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Facile Photochemical Synthesis of 5,10-Disubstituted [5]Helicenes by Removing Molecular Orbital Degeneracy

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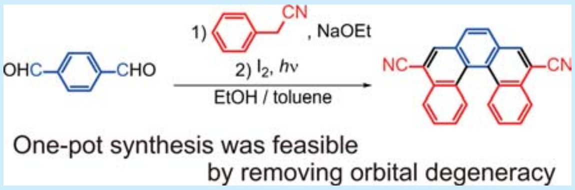
Supporting Information

ABSTRACT: Photocyclodehydrogenation is a key reaction to synthesize helicenes; however, because of overannulation, it is not applicable to the synthesis of [5]helicene. Introduction of a cyano group was found to remove the orbital degeneracy of the low-lying unoccupied MOs; consequently, the lowest excitation comprises a single transition involving the C_2-antisymmetric MO. Therefore, the problematic overannulation can be effectively suppressed. Moreover, in combination with the Knoevenagel reaction, a one-pot synthesis of 5,10-dicyano[5]helicene with 67% yield was accomplished.



Helicenes are helical polycyclic aromatic hydrocarbons in which the *ortho*-position of the aromatic rings are angularly annulated with an adjacent aromatic ring.[1−5] Their intrinsic helical structure is very attractive for application in organic nanomaterials because of the chiral π-conjugated system. Since the chirality of the molecules can be attributed to their helical structures, the whole molecule is involved in the chirality. The applications of helicenes have now expanded into several fields including photofunctional materials,[6−11] supramolecular chemistry,[12−17] and surface chemistry.[18−20]

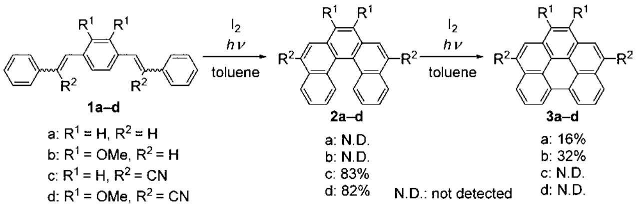
Photochemical methods are often used to prepare helicenes. The 6π-photocyclization of stilbene-type compounds followed by oxidation affords phenanthrene-type aromatic oligoacenes. This photocyclodehydrogenation reaction can be used toward the synthesis of very large helicene derivatives, such as [14]helicene.[21] By using this method, the preparation of [5]helicene from 1,2-di(2-naphthyl)ethene or 1,4-distyrylbenzene should be feasible. However, the [5]helicene product is itself also photoreactive, which leads to the formation of benzo[*ghi*]perylene as a result of overannulation. Since existing photochemical methods are not applicable to the synthesis of [5]helicenes, several research groups have developed alternative synthetic methods using olefin metathesis,[22] radical cyclization,[23] and metal-catalyzed cross-coupling reactions.[24]

Regarding the photochemical synthesis of helicenes, several methods have been proposed to overcome the limitation due to overannulation. Collins et al. carried out a photocyclization reaction of 1,2-di(2-naphthyl)ethene with Cu-based sensitizers using visible light and reported a significant increase in the yield of helicene.[25] Katz et al. introduced a bromine atom close to the reactive positions in the precursor to avoid secondary annulation.[26] In addition, Frimer et al. reported that [5]-helicene with maleic anhydride resists secondary annulation. They showed that the symmetry of the LUMO is opposite to that of the parent [5]helicene and explained the reactivity using the Woodward−Hoffmann rules.[27] However, as we will show in the following text, two degenerate low-lying unoccupied molecular orbitals (UMOs) exist in [5]helicene and the lowest excitation is not composed of the single transition. Therefore, the treatment beyond the use of the simple Woodward−Hoffmann rules is required.[28,29]

We now report the facile photochemical synthesis of 5,10-dicyano[5]helicene using a double photocyclodehydrogenation reaction of 1,4-bis(2-cyano-2-phenylethenyl)benzene. By the strategic introduction of a substituent in the precursor to remove the orbital degeneracy, photoreactivity could be controlled. By combining the Knoevenagel reaction, one-pot synthesis of 5,10-dicyano[5]helicene with 67% yield was accomplished from terephthalaldehyde and benzyl cyanide.

