Unexpected Solid-State Photochemistry of an α-Thiophenyl-α′-Thiophenyl-*S*,*S*-dioxo-Substituted Ketone
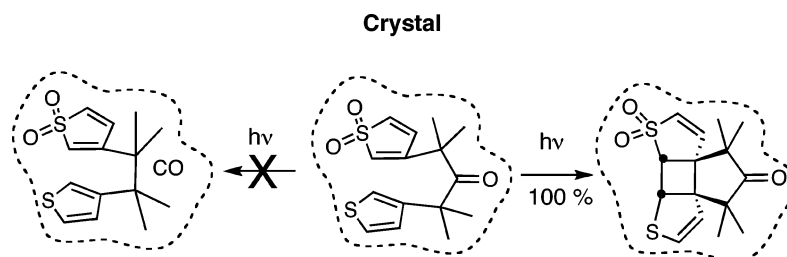
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Crystal

Samples of 2,4-dimethyl-2-(thiophen-3-yl)-4-(thiophen-3-yl-*S*,*S*-dioxo)pentan-3-one **2** were obtained by controlled MCPBA oxidation of 2,4-dimethyl-2,4-di(thiophen-3-yl)pentan-3-one **1**. Rather than the expected photodecarbonylation, UV−vis irradiation of **2** led to the intramolecular 2 + 2 photocycloaddition product **5** in quantitative yields (by GC and NMR) both in solution and in crystalline solid state. Detailed X-ray powder diffraction analyses revealed that the solid-state reaction of sulfone **2** occurs with a loss of long-range order despite retaining some birefringence under polarized microscopy.

Introduction

The photodecarbonylation of crystalline ketones is a promising method for the synthesis of structures with all carbon adjacent stereogenic quaternary centers (Scheme 1).[1] The reaction proceeds along the excited surface of suitably substituted ketones by sequential dissociation of the two α-bonds to generate two intermediate radical pairs (RP-1 and RP-2, Scheme 1). The *product*-limiting step is the loss of CO from RP-1 to give RP-2, which must be fast enough to compete with *return* to the starting material by re-forming the first broken bond. To occur in crystals, the overall reaction relies on the radical stabilizing energy of the α-substituents, which lower the activation energy of the bond-cleavage reactions.[2] While reactions in solution give mixtures of products from the free radicals

that are rapidly formed by diffusion in the high fluidity medium, reactions in crystals are highly selective, as the two radicals remain configurationally trapped within the reaction cavity formed by their close neighbors.

As part of our efforts to determine the scope of the reaction, we recently started to investigate the solid-state reactivity of ketones with heteroaromatic substituents. A recent example of this group is 2,4-dimethyl-2,4-di(thiophen-3-yl)pentan-3-one **1**, with methyl and thiophen-3-yl substituents on the two α-carbons (Scheme 2). With radical stabilizing abilities analogous to those of cumyl groups, the reactivity of compound **1** is analogous to that of dicumyl ketone, giving compound **4** in 100% yield by irradiating the solid as a nanocrystalline suspension.[3] In this paper, we report the results of our studies on the solid-state reactivity of the monosulfone derivative **2** and our attempts to prepare disulfone **3** (Scheme 2).

As indicated in Scheme 2, sulfone **2** was obtained by controlled MCPBA oxidation of **1**. Unlike dithiophene **1**, ketosulfone **2** did not undergo the expected photodecarbonylation reaction but an intramolecular 2 + 2 cyclization to form the tetracyclic compound **5** as the only product. All our attempts to prepare disulfone **3** by oxidation of **2** were unsuccessful as

(1) (a) Choi, T.; Peterfy, K.; Khan, S. I.; Garcia-Garibay, M. A. *J. Am. Chem. Soc.* **1996**, *118*, 2477. (b) Peterfy, K.; Garcia-Garibay, M. A. *J. Am. Chem. Soc.* **1998**, *120*, 4540. (c) Yang, Z.; Garcia-Garibay, M. A. *Org. Lett.* **2000**, *2*, 1963. (d) Yang, Z.; Ng, D.; Garcia-Garibay, M. A. *J. Org. Chem.* **2001**, *66*, 4468. (e) Campos, L. M.; Ng, D.; Yang, Z.; Dang, H.; Martinez, H. L.; Garcia-Garibay, M. A. *J. Org. Chem.* **2002**, *67*, 3749. (f) Ellison, M. E.; Ng, D.; Dang, H.; Garcia-Garibay, M. A. *Org. Lett.* **2003**, *5*, 2531. (g) Choe, T.; Khan, S. I.; Garcia-Garibay, M. A. *Photochem. Photobiol. Sci.* **2006**, *5*, 449.

