



[2+2] Photodimerization of (*Z*)-4-styrylpyridine through a cation– π interaction: formation of cis–cis–trans dimers

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ABSTRACT

The cis–cis–trans cyclobutanes are prepared by photodimerization of (*Z*)-4-styrylpyridine. A catalytic amount of HCl plays a key role in enhancing the [2+2] photocyclization reactions between (*Z*)- and (*E*)-4-styrylpyridines to give *r*-*cct* and *r*-*ctc* cyclobutane dimers through a cation– π interaction.

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[2+2] Photodimerization of (*E*)-alkenes has continued to attract the interest of researchers due to the difficulty in controlling the product stereoselectivities.¹ As the preorganization of substrates is a key to attaining high selectivities in the photodimerization reactions, a variety of approaches have been extensively explored using various organized media² and supramolecular systems.³ Among the four types of cyclobutane dimers, A–D (Fig. 1), types A and B can be obtained stereoselectively by these methods and type D is often produced by dimerization of cyclic (*Z*)-alkenes;⁴ however, there have been no reports of the selective formation of type C dimers (cis–cis–trans) by direct photochemical reactions of acyclic alkenes.⁵

Recently, we reported the stereoselective photodimerization of (*E*)-4-styrylpyridines⁶ through cation– π interactions,^{7,8} in which the interaction between the pyridinium and the phenyl rings produces a head-to-tail type alignment. We speculated that the [2+2] photodimerization of (*Z*)-styrylpyridines would produce type C dimers through a cation– π interaction, although the literatures suggest that the irradiation of (*Z*)-styrylpyridines results in isomerization to (*E*)-alkenes and cyclization to benzoquinolines.⁹ In this Letter, we report that the photodimerization of (*Z*)-4-styrylpyridine (**1**) in the presence of a catalytic amount of acid provides type C dimers **2** and **3**.

Irradiation of **1** in a 1.67 M MeOH solution with a 450 W high-pressure mercury lamp for 16 h at 23 °C under neutral conditions afforded known dimers **4**–**6**⁶ accompanied with a small amount of novel *r*-*cct* and *r*-*ctc*¹⁰ dimers **2** and **3** (Table 1, entry 1). The conversion and the product ratio were determined on the basis of ¹H NMR spectra. Photolysis in the presence of 0.05 equiv of concd hydrochloric acid resulted in remarkable changes in the product distribution with the yield of dimers **2** and **3** significantly increased compared to the reaction in the absence of an acid (entry 2). The highest yields for **2** and **3** were obtained in the presence of

0.1 equiv of the acid. It is interesting that increasing the amount of HCl to more than 0.1 equiv produces a decrease in the yield of **2** and **3** accompanied with an increase in **4**. The ratio of the type C dimer to the other dimers A and B, C/(A+B), clearly shows that 0.1 equiv of HCl is the most effective concentration for the formation of the type C dimer.

The structure of the new *r*-*ctc* dimer **3** was elucidated by X-ray crystallographic analysis.¹¹ As shown in Figure 2, one pyridine ring is placed between the two neighbouring phenyl rings. Comparison of the ¹H NMR spectrum of **2** with that of **3** confirmed the structure of **2** to be *r*-*cct*. The peaks of the four methine protons appeared at δ 4.62, 4.56 and 4.31 (each triplet) with the ratio of 1:1:2, which are very close to those of **3** (δ 4.64, 4.47 and 4.35, each triplet), strongly suggesting the type C (cis–cis–trans) framework structure of **2**. In addition, the magnetic equivalence of the protons in the two pyridine rings appeared at δ 8.33 (4H, d) and 6.94 (4H, d), which also supports the presence of a *r*-*cct* structure. It should be noted that no benzoquinolines⁹ were observed under these reaction conditions.

