

Photochemistry of Chiral Crystals

Absolute Asymmetric Photocyclization of a Photochromic Diarylethene Derivative in Single Crystals**

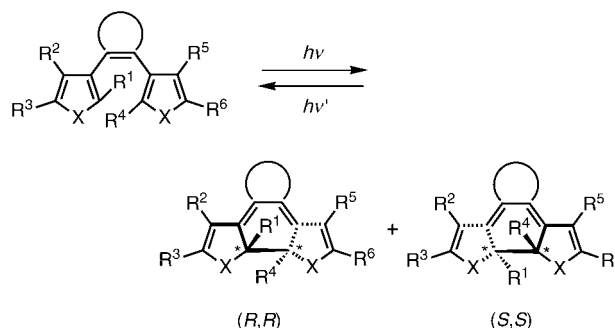
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In recent years there has been considerable scientific interest in the photochemistry of compounds in crystals.^[1] The topics

range widely from chemiluminescence in silicon nanocrystals^[2] to chemical reactivity in crystals.^[3] One unique aspect of crystal-phase reactions is topochemical reactivity. The crystal lattice provides a matrix for reactions with stereo-, regio-, and enantiospecificity. Enantiospecific reactions can take place in chiral crystals containing chiral auxiliaries such as chiral host molecules^[4] and covalently bonded chiral substituents.^[5] Moreover, an ensemble of achiral molecules can be transformed by reactions into chiral molecules on crystallization in a chiral space group. Such an asymmetric reaction in the absence of any outside chiral influence is referred to as absolute asymmetric synthesis.

The first example of absolute asymmetric synthesis, a gas/solid-phase reaction was carried out by Penzien and Schmidt.^[6] Absolute asymmetric synthesis in a photochemical intramolecular reaction was first reported by Scheffer and co-workers.^[7] The photochemical absolute asymmetric syntheses of 1,4-disubstituted phenylenediacrylate derivatives^[8] and ethyl 4-[2-(4-pyridyl)ethenyl]cinnamate^[9] are other typical examples of topochemical reactions.

Photochromic compounds characteristically exhibit two different chemical forms that are reversibly transformed from one to the other upon irradiation with light of appropriate wavelengths. Although numerous photochromic compounds have been reported, compounds that undergo reaction in the crystal phase are relatively rare.^[10] Some diarylethene derivatives undergo thermally irreversible and fatigue-resistant photochromic reactions even in single crystals. The photochemical conrotatory cyclization produces two enantiomeric closed-ring isomers (*R,R* and *S,S*), in which the chirality originates from asymmetric carbon atoms (Scheme 1).



Scheme 1. Photochromism of diarylethene. The photogenerated closed-ring form has two enantiomers, (*R,R*) and (*S,S*).

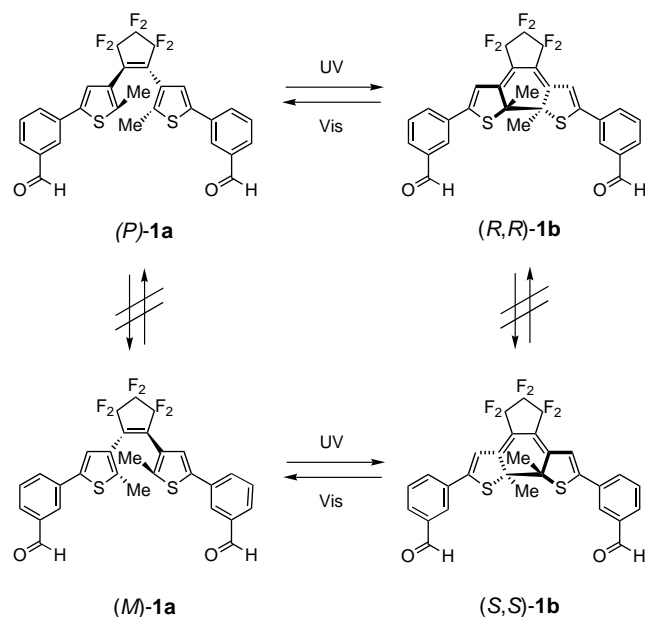
The photocyclization of diarylethene derivatives in solution, in general, results in the formation of two enantiomers in equal amounts. Even when a chiral substituent is introduced into the diarylethene, enrichment of one of the diastereomers hardly takes place.^[11] Enrichment of one of the enantiomers or diastereomers in photochemical reactions requires a chiral environment like that formed on complexation to a copper(I) center having chiral ligands^[12] or chiral crystal packing induced by a chiral substituent.^[13] If the open isomers would crystallize with chiral packing, absolute asymmetric photochromism, in which achiral compounds produce chiral products in the absence of any external chiral

