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Layered Compounds. XLII.[1] Syntheses and Properties of Layered Paracycloheterophanes

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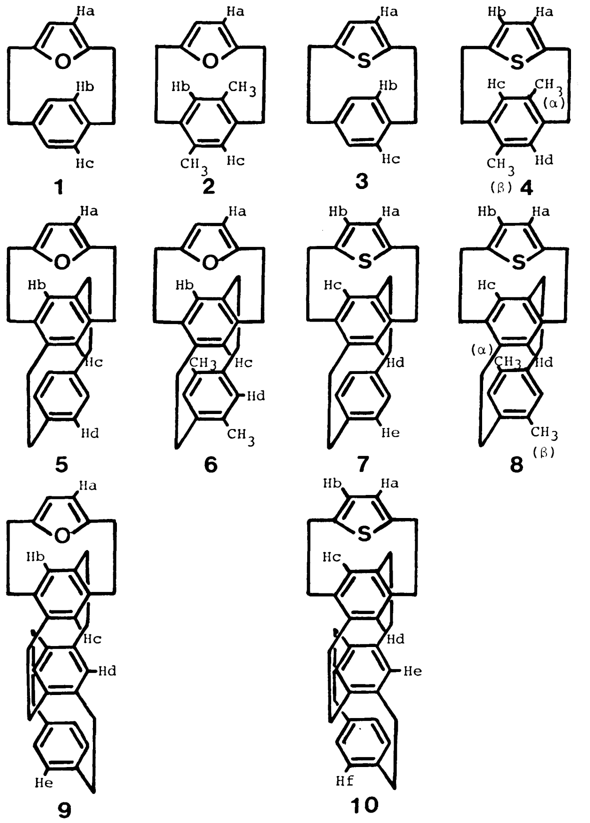
A series of multilayered paracyclofuranophanes and paracyclothiophenophanes were synthesized by cross-breeding Hofmann elimination method from mixed quaternary ammonium hydroxides. Their structures and conformations were elucidated by NMR analyses. In electronic spectra, paracyclothiophenophanes exhibited stronger transannular electronic interactions than paracyclofuranophanes whose absorption curves show unexpected resemblance to those of multilayered metaparacyclophanes. Paracyclofuranophanes and [2.2](2,5)furanophane underwent addition reaction with benzyne to give 1 : 1 and 1 : 2 adducts, respectively. Their structures and properties were also studied by spectral measurements.

In recent years, multilayered compounds in which three or more aromatic rings are mutually stratified have been extensively investigated from a viewpoint of transannular π-electronic interaction.[2—4] It has become apparent that such electronic interactions among aromatic rings and the internal strain due to face-to-face benzene ring compression are mainly responsible for a number of anomalous physical and chemical properties of layered compounds, and the interaction increases with an increase of layer number. These results have prompted us to study multilayered cyclophanes containing heteroaromatic ring such as furan and thiophene, **1**—**10**, which might demonstrate much information on the transannular electronic interaction between benzene and heteroaromatic rings and on their chemical properties.



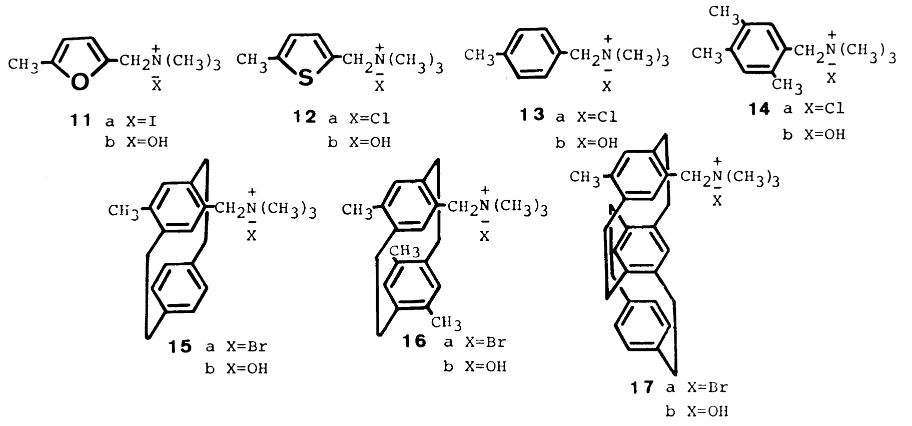
Scheme 1.

Results and Discussion

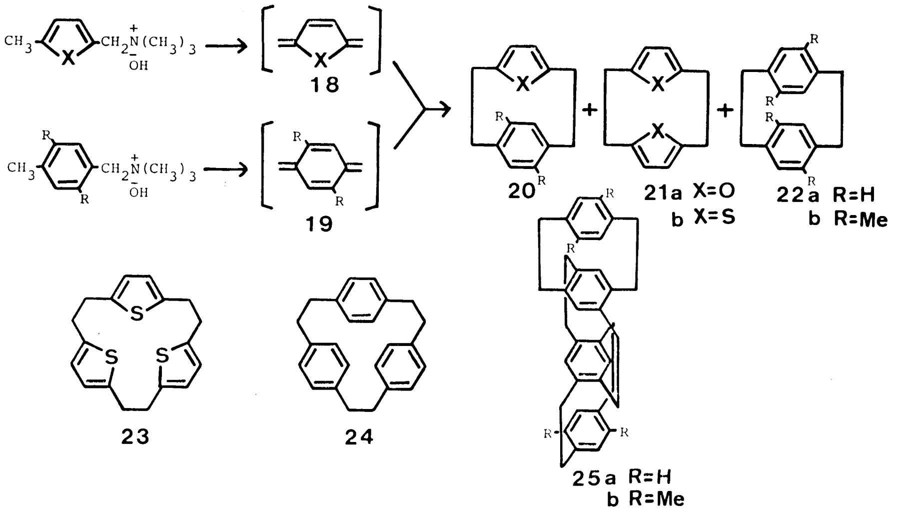
Syntheses. Although a number of synthetic methods have been recently developed for [2.2]cyclophane,[5] 1,6-Hofmann elimination method presented by Winberg *et al.*[6] is still very convenient and advantageous for the synthesis of multilayered [2.2]paracyclophane because of facile availability of the intermediary compounds.[2,3] In the present work we applied the same method for the syntheses of all paracycloheterophanes **1**—**10**. The syntheses of intermediates, quaternary ammonium salts **11**—**17**, were carried out in the same way as described in literatures.[2,3,6]