To obtain mechanistic insights into the dimerization process, changes in the product distribution according to the irradiation time were elucidated. Figure 3 shows the plots of the yields of dimers vs irradiation time in the presence of 0.1 equiv of HCl. As irradiation time was increased, (*Z*)-**1** rapidly decreased and (*E*)-**1** increased; irradiation for 30 min resulted in a 19% consumption of (*Z*)-**1** and the formation of (*E*)-**1** in 14% yield, suggesting that the isomerization of (*Z*)-**1** to (*E*)-**1** is an initial step in the formation

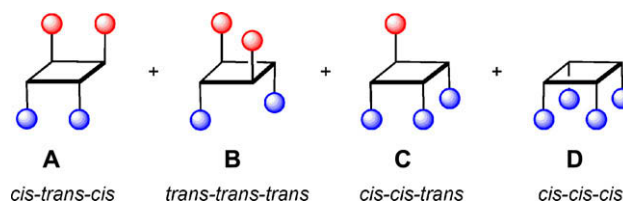
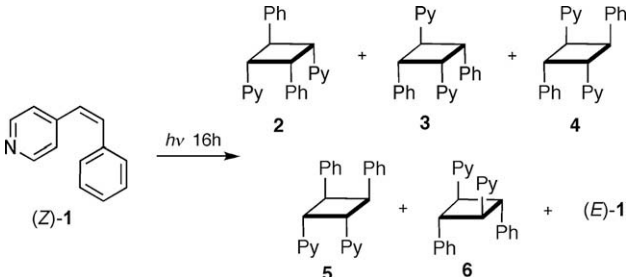


Figure 1. Schematic of four types of cyclobutane dimers.

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Table 1
UV irradiation of (Z)-1^a



Entry	HCl (equiv)	Conv (%)	Products ^b (%)						
			2	3	4	5	6	(E)-1	C/(A+B) ^c
1	0	82	6	4	33	30	13	14	0.13
2	0.05	81	24	15	31	19	4	7	0.72
3	0.1	94	32	18	33	8	5	4	1.09
4	0.3	95	25	11	36	16	6	6	0.62
5	0.5	94	20	8	43	18	7	4	0.41
6	1.0	97	9	4	55	19	9	4	0.16
7	3.0	98	0	3	61	20	13	3	0.03

^a A 1.67 M solution was employed unless otherwise noted.

^b Determined by ¹H NMR.

^c Ratio of (2+3)/(4+5+6).

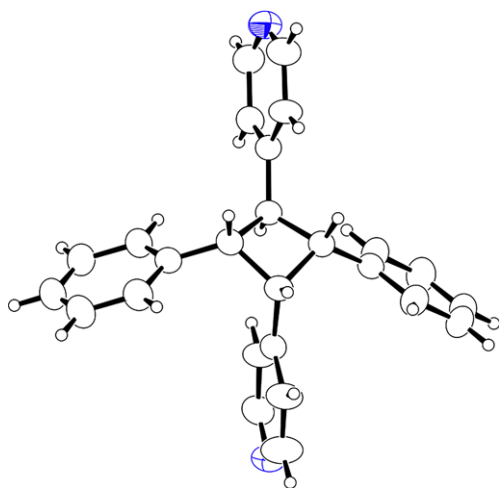


Figure 2. X-ray structure of **3**.

of the dimers. A remarkable feature is that when irradiation was continued for longer than 30 min, (E)-1 decreased with a concomitant increase in dimers **2–6**. This suggests that dimers **4–6** were produced by dimerization of (E)-1 as reported earlier⁶ and type C dimers **2** and **3** were produced from the photocycloaddition of (Z)-1 and (E)-1. The product distribution was almost unchanged when irradiation was continued for over 16 h.

It is well known that the E-Z isomerization of alkenes occurs not only by irradiation but also in the presence of an acid.¹² We confirmed that (Z)-1 is easily isomerized with hydrochloric acid; 28% isomerization was observed in the presence of 0.1 equiv of acid after 16 h. Therefore, the presence of excess acid leads to rapid isomerization of (Z)-1 to (E)-1, with a subsequent decrease in the yields of **2** and **3** (Table 1, entries 4–7). On the other hand, the photolysis of (Z)-1 in the absence of an acid also resulted in lower yields of **2** and **3** despite the relatively slower isomerization rate of (Z)-1 to (E)-1.

