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Exclusive Photodimerization Reactions of Chromone-2-carboxylic Esters Depending on Reaction Media

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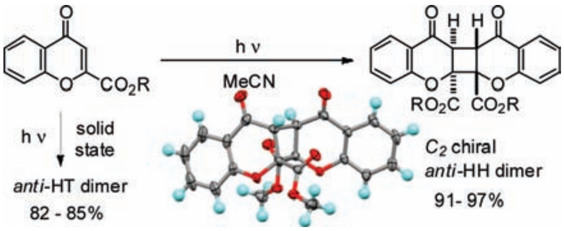
ABSTRACT



The irradiation of chromone-2-carboxylic esters resulted in the stereo- and regioselective formation of C_2 chiral *anti*-HH dimers from the triplet excited state. On the contrary, photolysis in the solid-state gave *anti*-HT dimers exclusively controlled by molecular arrangement in the crystal.

Stereoselective photochemical reactions have become key topics in organic photochemistry.[1] Many research efforts have concentrated on obtaining stereoselective photodimers using such intermolecular interactions as hydrogen-bonding, $\pi-\pi$, and cation$-\pi$ interactions. Solid-state photoreactions have also been reported for stereoselective dimerization.[2] In most cases, since several types of photodimers were produced, controlling the selectivity of the products is very hard. In rare cases, it was reported that alkyl 2-naphthoate selectively gave C_2 chiral cubane-like photodimers.[3] In another case, coumarin and thiocoumarin in an inclusion complex with a host−guest complex also gave *anti*-head-to-head dimers by the solid-state photoreaction.[4] These very rare reactions selectively lead to C_2 chiral photodimers. C_2 symmetry materials are very useful and widely used for ligands for catalytic asymmetric synthesis and synthetic materials. The development of a new reaction leading to C_2 chiral materials is strongly required.[5]

We have now found that the photolysis of 2-chromone-carboxylic esters in solution effectively gave C_2 symmetry chiral dimers exclusively in specific chemical yields; furthermore, solid-state photolysis selectively gave another type of *anti*-head-to-tail photodimers. Chromone benzo-γ-pyrone is the parent of a large number of naturally occurring compounds such as flavonoids and plant pigments. Excited simple chromone forms a triplet excited state, and most of

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(2) (a) Horspool, W. M. *Synthetic Organic Photochemistry*; Plenum Press: New York, 1984. (b) Coyle, J. C. *Photochemistry in Organic Synthesis*; The Royal Society of Chemistry: London, 1986; pp 163−188. (c) Griesbeck, A. G.; Mattay, J. *Synthetic Organic Photochemistry*; Marcel Dekker: New York, 2005; pp 141−160. (d) Yamada, S.; Uematsu, N.; Yamashita, K. *J. Am. Chem. Soc.* **2007**, *129*, 12100–12101.

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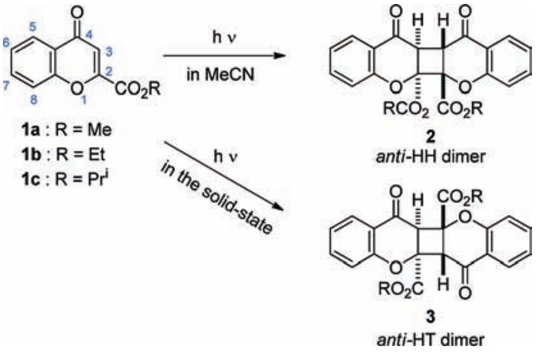
the energy is lost in the process of phosphorescence emission.[6] The irradiation of a high concentration of chromone gave two types of dimers with low efficiency.[7] We introduced an electron-withdrawing group at the 2-position that neutralized the strong push−pull character of the chromone's alkenyl group and perfectly controlled product selectivity by reaction media on the irradiation.