Cram and his coworkers first found out the formation of [2.2]paracyclo(2,5)furanophane **1** by the cross-breeding Hofmann degradation of 5-methylfurfuryltrimethylammonium hydroxide **11b** and *p*-methylbenzyltrimethylammonium hydroxide **13b**.[7] Similarly, we prepared [2.2]paracycloheterophanes **2**—**4** by cross-breeding reaction of the corresponding two quaternary ammonium hydroxides. A cross-breeding reaction generally produces a mixture of three main cyclophanes. For example, two intermediates, **18** and **19**, generated from pyrolysis of the corresponding quaternary ammonium hydroxides give cyclophane **20** from a cross coupling and cyclophanes **21**[6] and **22**[2,3,6] from homo-coupling. Besides them, [2.2.2](2,5)thiophenophane **23** was formed from **12** and [2.2.2]paracyclophane **24**[2] from **13** as minor products. Triple- and quadruple-layered paracycloheterophanes **5**—**10** were also synthesized by the same cross-breeding method using the corresponding multilayered quaternary ammonium salts **15**—**17**. In these cases, multilayered [2.2]paracyclophanes such as **25**[2,3] were formed as one of homo-coupling products.

The yields of cross coupling products are fairly low as compared with those of homo-coupling products and decrease with an increasing number of layers because multilayered cyclophanes and layered quinodimethane intermediates are relatively unstable. In the syntheses of layered paracyclophanes, a cross coupling product was easily separated from homo-coupling products by careful column chromatography on silica gel or alumina. However, some paracycloheterophanes were found to be very difficult to purify by means of conventional chromatography. This difficulty could be overcome by

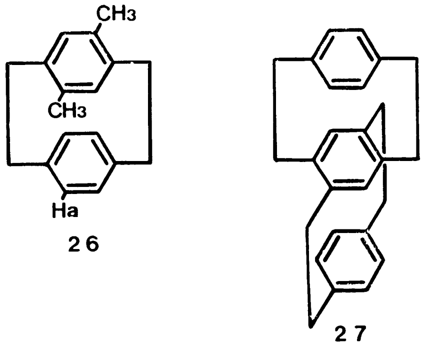


Scheme 2.



Scheme 3.

use of silica gel coated with silver nitrate, which adsorbed heteroaromatic nucleus more strongly. In addition, use of preparative gel permeation liquid chromatography was found to be advantageous.



Scheme 4.

Structures and NMR Spectra. The NMR specrtal data of multilayered [2.2]paracycloheterophanes are summarized in Table 1. The most remarkable feature is that the chemical shifts of all the aromatic protons appear at high field as in the case of multilayered [2.2]-paracyclophanes.[8] There has been observed a certain regularity for upfield shifts of the aromatic protons, since each benzene ring is stacked in parallel at regular intervals (mean value 3.06 Å).[9] The upfield shifts of the present paracycloheterophanes are relatively small and rather irregular. This suggests that heteroaromatic rings are not stacked in the same mode as that of benzene rings. Table 1 also shows that two thiophene protons of the paracyclothiophenophanes appear nonequivalently except for **3**. In the case of 4,7-dimethyl-[2.2]paracyclophane **26**, the aromatic protons Ha at pseudo-gem position to methyl group were observed to shift considerably downfield due to the steric compression effect.[8] Similarly the nonequivalence of the thiophene protons is interpreted to arise from a downfield shift of one of the protons, which is sterically compressed by pseudo-*gem* methyl or methylene group. The steric compression effect (—0.32 ppm) of methyl group in **4** is almost same as that (—0.36 ppm) in **26**. The steric compression effect of bridged methylene is generally not observed in a series of paracyclophanes as indicated by equivalence of outer aromatic protons in **25a** or **27**.[8] The appearance of such effect on thiophene proton indicates that the proton is very close to pseudo-*gem* methylene group owing to the bulkiness of sulfur atom. On the other hand, furan series shows no steric compression effect. Thus the NMR signal

Table 1. NMR data of layered paracycloheterophanes in carbon tetrachloride (δ value)

