ORGANIC LETTERS

2005
Vol. 7, No. 10
1895−1898

Large Molecular Motions Are Tolerated in Crystals of Diamine Double Salt of *trans*-Chlorocinnamic Acids with *trans*-1,2-Diaminocyclohexane

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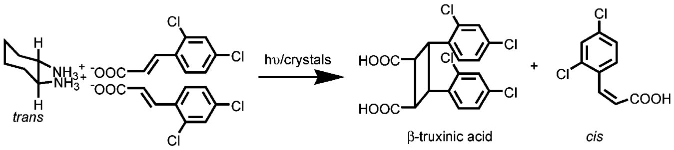
Received February 16, 2005

ABSTRACT



Contrary to the general assumption that photoreactions in crystals may not proceed with large molecular motions, a pedal-like motion prompted by electronic excitation is believed to be involved during the *β*-dimer formation from the crystals of the diamine double salt of *trans*-2,4-dichlorocinnamic acid and *trans*-1,2-diaminocyclohexane.

The pioneering work of Schmidt and co-workers that laid the foundation of solid-state bimolecular reactions has led to extensive investigation of the [2 + 2] photodimerization of cinnamic acids.[1] *trans*-Cinnamic acids crystallize in three polymorphic forms, namely, α, *β*, and *γ*, and exhibit distinct crystal-packing-dependent photochemical behavior.[2] Of the several strategies to explore aligning molecules in the crystalline state, the latest one involves the use of templates to orient guest molecules to favor photodimerization.[3]

During the course of the investigation of template-designed photodimerization of *trans*-cinnamic acids, we came across reactions that involve large molecular motions in the crystalline state, clear exceptions to the generally held notion that solid-state reactions involve very little motion.[2,4] Results of this study are presented in this Letter.

Using 1,2-*trans*-diaminocyclohexane as a template, we have explored the possibility of obtaining chiral *δ*-truxinate from *trans*-cinnamic acids. Whereas the α- and *β*-dimers

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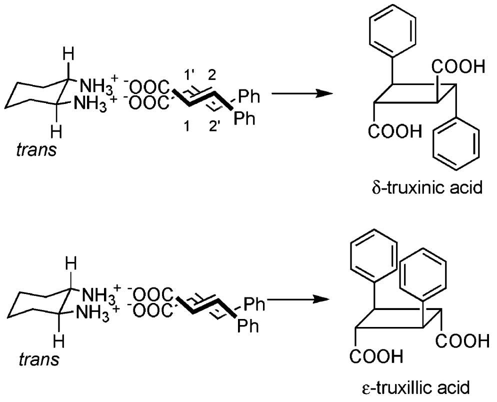
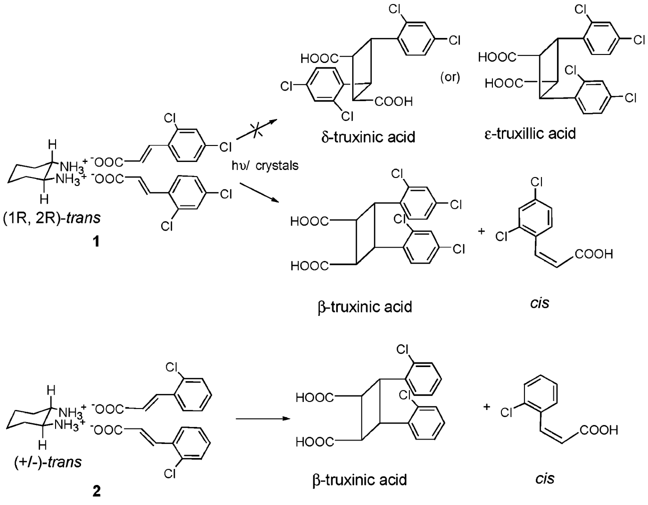
10.1021/ol050330u CCC: $30.25

result from α and β packing, respectively, formation of δ- and ϵ-dimers requires crisscross alignment of the alkene chromophore.[3e] The cycloadditon of 1,1′ and 2,2′ leads to δ-dimer, and the cycloaddition of 1′,2 and 1,2′ leads to ϵ-dimer as depicted in Scheme 1. Irradiation of the diamine double salt **1** formed between 1,2-*trans*-(*R*,*R*)-diaminocyclohexane and *trans*-2,4-dichlorocinnamic acid produced the mirror symmetric β-dimer instead of the anticipated δ- and/or ϵ-dimer (Scheme 2). Similar irradiation of diamine double salt **2** formed between 1,2-*trans*-(±)-diaminocyclohexane and *trans*-2-chlorocinnamic acid resulted in the cis isomer as the major product.[5] Both reactions as described below involve large molecular motions in the crystalline state.

