

Photoinduced Multiple *Z/E* Isomerizations of [2₆]Paracyclophenes

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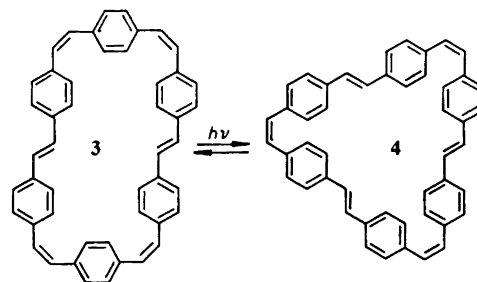
Sundahl, M., Wennerström, O., Raston, I. and Norinder, U., 1988. Photoinduced Multiple *Z/E* Isomerizations of [2₆]Paracyclophenes. – Acta Chem. Scand., Ser. B 42: 367–372.

A series of configurational isomers of [2₆]paracyclophenes have been prepared by multiple Wittig reactions. Photoinduced configurational changes at one, two or three double bonds have been observed and shown to occur by a one-photon process via the triplet state.

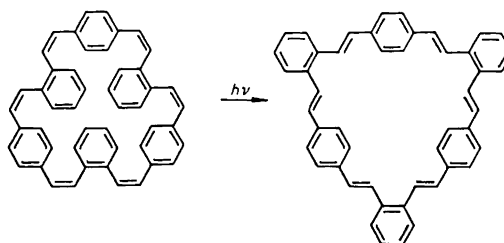
Photoinduced *Z/E* isomerizations and cyclisations of stilbenes have been extensively studied both theoretically and experimentally.* Both types of reactions are synthetically very useful and mechanistically important. The investigation of the excited singlet and triplet state surfaces has led to new insight and a deeper understanding of the complex photochemical processes involved. The geometry of the excited states of stilbene has been of particular interest.

Only recently, macrocycles containing *Z*- and/or *E*-stilbene units, large enough to permit configurational changes for steric reasons, have become available. Such macrocycles are often called cyclophenes.[§] Quite surprisingly, they are relatively stable to irradiation and fail to undergo intramolecular photocyclisation.² The cyclic geometric isomers seem to be more stable than their linear chain counterparts. The fluorescence spectra of some of these cyclophenes show an unusually large red shift upon excitation.³

In order to reach a better understanding of the importance of cyclic conjugation for excited state reactions in macrocycles with π -perimeters, we have studied the photoinduced *Z/E* isomerizations. In a preliminary communication we presented some evidence for configurational changes



Scheme 1.



Scheme 2.

induced at more than one double bond, by a single photon in [2₆]paracyclophenes, the latter being 36 π -perimeter compounds (Scheme 1).⁴ More recently, we have shown that the photoisomerization of a 30 π -perimeter macrocycle with six *Z* double bonds to the all-*E* isomer proceeds

*See e.g. Ref. 1.

[§]A cyclophene is a cyclophane with unsaturated bridges between the aromatic subunits in the cyclophane.

without ground state intermediates (Scheme 2).⁵ In this paper we present new evidence for the mechanism of the multiple *Z/E* photoisomerization of [2₆]paracyclophenes in support of our previous findings.

Synthesis of [2₆]paracyclophenes

The number of possible *Z/E* isomers well exceeds the number of probable ones. Still, at least six configurational isomers should be considered when discussing photoisomerizations, namely the all-*Z* isomer (1), the *Z,Z,Z,Z,Z,E* isomer (2), the *Z,Z,E,Z,Z,E* isomer (3), the *Z,E,Z,E,Z,E* isomer (4), the *Z,Z,E,Z,E,Z* isomer (5) and the *Z,E,E,Z,E,E* isomer (6). The remaining stereoisomers should be highly strained and will not be considered further. Of the six isomers 1–6, the first four have been prepared by carefully controlled, stereoselective Wittig reactions as described in the following.

The all-*Z* isomer (1) has been prepared by three different routes as shown in Scheme 3, all involving Wittig reactions as the key step.