Compound		ArH	(Fixed)[a]	CH_2	CH_3
1	Ha	5.52 (s, 2H)	5.49 (s, 2H)	2.9—2.35 (A_2B_2, 8H)	
	Hb	6.68 (s, 4H)	6.12 (d, 2H)		
	Hc		7.07 (d, 2H)		
2	Ha	5.51 (s, 2H)	5.62 (s, 2H)	3.2—2.3 (m, 8H)	2.11 (s, 6H)
	Hb	6.37 (s, 2H)	6.11 (s, 1H)		
	Hc		6.99 (s, 1H)		
3	Ha	6.12 (s, 2H)		3.4—2.6 (m, 8H)	
	Hb	6.08 (d, 2H)			
	Hc	6.98 (d, 2H)			
4	Ha	6.40 (ABd, 3.8 Hz, 1H)		3.5—2.7 (m, 8H)	1.77 (s, 3H)[b]
	Hb	6.08 (ABd, 3.8 Hz, 1H)			2.48 (s, 3H)[c]
	Hc	5.68 (s, 1H)			
	Hd	6.54 (s, 1H)			
5	Ha	5.29 (s, 2H)	5.22 (s, 2H)	3.4—2.2 (m, 16H)	
	Hb	5.75 (s, 2H)	5.18 (s, 1H)		
	Hc		6.17 (s, 1H)		
	Hd	6.15 (s, 4H)	6.13 (s, 4H)		
6	Ha	5.30 (s, 2H)	5.37 (s, 2H)	3.4—2.2 (m, 16H)	1.99 (s, 6H)
	Hb	6.18 (s, 2H)	5.72 (s, 1H)		
	Hc		6.70 (s, 1H)		
	Hd	5.78 (s, 2H)	5.89 (s, 2H)		
7	Ha, Hb	5.97 (ABq, 2.5 Hz, 2H)		3.4—2.2 (m, 16H)	
	Hc	5.03 (s, 1H)			
	Hd	6.00 (s, 1H)			
	He	6.16 (s, 4H)			
8	Ha	6.06 (ABd, 2.5 Hz, 1H)		3.5—2.2 (m, 16H)	1.87 (s, 3H)[b]
	Hb	5.97 (ABd, 2.5 Hz, 1H)			1.98 (s, 3H)[c]
	Hc	5.41 (s, 1H)			
	Hd	6.38 (s, 1H)			
	He	5.77 (s, 2H)			
9	Ha	5.21 (s, 2H)	5.15 (s, 2H)	3.3—2.0 (m, 24H)	
	Hb	5.50 (s, 2H)	4.96 (s, 1H)		
	Hc		5.84 (s, 1H)		
	Hd	5.26 (s, 2H)	5.20 (s, 2H)		
	He	6.06 (s, 4H)	5.99 (s, 4H)		
10	Ha, Hb	5.87 (ABq, 3 Hz, 2H)		3.4—2.1 (m, 24H)	
	Hc	4.80 (s, 1H)			
	Hd	5.74 (s, 1H)			
	He	5.19 (s, 2H)			
	Hf	6.02 (s, 4H)			
21a		5.90 (s, 4H)		2.65 (bs, 8H)	
21b		6.72 (s, 4H)		3.5—2.7 (A_2B_2, 8H)	
23		6.44 (s, 6H)		2.99 (s, 12H)	

a) **1**, **5**, and **9** in CS_2; **2** in $CDCl_3$; **6** in 2 : 1 $CDCl_3$-CS_2. b) α-CH_3. c) β-CH_3.

of the furan protons remains to be a singlet even at low temperature which may give rise to fixation of the furan ring. It seems reasonable to assume that the stacking modes of furan and thiophene rings are quite different from each other. In order to elucidate these structural problems, X-ray crystallographic analyses of triple-layered paracycloheterophanes **5** and **8** were very recently carried out by Kasai and his coworkers (Figs. 1 and 2).[10] Thus the furan ring is stacked at some angle on the faced benzene ring just like [2.2]metaparacyclophane.[11] The geometry is consistent with the spectral behavior described above. On the other hand, the thiophene ring is stacked in parallel on the faced benzene ring like [2.2]paracyclophane,[12] but it is slidden in such a way that the thiophene proton comes close to pseudo-*gem* methylene group as predicted by NMR analysis.

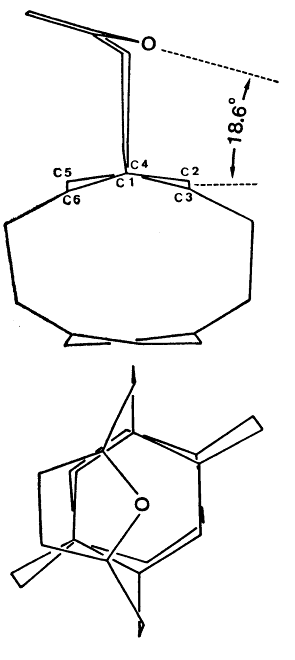


Fig. 1. Profile of triple-layered paracyclofuranophane **5**. Intramolecular non-bonded distances (Å); O···C1, 2.860; O···C2, 2.927; O···C3, 3.054; O···C4, 2.820; O···C5, 3.011; O···C6, 3.173.

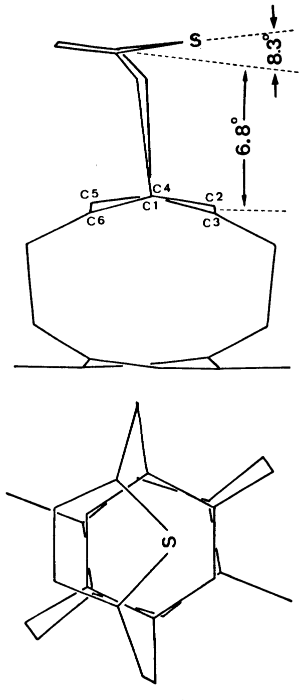


Fig. 2. Profile of dimethyl triple-layered paracyclothiophenophane **8**. Intramolecular non-bonded distances (Å); S···C1, 3.121; S···C2, 3.049; S···C3, 3.197; S···C4, 3.122; S···C5, 3.436; S···C6, 3.597.

The structural difference between furanophane and thiophenophane is mainly due to larger bulkiness of sulfur atom relative to oxygen atom.

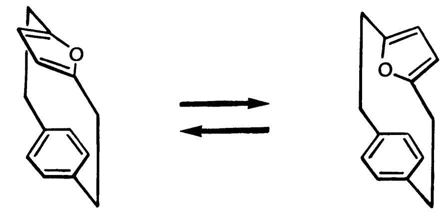
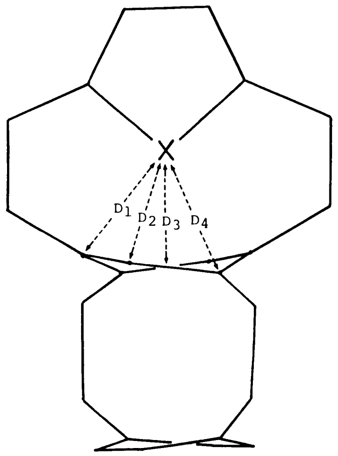


Fig. 3. Ring inversion of [2.2]paracyclofuranophane **1**.



	D1	D2	D3	D4
X=O	2.91Å	3.01	3.14	3.28
X=S	2.44	2.61	2.63	2.88

Fig. 4. Non-bonded distances between heteroatom and faced benzene in the transition state of the interconversion process.