(2) Campos, L. M.; Garcia-Garibay, M. A. Photochemical Decarbonylation of Ketones: Recent Advances and Reactions in Crystalline Solids. In *CRC Handbook of Organic Photochemistry*; Horspool, W. M., Ed.; CRC Press: Boca Raton, FL, 2003.

(3) (a) Resendiz, M. J. E.; Taing, J.; Garcia-Garibay, M. A. *Org. Lett.* **2007**, *9*, 4351. (b) Veerman, M.; Resendiz, J. M. E.; Garcia-Garibay, M. A. *Org. Lett.* **2006**, *8*, 2615.
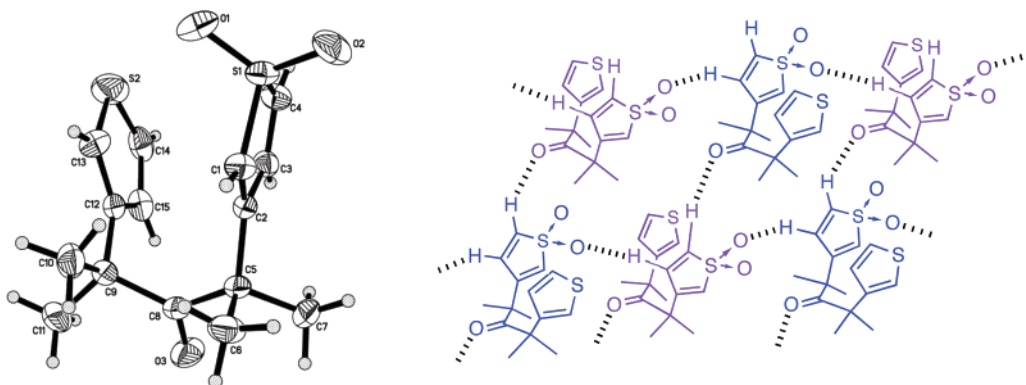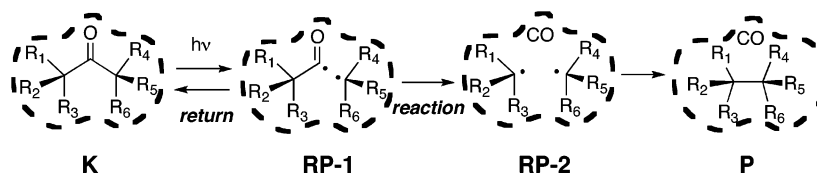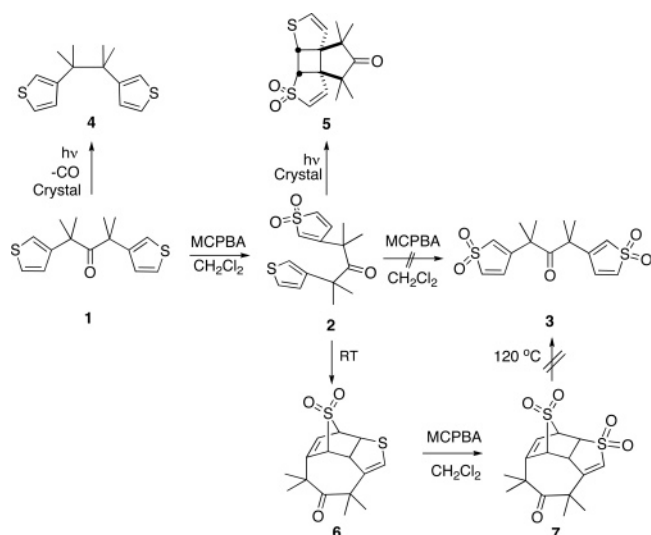
FIGURE 1. (Left) ORTEP diagram of ketosulfone **2** at the 30% probability level. The distances between C2—C12 and C1—C13 are 3.159 and 3.821 Å, respectively. (Right) Schematic of the packing structure of **2** (please see text). Space group *Cc*.