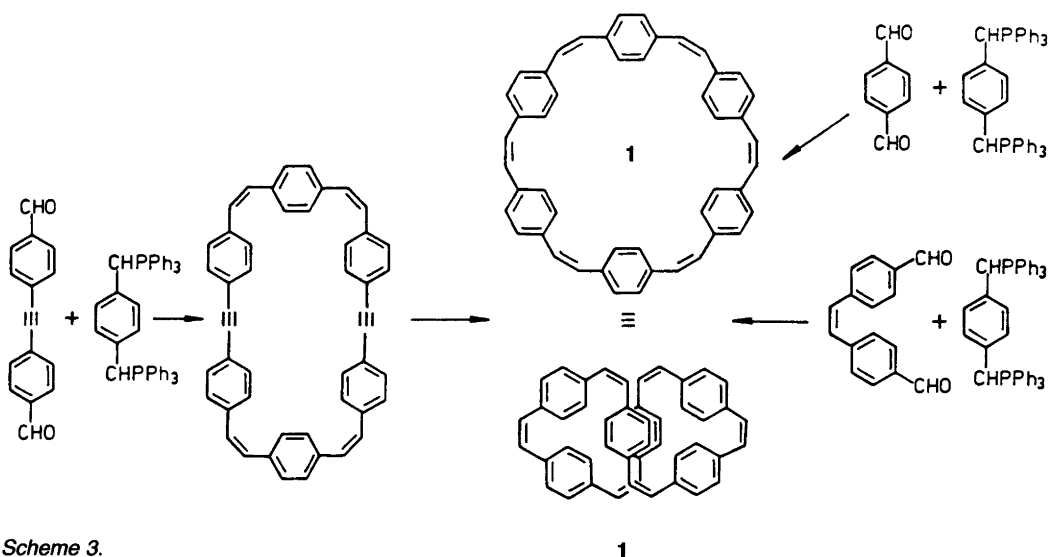
The *Z,Z,Z,Z,Z,E* Isomer (2) was prepared from (*Z*)-stilbene-4,4'-dicarbaldehyde, two equiv. of the bisphosphonium salt derived from 1,4-bis(bromomethyl)benzene followed by one equiv. of the (*E*)-stilbene-4,4'-dicarbaldehyde in a one-pot Wittig reaction (Scheme 4). The order

of addition of the dialdehydes is important. No product was observed when the two dialdehydes were added in reverse order.

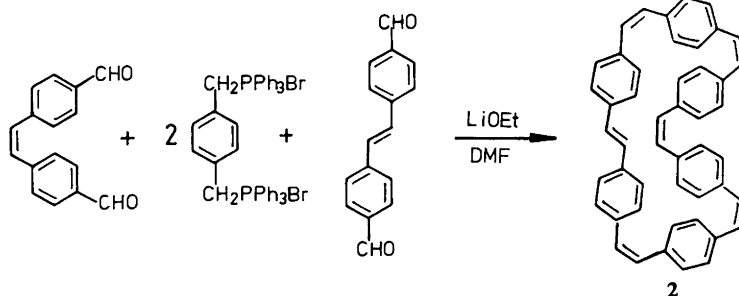
The synthesis of the *Z,E,Z,E,Z,E* isomer (4) has been reported elsewhere.⁴ It was prepared by a stereoselective three-fold Wittig reaction of (*Z*)-4'-(bromomethyl)stilbene-4-carbaldehyde.

The *Z,Z,E,Z,Z,E*-isomer (3) was prepared from (*E*)-stilbene-4,4'-dicarbaldehyde and the bisphosphonium salt derived from 1,4-bis(bromomethyl)benzene by a four-fold and stereoselective Wittig reaction as described earlier.⁶

The structures of the four isomers 1–4 follow from their MS and ¹H NMR spectra (Table 1) as well as from chemical evidence. On hydrogenation, all four isomers are converted to the same product, viz. [2₆]paracyclophane. The photochemical interconversions and the iodine-promoted isomerizations described below give further support for the assigned structures. The ¹H NMR spectra of the isomers 1–4 are particularly illustrative, and clearly reflect the different symmetries of the isomers (Table 1). At room temperature, the benzene rings as well as the *E*-vinylene bridges rotate fast on the NMR time scale, and thus some of the resonance signals are averaged. The most symmetric isomer, all-*Z*-[2₆]paracyclophane (1), gives only two singlets in a ratio of 2:1. The *Z,E,Z,E,Z,E* isomer (4) is less symmetric but still has a three-fold axis of sym-



Scheme 3.