Scheme 1



Scheme 2



The diamine double salts **1** and **2** were prepared by mixing 2 equiv of cinnamic acids and 1 equiv of 1,2-diaminocyclohexane in methanol/ether solution followed by evaporation of the solvent. The stoichiometry of the double salt was determined using ^{1}H NMR. X-ray-quality single crystals of diamine double salts **1** and **2** were obtained by recrystallization in ethanol and acetonitrile, respectively. The melting points of salts **1** and **2** are 145−152 and 118−122 °C, respectively. The crushed crystals of salts **1** and **2** were sandwiched between Pyrex plates, sealed with Parafilm and irradiated using a 450 W medium-pressure mercury arc lamp. Irradiation of the salt at high temperatures (50, 65, and 75 °C) was carried out by placing this setup on a hot plate. The temperature of the hot plate was monitored using a thermocouple. The crystals neither melted nor decomposed during irradiation at these temperatures. The products were isolated as acids by addition of aqueous HCl and converted to methyl esters (cis isomers and dimers) by the addition of diazomethane.

The *trans*-2,4-dichlorocinnamic acid packs in the β form in the crystalline state leading to the mirror symmetric β-truxinate.[1a] The X-ray structure revealed the packing of neighboring molecules to possess a short distance of 3.77 Å (Figure 1).

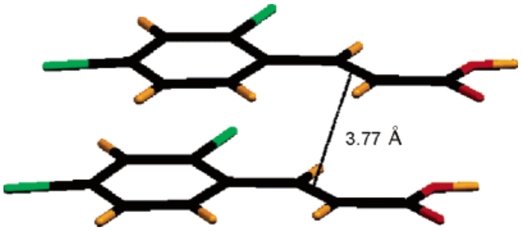


Figure 1. Packing of *trans*-2,4-dichlorocinnamic acid in the β-form in the crystalline state.

Contrary to the literature report[3e] on the photoreaction of diamine double salt of *trans*-cinnamic acid with *trans*-1,2-diaminocyclohexane, which gave predominantly the ϵ-truxillate, irradiation of salt **1** yielded β-truxinate as the major product (49% at 57% conversion) along with the cis isomer (6%) and δ-truxinate (2%) (Scheme 2, Table 1). The

Table 1. Time- and Temperature-Dependent Study for the Formation of Cis vs β-Dimer on Photolysis of Salts **1** and **2**

temp (°C)	duration of irradiation (h)	% conversion	β-truxinate (%)	cis (%)	δ-dimer (%)
		salt **1**			
rt	3	8	7	1	
rt	12	35	30	4	1
rt	21	45	38	5	2
rt	32	57	49	6	2
		salt **2**			
0	10	4	0	4	0
rt	10	19	2	16	1
40	10	23	3	19	1
65	10	26	3	22	1
70	10	34	4	28	2

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[5] As the photoreaction of chiral salt **1** produced chiral δ-dimer only in 1−2% yield, the salt **2** was made using (±)-*trans*-1,2-diaminocyclohexane.

increased yields of the β-truxinate and the cis isomer upon irradiation of **1** at elevated (50, 65, 75 °C) temperatures suggest a faster reaction.

To investigate the origin of the major product, β-truxinate, the crystal structure of salt **1** was determined. The X-ray crystal structure analysis of the diamine double salt **1** revealed the reactive olefins to be crisscrossed and the distances between the ends of the alkenes to be unequal (3.39 and 4.55 Å, Figure 2). β-Dimer formation requires both the reactive olefins to be aligned in a parallel fashion. Therefore, a conversion of the crisscrossed olefins to a parallel alignment must have occurred prior to dimer formation.