1,4-Distyrylbenzene **1a** is known to undergo photocyclodehydrogenation upon irradiation with UV light in the presence of iodine. However, the yield of [5]helicene **2a** is generally low due to overannulation, producing benzo[*ghi*]perylene **3a** as a main product (Scheme 1).[26,30] By using 1,4-bis(2-cyano-2-phenylethenyl)-2,3-dimethoxybenzene **1d** instead of **1a**, the overannulation was suppressed to give [5]helicene **2d** in 82% yield. Therefore, we investigated the substituent effects on photoreactivity. When compound **1b** bearing the 2,3-dimethoxy functionality was used, the overannulation was observed.

Scheme 1. Photochemical Synthesis of [5]Helicene from 1,4-Distyrylbenzene



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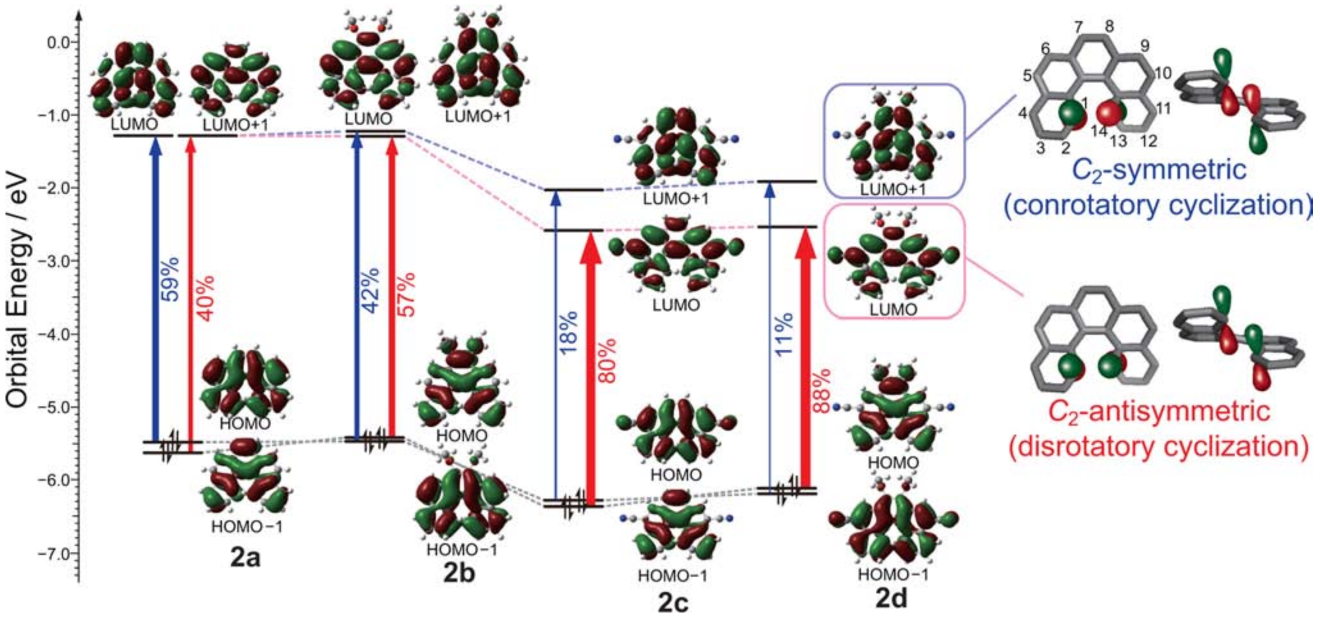


Figure 1. Orbital correlation diagram for compounds **2a**−**d**. The blue/red arrows represent the transitions to the C_2-symmetic/C_2-antisymmetric UMOs. The phase of the atomic orbitals in the C_2-symmetric UMO is suitable for a photochemical conrotatory cyclization reaction.

