

A Template-Controlled Solid-State Reaction for the Organic Chemistry Laboratory

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We have devised an organic chemistry experiment that introduces undergraduates to principles of solid-state and supramolecular chemistry. Both areas, despite being relevant to a number of technologically important fields (e.g., materials science, catalysis, nanotechnology), have been slow to emerge in the undergraduate curriculum (1–3). The experiment employs molecules that act as linear hydrogen-bond templates (cf. DNA) by directing a [2 + 2] photodimerization, stereospecifically, and in near quantitative yield in the solid state (4–6). The photoreaction occurs in a solvent-free environment, does not involve byproducts, and may be induced by way of sunlight. The template molecules may also be recycled. These factors also provide an opportunity to introduce the students to aspects of the field of green chemistry (7). The experiment, which is completed in two laboratory periods, utilizes simple materials based on functional groups familiar to sophomore and advanced undergraduates, which makes the experiment readily accessible to most curricula.

Background

Geometry requirements for a molecule to undergo [2 + 2] photodimerization in the solid state have been outlined by Schmidt (8). According to Schmidt, two carbon–carbon double (C=C) bonds will typically undergo a [2 + 2] photodimerization in the solid state if the two bonds are aligned parallel and separated by less than 4.2 Å. The solid-state structure of the *pure* reactant used in this experiment, *trans*-1,2-bis(4-pyridyl)ethylene (4,4'-bpe, Figure 1A), does not conform to these two geometry criteria and 4,4'-bpe is, consequently, photostable (9).

Co-crystallization of 4,4'-bpe with an equimolar amount of resorcinol (res, Figure 1B) from a common organic solvent (i.e., ethanol) produces crystals of a supramolecular (1,

4) compound, 2(res)·2(4,4-bpe) (Figure 1C), that consists of discrete four-component hydrogen-bonded molecular assemblies. Each assembly is held together by four O–H...N hydrogen bonds. Owing to the stereochemical properties of res, the C=C bonds of 4,4'-bpe within the hydrogen-bonded assemblies are aligned parallel and separated by a distance of 3.65 Å, a suitable distance for a [2 + 2] photodimerization. Upon exposure to ultraviolet (UV) radiation from either an artificial source (e.g., UV lamp) or the sun, a single photodimer of 4,4'-bpe, namely *rac*-1,2,3,4-tetrakis(4-pyridyl)cyclobutane (4,4'-tpcb), with a structure consistent with the orientation prior to reaction in 2(res)·2(4,4'-bpe) forms in the solid state in quantitative yield (Scheme I). The formation of the photoproduct can be determined by ¹H NMR spectroscopy.

Experiment Part A: Synthesis and Photoreaction

Reagents

All reagents and solvents were used as received from Aldrich Chemical Co. unless otherwise stated. The experiment per student requires: res (0.160 g), 4,4'-bpe (0.340 g), ethanol (6 mL), 1:1 ethanol–water solution (2 mL), 10:1 ethylacetate–ethanol solution (100 mL), 1 M NaOH solution (5 mL), 10% HCl solution (5 mL), dichloromethane (60 mL), diethyl ether (60 mL), and sodium sulfate (5 g).

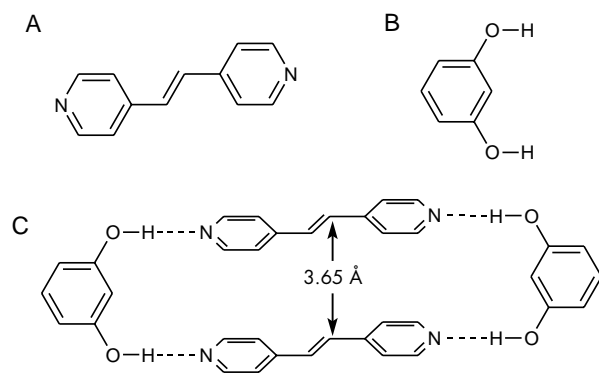
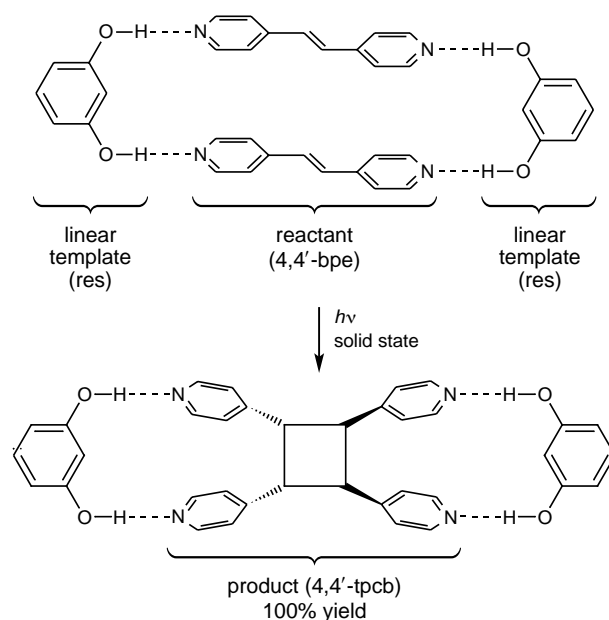


Figure 1. Structures of (A) 4,4'-bpe, (B) res, and (C) 2(res)·2(4,4'-bpe).