SCHEME 1

SCHEME 2

a very rapid 4 + 2 cycloaddition reaction to the tetracyclic compound **6** takes place under a variety of oxidative conditions. As indicated in Scheme 2, further oxidation of **6** led to the isolation of disulfone **7**, which failed to yield the desired ketodisulfone **3** by a retro-Diels—Alder reaction.

Results and Discussion

Synthesis. Samples of 2,4-dimethyl-2,4-di(thiophen-3-yl)-pentan-3-one **1** were prepared as reported in our previous paper[3a] and submitted to various oxidation reagents. The best conditions for the preparation of ketosulfone **2** from dithiophenyl ketone **1** involved mild oxidizing conditions with 3 equiv of *m*-CPBA for 1.5 h at room temperature.[4] Compound **2** was obtained in 30% yield as a white crystalline solid with mp = 123 °C along with ca. 70% of unreacted ketone **1** (Scheme 2). The ^{1}H and

^{13}C NMR spectra of **2** were characterized by two sets of signals for each proton and carbon, as expected from the reduced asymmetry of the structure. In addition to the C=O stretching frequency band in the FTIR spectrum, which shifted upon oxidation from 1682 to 1686 cm^{-1}, there was a set of stretching bands at 1287, 1144, and 1121 cm^{-1} that can be assigned to the O=S=O group.

We were not able to find conditions for the synthesis of ketodisulfone **3** from either **1** or **2**. Extended reaction times with **1** resulted in complex mixtures due to side reactions that included the formation of the highly crystalline 4 + 2 adduct **6** (Scheme 2) and its *S*-oxidation products. The intramolecular Diels—Alder reaction of **6** is dependent on solvent polarity with a half-life that varies from ca. 10 days in CDCl$_3$ (see page S13 in Supporting Information for more data on this experiment) to a few hours in AcOH at room temperature.[5] This observation is consistent with previously reported intermolecular reactions of thiophene 1,1-dioxides, which have half-lives ranging from 14 to 68 min at 30 °C.[6] The formation of compound **6** can be inferred by the ^{1}H NMR shift of two vinylic protons to higher field values and by the splitting of the methyl group signals from two to four peaks. The assignment of the regioselectivity was based on the well-known ability of thiophene *S,S*-dioxides (and *S*-monoxides) to act as electron-deficient dienes, with reactivity inverse to that of common Diels—Alder reactions.[7] Given that this reaction takes place while samples of **2** are left to crystallize, it was important to identify the specimens used for the solid-state photochemical experiments very carefully.

(4) Barbarella, G.; Favaretto, L.; Sotgiu, G.; Zambianchi, M.; Antolini, L.; Pudova, O.; Bongini, A. *J. Org. Chem.* **1998**, *63*, 5497.

(5) The transformation of **2** to **6** goes to completion in as little as 2 h while stirring **2** in 1:1 acetic acid/methylene chloride mixtures followed by addition of hydrogen peroxide.

(6) Nakayama, J.; Nagasawa, H.; Sugihara, Y.; Ishii, A. *Heterocycles* **2000**, *52*, 365.