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agent, would be possible. Herein we report on the absolute asymmetric photocyclization of achiral 1,2-bis(5-*m*-formylphenyl-2-methyl-3-thienyl)perfluorocyclopentene (**1a**) in chiral crystals (Scheme 2).



Scheme 2. Enantioselective photochromic reaction of (*M*)-**1a** and (*P*)-**1a** in single crystals.

The achiral diarylethene **1a** was synthesized from 2,4-dibromo-5-methylthiophene in four steps according to previously reported methods (see Supporting Information). The formyl substituents were introduced at the *meta* positions of the two phenyl groups. The structure of **1a** was confirmed by mass spectrometry, ^1H NMR and UV/Vis spectroscopy, and elemental analysis.^[14]

Figure 1 shows the absorption spectrum of **1a** and racemic **1b** in ethyl acetate solution. Upon irradiation with 313-nm light **1a** underwent a photochromic reaction. The colorless solution of **1a** ($\lambda_{\text{max}} = 255 \text{ nm}$, $\epsilon_{\text{max}} = 45\,000 \text{ M}^{-1} \text{ cm}^{-1}$) became blue, and the absorption maximum was observed at 588 nm ($\epsilon_{\text{max}} = 15\,000 \text{ M}^{-1} \text{ cm}^{-1}$). The color change is due to the generation of the closed-ring isomer **1b**. The conversion

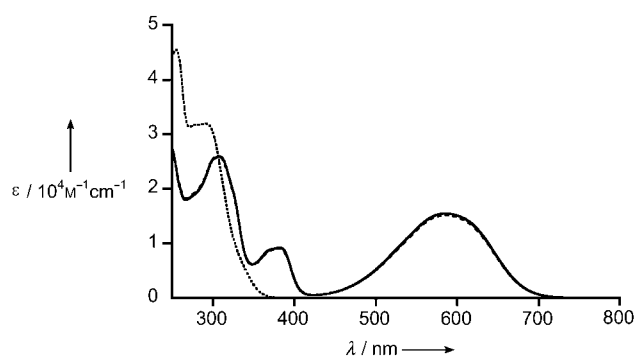


Figure 1. Absorption spectra in ethyl acetate for the open-ring isomer **1a** (.....), closed-ring isomer **1b** (—), and the photostationary state under irradiation with 313-nm light (-----).

ratio on photoirradiation with 313-nm light from the open- to the closed-ring isomer was 98 %. Upon irradiation with 578-nm light the blue solution once again became colorless, and the open-ring isomer formed.

Colorless needles of **1a** were obtained from solution in acetonitrile. The absolute crystal structure was determined by X-ray crystallographic analysis. Two different kinds of crystals, (*M*)-**1a** and (*P*)-**1a** (Scheme 2), which are mirror images of each other, were obtained in the same sample tube.^[15] Figure 2a shows the packing diagram of (*P*)-**1a**. Single crystals of (*P*)-**1a** adopt the monoclinic chiral space group $P2_1$, although no optically active unit is incorporated in the diarylethene unit. In the crystal the open-ring isomer was restricted to only one conformation in which the hexatriene unit adopted a *P* helix. The distance between the reactive carbon atoms is 3.54 Å, which is short enough for the reaction to take place in the crystal phase. The molecular configuration and packing of crystal (*M*)-**1a** is the mirror image of that of (*P*)-**1a**.

