonyl)ethyl]benzene (13.4 g, 27.2 mmol) in CH_2Cl_2 (1 L) over a period of 5 h. The mixture was refluxed for an additional 3 h. After cooling, it was washed with water (3 × 1 L), and the organic phase was concentrated to a volume of ca. 300 mL. The same reaction and workup procedure were repeated three times on the same scale. To the combined concentrates was added concentrated HCl (100 mL) and the mixture was stirred for 1 h at room temperature. The organic layer was washed with water, dried with $MgSO_4$, filtered, and the filtrate was concentrated to dryness. The residue was diluted with MeOH, the resultant crystals were collected by filtration, washed with MeOH, and dried in vacuo to give [3.3]metacyclophane-2,11-dione (7.82 g, 55%) as colorless crystals.[30a] A mixture of the ketone (10.0 g, 37.9 mmol), hydrazine hydrate (100%, 45 mL), KOH (30 g), and diethylene glycol (200 mL) was heated at 130°C for 3 h and then at 200°C for an additional 3 h with stirring. The cooled reaction mixture was poured into dilute HCl (800 mL) and extracted with CH_2Cl_2 (900 mL). The combined extracts were passed through a short SiO_2 column and the eluate was concentrated to dryness in vacuo to give **4** as colorless crystals (8.37 g, 93%).[30a]

5,7,14,16-Tetrakis(chloromethyl)[3.3]metacyclophane (5a):[11][12] To a stirred mixture of [3.3]metacyclophane (**4**) (0.50 g, 2.12 mmol), $ClCH_2OCH_3$ (3.83 mL, 50.4 mmol), and CS_2 (100 mL), was added $TiCl_4$ (5.60 mL, 51.1 mmol) over a period of 10 min at 0°C. The mixture was allowed to warm up to room temperature and stirred overnight. The reaction mixture was poured into ice/water and extracted with CH_2Cl_2. The combined extracts were washed successively with water and brine, dried with $MgSO_4$, filtered, and the filtrate was concentrated to dryness in vacuo. The residue was recrystallized from CH_2Cl_2/hexane (1:10) to give tetrachloride **5a** (0.84 g, 92%) as pale yellow prisms, m.p. 120–123°C. – ^{1}H NMR: δ = 2.20–2.94 (m, 12 H, $-CH_2CH_2CH_2-$), 4.46 (s, 8 H, $-CH_2Cl$), 6.97 (s, 2 H, Ar), 7.06 (s, 2 H, Ar). – EIMS (70 eV); *m/z:* 428 [M$^+$]. – $C_{22}H_{24}Cl_4$ (428.1): calcd. C 61.42, H 5.62; found C 61.81, H 5.87.

5,7,14,16-Tetrakis(bromomethyl)[3.3]metacyclophane (5b):[12] A mixture of tetrachloride **5a** (0.70 g, 1.63 mmol), DMF (4.8 mL), EtBr (42.5 mL, 285 mmol), and NaBr (0.67 g) was heated for 5 d. The mixture was concentrated, the residue was added to concentrated HCl (50 mL), and the organic material was extracted with CH_2Cl_2. The combined extracts were washed successively with water and brine. After removal of the solvent, the residue was recrystallized from CH_2Cl_2/hexane (1:3) to give tetrabromide **5b** as a white powder (0.94 g, 86%). The spectroscopic and physical properties of this compound were in complete agreement with those of an authentic sample.[11]

[3$_4$](1,2,4,5)Cyclophane (3): To a stirred suspension of NaH (60%, 660 mg, 16.5 mmol, washed with hexane) in DMF (300 mL) was added dropwise a mixture of tetrabromide **5b** (1.49 g, 2.45 mmol) and TosMIC (**6**) (2.10 g, 10.9 mmol) in DMF (300 mL) over a period of 8 h at room temperature. After completion of the addition, the mixture was stirred overnight. The DMF was removed under reduced pressure and water was added to the residue. The mixture was extracted with CH_2Cl_2, the combined extracts were washed with brine, concentrated, and the resultant crystals were collected by filtration to give 2,11-diisocyano-2,11-bis(4-tolylsulfonyl)[3$_4$](1,2,4,5)cyclophane (**7**) as white solid (1.22 g, 74%). – ^{1}H NMR: δ = 2.48 (s, 6 H, $ArCH_3$), 3.10 (d, J = 15.5 Hz, 4 H, $ArCH_2-$), 4.08 (d, J = 14.9 Hz, 4 H, $ArCH_2-$), 7.01 (s, 2 H, ArH), 7.43 (d, J = 8.3 Hz, 4 H, ArH), 7.43 (s, 2 H, ArH), 8.02 (d, J = 8.3 Hz, 4 H, ArH). – To freshly distilled liquid NH_3 (ca. 30 mL) was added Li (300 mg, 43 mmol) in one portion. To the mixture were added the cyclic TosMIC adduct **7** (531 mg, 0.79 mmol) in

