

Dianions from Cyclophanes with Unsaturated Bridges; Cyclic Conjugation in 22—38 π -Electron Perimeter Systems*

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A series of new cyclophanes with unsaturated bridges, formally containing π -systems with 18—48 π -electrons was synthesized. Several of these cyclophanes containing $4n$ perimeters can be reversibly reduced to their dianions with $4n+2$ perimeters. This reversible two-electron process can conveniently be studied by cyclic voltammetry. The electrochemical data reveal a chemically significant difference between the neutral $4n$ and $4n+2$ systems even for large n . A good correlation between calculated energies of the LUMO orbitals and the reversible reduction potentials has been obtained. Recent theories of resonance energies in neutral molecules and dianions with conjugated perimeters have been tested. The question whether resonance energies or more simply the frontier orbitals should be used to rationalize the behavior of the cyclophanes and their dianions is discussed.

Molecules with large cyclic π -systems have fascinated both synthetic organic and theoretical chemists for a long time. The classical examples of such molecules are the annulenes¹ and the bridged annulenes^{2,3} which by now have been extensively studied. The annulenes can be made more stable by incorporation of aromatic rings but usually this also quenches the properties of interest as annulene derivatives e. g. their ability to sustain ring currents in magnetic fields.^{4,5} This is generally true for benzene rings, regardless of whether they are bonded at the *ortho* or *para* positions, and holds also for thiophene and, to a lesser extent, furan rings. There are thus many examples of compounds which, somewhat discouragingly, lack any interesting annulene character due to the presence of local aromatic rings in larger conjugated systems. A thorough investigation of large cyclophanes has also been hampered by the relatively complex synthetic routes to larger cyclophanes with unsaturated bridges. However, such compounds can now be readily prepared by multiple Wittig reactions, and we have recently developed an efficient synthetic route.⁶

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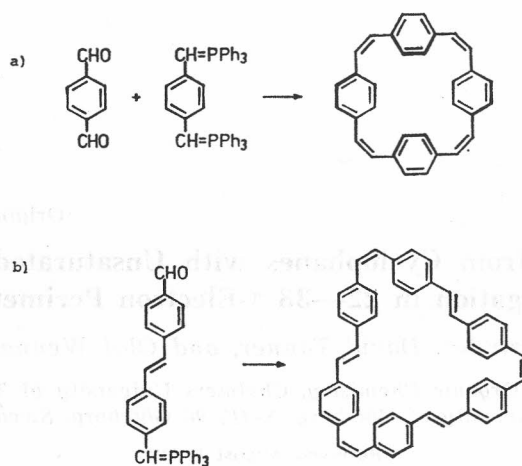


Figure 1. Two types of multiple Wittig reactions which give cyclophanes; ^a a dialdehyde is reacted with a bisphosphonium salt and base, ^b a monoaldehyde-monoylid undergoes self-condensation.

In Figure 1 two major types of Wittig reactions are shown which give cyclic products. The first one occurs between a dialdehyde and a bisphosphonium salt in the presence of base, schematically represented by a bisylid, to give a cyclophane containing an equal multiple of the two components. The second type of reaction occurs between molecules of monoaldehyde-monoylids to give cyclophanes with any number, even or odd, of the aromatic building block. Usually the smallest unstrained ring is the major isolable product from these types of Wittig reactions. The reaction conditions have been optimised to give the best possible yield of *cis* double bonds.⁶ Note the strict alternation of *cis* and *trans* configuration at the double bonds in the [2₆]paracyclophane-hexane in Scheme 1.