However, when compound **1c** bearing a cyano group at R^2 was used, overannulation was effectively suppressed to afford [5]helicene **2c** in 83% yield.[31]

To investigate the difference in reactivity, a TD-DFT calculation[32] was performed on **2a**−**d** at the B3LYP/6-31G(d) level.[33] Not only the shape of the LUMO but also the composition of the transition was analyzed. According to the Woodward−Hoffmann rules, conrotatory cyclization is a symmetry-allowed process in the excited state when dealing with a 22π electron system, i.e., a $(4n+2)\pi$ system. However, in the [5]helicene framework, the degeneracy of the low-lying UMOs, LUMO and LUMO+1, must be considered. As seen in Figure 1, the lowest excitation of the parent [5]helicene **2a** consists of two transitions: (i) one from HOMO to LUMO and (ii) the other from HOMO−1 to LUMO+1, both of which contribute almost equally, 59 and 40%, respectively (Table 1).

Table 1. Composition of Transition and Product upon Photo-irradiation[a]

	composition of transition		
helicene	C_2-symmetric[b]	C_2-antisymmetric[b]	product (yield, %)
2a	0.59	0.40	benzoperylene (16)[c]
2b	0.42	0.57	benzoperylene (32)[c]
2c	0.18	0.80	[5]helicene (83)[c]
2d	0.11	0.88	[5]helicene (82)[c]
4	0.03	0.95	[5]helicene (88)[d]
5	0.34	0.61	[5]helicene (82)[e]
6	0.47	0.50	benzoperylene (98)[e]

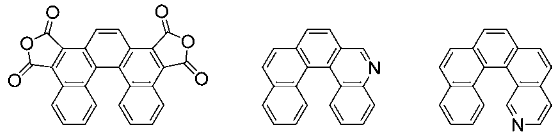
[a] When benzo[*ghi*]perylene was obtained, [5]helicene was not detected and vice versa. [b] The contributions of transitions in the lowest excitation state. [c] 1,4-Distyrylbenzene derivative **1a**−**d** (0.15 mmol) and I_2 (0.15 mmol) in toluene (45 mL) were irradiated by a superhigh-pressure Hg lamp for 36 h (this work). The byproduct of the photoreaction was not determined. For the photoirradiation of **1a** and **1b**, monocyclized products have been detected by mass spectrometry. [d] Reference 27. [e] Reference 38.

The phases of the atomic orbitals in the LUMO positioned at the reactive carbons (C-1 and C-14) are suitable for a photochemical conrotatory cyclization, while a disrotatory cyclization is predicted when a transition to the LUMO+1 is considered. Between the alternative processes, we only considered the conrotatory cyclization because it is both thermodynamically and kinetically favorable; the conrotatory product is more stable because of the disrotatory product has a distorted geometry owing to the two hydrogens being on the same side. In addition, a higher activation energy is expected for the disrotatory cyclization because of the large displacement required during the disrotatory process, whereas there is geometrical similarity between the conrotatory product and the original [5]helicene.[34] The overannulation is considered to take place for [5]helicene **2a** owing to the following two reasons: (i) an appropriate conical intersection or avoided surface crossings connecting the photocyclized product[35] is formed by the contribution of the C_2-symmetric UMO (59%) or (ii) the activation energy in the excited state for the conrotatory cyclization is sufficiently lowered by the positive orbital interaction in the C_2-symmetric UMO.[36]