Another striking feature in NMR data is that aromatic protons of benzene ring faced to heteroaromatic ring appear to be nonequivalent in thiophene series and to be equivalent in furan series. These phenomena can be explained to arise from the fixation of thiophene ring in the former series and the rapid interconversion of furan ring in the latter series as shown in Fig. 3.[13] We studied the dynamic behavior of a series of paracyclofuranophanes by variable temperature NMR spectroscopy. When the temperature is lowered, coalescence occurs and the aromatic protons of the faced benzene ring become nonequivalent (Table 1). Activation energy ΔG^{*} for the interconversion process was calculated by peak separation method according to Gutowsky and Holm[14] (Table 2). The flipping in triple- and quadruple-layered paracyclofuranophanes is appreciably easier than that in double-layered one. This can be explained in terms of the geometry of the faced benzene ring. Molecular model of **1** shows that the benzene ring is deformed into a boat shape like [2.2]paracyclophane.[12] On the other hand, as indicated by X-ray analysis of **5**, the inside benzene ring of multilayered cyclophane is deformed into a twist form which is caused by pulling up and down with two pairs of methylene bridges. Such structural changes of the faced benzene ring are considered to lower the steric barrier for the flipping of the furan ring.

The thiophene ring of paracyclothiophenophanes was, at the beginning, expected to flip at high temperature. However, they showed no change in their NMR spectra up to 150 °C but appreciable decomposition above this temperature. For understanding of the conformational behavior of furan and thiophene, it is advisable to in-

TABLE 2. ACTIVATION ENERGY ΔG_c (kcal/mol), RATE CONSTANT K_c (s^{-1}), LIFE TIME τ_c (s), COALESCENCE TEMPERATURE T_c (°C), AND PEAK SEPARATION $\Delta\nu$ (Hz) OF FACED BENZENE PROTONS FOR THE INVERSION PROCESS OF PARACYCLOFURANOPHANES

Compound	**1**	**2**	**5**	**6**	**9**
ΔG_c	11.4	11.9	10.4	10.2	10.2
K_c	1.26×10^2	1.17×10^2	1.22×10^2	1.28×10^2	1.17×10^2
τ_c	3.97×10^{-3}	4.25×10^{-3}	4.10×10^{-3}	3.91×10^{-3}	4.26×10^{-3}
T_c	−39	−29	−58	−62	−63
$\Delta\nu$	53.1	53.1	57.0	57.7	52.9

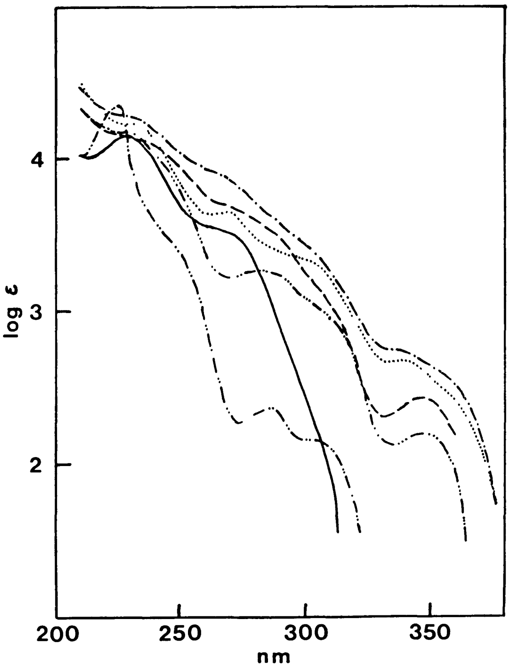


Fig. 5. Electronic spectra of multilayered paracyclothiophenophane **3** (——), **7**(----), and **10** (—·—), together with multilayered paracyclophanes **22a** (—··—), **27** (—···—), and **25a** (······) in cyclohexane.

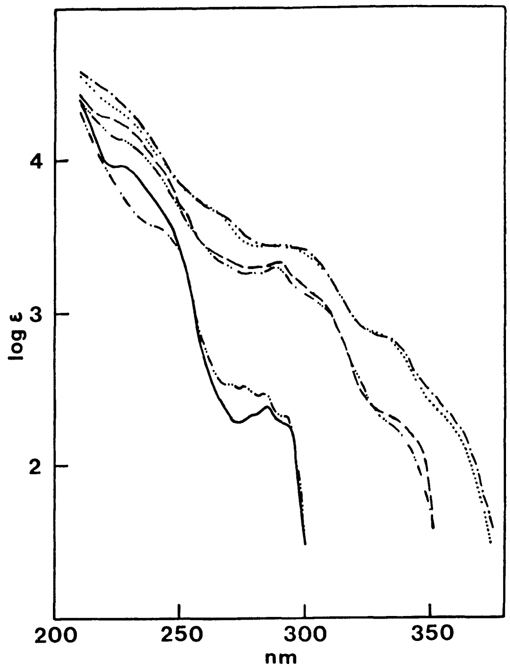
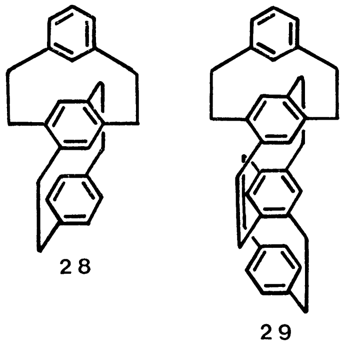


Fig. 6. Electronic spectra of multilayered paracyclofuranophanes **1** (——), **5** (----), and **9** (—·—), together with [2.2]metaparacyclophane (—··—), **28** (—···—), and **29** (······) in cyclohexane.

quire the non-bonded distances between heteroatom and faced benzene in the transition state where heteroaromatic ring is perpendicular to benzene ring. A minute calculation was performed on a computer using X-ray data of **5** and **8** as shown in Fig. 4.[10] The non-bonded distances for paracyclofuranophane are comparable to van der Waals distance (3.10 Å) of oxygen and benzene, supporting that the ring flipping is feasible according to temperature condition. On the other hand, the non-bonded distances for paracyclothiophenophane are much smaller than van der Waals distance (3.55 Å) of sulfur and benzene. The resulting large steric barrier inhibits the flipping process of thiophene ring.