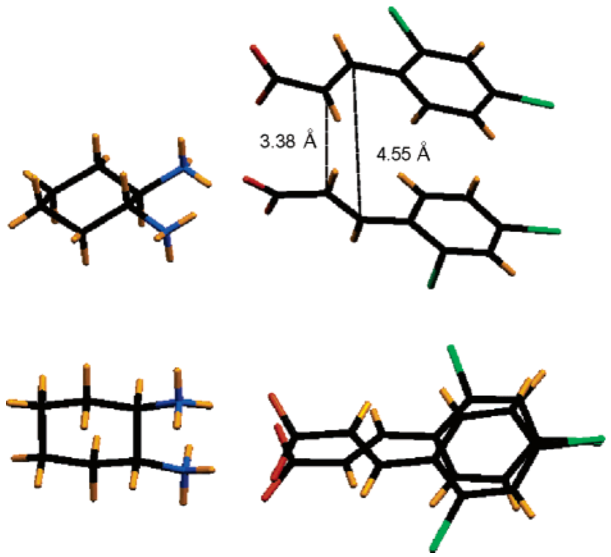
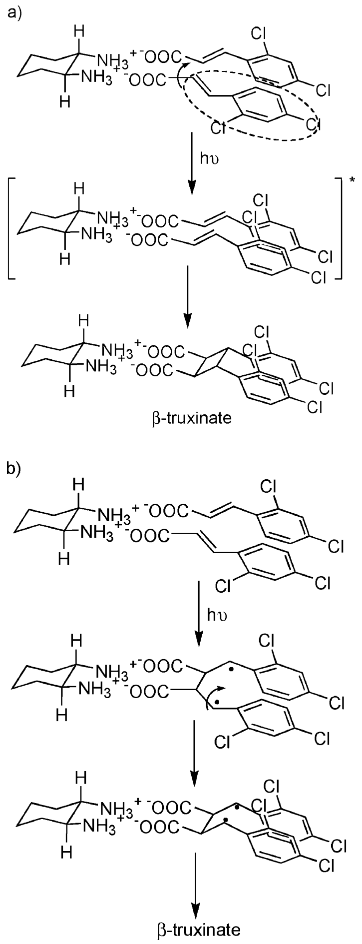


Figure 2. (a) Crystal structure of diamine double salt **1** showing alkene distances. (b) Crystal structure of salt **1** viewed along the "a" axis showing a crisscross alignment of olefins.

We speculate that such a converison is prompted by a pedal-like motion of one of the olefins of the salt prior to dimer formation (Scheme 3a).[6] This type of motion has been reported previously during the photoreaction of the hydrogen bonded complex between *trans*-cinnamamide and phthalic acid in the crystalline state.[7] The formation of the cis isomer (from trans−cis isomerization) along with the β-dimer suggests a "loose" packing that would allow a large degree of motion of the reacting olefin. The possibility of large crankshaft-type motion in crystals of highly congested bis-(triarylmethyl)peroxide has been reported by Garcia-Garibay and co-workers.[8] The possibility of dynamic disorder through C−C rotations in the crystals of *trans*-stilbene has been noted by Ogawa and co-workers.[9] Thus, rotations of parts of molecules in crystals, although uncommon, are not unknown.

Scheme 3



At least four possible mechanisms could be visualized for the formation of β-dimer: (a) Defect sites where the two olefins are prealigned in favor of the β-dimer function as the loci of dimerization. (b) Addition occurs by a concerted supra−supra process in the excited state. (c) Excitation prompts rotation of one olefin to yield the arrangement shown in Scheme 3a. This excited pair (excimer) dimerizes in a concerted fashion. (d) The [2 + 2]-photodimerization is a stepwise process, initiated by the covalent bond formation between the olefinic carbons at the shorter ends (3.39 Å) to form a biradical intermediate (Scheme 3b). Rotation of one of the 2,4-dichloro ethyl benzyl radicals followed by ring closure would lead to the β-truxinate. We believe that our results cannot be accommodated by mechanisms a and b. Unless defects of the same type are continuously generated, a high yield of a single dimer is unlikely. Concerted addition without rotation would not lead to the β-dimer. Also, the two reacting ends are not of equal distance (Figure 2a). Such an arrangement would not favor simultaneous addition at both ends. At this stage, we are unable to distinguish between the possibilities c and d.

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As noted in Table 1, the dimer is accompanied by small amounts of the cis isomer. On the basis of the study of several *cis*-cinnamic acid derivatives, Schmidt and coworkers have suggested cis−trans isomerization in the solid state to involve an unstable cyclobutane intermediate.[10] As seen in Figure 3, the ratio of the cis isomer and cyclobutane varies slightly with the temperature. Had the formation of the cyclobutane intermediate, as suggested previously, been the rate-determining step and had the dimer failed to thermally revert, one would expect the ratio of the dimer to the cis isomer to be independent of the temperature.