Scheme I. Schematic of the template-controlled [2 + 2] photodimerization of 4,4'-bpe.

Equipment

The following equipment is required: test tubes, Pasteur pipets, spatula, hot plate with magnetic stirrer, stir bar, filter flask, Büchner funnel, mortar and pestle, photocopier transparency films (suitable type and supplier: 3M transparency films for copiers, brand PP2500), masking tape, 50-mL beaker, 100-mL measuring cylinder, 125-mL extraction funnel, 25-mL Erlenmeyer flasks, 100-mL Erlenmeyer flasks, 100-mL round-bottom flasks, filter paper, rotary evaporator, ice bath, NMR tubes, thin-layer chromatography (TLC) plates (4), and a photoreactor equipped with a Hg vapor lamp (ACE Glass Inc.).

Procedure

All materials prepared and isolated during the experiment are characterized by melting point and TLC (eluent: 10:1 ethylacetate–ethanol). Samples of 2(res)·2(4,4'-bpe) before and after UV-irradiation are analyzed by ^1H NMR spectroscopy (solvent: methyl sulfoxide- d_6).

Crystallization of 4,4'-bpe

4,4'-Bpe (0.100 g) is placed in a test tube and dissolved in a hot 1:1 mixture of ethanol and water (2 mL). The solution is then quickly filtered through a cotton plug, 4.0 mL of water are added, and the mixture is heated until a clear solution is obtained. Upon standing for a period of 20–30 minutes, colorless crystals of 4,4'-bpe form and are isolated using vacuum filtration.

Crystals of 2(res)·2(4,4'-bpe)

4,4'-Bpe (0.240 g) is dissolved in hot ethanol (5.0 mL) and the solution is filtered through a cotton plug. Res (0.160 g) is then separately dissolved in hot ethanol (1.0 mL) and the resulting solution is added to the solution of 4,4'-bpe. The resulting mixture is then heated to boiling, cooled to room temperature, and left to stand for a period of approximately 20 minutes in an ice bath. Colorless crystals of 2(res)·2(4,4'-bpe) are isolated by vacuum filtration. A sample of the crystals is analyzed by ^1H NMR spectroscopy.

Photoreaction

The samples of crystallized 4,4'-bpe and 2(res)·2(4,4'-bpe) are each ground using a mortar and pestle. A portion of the ground sample of 4,4'-bpe (0.025 g) is then placed between two precut transparency films (dimensions 10.8-cm \times 14.0-cm). The films are fastened together using masking tape. The same procedure is repeated for a portion of the ground sample of 2(res)·2(4,4'-bpe) (0.100 g). The two ground samples are then irradiated for a period of approximately 18 hours in a photoreactor equipped with a 500-W broadband medium-pressure Hg lamp. The remaining ground sample of 2(res)·2(4,4'-bpe) is placed between two transparency films and exposed to sunlight for a period of approximately six hours (both winter and summer months are acceptable). The experiment can also be performed using sunlight as the sole UV source, which eliminates the need to employ a photoreactor.

Experiment Part B: Isolation and Identification of Photoproduct

Characterization of Irradiated Samples

After UV-irradiation, each sample is scraped off the transparency films using a spatula and is analyzed by TLC. The resulting chromatograms are compared to those before irradiation. The irradiated sample of 2(res)·2(4,4'-bpe) is analyzed by ^1H NMR spectroscopy.

Recovery of the Photoproduct

A sample of irradiated 2(res)·2(4,4'-bpe) (approximately 0.080 g) is placed in a small Erlenmeyer flask. A 1 M NaOH solution (5.0 mL) is then added to the flask and the mixture is heated to boiling on a hot plate with *vigorous stirring* using a magnetic stirrer. After a period of 5–10 minutes, the green solution is allowed to cool to room temperature and the product is extracted using three portions of dichloromethane (3 \times 20 mL). The organic extracts are then combined and dried over sodium sulfate. The solvent is then removed using a rotary evaporator to give 4,4'-tpcb as a yellow powder.