Electronic Spectra. It is well-known that the transannular electronic interaction between two chromophores which are closely fixed with each other affects strongly the electronic spectra.[15] Multilayered [2.2]-paracyclophanes exhibited strong bathochromic and hyperchromic effects in their spectra with an increasing number of the layers, which were theoretically explained by both exciton and charge-transfer interactions.[16] As shown in Figs. 5 and 6, the present multilayered paracycloheterophanes show an analogous tendency, and the characteristic absorptions of the heteroaromatic rings disappear successively as the number of layer increases. The bathochromic shifts of the thiophene series are more significant than those of the furan series, indicating that thiophene interacts more strongly with benzene than furan. Incidentally, the absorption curves of the former show unexpected resemblance to those of multilayered paracyclophanes **25a** and **27** (Fig. 5) and the spectra of the latter to those of the corresponding multilayered metaparacyclophanes **28** and **29** (Fig. 6).[17] These spectral properties seem to be partly attributable to the stacking modes of paracyclothiophenophane similar to multilayered paracyclophane and paracyclofuranophane to multilayered metaparacyclophane. The transannular electronic interactions are also observed in the cases of [2.2](2,5)thiophenophane **21b**, [2.2.2](2,5)thiophenophane **23**, and [2.2](2,5)furanophane **21a** (Fig. 7). Thiophene or furan itself has no absorption in the ultraviolet region above 230 nm.[18] These cyclophanes clearly show bathochromic shifts or


28

29

Scheme 5.

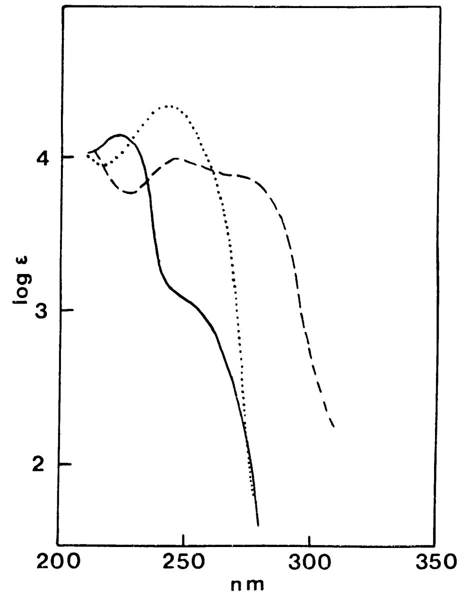


Fig. 7. Electronic spectra of heterophanes **21a** (——), **21b** (----), and **23** (······) in cyclohexane.

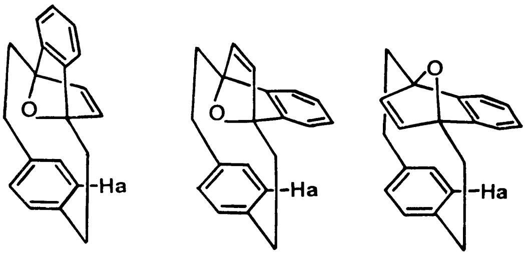
appearance of new peaks in the longer wavelength. The stronger effect in **21b** relative to that in **21a** suggests that d-orbitals of sulfur atom plays significant role in the interaction.

TCNE Complexes. The transannular electronic interaction in cyclophane system is usually reflected in the increase of the π-basicity, in other words, the interaction brings a strong donor character to that system.[2,3,19] The absorption maxima of charge-transfer complexes of the present paracycloheterophanes and tetracyanoethylene (TCNE) are summarized in Table 3. As the number of layers increases, the absorption maxima shift to longer wavelength as seen in the case of multilayered [2.2]paracyclophane.[2,3] Although furan and thiophene have lower ionization potentials (9.00 and 9.10 eV, respectively) than benzene (9.52 eV), the CT bands of multilayered paracycloheterophanes with more than three layers appear at rather shorter wavelength than those of paracyclophane analogues. Evidently the electronic interaction between heteroaromatic and benzene rings is less effective than that between benzene rings. Table 3 also shows that thiophene series has stronger interaction than furan series.

Table 3. Absorption maxima of TCNE complexes (nm) in CH_2Cl_2

2,5-Dimethylfuran	574
2,5-Dimethylthiophene	416, 556
p-Xylene	460
Durene	480
Furanophanes	
1	563
2	563
5	584
6	622
9	570
21a	588
Thiophenophanes	
3	538
4	572
7	626
8	644
10	655
21b	545

Addition Reaction with Benzyne. Layered cyclophanes offer many example of unusual addition reactions.[20] In particular, furanophanes have shown to undergo Diels-Alder reactions to give polycyclic compounds bearing unique skelton.[7,21] However, the present paracyclofuranophanes did not react with ordinary dienophiles such as maleic anhydride, dimethyl acetylenedicarboxylate, and tetracyanoethylene. When benzyne was used as a dienophile, paracyclofuranophanes **1** and **5** gave 1 : 1 adduct respectively. Three types of conformations are possible for these adducts, *e.g.*, **30**, **31**, and **32** from **1**. In the structures **31** and **32**, the NMR signals of Ha protons would shift significantly to high field due to magnetic anisortropy of the fused benzene ring. The NMR spectra of the adducts are consistent with the structures **30** and **33** (Fig. 8). Moreover, examination with molecular model indicates that the structures **31** and **32** are sterically unfavorable because there are considerable repulsion between the fused benzo group and faced benzene rings.



30 31 32

Scheme 6.