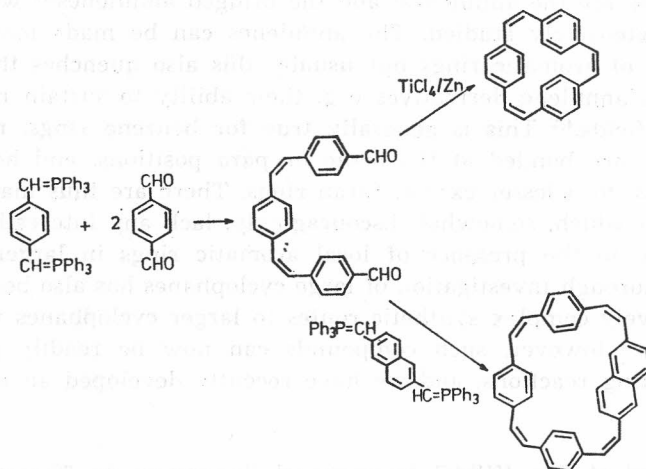


Figure 2. Synthesis of cyclophanes via an intermediate dialdehyde.

By a variation of the procedure, including a reductive coupling of the intermediate aldehyde, a variety of cyclophanes can be prepared. Two examples are shown in Figure 2. The combination of multiple Wittig reactions and McMurry reactions will certainly prove to be a powerful method for the synthesis of new cyclophanes.

Most of the cyclophanes which we have prepared behave as normal aromatic compounds and show little, if any, effect of the cyclic conjugation and the formal resemblance to higher annulenes. However, in this respect, one property is a distinct exception. Some of the cyclophanes can be reduced reversibly to their dianions, a process which is most conveniently studied by cyclic voltammetry.⁷ Moreover, the reduction is in most cases a completely reversible two-electron process which is quite unique for aromatic hydrocarbons.

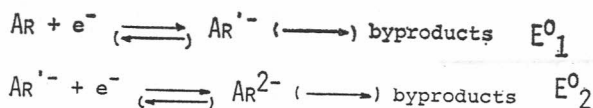


Figure 3. Two step reduction of an aromatic compound to the anion radical and the dianion.

As a rule, the reduction of the radical anion requires a more negative potential than the reduction of the neutral compound due to interelectronic repulsion (Figure 3).⁸ However, this is not the case for a number of cyclophanes with unsaturated bridges, some of which are shown in Figure 4.

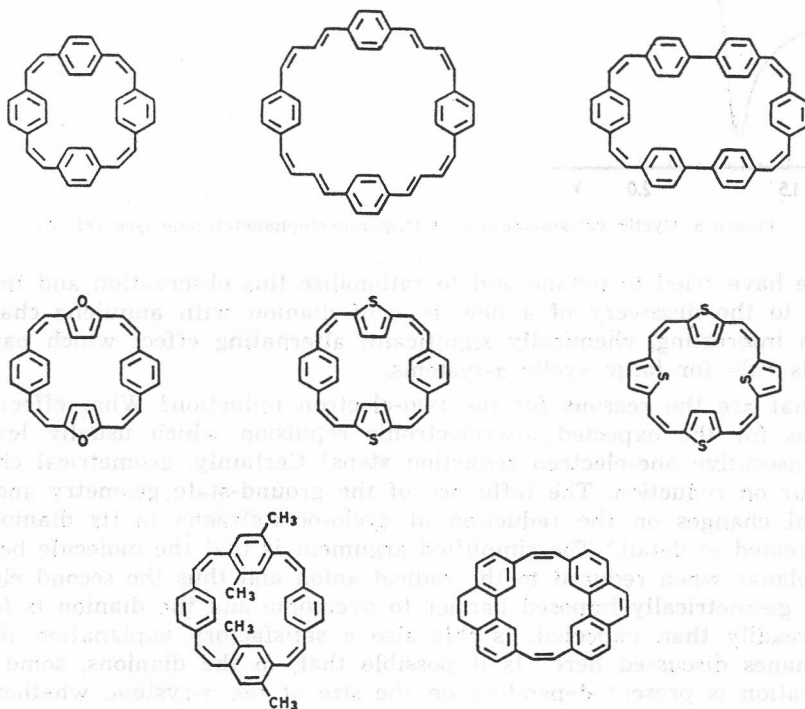


Figure 4. Cyclophane which are reduced reversibly to their dianions in DMF.