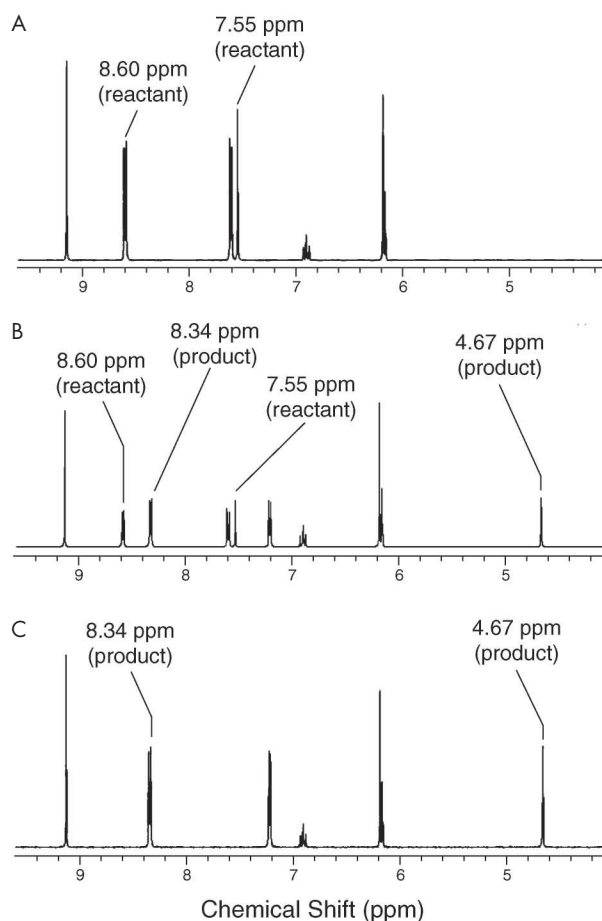


Figure 2. ^1H NMR spectra of 2(res)·2(4,4'-bpe): (A) before photoreaction (time: 0 hours, yield: 0%), (B) during photoreaction (time: 4 hours, yield: 55%), and (C) after photoreaction (time: 18 hours, yield: 100%).

Recovery of the Template

The aqueous solution remaining upon extraction of 4,4'-tpcb is acidified using 10% HCl until the solution is acidic to litmus and the color changes from green to yellow or red. The template is then extracted from the aqueous solution using three 20-mL portions of diethyl ether. The organic layers are combined, dried over sodium sulfate, and the solvent is removed using a rotary evaporator leaving the res template as a pink or red oil, which solidifies on standing. The green and red colors are the result of trace quantities of mono- and doubly-deprotonated resorcinol anions.

Hazards

The experiment involves the use of irritant (methyl sulfide-*d*₆, 4,4'-bpe), toxic (dichloromethane, res), corrosive (sodium hydroxide, hydrochloric acid), and flammable (ethanol, ethyl acetate, dichloromethane, diethyl ether) chemicals. Dichloromethane is a suspected human carcinogen. Prescribed laboratory guidelines for handling each chemical should be followed. UV light is hazardous to the eyes. Teaching assistants monitoring the reaction should wear UV glasses.

Results and Discussion

While the formation of a photoproduct from 2(res)·2(4,4'-bpe) and the photostability of pure 4,4'-bpe are easily demonstrated by a comparison of melting points and chromatograms, the identification of the photoproduct 4,4'-tpcb is determined by ¹H NMR spectroscopy (Figure 2). Specifically, comparison of the ¹H NMR spectra of 2(res)·2(4,4'-bpe) before, during, and after UV-irradiation reveals the appearance of a diagnostic singlet at 4.67 ppm, which corresponds to the methine protons of the cyclobutane ring.

Concomitant with this observation is the disappearance of the singlet at 7.55 ppm, which corresponds to the protons of the C=C bond of 4,4'-bpe. The yield of the photoreaction can be quantified by integrating the doublets centered at 8.60 ppm and 8.34 ppm, which correspond to the α-hydrogen atoms of the pyridines of 4,4'-bpe and 4,4'-tpcb, respectively. Typical yields are in the 80 to 100% range for both the photoreactor and sunlight experiments. Moreover, the emergence of the cyclobutane and pyridine protons indicates that a photoreaction leading to the formation of the C—C bonds has occurred in the solvent-free environment of the solid state. The reversible nature of the interaction between the template and reactants is demonstrated by the acid–base reaction that results in deprotonation of res and the subsequent isolation of the template. The recovery of the template illustrates that the template can be recycled.

Summary

We have described an experiment for the organic chemistry laboratory that involves a template-controlled solid-state reaction. The experiment utilizes a template to direct the assembly of an olefin in the solid state that undergoes a [2 + 2] photodimerization. The ready accessibility of the materials makes the experiment accessible to most organic curricula. The introduction of supramolecular and solid-state chemistry to undergraduates is significant in light of the increasing importance of these areas to biochemistry, materials science, and nanotechnology.

Acknowledgment

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^uSupplemental Material

Instructions for the students and notes for the instructor are available in this issue of *JCE Online*.

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