Of the two low-lying UMOs, the C_2-antisymmetric UMO is effectively stabilized by the cyano substituents in the C-5 and C-10 positions (Figure 1). The C_2-symmetric UMO of **2a** has a small orbital coefficient at the C-5 and C-10 positions, whereas the C_2-antisymmetric UMO has large coefficients. Therefore, the C_2-antisymmetric UMO could be selectively stabilized by presence of electron-withdrawing groups at C-5 and C-10. Owing to the stabilization of the C_2-antisymmetric UMO, the lowest excitation of **2c** is mainly composed of the transition from the HOMO−1 to LUMO up to 80%, in which the phase of the LUMO is not suitable for the conrotatory cyclization reaction (Table 1). Hence, the photoreactivity of **2c** and **2d** was successfully suppressed by the cyano substituents. On the other hand, methoxy substitution at the C-7 and C-8 positions does not affect the energy level of the MO and therefore the reactivity.[37]

To check the effect of the electron-withdrawing substituents on the photoreactivity, a photoirradiation experiment was performed using **2a** and **2c**, and the dimethyl ester derivative of **8c** (**9**). The reactions were monitored by ^{1}H NMR spectroscopy (Figures S1 and S2, Supporting Information). The MOs of **2c** and **9** were very similar (Figure S3, Supporting Information). The parent [5]helicene **2a** was converted to benzoperylene **3a** in 73% yield after irradiation with UV light for 1 h, whereas the cyano-substituted compound **2c** and the carbonyl-substituted compound **9** remained intact under the same reaction conditions. Therefore, it was confirmed experimentally that the electron withdrawing group at the C-5 and C-10 positions provides remarkable photostability to [5]helicenes.

We also checked the validity of our theoretical predictions. The [5]helicenes **4**[27] and **5**[38] have been reported to display no photoreactivity, and **6**[38] was reported to be photoreactive (Figure 2).[39] Using DFT calculations, the ratio of excitation to the C_2-symmetric UMO has been calculated to be 3%, 34%, and 47% for **4**, **5**, and **6**, respectively. These results indicate that when the ratio of excitation to the C_2-symmetric UMO is larger than 42%, the photoreaction can proceed; however, when the ratio is smaller than 34%, the photoreaction does not proceed.

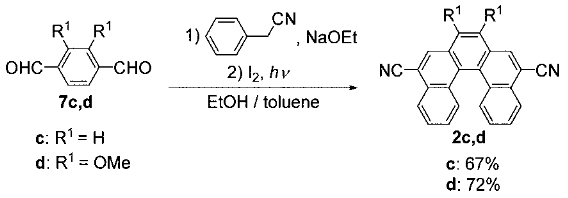


4 **5** **6**

Figure 2. [5]Helicenes whose photoreactivity was reported.

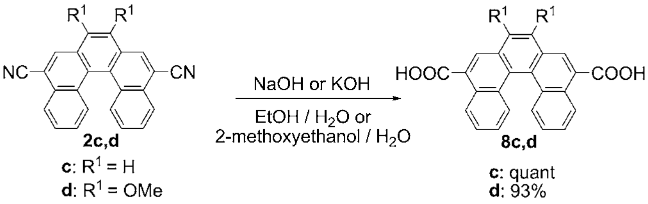
The starting materials for the photocyclodehydrogenation, **1c** and **1d**, were synthesized via the Knoevenagel condensation reaction. Therefore, a one-pot synthesis was performed starting from terephthalaldehyde and benzyl cyanide (Scheme 2). A quartz flask charged with terephthalaldehyde, benzyl cyanide, sodium ethoxide, and ethanol was stirred at 50 °C for 4 h, and then after the addition of iodine the mixture was irradiated using a mercury lamp for 64 h to afford 5,10-dicyano[5]-helicene **2c** in 67% yield. The reaction was also successful for a 7,8-methoxy substituted compound **2d**.