As shown in Fig. 9, the electronic spectra of these adducts exhibit unexpected large bathochromic and hyperchromic shifts. The CT bands of their TCNE complexes also appear at longer wavelength than predicted; **30**, $\lambda_{\max}$ 505 and 570(sh) nm; **33**, $\lambda_{\max}$ 530(sh)

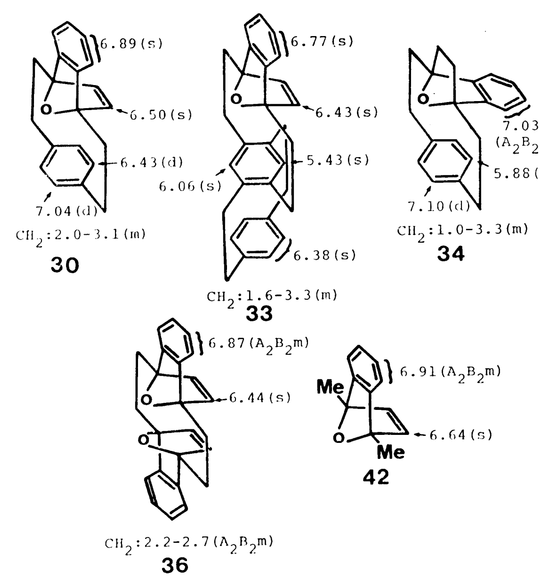


Fig. 8. NMR data of benzyne adducts (δ value in deuteriochloroform).

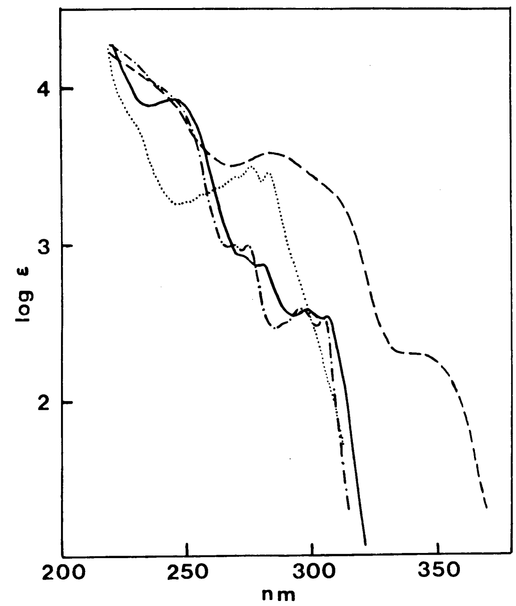
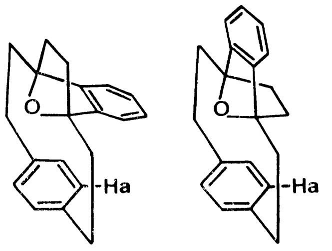


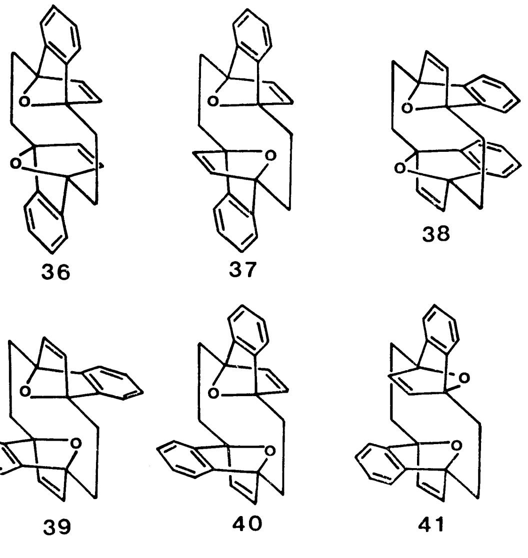
Fig. 9. Electronic spectra of benzyne adducts **30** (——), **33** (----), **34** (—·—), and **36** (······) in tetrahydrofuran.

and 634 nm in dichloromethane. These data apparently indicate the presence of strong transannular electronic interaction in the adducts. A direct interaction between the two benzene rings does not seem to take place. Therefore, either olefinic group or oxygen atom is predicted to take part in the electronic interaction. In order to obtain further evidence, the olefinic group of **30** was saturated by catalytic reduction using Pd–C. Surprisingly, the hydrogenation gave dihydro compound **34** accompanied by an inversion of the conformation instead of **35** with retention. The structure of **34** is assigned by its NMR spectrum. Thus the Ha proton drastically shifts to high field compared to Ha proton of **30**, which is due to magnetic anisotropy of the fused benzo group. Probably, the conformational change arises from an increasing steric hindrance of ethano group with Ha proton in **35**, as compared to that of fused benzo group with Ha proton in **34**. The electronic spectrum of **34** is similar to that of adduct **30** (Fig. 9) and the absorption maxima of its TCNE complex, 490 and 570 nm in CH_2Cl_2, are almost same as those of **30**. These facts suggest that there is no essential difference between the electronic interactions in **30** and **34**, and thereby oxygen atom makes considerable contribution to the interaction in both adducts **30** and **33**.



Scheme 7.

Battiste and Kapicak[22] reported that [2.2](2,5)furanophane **21a** underwent a Diels-Alder reaction with benzyne to give non-internally cyclized 1 : 1 adduct and 1 : 2 adduct, and that an *anti* structure for the latter bis-adduct would be favored over others on the basis on *anti* structure of **21a** and steric requirement of benzyne approaching. We have carried out the same addition reaction of **21a** with benzyne generated from anthranilic acid and obtained 1 : 2 adduct in 16% yield. Of six possible conformations **36**—**41** for the adduct other than sterically unfavorable structures with outmost oxygen like **32**, the structure **36** is most favorable from NMR data (Fig. 8) which show 0.2 ppm upfield shift for olefinic proton and invariable shift for aromatic proton as compared with a reference compound **42**.[23] The other structures are therefore in conflict with the NMR data. Thus, the structures **40** and **41** would not give any symmetrical NMR pattern. The olefinic proton of **37** would be expected to shift rather to downfield by a deshielding effect of closely placed



Scheme 8.

oxygen atom. In **38** or **39**, one would predict the olefinic signal to be identical to that of **42** and the aromatic signal to be different from that of **42**. The electronic spectrum of the adduct and the CT spectrum of its TCNE complex ($\lambda_{\max}$, 410 and 544 nm in CH_2Cl_2) exhibit unusual transannular electronic interaction as in the case of **30** and **33**.