For most of the compounds the cyclic voltammogram closely resembles the theoretical one for a reversible two-electron process, and there can be no doubt about the stoichiometry or the nature of the product.⁷ The cyclic voltammogram of the reduction of [2₄]paracyclophanetetraene is shown in Figure 5.⁷

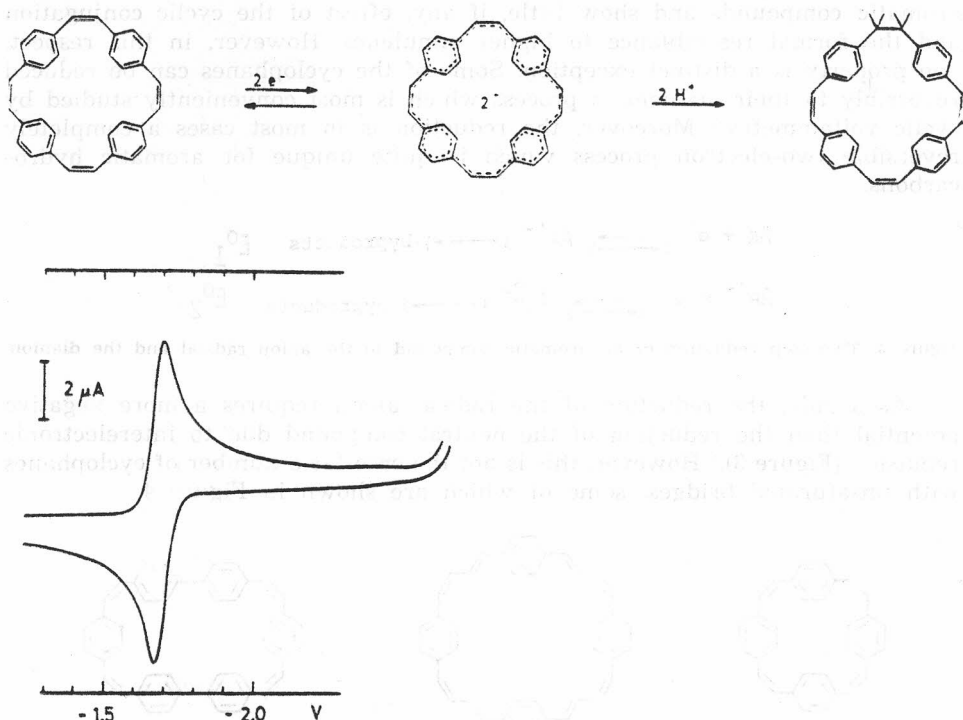


Figure 5. Cyclic voltammogram of [2₄]paracyclophanetetraene (see ref. 7).

We have tried to pursue and to rationalise this observation and this has led us to the discovery of a new type of dianion with annulene character and an interesting, chemically significant, alternating effect which parallels Hückels rule for large cyclic π -systems.

What are the reasons for the two-electron reduction? What effect compensates for the expected interelectronic repulsion which usually leads to two consecutive one-electron reduction steps? Certainly, geometrical changes do occur on reduction. The influence of the ground-state geometry and geometrical changes on the reduction of cyclo-octatetraene to its dianion has been treated in detail.⁸ The simplified argument is that the molecule becomes more planar when reduced to the radical anion and thus the second electron has no geometrically imposed barrier to overcome and the dianion is formed more readily than expected. Is this also a satisfactory explanation for the cyclophanes discussed here? Is it possible that, in the dianions, some extra stabilisation is present depending on the size of the π -system, whether it is formally of the $4n$ or $(4n+2)$ type?