Scheme 1. Selective Photodimerization of Chromone-2-carboxylic Esters **1a**−**c** upon Irradiation in Solution and Solid State



Chromone-2-carboxylic esters **1a**−**c** were examined toward photolysis in the solution and the solid state (Scheme 1).[8] When a 0.05 M MeCN solution of methyl chromone-2-carboxylate **1a** was irradiated with a 500 W high-pressure mercury lamp under argon for 1 h, an effective and an exclusive dimerization reaction occurred leading to single stereoisomer **2a** in 91% yield (Table, entry 1). The irradiation of other chromone-2-carboxylic esters **1b**,**c** under the same conditions also gave identical types of dimers **2b**,**c** in 91 and 97% yields (entries 3 and 4). The structure and stereochemistry were suggested by the spectral data. The mass spectroscopy of the product indicated the dimeric structure, where four types are possible: *syn*-HT (*syn*-head-to-tail), *anti*-HT (*anti*-head-to-tail), *syn*-HH (*syn*-head-to-head), and *anti*-HH (*anti*-head-to-head). Two types of *anti*-HH and *syn*-HT dimers are C_2 chiral. Finally, the structure of *anti*-HH dimers **2a** and **2b** was unequivocally established by single-crystal X-ray crystallographic analysis (Figures S1 and S2, Supporting Information). The structure of **2c** was determined by comparison of the spectral data with those of other dimers **1a**,**b**.

Table 1. Photochemical Dimerization of **1** in Solution and Solid State

entry	compd	media	time (h)	convn (%)	yield^d (%) **2**	yield^d (%) **3**	$\Phi_{\text{dim}}{}^e$
1	**1a**	MeCN^a	1.0^b	87	91	0	0.17 (0.31)^f
2	**1a**	MeCN^{a,c}	1.0^b	97	91	0	0.22
3	**1b**	MeCN^a	1.0^b	97	91	0	0.16
4	**1c**	MeCN^a	3.0^b	76	97	0	0.11
5	**1a**	solid	40.0	80	0	85	
6	**1b**	solid	6.0	0	0	0	
7	**1c**	solid	2.0	81	0	82	

[a] Each 0.05 M of MeCN solution of **1a**−**c** was irradiated with a 500-W high-pressure mercury lamp. [b] The reaction was reached at the photostationary state in the cited irradiation time. [c] Benzophenone (BP) (0.1 M) was used as a triplet sensitizer. [d] Chemical yields were determined on the basis of consumed chromones **1a**−**c**. [e] The 365 nm line was used for quantum yield determination. [f] A 0.4 M MeCN solution of **1a** was irradiated.

The quantum yield for the dimerization was 0.17 when 0.05 M of **1a** was irradiated with a 365 nm line (Table 1, entry 1). The efficiency of dimerization was considerably influenced by the concentration of chromone, and $\Phi = 0.31$ was observed at a concentration of 0.4 M (Table 1, entry 2). All other chromone derivatives **1b** and **1c** also showed a good value above 0.11 (Table 1, entries 3 and 4).

The dimerization of chromone **1a** was effectively sensitized by triplet sensitizers such as benzophenone (BP) (entry 2), and the Φ value slightly improved more than the direct irradiation. The dimerization reaction was also effectively quenched by stilbene, indicating that dimerization proceeds from the triplet excited state, in contrast to the behavior of the excited state of simple chromone that exhibits strong phosphorescence, and ineffective dimerization proceeds from the singlet excited state.[7a] The introduction of an ester function at the 2-position of the chromone makes the dimerization more effective.

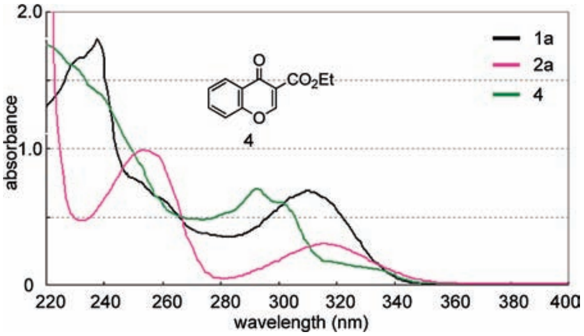


Figure 1. Absorption spectra of **1a** and **4** in each 1.0 × 10^{-4} mol L^{-1} and photodimer **2a** in 5.0 × 10^{-5} mol L^{-1} concentration in MeOH.