Experimental

Melting points are uncorrected. All solvents are of reagent grade. NMR spectra were taken with a Hitachi Perkin-Elmer R-20 spectrometer (60 MHz) using tetramethylsilane as an internal standard. MS and UV spectra were measured with a Hitachi RMU-7 spectrometer (70 eV) and a Hitachi EPS-3T spectrophotometer, respectively. A general procedure of Hofmann elimination reaction was described in detail in the experimental part of 4,7-dimethyl[2.2]paracyclo(2,5)furanophane **2**. Chromatography was usually done with silica gel (Merck, activity II—III) of 20 to 100 times of a mixture to be separated. Silica gel coated with silver nitrate was made as follows: silica gel (100 g) was shaken sufficiently with silver nitrate (20 g) in 100 ml of distilled water, and then water was removed using a rotary evaporator. The residual silica gel coated with silver nitrate was activated on standing overnight in an oven at 110 °C and used with care to avoid exposure to light.

4,7-Dimethyl[2.2]paracyclo(2,5)furanophane **2**. 5-Methylfurfuryltrimethylammonium iodide **11a**[6] (15 g, 53 mmol) and duryltrimethylammonium chloride **14a**[3] (10 g, 44 mmol) were dissolved in 500 ml of distilled water and passed through ion exchange column packed with Dowex 1-X8 ion exchange resin which was previously converted to hydroxide form. The eluted aqueous solution of **11b** and **14b** was mixed with xylene (50 ml) and phenothiazine (50 mg). The mixture was heated with stirring in a nitrogen atmosphere, and water was removed by azeotropic distillation using a Dean-Stark type of water separator. After removal of water, reflux was continued for additional 10 h. Insoluble polymer was filtered off and washed with xylene. The filtrate and washing were combined, dried over anhyd magnesium sulfate, and evaporated. The residue was chromatographed on silica gel using petroleum ether as an eluent. There was eluted first a mixture of 4,7-dimethyl[2.2]paracyclo(2,5)furanophane **2** and 4,7,12,15-tetramethyl[2.2]paracyclophane **22b**,[2,3] and then [2.2](2,5)furanophane **21a**[6] (0.6 g). The mixture was rechromatographed on silica gel coated with silver nitrate. Elution with 1 : 1 petroleum ether–ether gave first **2** (884 mg, 9%) and then **22b** (674 mg). Recrystallization of **2** from petroleum ether afforded colorless plates, mp 63.0—64.5 °C.

MS *m/e* 226 (M^+). Found: C, 85.02; H, 8.08%. Calcd for $C_{16}H_{18}O$: C, 84.91; H, 8.01%.

[2.2]Paracyclo(2,5)thiophenophane **3**. In the same way as **2**, the cross-breeding reaction of the quaternary hydroxides derived from 5-methylthenyltrimethylammonium chloride **12a**[6] (4 g, 19 mmol) and *p*-methylbenzyltrimethylammonium chloride **13a** (9.6 g, 48 mmol) gave a mixture of the desired cyclophane **3**, [2.2]paracyclohpane **22a**, [2.2](2,5)thiophenophane **21b**, [2.2.2](2,5)thiophenophane **23**, and [2.2.2]paracyclophane **24**. After usual column chromatography on silica gel and then on silica gel coated with silver nitrate, preparative gel permeation liquid chromatography gave pure **3** (92 mg, 2.3%), colorless prisms from 1 : 1 hexane–benzene, mp 230—231 °C (sealed tube).

MS *m/e* 214 (M^+). Found: C, 78.67; H, 6.36%. Calcd for $C_{14}H_{14}S$: C, 78.48; H, 6.59%.

4,7-Dimethyl[2.2]paracyclo(2,5)thiophenophane **4**. The cross-breeding reaction of the quaternary hydroxides derived from 5-methylthenyltrimethylammonium chloride **12a** (3.0 g, 14.6 mmol) and duryltrimethylammonium chloride **14a** (2.7 g, 11.9 mmol) gave a mixture of **4**, **21b**, and **22b**. The desired cyclophane **4** was separated as in the case of **2**, 50 mg (1.7%), colorless plates from petroleum ether, mp 125.0—126.0 °C.

MS *m/e* 242 (M^+). Found: C, 79.62; H, 7.62; S, 13.06%. Calcd for $C_{16}H_{18}S$: C, 79.29; H, 7.48; S, 13.23%.

Triple-layered Paracyclofuranophane **5**. The cross-breeding reaction of two quaternary ammonium hydroxides (derived from **11a**, 9.4 g, 33.4 mmol and **15a**, 5.0 g, 13.4 mmol) gave a mixture of **5**, **21a**, and quadruple-layered paracyclophane **25a**. The desired cyclophane **5** was separated by column chromatography on silica gel ,300 mg (6.8%), colorless plates from hexane, mp 117.0—118.0 °C.

MS *m/e* 328 (M^+). Found: C, 87.60; H, 7.16%. Calcd for $C_{24}H_{24}O$: C, 87.76; H, 7.36%.

Dimethyl Triple-layered Paracyclofuranophane **6**. In this case, anion exchange process was carried out by use of silver oxide instead of ion exchange resin. Thus, two quaternary ammonium salts **11a** (0.7 g, 2.5 mmol) and **16a** (1.0 g, 2.5 mmol) were stirred with two equivalents of fresh silver oxide in 30 ml of distilled water for a few hours. After filtration, the aqueous solution was pyrolyzed in the same way as **2**. Column chromatography of the products on silica gel using 1 : 9 benzene–hexane for elution gave first tetramethyl quadruple-layered paracyclophane **25b**, then [2.2](2,5)furanophane **21a** and finally the desired cyclophane **6** (20 mg, 2.2%), colorless prisms from petroleum ether, mp 127.0—128.0 °C.