Scheme 4.

metry perpendicular to the averaged molecular plane. The 36 protons are now divided into four sets: 6+6 olefinic and 12+12 aromatic protons. The *Z,Z,E,Z,Z,E* isomer (**3**) has only a two-fold axis of symmetry, and has three sets of four olefinic protons and three sets of eight aromatic protons. Finally, the *Z,Z,Z,Z,Z,E* isomer (**2**) has only one apparent axis of symmetry. The 36 protons are now divided into six sets of olefinic and six sets of aromatic protons (Table 1).

By inspection of the NMR spectra in Table 1 it is clear that one can select one or several characteristic signals for each isomer in order to analyze mixtures of the four isomers by ¹H NMR spectroscopy.

The UV spectra of the four isomers **1–4** are less characteristic. We conclude that isomer **3** is the most planar one, followed by isomer **4** (Table 1).

Photoisomerizations

In a preliminary communication we discussed the photoisomerization of the two isomers **3** and **4**.⁴

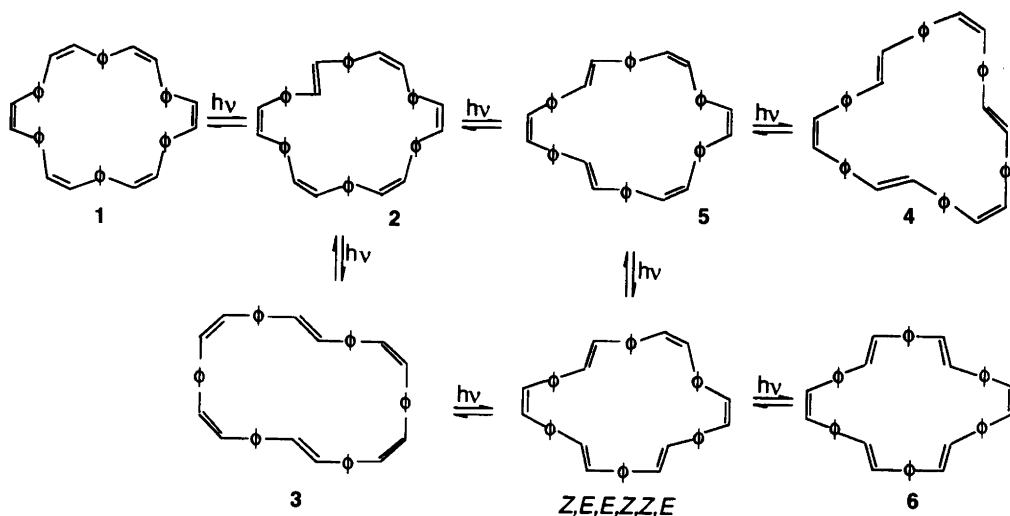
On irradiation in a Rayonet reactor at 300 nm (maximum intensity around 300 nm) the two isomers interconverted. By starting with either of the two isomers, a photostationary state was reached, yielding a mixture of **3** and **4** in a ratio of 1:3. Some photodecomposition also occurred. When the reaction was followed by ¹H NMR spectroscopy, no intermediate was detected (< 5% of an isomer). If all the sterically reasonable configurational isomers of [2₆]paracyclophene are considered (Scheme 5), it is clear that there exists more than one route for the *Z/E* photoisomerization of isomers **3** and **4**. By assuming that only one double bond changes configuration in each photoreaction, which we call a stepwise process, it is possible to define several routes for the isomerization of isomers **3** and **4**. Multi-step processes, by which is meant that more than one configurational change occurs in each photoreaction, are also possible.

The successful synthesis of all-*Z*-[2₆]paracyclophene (**1**) made further experimental studies of the mechanism of the photoisomerization pos-

Table 1. ¹H NMR, UV and MS data for the four isomers **1–4**.