Both (*M*)-**1a** and (*P*)-**1a** underwent photochromic reaction in single crystals. Upon irradiation with 366-nm light the single crystals turned blue, and the blue color disappeared upon irradiation with visible light ($\lambda > 500 \text{ nm}$). The coloration/decoloration cycles could be repeated more than 100 times without change in the crystal shape. The color of the crystal was observed under polarized light at the (001) face. Figure 2b shows the plot of absorption versus the angle of the incident polarized light at the (001) face of the chiral crystal,

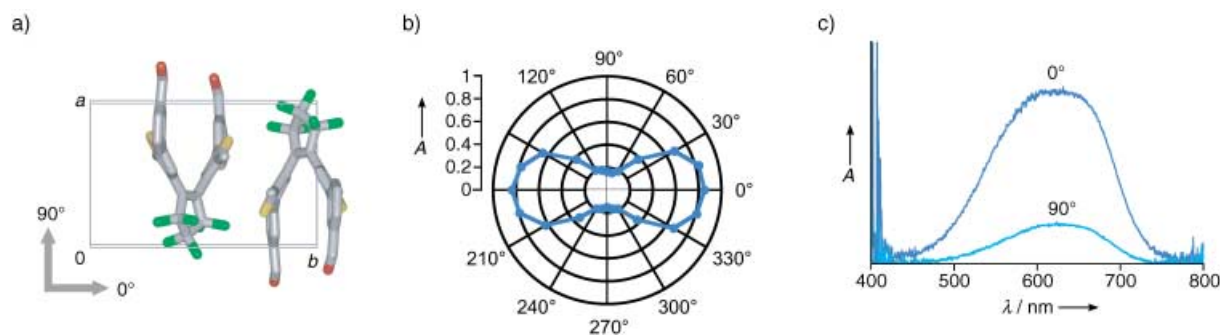


Figure 2. a) Packing diagram of (*P*)-**1a** in the chiral crystal projected to the (001) face (S: yellow; O: red; F: green). b) Plot of absorption versus angle of incident polarized light ($\lambda = 620 \text{ nm}$). c) Polarized absorption spectra of the (001) face. A = absorbance.

and Figure 2c shows the absorption anisotropy. At a certain angle the crystal has a deep color (0°). When the crystal is rotated by as much as 90° , the intensity of the color decreases. The changes of color intensity on rotating the crystal sample indicate that the closed-ring isomers are regularly oriented in the crystal and that the photochromic reaction takes place in the crystal lattice. Upon irradiation with visible light ($\lambda > 500$ nm), the crystal returns to the colorless original state.

The enantioselectivity of the cyclization process in solution as well as in single crystals of (*M*)-**1a** and (*P*)-**1a** was examined by HPLC analysis of the products with a chiral column.^[16] A monitoring wavelength of 588 nm was used, because only the closed-ring isomers have absorption in the visible region. After a solution of achiral **1a** in hexane, ethyl acetate, or ethanol had been irradiated ($\lambda = 313$ nm), a racemic mixture of the two enantiomeric products **1b** was observed; enantioselective cyclization was not observed (Figure 3a).