These observations lead to a plausible mechanism for the formation of dimers **2–6** as shown in Scheme 1. The significant effect of the

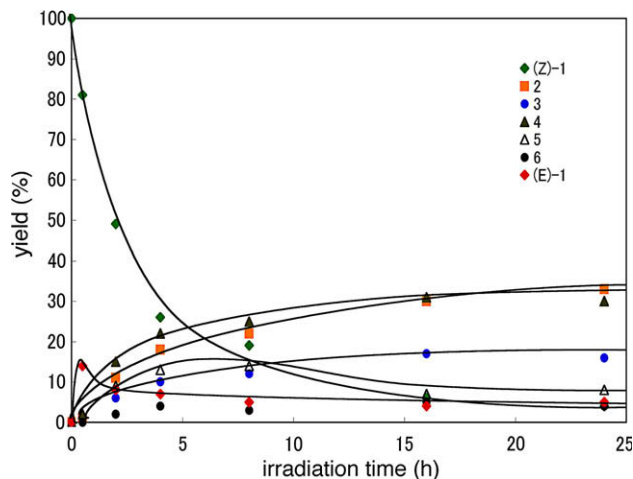
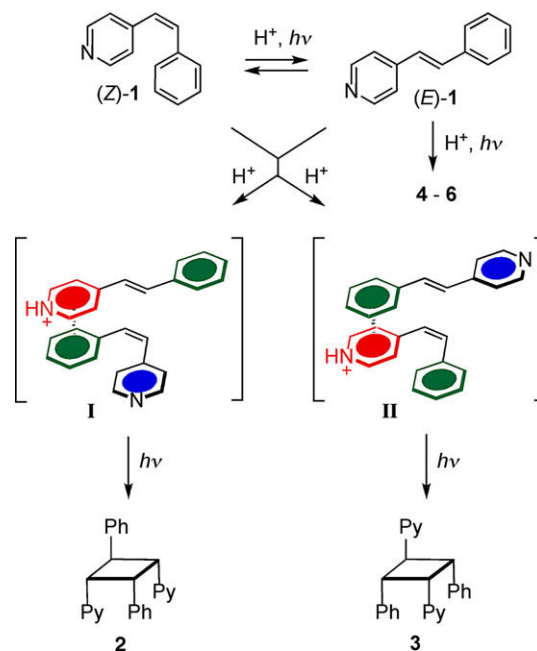


Figure 3. Plots of product yields by irradiation time.

catalytic amount of acid on the formation of type C dimers **2** and **3** suggests a contribution from the cation- π interaction between the pyridinium and phenyl rings of (Z)-1 and (E)-1. The transition models **I** and **II** are expected to result from intermolecular cation- π interactions that create favourable conditions for the [2+2] photocycloaddition reaction between (Z)-1 and (E)-1 to give **2** and **3** in acceptable yields, respectively. At the same time, the acid enhances Z-E isomerization thereby creating conditions that are unfavourable for the reaction of (Z)-1 and (E)-1. As a result, 0.1 M equiv of acid is the most effective for the production of **2** and **3**.

There are several reports for the synthesis of type C dimers from acyclic alkenes.^{13–16} In these cases, however, except for the intramolecular photocycloaddition of tethered styrylpyridines,¹³ the dimers were produced by the isomerization of type A and B dimers with TFA¹⁴ or strong bases.^{15,16} On the other hand, in the present reactions no isomerization was detected for dimers **4** and **5** in a 3.0 M HCl solution. To the best of our knowledge this is the first synthesis of type C dimers by direct photodimerization of acyclic alkenes.



Scheme 1. Plausible pathway for the formation of dimers.

In conclusion, we have found that *r*-cct and *r*-ctc dimers **2** and **3** were directly produced by [2+2] photocycloaddition of (*Z*)-4-styrylpyridine through a cation– π interaction. A catalytic amount of hydrochloric acid plays a key role in the formation of cation– π complexes between (*Z*)-**1** and (*E*)-**1**, which enables the synthesis of cis–cis–trans dimers that cannot be obtained by general photocycloaddition reactions.

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Supplementary data

Supplementary data (experimental details, ¹H NMR spectra of **2** and **3**, and single crystal X-ray analysis of **3**) associated with this article can be found, in the online version, at [doi:10.1016/j.tetlet.2010.03.005](https://doi.org/10.1016/j.tetlet.2010.03.005).

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