It is known from an X-ray investigation of [2₄]paracyclophanetetraene that the cyclophane is not very planar.⁹ The benzene rings are tilted ca. 35° out of the average molecular plane. Some of the other cyclophanes must be even less planar while some, with thiophene or furan rings, might be slightly more planar. Thus, geometrical changes might be important and must be considered. The energy for a completely planar conformation of [2₄]paracyclophanetetraene was calculated by a molecular mechanics model to be 5.8 kcal/mol higher than the ground state.¹⁰

One important observation is that only cyclophanes with a formal perimeter of $4n$ π -electrons are reversibly reduced to the dianions. A simple Hückel calculation with constant β -values reveals that in most of these cases there are nondegenerate LUMO and HOMO orbitals.¹¹ These can be regarded as originating from the degenerate nonbonding orbitals in the $4n$ -annulenes which have been split by the incorporation of the benzene rings. The NHOMO and NLUMO are degenerate or near-degenerate (Figure 6).

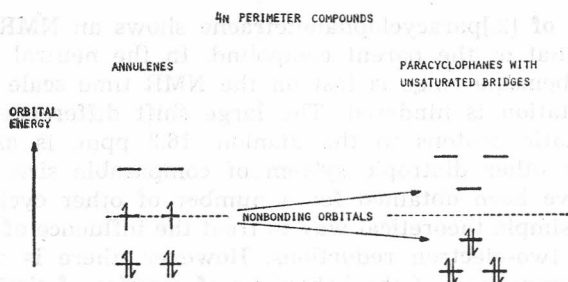


Figure 6. MO scheme from Hückel calculations on planar annulenes and paracyclophanes with unsaturated bridges.

Furthermore, there is a good correlation between the energies of the LUMO orbitals and the reduction potentials for the reversible two-electron process for a series of carbo-cyclophanes (Figure 7).¹¹

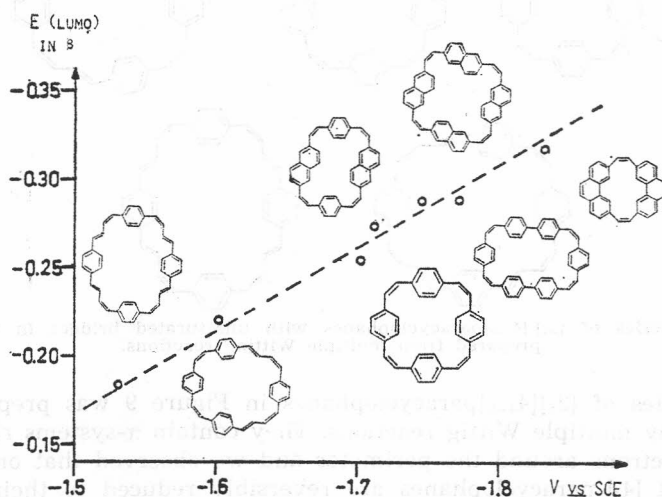


Figure 7. Correlation of LUMO orbital energies from Hückel calculations with reduction potentials for reversible two-electron processes.

A β -value of 50.1 kcal/mol can be calculated from the straight line. Apparently, the Hückel approximation works reasonably well for these delocalised dianions which shows that they must be fairly planar, more so than the neutral cyclophanes which is supported by some results obtained in Köln by Müllen and co-workers (Figure 8).¹²

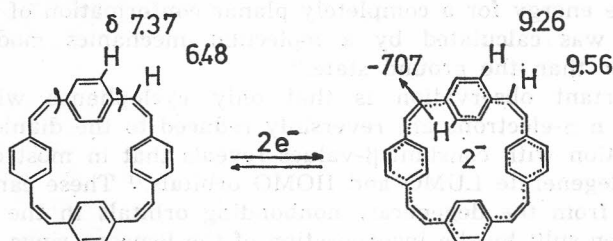


Figure 8. ^1H NMR chemical shifts for $[2_4]$ paracyclophanetetraene and its dianion from ref. 12.

The dianion of $[2_4]$ paracyclophanetetraene shows an NMR spectrum very different from that of the parent compound. In the neutral cyclophane, the rotation of the benzene rings is fast on the NMR time scale whereas in the dianion such rotation is hindered. The large shift difference between outer and inner aromatic protons in the dianion, 16.3 ppm, is as large as that observed in any other diatropic system of comparable size. Essentially the same results have been obtained for a number of other cyclophanedians.