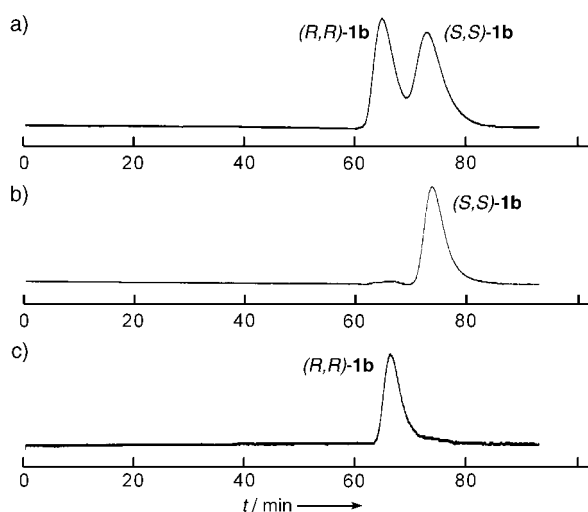


Figure 3. HPLC traces (monitored at $\lambda = 588$ nm) for the products obtained from a) the photocyclization reaction of **1a** in hexane solution, b) the photocyclization reaction in single crystals of (*M*)-**1a**, and c) the photocyclization reaction in single crystals of (*P*)-**1a**.

In the single crystals the selectivity of the photogenerated enantiomers was dramatically changed, as shown in Figure 3b and 3c. The irradiation wavelength was 400 nm. The chiral crystal (*P*)-**1a** gave optically pure (*R,R*)-**1b**, and (*M*)-**1a** gave pure (*S,S*)-**1b** by topochemical photocyclization. Table 1 shows the relationship between conversion and enantiomeric excess (*ee*). The reaction was still quite enantioselective up to a conversion of around 10% and decreased slightly at higher conversions. The decrease of selectivity is attributable to distortion of the crystal lattice as the reaction proceeds.

Direct observation of the photocyclization process by using an in situ X-ray crystallographic method^[17] would be very helpful to understand the details of the enantioselective reaction along with topochemical photocyclization in the crystal phase. To study the reaction process by X-ray crystallography, we required a conversion higher than 5%. At $\lambda = 400$ nm the chiral crystals (*M*)-**1a** and (*P*)-**1a** have an

Table 1: Asymmetric induction in the photochromism of crystals of (*P*)-**1a** and (*M*)-**1a**.

Conversion [%] ^[a]	<i>ee</i> [%] ^[b,c]	Chirality
12.0	94	(<i>R,R</i>)
10.8	96	(<i>S,S</i>)
7.9	97	(<i>R,R</i>)
7.3	95	(<i>R,R</i>)
4.3	93	(<i>S,S</i>)
1.8	96	(<i>R,R</i>)
1.7	98	(<i>S,S</i>)
0.6	99	(<i>R,R</i>)

[a] Determined by HPLC (monitored at $\lambda = 310$ nm) with a Wakosil 5SIL column and eluting with dichloromethane. [b] Determined by HPLC (monitored at 588 nm) with a Chiralpack AD-H column and eluting with hexane/2-propanol/ethanol (99/0.9/0.1 volume ratio). [c] The error of the *ee* values was less than $\pm 2\%$.

absorption tail, and the absorption of the closed-ring isomer is minimum. Thus, we irradiated the (100) face selectively with polarized light ($\lambda = 400$ nm) for 80 h.^[17f,g]

The final molecular structure of the closed-ring isomer (*R,R*)-**1b** and the structure of the open-ring isomer (*P*)-**1a** are shown in Figure 4. The positions of the sulfur atoms S1B and