Table 3. Summary of crystallographic data and refinement details

Compound	**3**	**13**	**15**
Empirical formula	$C_{24}H_{28}$	$C_{28}H_{28}N_2$	$C_{28}H_{28}N_2$
Crystal color, habit	colorless, plate	yellow, prismatic	colorless, prismatic
Solvent	benzene	chloroform	ethyl acetate
Crystal size [mm]	0.40 × 0.50 × 0.40	0.20 × 0.20 × 0.20	0.40 × 0.60 × 0.50
Crystal system	triclinic	monoclinic	monoclinic
Space group	$P-1$ (no. 2)	$P2_1/c$ (no. 14)	$P2_1/c$ (no. 14)
Temperature [°C]	23 ± 1	23 ± 1	20 ± 1
a [Å]	8.894(4)	13.080(2)	8.094(3)
b [Å]	12.276(3)	8.049(2)	17.176(3)
c [Å]	7.877(2)	19.525(2)	14.983(3)
α [°]	91.44(2)	90	90
β [°]	95.33(3)	93.07(1)	102.68(2)
γ [°]	74.42(2)	90	90
V [Å^3]	824.9(4)	2052.6(6)	2032.0(9)
Z	2	4	4
$D_{\text{calcd.}}$ [g cm^{-3}]	1.274	1.270	1.283
F(000)	344.00	840	840
μ [cm^{-1}]	0.71 (Mo)	0.74 (Mo)	5.68 (Cu)
$2\theta_{\max}$ [°]	55.1 (Mo)	55.0 (Mo)	120.3 (Cu)
No. of reflections:			
measured	4072	5267	3401
independent	3784	5051	3154
R_{int}	0.078	0.047	0.080
No. of observations [$I > 3.00\sigma(I)$]	1188	1598	2620
No. of parameters	330	272	440
Reflection/Parameter ratio	3.60	5.87	5.95
R	0.053	0.058	0.053
R_w	0.034	0.049	0.051
S	2.08	1.87	4.56
Max. Δ/σ	0.13	3.86	0.00
Max. $\Delta\rho$ [e$^-$ nm^{-3}]	0.20	0.35	0.27

Et_2O (15 mL) and EtOH (230 mg, 5.0 mmol). The mixture was stirred below −40°C for 2 h and then the liquid NH_3 was allowed to evaporate. The residue was added portionwise to water and the mixture was acidified with concentrated HCl. The mixture was extracted with CH_2Cl_2, the combined CH_2Cl_2 extracts were washed with water, dried with $MgSO_4$, filtered, and removal of the solvent afforded a white solid (210 mg, 85%). All spectroscopic and physical properties were in complete agreement with an authentic sample.[11] The crystals for X-ray crystallography were grown by slow evaporation from benzene solution to give colorless plates.

[3$_4$](1,2,4,5)Barrelenophanedicarbonitrile (13): A mixture of **3** (40.5 mg, 0.13 mmol), dicyanoacetylene (**12**) (50.0 mg, 0.66 mmol), and toluene (5 mL) was refluxed for 2 h. The mixture was concentrated and the residue was chromatographed on silica gel with $CHCl_3$ to give barrelenophane **13** (38.7 mg, 76%) as yellow needles ($CHCl_3$), m.p. 250°C (decomp.). − IR (KBr) $\tilde{\nu}$ = 2207 (−CN) cm^{-1}. − ^1H NMR: δ = 2.85−1.87 (m, 24 H, $-CH_2CH_2CH_2-$), 3.95 (s, 2 H, −CH−), 6.75 (s, 2 H, ArH). − ^{13}C NMR: δ = 28.2, 30.6, 32.1, 61.8, 114.8 (−CN), 129.4, 137.7, 139.2, 139.7. − UV/Vis (CH_2Cl_2): $\lambda_{\max}$ = 292 nm (ε = 1609), 408 (ε = 347). − FAB HRMS: $C_{28}H_{28}N_2$; *m/z*: calcd. 392.2252; found 392.2251. − The crystals for X-ray crystallography were grown by slow evaporation from $CHCl_3$ solution to give yellow crystals.

[3$_4$](1,2,4,5)Semibullvalenocyclophanedicarbonitrile (15): A solution of **13** (132.8 mg, 0.34 mmol) in dry CH_2Cl_2 (850 mL) was irradiated using a high-pressure Hg lamp (400 W) through a Pyrex filter under argon for 45 min at room temperature. The solution was concentrated and the concentrate was recrystallized from CH_2Cl_2/MeOH to give **15** as pale yellow crystals (66.4 mg, 50%), m.p. > 300°C. − IR (KBr) $\tilde{\nu}$ = 2230 and 2220 (−CN) cm^{-1}. − ^1H NMR: δ = 1.72−3.13 (m, 24 H, $-CH_2CH_2CH_2-$), 3.26 (s, 1 H, −CH−C=), 5.73 (s, 1 H, −CH=C−), 6.98 (s, 1 H, ArH), 7.00 (s, 1 H, ArH). − ^{13}C NMR (68 MHz): δ = 23.9, 24.5, 26.1, 26.8, 27.6, 28.5, 28.7, 29.5, 29.8, 45.2, 57.0, 64.1, 72.6, 97.3, 114.3 (−CN), 117.0 (−CN), 127.3, 130.5, 132.5, 135.7, 136.2, 137.3, 138.2, 139.2, 153.1. − UV (CH_2Cl_2): $\lambda_{\max}$ = 286 nm (ε = 3545), 305 (ε = 2915). − FABMS; *m/z*: 393 [M$^+$]. − $C_{28}H_{28}N_2 \cdot 0.5\,H_2O$ (401.2): calcd. C 83.75 H 7.28, N 6.98; found C 84.03, H 7.04, N 7.06. − The crystals for X-ray crystallography were grown by slow evaporation from AcOEt solution to give colorless crystals.

Pyrolysis of Compound 13: In a nitrogen-purged quartz tube, barrelenophane **13** was pyrolized at 530°C under vacuum for a few minutes. The product in the quartz tube was dissolved in CH_2Cl_2, the solution was concentrated, and the residue was chromatographed on silica gel with toluene to give [3$_4$]cyclophane **3** (70%).

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