	¹ H NMR data		UV data		MS data abs. mass
	Aromatic protons	Olefinic protons Z bonds E bonds	λ _{max} /nm	(ε/l mol ⁻¹ cm ⁻¹)	
1	7.10 ^a	6.45 ^a	319	(25 800)	612.277 ^e
2	7.4–7.0 ^d	6.65 ^b 6.95 ^a 6.45 ^a 6.60 ^b	329	(37 300)	– ^e
3	7.40, 7.30 ^c 7.25 ^a	6.45 ^b 6.95 ^a	342	(98 000)	612.289 ^e
4	7.20, 7.10 ^c	6.65 ^a 6.8 ^a	330	(86 400)	612.280 ^e

^aSinglet. ^bAB-pattern, *J*_{AB} = 12 Hz. ^cAA'BB' pattern, *J*_{AB} = 8 Hz. ^dThree overlapping AA'BB' patterns. ^eLow resolution mass spectra of the four isomers **1–4** showed main peaks for M⁺ (612) and M²⁺ (306).



Scheme 5. Schematic representation for stepwise interconversion of configurational isomers of $[2_6]$ paracyclophenes. Φ = parasubstituted benzene ring.

sible. Irradiation of **1** in benzene or dichloromethane at 300 nm resulted in a rapid conversion of **1** into a mixture of isomers **3** and **4**. At low conversions, the ratio of **3** to **4** was ca. 2:1 but this ratio slowly changed towards the previously observed photostationary state of 1:3. No clear evidence for the presence of an intermediate was obtained (< 5% by NMR-methods). Treatment of **1** with traces of iodine in the dark resulted in slow formation of isomer **3**, possibly *via* isomer **2**. No trace of isomer **4** was observed, nor did isomers **3** and **4** react with iodine under identical conditions.

If the isomerization of **1** to **3** and **4** occurs by a stepwise mechanism, i.e. only one double bond changes configuration in each photoreaction, then isomer **2** must be an intermediate (Scheme 5). The $[2_6]$ paracyclophene **2** is an important isomer for the experimental proof that the photoisomerization does not occur by a stepwise mechanism. The synthesis of **2** is described above. Irradiation of the pure isomer as well as a mixture of isomers **1** and **2** at 300 nm resulted in rapid formation of a mixture of **3** and **4**. In both experiments, the initial ratio of **3** to **4** was ca. 2:1. No formation of **1** was observed by NMR methods upon irradiation of **2** in the first experiment, and the ratio stayed approximately constant in

the second experiment. These results are not consistent with the hypothesis that the photoisomerization occurs by a stepwise process, but clearly indicate that the isomerization occurs by a direct process which involves multiple configurational changes in each photoreaction.

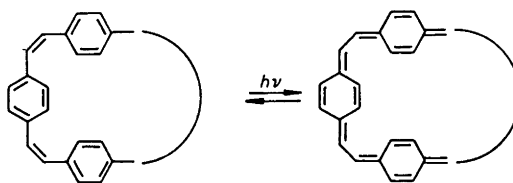
The remaining problem of whether the isomerization takes place in the singlet or triplet state or, alternatively, occurs via some unknown intermediate of different structure, was solved by using a sensitizer. Biacetyl was chosen as sensitizer since its singlet and triplet states have proper energies and the simple structure causes no complications in the NMR analysis of the mixture. Samples of **1** and **2** in deuteriobenzene with and without biacetyl were sealed off under vacuum and irradiated at >400 nm (see Experimental). No reaction was observed in the sample that did not contain biacetyl. The biacetyl-containing sample was rapidly and smoothly converted to a mixture of **3** and **4**. As before, the initial ratio of **3** to **4** was ca. 2:1, which on prolonged irradiation slowly changed toward the photo-equilibrium value 1:4. Thus, it is clear that the photoinduced interconversion of the isomers of $[2_6]$ paracyclophene is a direct process which takes place in the lowest triplet state.