MS *m/e* 356 (M^+). Found: C, 87.72; H, 7.87%. Calcd for $C_{26}H_{28}O$: C, 87.60; H, 7.91%.

Triple-layered Paracyclothiophenophane **7** *and [2.2.2](2,5)-Thiophenophane* **23**. The cross-breeding reaction of the quaternary hydroxides derived from two ammonium salts **12a** (7 g, 34 mmol) and **15a** (5 g, 13 mmol) and the subsequent column chromatography on silica gel with 1 : 9 benzene–hexane gave first **21b**, and then a mixture of **7** and quadruple-layered paracyclohpane **25a**. From final fraction [2.2.2](2,5)-thiophenophane was obtained as colorless crystals (348 mg, 3.1%), mp 124 °C.

MS *m/e* 330 (M^+). Found: C, 65.45; H, 5.49%. Calcd for $C_{18}H_{18}S_3$: C, 65.44; H, 5.45%.

The desired cyclophane **7** was purified by column chromatography on silica gel coated with silver nitrate, 22 mg (0.5%), colorless prisms from 1 : 3 carbon tetrachloride–acetone, mp 177 °C with dec.

MS *m/e* 344 (M^+). Found: C, 83.50; H, 6.88%. Calcd for $C_{24}H_{24}S$: C, 83.69; H, 7.02%.

Dimethyl Triple-layered Paracyclothiophenophane **8**. As usual, the desired cyclophane **8** was obtained from the cross-breeding reaction of two quaternary ammonium hydroxides (from **12a**, 4 g, 19 mmol and **16a**, 4.6 g, 11 mmol), followed by column chromatography on silica gel and then on silica gel coated with silver nitrate, yield 33 mg (0.8%), colorless plates from petroleum ether, mp 149—151.5 °C with dec.

MS *m/e* 372 (M^+). Found: C, 83.96; H, 7.73%. Calcd for $C_{26}H_{28}S$: C, 83.83; H, 7.58%.

Quadrulpe-layered Paracyclofuranophane **9**. The usual cross-breeding reaction of two quaternary ammonium hydroxides (derived from **11a**, 3.03 g, 10.8 mmol and **17a**, 3.00 g, 6.0 mmol) followed by chromatogrphy on silica gel with 1 : 9 benzene–hexane gave the desired cyclohpane **9** (56 mg, 2%), colorless plates from 1 : 3 carbon tetrachloride–acetone, mp 176—178 °C.

MS *m/e* 458 (M$^+$). Found: C, 88.94; H, 7.27%. Calcd for $C_{34}H_{34}O$: H, 89.04; H, 7.47%.

Quadruple-layered Paracyclothiophenophane ***10***. The cross-breeding reaction of two quaternary ammonium hydroxides (derived from **12a**, 3.5 g, 17 mmol and **17a**, 3.0 g, 6 mmol) and subsequent purification by column chromatography on silica gel with 1 : 9 benzene–hexane gave the cyclophane **10** (40 mg, 1.4%), colorless prisms from 1 : 3 carbon tetrachloride-acetone, dec 195 °C.

MS *m/e* 474 (M$^+$). Found: C, 85.30; H, 6.99%. Calcd for $C_{34}H_{34}S$: C, 86.04; H, 7.22%.[24]

Addition Reaction of [2.2]Paracyclo(2,5)furanophane ***1*** *with Benzyne.* Anthranilic acid (525 mg, 3.83 mmol) in 25 ml of 1,2-dimethoxyethane and isopentyl nitrite (672 mg, 5.74 mmol) in 25 ml of 1,2-dimethoxyethane were added dropwise and simultaneouly with stirring for one hour into a refluxed solution of **1** (253 mg, 1.28 mmol) in 25 ml of 1,2-dimethoxyethane. After the addition, reflux was continued for additional 30 min. Sodium hydroxide solution (1.7 M, 300 ml) was added in the cooled mixture, and the mixture was extracted with benzene. The extract was washed with water, dried over anhyd sodium sulfate, and evaporated *in vacuo*. The residue was taken up in carbon tetrachloride and subjected to column chromatography on silica gel or alumina to give the adduct **30** (85 mg, 24%), colorless plates from hexane, mp 84.5—85.5 °C.

MS *m/e* 274 (M$^+$). Found: C, 87.56; H, 6.43%. Calcd for $C_{20}H_{18}O$: C, 87.56; H, 6.61%.

Addition Reaction of Triple-layered Paracyclofuranophane ***5*** *with Benzyne.* In the same way as **30**, the adduct **33** was obtained from the benzyne reaction of **5** (235 mg, 0.72 mmol), yield 230 mg (79%), colorless columns from toluene, mp 245—252 °C with dec.

MS *m/e* 404 (M$^+$). Found: C, 89.13; H, 6.84%. Calcd for $C_{30}H_{28}O$: C, 89.07; H, 6.98%.

Addition Reaction of [2.2](2,5)Furanophane ***21a*** *with Benzyne.* [2.2](2,5)Furanophane **21a** (501 mg, 2.66 mmol) was allowed to react with anthranilic acid (1.09 g, 8.0 mmol) and isopentyl nitrite (1.61 ml, 12 mmol) in the same way as **30**. The usual purification of the crude product gave 1 : 2 adduct **36** (142 mg, 16%), colorless plates from toluene, dec 220 °C.

MS *m/e* 340 (M$^+$). Found: C, 84.85; H, 5.81%. Calcd for $C_{24}H_{20}O_2$: C, 84.68; H, 5.92%.

Hydrogenation of Adduct ***30***. The adduct **30** (85 mg, 0.31 mmol) was hydrogenated in the presence of a 5% Pd–C in 20 ml of tetrahydrofuran until hydrogen absorption was ceased. The mixture was filtered and the filtrate was condensed. Column chromatography of the residue on alumina gave dihydro compound **34** (58 mg, 68%), colorless plates from hexane, mp 95—96 °C.

MS *m/e* 276 (M$^+$). Found: C, 87.21; H, 6.97%. Calcd for $C_{20}H_{20}O$: C, 86.92; H, 7.26%.

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