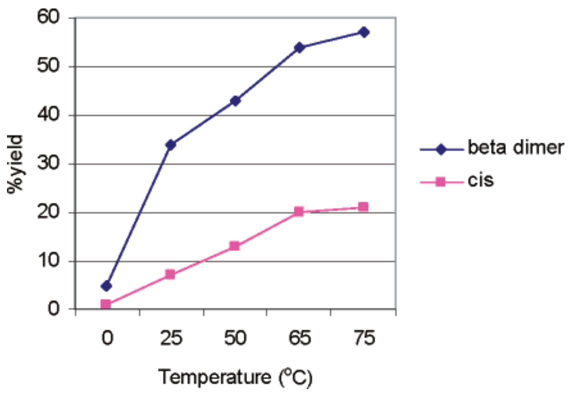

Figure 3. Temperature dependence of the cis isomer and cyclobutane from salt of **1**. The salt was photolyzed for the same duration (20 h) at all temperatures.

The photobehavior of the diamine salt of *o*-chlorocinnamic acid and (±)-*trans*-1,2-diaminocyclo-hexane **2** was quite different from that of salt **1**. Photolysis of salt **2** gave the cis isomer as the major product (26%), and both β- (7%) and δ-dimers (3%) were formed as minor products for an overall conversion of 36% (Table 1). Photolysis of salt **2** at elevated temperatures (40, 65, 75 °C) led to an increased yield of the cis isomer and the β-truxinate (Table 1). The above results suggest that the *o*-chloro cinnamate, unlike the 2,4-dichlorocinnamate, does not orient the cinnamate groups effectively for photodimerization. The lack of ordered packing of the cinnamate groups of *trans*-1,2-diaminocyclohexane salt of *o*-chloro-cinnamic acid (**2**), as evident from the crystal structure, explains the poor dimerization yield (Figure 4). The diaminocyclohexane dication is hydrogen bonded to three nearest cinnamate molecules of which two are arranged in a crisscross fashion with alkene−alkene end distances of 4.15 and 4.7 Å. The third cinnamate molecule is placed farther away, with alkene−alkene end distances of >5 Å. On excitation of **2**, due to the presence of vacant space around the molecule, the cinnamate ion can undergo geometric isomerization in the excited state, leading to formation of the cis isomer. The absence of mixed dimers from *cis*- and *trans*-olefins or homodimers from the *cis*-olefins during irradiation of salts **1** and **2** must be due to the loss of long-range order in the crystal when trans−cis isomerization occurs. Results presented above show that diamine double salts can assemble two olefins in the crystalline state. To probe whether they can do the same in solution, we are currently pursuing solution photochemistry of these salts.

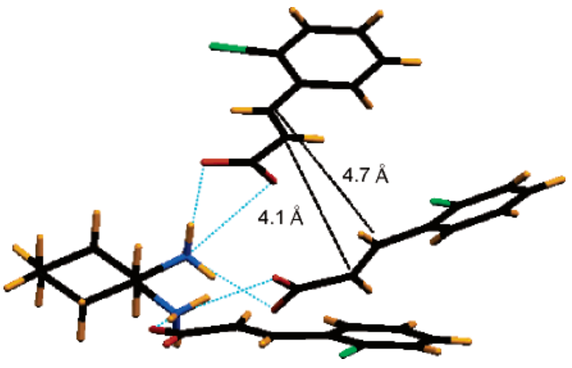

Figure 4. Crystal structure of salt **2** showing three closely lying cinnamate molecules hydrogen bonded to the *trans*-1,2-diaminocyclohexane moiety; only the closely lying cinnamate pair alkene−alkene distances are shown.

The basic solid-state chemistry principle, namely, the "topochemical postulate", was formulated on the assumption that molecules present in the crystals do not undergo large degrees of motion upon excitation. The two examples provided in this report suggest exceptions to the well accepted topochemical postulate. We and others had shown previously that for photodimerization, the olefinic bonds need not to be parallel (within 4.2 Å) to one another in a crystal.[11] In 7-methoxy coumarin, an "in plane" motion allowed the crisscrossed olefinic bonds to become parallel.[11b] In one of the examples presented here, much larger motion is needed to achieve a parallel arrangement so that dimerization could occur. Photochemistry has evolved from such exceptions to established postulates. It remains to be seen if these exceptions have any wide implications for the field.

Acknowledgment. V.R. thanks the NSF for financial support (CHE-0212042). J.T.M. thanks the Louisiana Board of regents through the Louisiana Educational Quality Support Fund for purchase of the Bruker APEX diffractometer.

Supporting Information Available: Crystal structure coordinates and tables of positional and thermal parameters, bond lengths, and bond angles; ^{1}H NMR data of salts and dimers. This material is available free of charge via the Internet at http://pubs.acs.org.

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