Discussion and conclusions

The triplet-sensitized *Z/E* isomerization of [2₆]paracyclophene is quite analogous to that of [2₆]orthoparacyclophene (Scheme 1). The latter reaction involves a six-fold change of configuration (quantum yield 0.62).⁵ The multiplicity of the configurational changes ranges from single (2→3), to double (2→4 and 1→3), and finally to three-fold (3→4 and 1→4).

There are several examples of large cyclophanes with π -perimeters which do not undergo photocyclisation to dehydrophenanthrenes of *Z/E* isomerization easily in the singlet state, although there seems to be little steric hindrance for these reactions.^{2,8} One important factor for the understanding of the photoreactivity of cyclophanes is the geometry of the excited states. In simple stilbenes, there is a strong driving force for twisting the double bond in the excited state to generate two orthogonal π -systems, regardless of the multiplicity or change distribution of the excited states.⁷ This type of geometrical change upon excitation must not necessarily occur in the cyclophanes which contain stilbene units. Fluorescence studies of some larger cyclophanes of this type have revealed a large red shift of the emission, indicative of a considerable geometrical change on going from the ground state to the first excited singlet state.³ Since the cyclophanes are far from planar in the ground state and generally contain localized π -systems, a more planar geometry with some quinoid character for the benzene rings is a reasonable assumption for the geometry of the first excited singlet state (Scheme 6). Simple Hückel molecular orbital theory gives the same bond order for the first excited state as for the dianion of an alternant hydrocarbon of the type discussed here.⁹ The dianions of several π -perimeter cyclophanes with $4n+2$ π -electrons have been shown to form relatively planar delocalized π -systems,⁹ which lends some support to the idea that the excited states of cyclophanes, π -perimeter compounds, are more planar than their ground states.

The relative ground state energies of the four isomers 1–4 of [2₆]paracyclophene are incompletely known. The iodine-promoted isomerization of 1 gave 3 probably via 2. However, the relative energies of 3 and 4 could not be determined by this method. In principle, heats of hydrogenation could be determined, but the ex-



Scheme 6.

pected difference between the values for 3 and 4 is smaller than the experimental error. Similarly, molecular mechanics calculations, which are accurate for most hydrocarbons, would still give a crude estimate of the relative energies.

The triplet-sensitized isomerizations of 1 and 2 to 3 and 4 resulted in an initial ratio of the products of 2:1, which might reflect the relative energies of the triplet states of 3 and 4 or, alternatively, the relative activation energies on the triplet energy surface. The triplet-sensitized isomerization of 3 and 4 resulted in a photo-stationary state with a 1:4 ratio of the two isomers. It is reasonable to assume that the triplet states are relatively long-lived in order to allow for mutual interconversions, i.e. $S_0(3) + T_1(4) \rightleftharpoons T_1(3) + S_0(4)$ is fast. The simplest rationalization of the observed photoequilibrium is then that $T_1(3) > T_1(4)$, where T_1 represent the energy $T_1 - S_0$. However, a definite analysis of the energetics of the singlet and triplet surfaces of [2₆]paracyclophanes requires further work.

Available experimental data on the photoreactivity of macrocyclic π -perimeter compounds indicate that they react differently from open-chain compounds with linear π -systems. It appears that cyclic conjugation plays an important role for the excited state reactions even in compounds with large π -perimeters. The experimental results are still too few, and more definite conclusions on the scope and limitations of π -perimeter influence on photoreactivity require further work.

Experimental

All-Z-[2₆]paracyclophene (1). The bisphosphonium salt derived from triphenylphosphine and 1,4-bis(bromomethyl)benzene (0.4 mmol), and (*Z*)-4,4'-stilbenedialdehyde (0.4 mmol) were dissolved in dry DMF (75 ml) under a nitrogen atmosphere. The mixture was cooled to -40°C and lithium ethoxide in ethanol was added slowly