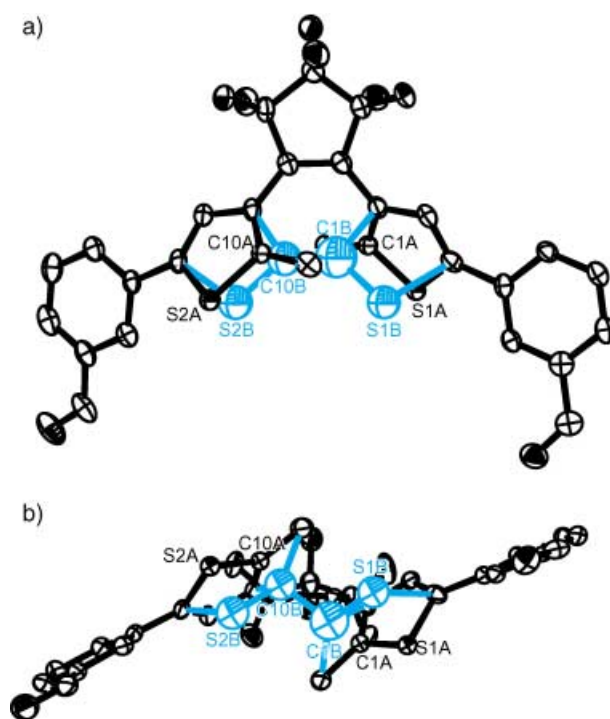


Figure 4. X-ray crystal structure of (*P*)-**1a** after irradiation with 400-nm light: a) top and b) side views (ORTEP drawings). Blue atoms and bonds represent the photogenerated closed-ring moieties of (*R,R*)-**1b** whose occupancy was estimated to be roughly 9%. Hydrogen atoms are omitted for clarity.

S2B and carbon atoms C1B and C10B, which are affected by irradiation, were found (see Supporting Information). The structure change indicates that the topochemically controlled cyclization reaction proceeds in the crystal lattice of open-ring

isomer (*P*)-**1a**. The yield of the photogenerated (*R,R*)-**1b** was estimated from the occupancy factors to be approximately 9%.

In conclusion, chiral crystals of (*M*)-**1a** and (*P*)-**1a** were obtained by recrystallization of the achiral molecule **1a** from acetonitrile. The crystals underwent highly enantioselective photocyclization, while racemic mixtures were obtained for the reaction in solution. This is the first report on absolute reversible photocyclization reactions in chiral crystals. The asymmetric photochromic material has potential application in nonlinear optics, for example, in switchable second-harmonic generation devices.

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- [14] Physical properties of **1a**: m. p. 137–138 °C; ¹H NMR (200 MHz, CDCl₃, 25 °C, TMS): δ = 2.01 (s, 6H), 7.38 (s, 2H), 7.57 (t, J = 8 Hz, 2H), 7.78–7.83 (m, 4H), 8.04 (s, 2H), 10.06 ppm (s, 2H); UV/Vis (ethyl acetate): λ_{max} (ε): 255 (45 000), 292 (32 000); MS: m/z: 576 [M⁺]; elemental analysis calcd (%) for C₂₉H₁₈F₆O₂S₂: C 60.41, H 3.15; found: C 60.28, H 3.16.
- [15] Crystallographic data for (*P*)-**1a**, (*P*)-**1a'**, which is the (*P*)-**1a** after photoirradiation for 80 h, and (*M*)-**1a**: Recorded at 123 K with MoK_α radiation: (*P*)-**1a**: a = 8.3543(18), b = 13.106(3), c = 11.347(3) Å, β = 93.389(4)°, monoclinic, space group P₂₁, Z = 2, 5592 measured reflections, 3477 unique (R_{int} = 0.0306), 354 parameters, R₁ = 0.0432 [I > 2σ(I)] and wR₂ = 0.1029 (for all data), Flack parameter χ = −0.10(9); (*P*)-**1a'**: a = 8.374(2), b = 13.050(4), c = 11.314(3) Å, β = 93.637(5)°, monoclinic, space group P₂₁, Z = 2, 8310 measured reflections, 4894 unique (R_{int} = 0.0283), 369 parameters, R₁ = 0.0442 [I > 2σ(I)] and wR₂ = 0.0948 (for all data), Flack parameter χ = −0.09(8); (*M*)-**1a**: a = 8.3543(18), b = 13.106(3), c = 11.347(3) Å, β = 93.389(4)°, monoclinic, space group P₂₁, Z = 2, 5693 measured reflections, 3536 unique (R_{int} = 0.0247), 354 parameters, R₁ = 0.0488 [I > 2σ(I)] and wR₂ = 0.1290 (for all data), Flack parameter χ = −0.02(12). CCDC-194695 ((*P*)-**1a**), CCDC-194696 ((*P*)-**1a'**), and CCDC-194694 ((*M*)-**1a**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: (+44) 1223-336-033; or deposit@ccdc.cam.ac.uk).
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