There is no simple theoretical way to treat the influence of the geometrical changes on the two-electron reductions. However, there is a chemical way to do this. By comparison of the behaviour of a series of similar cyclophanes with an increasing number of π -electrons one can hopefully exclude geometrical factors as being solely responsible for the unusual process.

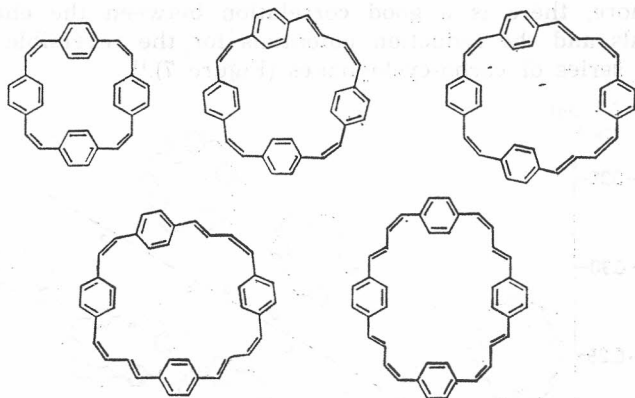


Figure 9. A series of $[2_n][4_{n-4}]$ paracyclophanes with unsaturated bridges ($n = 4, 3, 2, 1, 0$) prepared from multiple Wittig reactions.

The series of $[2_n][4_{n-4}]$ paracyclophanes in Figure 9 was prepared in our laboratory by multiple Wittig reactions. They contain π -systems ranging from 24 to 32 electrons around the perimeter and we observed that only the $[2_4]$ -, $[2_2][4_2]$ -, and $[4_4]$ -paracyclophanes are reversibly reduced to their dianions.¹³ A similar series of naphthalenophanes is shown in Figure 10. The bi- and

tetra-naphthalenophanes are reversibly reduced to their dianions as observed by cyclic voltammetry.¹¹

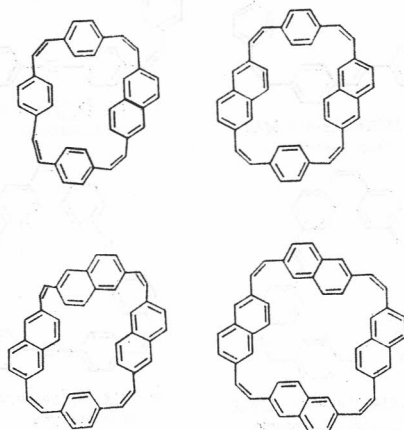


Figure 10. A series of $[2_4](2,6)$ naphthalenoparacyclophanes with one, two, three, and four naphthalene units.

It is interesting to note that for certain series of paracyclophanes the Hückel calculations give identical HOMO and LUMO orbital energies for all members of the series, regardless of ring size (Figure 11).

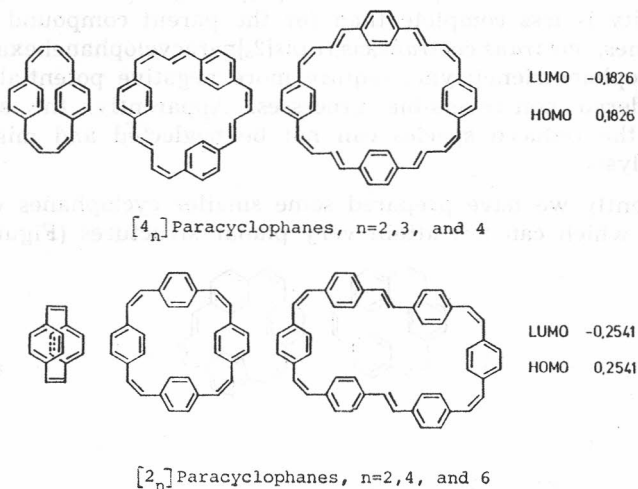


Figure 11. Two series of paracyclophanes with unsaturated bridges with the same LUMO orbital energies from Hückel calculations within each of the series.