Scheme 2. One-Pot Synthesis of [5]Helicene Derivative Starting from Terephthalaldehyde and Benzyl Cyanide



Using our method, the 5,10-dicyano-substituted [5]helicene could be synthesized. Therefore, we have tried to extend the π-conjugation at the C-5 and C-10 positions. 5,10-Diaryl-substituted [5]helicenes have been synthesized using a Suzuki–Miyaura coupling, but several steps are required.[40] We have successfully converted the cyano group into the carboxylic acid after synthesis of the [5]helicene skeleton (Scheme 3). This facile modification allows our method to be useful in extending the π-system at the C-5 and C-10 positions.

Scheme 3. 5,10-Functionalization of [5]Helicene



An interesting feature of the molecular orbitals in [5]helicene is the existence of nearly degenerate MOs near the HOMO and LUMO. Figure 3 shows the orbital correlation diagram of the reactants in the photochemical reaction, (*cis,cis*)-1,4-distyrylbenzene **1a** and (*cis,cis*)-1,4-bis(2-cyano-2-phenylethenyl)-benzene **1c**. As shown in this diagram, there is no degeneracy in the frontier orbitals. The lowest excitation is dominantly the HOMO to LUMO transition. Therefore, the only possible pericyclic reaction is the conrotatory cyclization in the excited state, which is typical for $(4n+2)\pi$ systems. This feature is utilized in the design of photochromic compounds, such as diarylethenes or fulgides.[41−43]

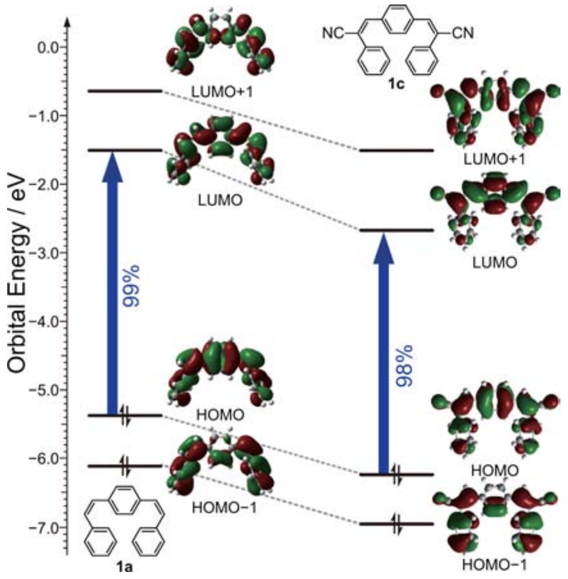


Figure 3. Orbital correlation diagram of **1a** and **1c**.

Moreover, as shown in Figure 3, cyano substitution does not influence the relative orbital energy of compound **1**, which is the reason why the reactivity of the first photocyclization was retained even after the cyano substitution. These results show that the cyclization of [5]helicenes is different from regular $(4n+2)\pi$ electron pericyclic reactions, which is in a marked contrast to the first cyclization. The unique degeneracy of MOs allows us to control the photoreactivity by cyano substitution. The utilization of this unique MO has potential application in both photochemical and thermal pericyclic reactions.

In conclusion, 5,10-dicyano[5]helicene was synthesized photochemically using a double photocyclodehydrogenation reaction of 1,4-bis(2-cyano-2-phenylethenyl)benzene. By incorporating the cyano or carbonyl substituents, the C_2-antisymmetric UMO of the two nearly degenerate low-lying UMOs is selectively stabilized and the lowest excitation becomes mainly composed of a single transition where the phase of the UMO is not suitable for conrotatory cyclization.

By removing the orbital degeneracy, the photoreactivity was successfully controlled. Moreover, in combination with the Knoevenagel reaction, a one-pot synthesis of 5,10-dicyano[5]-helicene in 67% yield from terephthalaldehyde and benzyl cyanide was accomplished.

ASSOCIATED CONTENT

Supporting Information

Experimental details, ^{1}H and ^{13}C NMR spectra, Cartesian coordinates of the optimized structures, and the calculated excited states. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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