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Role of Cation−π Interactions in the Photodimerization of *trans*-4-Styrylpyridines

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Controlling the regio- and stereoselectivities during the photocyclodimerization of alkenes is one of the key subjects in synthetic organic photochemistry.[1] To this end, much effort has been directed toward the use of various organized media and supramolecular environments, such as crystals,[2] clays,[3] cyclodextrines,[4] zeolites,[5] biomolecules,[6a] micelles,[6b] hydrogen-bonding templates,[6c] and self-assembled cages[6d] and hosts.[6e] Another approach is the employment of a molecule having a self-assembling property; however, there are few successful examples in solution except for the case using supramolecular assistance.[7]

We were interested in a reported [2 + 2]-photodimerization reaction of *trans*-styrylpyridines, in which a *syn* head-to-tail (HT) dimer is obtained as the major product only in an acidic solution.[8,9] However, this remarkable effect of the acid on the product distribution still remains unexplained. On the basis of our recent studies regarding the application of a pyridinium−π interaction toward organic synthesis,[10,11] we envisioned that the pyridinium−π interactions could be significantly responsible for the remarkable acid effect on the stereoselectivity during the photodimerization of the *trans*-styrylpyridines.

In this communication, we describe that the pyridinium−π interaction between substrates plays an essential role in the selective formation of the *syn*-HT dimer during the photolysis of *trans*-4-styrylpyridines in acidic media (Scheme 1). Furthermore, a revised structure for one of the product dimers was also proposed. In order to explore the contribution of the cation−π interaction[12] to the product selectivity, the effects of the acid concentration and the substituent on the aryl ring on the product distribution were investigated along with the structural confirmation of the product dimers by an X-ray crystallographic analysis. In addition, the differences in the X-ray packing structures of **1a** and **1a**·HCl were clarified.

The photochemical reaction of *trans*-4-styrylpyridine was first investigated under neutral conditions. Irradiation of *trans*-4-styrylpyridine **1a** in a 1.66 M methanol solution with a 450 W high-pressure mercury lamp for 17 h afforded *cis*-4-styrylpyridine **6a** as the major product with three minor dimers **2a**−**4a** as shown in Table 1 (entry 1). The photolysis in the presence of 1 equiv of concentrated hydrochloric acid resulted in remarkable changes of the product distribution (entry 2); the *syn*-HT adduct **2a** increased to become a major product along with a significant decrease in **6a**. As the amount of HCl loading increased, the *syn*-HT product **2a** dramatically increased and the *cis*-isomer **6a** decreased (entries 2−6), whereas the acid exerted little effect on the yields of **3a** and **4a**. Figure 1 clearly shows the product distribution dependence on the HCl amount. The product distribution was almost constant for more than a 3 equiv loading of HCl. This is in agreement with the ^{1}H NMR studies in which more than 3 equiv of HCl is required for protonation of the substrates. These observations indicate that the intermediate styrylpyridinium salt enhances the formation of a preorganizing head-to-tail type molecular dimer as shown in Scheme 1. The decrease in the *cis*-isomer **6a** can be explained as a result of the accelerated formation of **2a**.

Scheme 1. Selective Formation of *syn*-HT Dimer in the Presence of HCl

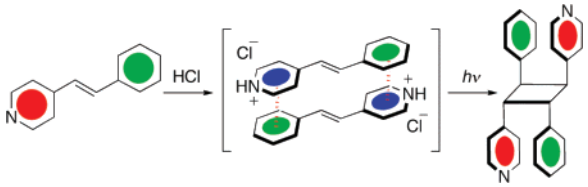
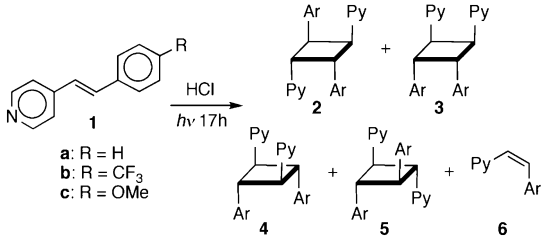


Table 1. Product Distribution of Photodimerization of **1a**−**1c**



entry	compd	HCl (equiv)	conv (%)	Products (%)[a,b] 2	3	4	5	6
1	**1a**	0	81	20	14	14	0	52
2	**1a**	1	91	50	10	14	0	26
3	**1a**	2	90	58	8	12	0	22
4	**1a**	3	96	64	13	13	0	10
5	**1a**	5	95	67	9	15	0	9
6	**1a**	10	96	71	7	14	0	8
7	**1b**	3	94	27	24	0	6	43
8	**1c**	3	94	95	2	0	0	3

[a] Determined by HPLC and ^{1}H NMR. [b] The structures of **2**−**4** were determined by X-ray crystallographic analyses; see Supporting Information.

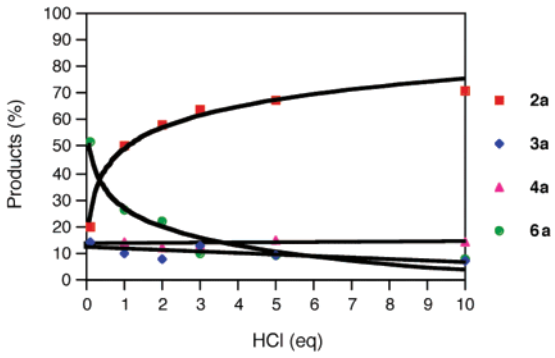


Figure 1. Product distribution dependence on the HCl amount.