Some of these cyclophanes, e.g. the $[4_2]$ - and $[2_3]$ paracyclophanes are definitely non-planar while others are difficult to prepare, e.g. the $[4_3]$ paracyclophane. However, we have recently prepared some $[2_6]$ paracyclophanes with unsaturated bridges to test the predictions from the Hückel calculations (Figure 12).

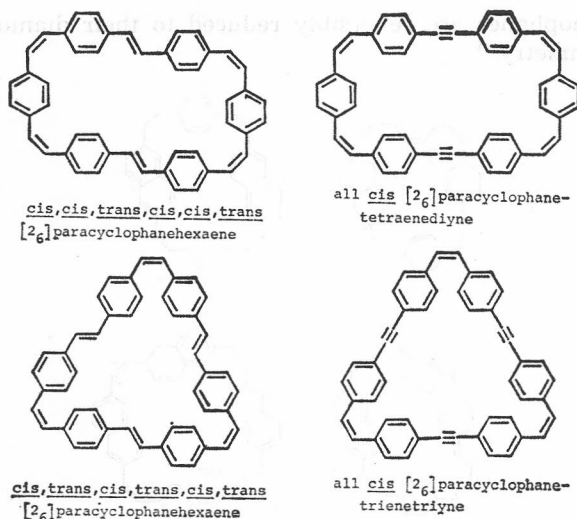


Figure 12. [2₆]Paracyclophanes with unsaturated bridges prepared by multiple Wittig reactions.

The four cyclophanes in Figure 12 are all identical within the simplest Hückel approximation. Two of the compounds, *cis,cis,trans,cis,cis,trans*[2₆]paracyclophanehexaene and all *cis*[2₆]paracyclophanetetraenediayne, are reversibly reduced at exactly the same potential as [2₆]paracyclophanetetraene although the reversibility is less complete than for the parent compound.¹⁴ The other two cyclophanes, *cis,trans,cis,trans,cis,trans*[2₆]paracyclophanehexaene and all *cis*[2₆]paracyclophanetrienetriayne, require more negative potentials for reduction and undergo non-reversible processes. Apparently, the stability and reactivity of the reduced species can not be neglected and might interfere with the analysis.

More recently we have prepared some smaller cyclophanes with unsaturated bridges which can not attain very planar structures (Figure 13).

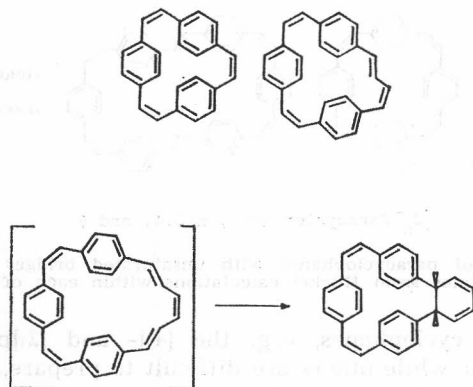


Figure 13. Paracyclophanes with three benzene rings and three unsaturated bridges which have been prepared by multiple Wittig reactions and titanium-mediated reductive couplings of dialdehydes.

Even the previously known [2₃]paracyclophanetriene undergoes an electrochemical reduction at the same potential as *cis*-stilbene (-2.20 V *vs* SCE) although the neutral molecule has the three benzene rings essentially perpendicular to the double bonds.¹⁵ The slightly larger [2.2.4]paracyclophanetraene, which has a formal $4n$ perimeter and which can attain a more planar conformation, is reduced reversibly at -1.89 V *vs* SCE, which is *ca.* 260 mV more negative potential than predicted from Hückel calculations on the planar compound. Unfortunately, the next homolog, [2.2.6]paracyclophanepentaene, undergoes a facile electrocyclic ring closure on attempted synthesis.