When ethyl chromone-3-carboxylate **4** was also irradiated under the same conditions, dimerization did not proceed. Figure 1 shows the absorption spectra of **1a**, **4**, and **2a**. Ethyl chromone-3-carboxylate **4** shows $\pi\pi^*$ absorption (280−310 nm) and $n\pi^*$ absorption bands (310−350 nm). The lowest excited state may be $n\pi^*$, which is unreactive toward dimerization. On the other hand, chromone-2-carboxyxlic esters **1a**−**c** with two electron-withdrawing carbonyl groups

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on both sides of the alkenyl group showed a $\pi\pi^*$ absorption band at 290−350 nm. The reactive $^3\pi\pi^*$ leading to dimers becomes the lowest excited state.

Next, the solid-state photodimerization reaction of **1a**−**c** was examined. Powdered **1a** sandwiched with two Pyrex glasses was irradiated at room temperature with a 500 W high-pressure mercury lamp for 40 h. At this point, 80% of the starting materials were converted to the product; fortunately, the crystallinity was maintained as such. The structure of the isolated unique dimer was different from **2a** and was determined as *anti*-HT dimer **3a** (entry 5). But **1b** was inert toward solid-state photolysis (entry 6), and the photolysis of chromone **1c** proceeded most effectively and also gave *anti*-HT dimer **3c** whose structure was unequivocally established by X-ray crystallographic analysis (entry 7 and Figure S3, Supporting Information). The structure of **3a** was determined by the comparison of the spectral data with those of **3c** and the molecular arrangement in the crystal of **1a**.

Molecular arrangement in the crystals of all chromones **1a**−**c** was analyzed by X-ray crystallographic analysis. The chromone molecules of **1a** in the crystal lattice were arranged in parallel to form *anti*-HT dimer **3a**; however, the center-to-center distance of reacting alkenyl groups was 4.09 Å, which is near the limitation of promoting 2 + 2 photocycloaddition by Schmidt's rule (<4.2 Å).[9] (Figure 2) In the case of **1b**, chromone molecules were arranged slip off each other, and reacting alkenyl groups were placed at a distance of 4.70 Å (Figure S5, Supporting Information). The packing of **1c** resembled that of **1a**, and reacting alkenyl groups were placed very closely by 3.78 Å (Figure S6, Supporting Information). These facts strongly support the following experimental results: **1b** was inert toward irradiation, but **1c** was effectively transformed to cyclobutane dimer **3c**.

All chromone dimers **2a**−**c**, **3a**, and **3c** were stable for usual handling; in particular, *anti*-HH dimers **2a**−**c** did not decompose even at melting points. Dimers also have absorption band in the longer wavelength region than monomers **1a**−**c** (Figure 1). Irradiation of a low concentration (0.005 M) of dimer **2a** with a Pyrex-filtered light quantitatively gave starting chromone **1a**. However, in the reaction of **1a**−**c**, high conversion was performed because excited dimers **2** may work as a triplet sensitizer resulting in effective dimerization of **1** (Table 1, entries 1−4).

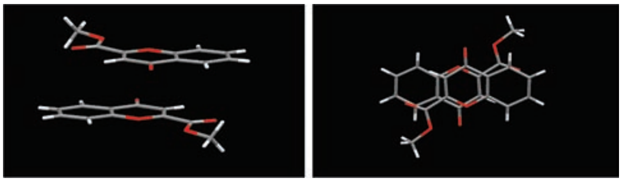

Figure 2. Packing diagram of **1a**. Center to center distance of reacting alkenyl bonds was 4.09 Å.

In conclusion, the stereoselective dimerization of chromone derivatives with an electron-withdrawing substituent at the 2-position proceeded effectively, and the dimeric structure was determined as C_2 chiral *anti*-HH stereochemistry. On the contrary, the solid-state reaction exclusively gave *anti*-HT dimers where the pathway of dimerization was controlled by the molecular arrangement in the crystal. C_2 symmetry materials are very useful and widely used for synthetic materials, especially ligands for catalytic asymmetric synthesis. This reaction provides a very useful method for synthesizing C_2 chiral materials because the photodimerization proceeded effectively and the dimers possess modifiable functional groups such as ketone carbonyl and ester groups.

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Supporting Information Available: Experimental procedures, crystal data of **1a**−**c**, *anti*-HH dimers **2a**,**b**, and *anti*-HT dimer **3c**. This material is available free charge via the Internet at http://pubs.acs.org.

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