to allow the coloured ylid formed to react with aldehyde groups between successive additions. When no colour was observed upon addition of base, the reaction mixture was allowed to reach room temperature and then diluted with water (75 ml). The mixture was extracted with diethyl ether (3×50 ml). The combined ether fractions were washed with water several times, dried over magnesium sulfate and then the solvent was evaporated. The residue was subjected to chromatography on silica gel (preparative TLC) with tetrachloromethane as eluent. The first band contained a mixture of the all-*Z* and the *Z,Z,Z,Z,Z,E* isomers of [2₆]paracyclophane (12 mg, 10% yield, isomer ratio 3:7). Hydrogenation of the isomeric mixture (palladium on charcoal in ethanol) gave pure [2₆]paracyclophane. Although the two isomers could be purified by repetitive preparative TLC, the pure all-*Z* isomer was more conveniently prepared by selective *cis* hydrogenation of [2₆]paracyclophanetetraenediyne (100 mg) in benzene (50 ml, *p.a.*) over palladium on calcium carbonate (20 mg). For NMR, UV and MS data, see Table 1.

Z,Z,Z,Z,Z,E-[2₆]paracyclophane (2). The bis-(triphenylphosphonium) salt of 1,4-bis(bromomethyl)benzene (6 mmol) and (*Z*)-4,4'-stilbenedialdehyde (3 mmol) were dissolved in dry DMF (200 ml). The mixture was cooled to -40°C and the flask was flushed with nitrogen. Lithium ethoxide in ethanol (6 mmol) was added over a period of 5–6 h. When no colour from the ylid was observed, (*E*)-stilbenedialdehyde (3 mmol) was added, followed by more lithium ethoxide in ethanol (6 mmol) until all of the phosphonium salt had been consumed.

The reaction mixture was allowed to reach room temperature and was diluted with water (200 ml). The mixture was extracted three times with diethyl ether. The combined ether fractions were washed with water several times, dried over magnesium sulfate and the solvent evaporated. The residue was separated on silica gel with dichloromethane as eluent. The first fraction was further purified by chromatography on silica gel, but using tetrachloromethane as eluent. Repeated preparative TLC finally gave three fractions; the first (12 mg) consisted of mainly the all-*Z* isomer of [2₆]paracyclophane (1.3%), the second (35 mg) was the desired *Z,Z,Z,Z,Z,E*

isomer (1.9%), which was further purified by crystallization from dichloromethane/methanol. The third fraction contained a mixture of the desired isomer 2 and the *Z,Z,E,Z,E* isomer 3. Hydrogenation of 2 (palladium on charcoal in ethanol) gave pure [2₆]paracyclophane.

Photoisomerizations. The cyclophanes were dissolved in benzene-*d*₆ in NMR tubes. The solutions were de-gassed on a vacuum line by three freeze-pump-thaw cycles. The NMR tube was then sealed. In some cases biacetyl was added as a sensitizer. The samples were irradiated in a Rayonet reactor with light of maximum intensity around 300 nm and cooled by air. A saturated solution of sodium nitrite was used as a filter solution in the experiments with added photosensitizer to avoid direct excitation of the cyclophanes. This was checked by irradiation of the samples, without biacetyl, using the filter solution. No reaction was observed. All photoisomerization experiments were followed by ¹H NMR spectroscopy using either a Bruker WH 270 or a Varian XL400 instrument.

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References

1. Turro, N. J. *Modern Molecular Photochemistry*, Benjamin, Menlo Park 1978 and references therein.
2. Thulin, B. and Wennerström, O. *Acta Chem. Scand., Ser. B* 37 (1983) 589.
3. Norinder, U., Sandros, K. and Wennerström, O. *Acta Chem. Scand., Ser. B* 38 (1984) 4787.
4. Norinder, U., Tanner, D. and Wennerström, O. *Tetrahedron Lett.* (1983) 5411.
5. Sundahl, M., Wennerström, O., Sandros, K. and Norinder, U. *Tetrahedron Lett.* (1986) 1063.
6. Raston, I. and Wennerström, O. *Acta Chem. Scand., Ser. B* 36 (1982) 655.
7. Turro, N. J. *Photochem. Photobiol.* 9 (1969) 555.
8. Staab, H. A. and Diederich, F. *Chem. Ber.* 116 (1983) 3487.
9. Müllen, K., Unterberg, H., Huber, W., Wennerström, O., Norinder, U., Tanner, D. and Thulin, B. *J. Am. Chem. Soc.* 106 (1984) 7514.

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