To conclude this part of the paper it might be fair to state that certain cyclophanes on reduction to dianions form new and interesting $(4n+2)$ π -systems with delocalisation of the extra charge over the entire molecule

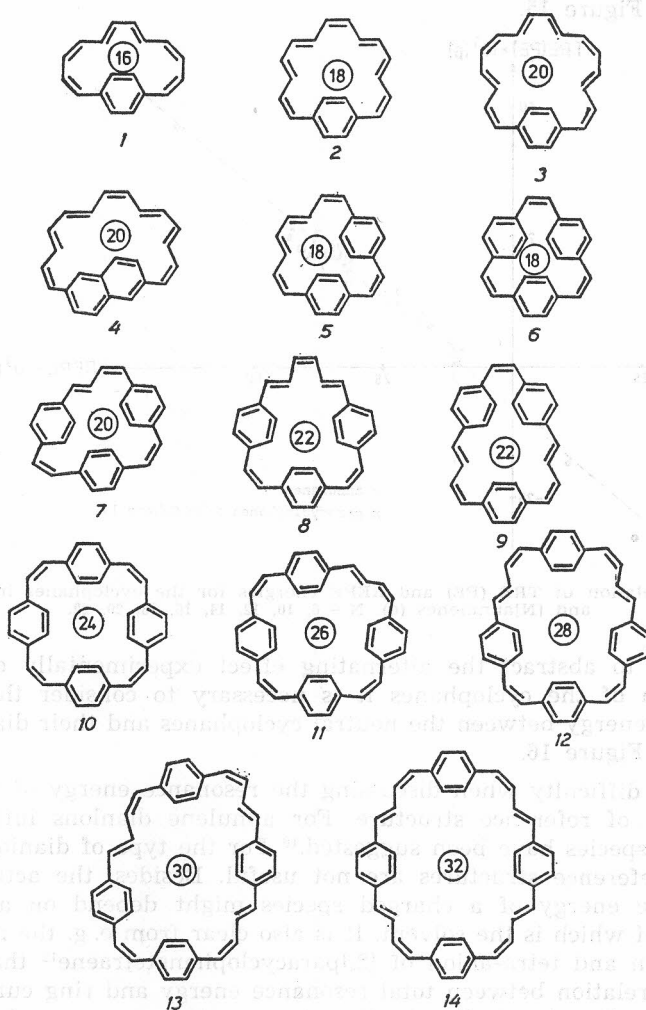


Figure 14. Cyclophanes with conjugated π -systems around the perimeter ranging from 16 to 32 electrons for which TRE and RE energies have been calculated.

as apparent from ^1H NMR data. Steric factors are less important in the dianions than in the neutral molecules. In contrast to the neutral cyclophanes, local aromatic rings present no severe hinder to delocalisation of the π -electrons over the entire molecule.

We have also tried to match our experimental results with present theories of resonance stabilisation. The resonance energies of Hess and Schaad¹⁶ and of Trinajstić and co-workers¹⁷ have been calculated for a series of cyclophanes, mainly paracyclophanes with unsaturated bridges and some of their dianions (Figure 14).

Not surprisingly, all of the compounds are aromatic regardless of the size of the perimeter. It is evident that the effect of the local aromatic rings dominates. The two methods give similar results for the neutral cyclophanes as shown in Figure 15.