Although the structures of the dimers have already been determined by ^{1}H NMR and MS spectral analyses,[9] we reinvestigated them based on an X-ray structural analysis for the first time.

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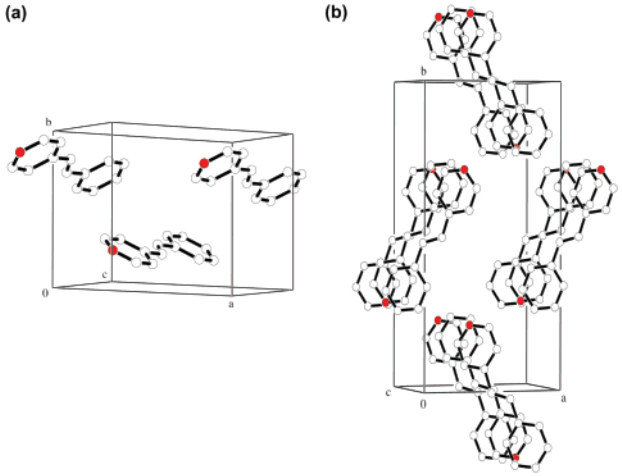

Figure 2. X-ray packing structures for (a) **1a** and (b) **1a**·HCl. Hydrogen atoms were omitted for clarity. The nitrogen atoms are indicated with a red color.

The X-ray structures proved that **2a** and **3a** were *syn*-HT and *syn*-HH dimers, respectively, which are in agreement with those reported in the literature.[9] More important, the X-ray analysis of **4a** provided a revised structure from the reported *anti*-HT to *anti*-HH.

Irradiation of compound **1b** having a strong electron-withdrawing CF_3 group in the presence of 3 equiv of concentrated HCl resulted in a significantly lower selectivity compared with the case of **1a** (entry 7); the relative yields of **2b** and **6b** are 27 and 43%, respectively. On the other hand, the photodimerization of **1c** possessing a methoxy group resulted in a significantly higher selectivity; the 95% formation of the *syn*-HT dimer **2c** was observed along with a small amount of **3c** (entry 8). The fact that the selectivity of the *syn*-HT dimer **2** is on the order of **1c** > **1a** > **1b** and that of the *cis*-isomer **6b** is in the opposite order clearly shows the important role of the electron density around the π-component in the orientation of the dimerization and the acceleration of the formation of **2**. Because an electrostatic interaction is the major force of the cation$-\pi$ interaction,[12,13] the substituent effects strongly suggest the significant contribution of the cation$-\pi$ interaction in this reaction. Although an explanation was proposed for this selectivity, in which the contribution of the charge repulsion between the pyridinium cations is the main factor,[9] this cannot satisfy the observed acceleration of the formation of **2**. Moreover, this charge repulsion model cannot explain the fact that the *syn*-HH dimer **3** decreased in the order of **3b** > **3a** > **3c**.

A comparison of the X-ray structures of **1a** and its HCl salt supported the existence of the pyridinium$-\pi$ interaction during the photodimerization. The packing diagrams of **1a** and its salt are shown in Figure 2a and 2b. Figure 2a clearly shows that the phenyl and the pyridyl groups are separated from each other and no stacking orientation is observed. On the contrary, the molecules of the HCl salts are alternately packed in an antiparallel alignment. The phenyl and the pyridinium rings are arranged face-to-face with the distance between them being 3.295 Å, suggesting the existence of the intermolecular cation$-\pi$ interaction between them. It has been reported that the photolysis of this salt in the solid state provided the *syn*-HT dimer **2a** in high yield.[14] This indicates the similarity of the alignment structures in crystal and in solution. The related pyridinium systems also show a similar head-to-tail type alignment.[15]

The excitation of a CT complex is also a powerful method for the selective photocycloaddition.[16] A charge-transfer absorption is often observed in related systems.[17] However, no CT bands were observed in the absorption spectra of the HCl salts of **1a**$-$**1c** in methanol. Recently, we elucidated the origin of the interaction between the pyridinium and the aromatic rings by ab initio calculations,[13] in which the long-range interactions, such as the electrostatic and inductive interactions, predominate. Therefore, even if a charge-transfer interaction is involved in this system, the major contributor would be a cation$-\pi$ interaction.

All of these results described here lead to the conclusion that pyridinium$-\pi$ interactions govern the alignment of the *trans*-styrylpyridinium cation in solution, the irradiation of which would result in the selective formation of the *syn*-HT dimer.

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Supporting Information Available: Experimental details and characterization of new compounds. ^{1}H NMR spectra for **4a**, **2b**, **3b**, **5b**, **2c**, and **3c**. X-ray crystallographic data and CIF files for **1a**, **1a**·HCl, **2a**, **3a**, and **4a**. This material is available free of charge via the Internet at http://pubs.acs.org.

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