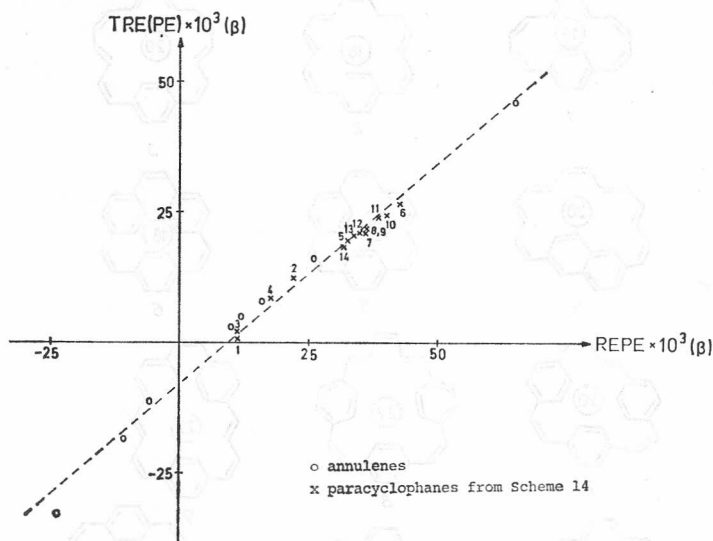


Figure 15. Correlation of TRE (PE) and REPE energies for the cyclophanes in Figure 14 (x) and [N]annulenes (o), N = 6, 10, 12, 14, 16, 18, 20, 22.

In order to abstract the alternating effect experimentally observed for the reduction of the cyclophanes it is necessary to consider the difference in resonance energy between the neutral cyclophanes and their dianions (TRE) as shown in Figure 16.

A major difficulty when discussing the resonance energy of the dianions is the choice of reference structure. For annulene dianions infinitely large and charged species have been suggested.¹⁸ For the type of dianions discussed here, such reference structures are not useful. Besides, the actual value of the resonance energy of a charged species might depend on a number of factors, one of which is the solvent. It is also clear from e. g. the ring currents in the dianion and tetra-anion of [2₄]paracyclophanetetraene¹² that there can be no direct relation between total resonance energy and ring current effects. It seems as if the chemically significant properties are more closely related to the frontier orbitals than to the total resonance energy. For a discussion






CYCLOPHANE	TOPOLOGICAL RESONANCE ENERGIES		
	NEUTRAL COMPOUND	DIANION	DIFFERENCE
	0.7864 (.0246)	0.5912 (.0174)	0.1952 (.0072)
	0.8100 (.0238)	-0.4544 (.0126)	0.3556 (.0112)
	0.7694 (.0214)	0.6218 (.0164)	0.1476 (0.0050)
	0.7876 (.0207)	0.4822 (.0121)	0.3054 (.0086)
	0.7422 (.0186)	0.6186 (.0147)	0.1236 (.0039)

Figure 16. Topological resonance energies (TRE and TREPE in β) for a series of $[2_n]_{[4-n]}$ paracyclophanes with unsaturated bridges ($n = 4, 3, 2, 1$, and 0).

of the dianions of the cyclophanes presented here, Hückel molecular orbitals describe the chemistry fairly well whereas the total resonance energies mask the interesting properties of the cyclophanes somewhat, due to the presence of local aromatic rings.

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SAŽETAK

**Dianioni ciklofana s nezasićenim mostovima;
ciklička konjugacija u sistemima s 22—38 π -elektrona na perimetru**

U. Norinder, D. Tanner i O. Wennerström

Sintetiziran je niz novih ciklofana s nezasićenim mostovima, koji formalno sadrže π -sisteme s 18—48 π -elektrona. Neki od ovih ciklofana s $4n$ perimetrima mogu se reverzibilno reducirati u odgovarajuće dianione s $4n+2$ perimetrima. Taj reverzibilni dvoelektronski proces može se pogodno proučavati cikličkom voltametrijom. Elektrokemijski podaci pokazuju kemijski značajnu razliku između neutralnih $4n$ i $4n+2$ sistema, čak i za velike n . Dobivena je dobra korelacija između izračunanih energija LUMO orbitala i reverzibilnih redukcijskih potencijala. Provjerene su novije teorije rezonancijskih energija u neutralnim molekulama i dianionima s konjugiranim perimetrima. Razmotrena je upotreba rezonancijskih energija, odnosno energija graničnih orbitala, radi interpretacije ponašanja ciklofana i njihovih dianiona.