(7) Various examples illustrating thiophene dioxides as four π-electron components: (a) Nakayama, J.; Sugihara, Y. *Top. Curr. Chem.* **1999**, *205*, 131. (b) Li, Y.; Thiemann, T.; Sawada, T.; Mataka, S.; Tashiro, M. *J. Org. Chem.* **1997**, *62*, 7926. (c) For thiophene *S*-monoxides acting as dienes in the [4 + 2] cycloaddition, see: Thiemann, T.; Ohira, D.; Li, Y.; Sawada, T.; Mataka, S.; Rauch, K.; Noltemeyer, M.; de Meijere, A. *J. Chem. Soc., Perkin Trans. 1* **2000**, 2968.
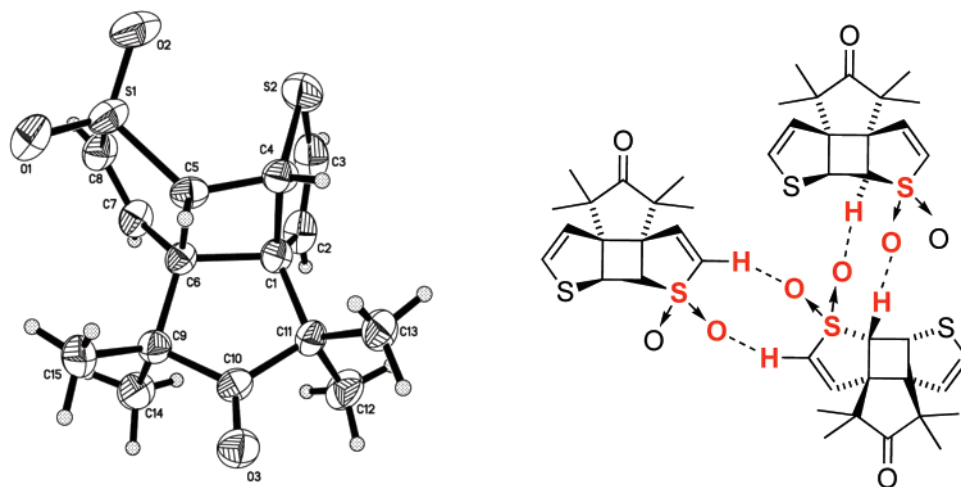
FIGURE 2. (Left) ORTEP diagram of tetracyclic cyclopentanone **5** at the 30% probability level and (right) representation of the two complementary hydrogen-bonding motifs in the packing structure of **5** with the atoms involved highlighted in red (please see text for details). Space group $P2_1/n$.

Stirring monosulfone **6** with excess *m*-CPBA at room temperature for 48 h led to compound **7** in 50% yield at high (>90%) conversion. Heptanone **7** was characterized by a shift of all the vinylic, methine, and methyl protons, and the oxidation state was assigned with the help of X-ray diffraction analysis of single crystals obtained from hexane/ethyl acetate mixtures solved in space group *Cc*.[8] In an attempt to obtain disulfone **3**, samples of **7** were refluxed in xylenes and monitored until the starting material had disappeared. This treatment yielded a complex mixture of unidentified products with no major ^{1}H NMR signals consistent with those expected for compound **3**.

Photoproduct Analyses. Photolysis on crystals of **2** reacted smoothly to give a single product in 100% conversion in a very clean solid-to-solid reaction. Notably, 50 mg scale reactions could also be completed with sunlight within 2 h and with no apparent changes in the crystalline specimens. However, the product observed in this case was not the result of the expected α-cleavage and decarbonylation, but the result of a photochemically allowed 2 + 2 cycloaddition. The 2 + 2 adduct **5** was characterized by the ^{1}H NMR shift of two vinylic signals to higher field values as well as the appearance of two additional signals arising from the newly diastereotopic methyl groups. Similarly, solutions of **2** photolyzed in benzene, acetone, or cyclohexane provided with full conversion to adduct **5** within 15 min with no side reactions detected by NMR (Scheme 2). Please refer to the Experimental Section for details on both solid-state and solution photochemical transformations.

Singe Crystal X-ray Diffraction Analysis. Successful structure elucidation by single-crystal X-ray diffraction was possible for compounds **2**, **5**, and **7**. Small crystals of compound **2** obtained by slow evaporation from diethyl ether were analyzed at 298 K, and their structure was solved in the monoclinic space group *Cc* with one molecule per asymmetric unit and four molecules per unit cell.[9] The structure of **2** reveals a molecular conformation well-suited for intramolecular 2 + 2 photodimer-

ization with close distances between the double bonds of the thiophene (C12−C13) and thiophene-*S,S*-dioxide (C1−C2) components (Figure 1). The C2,C12 and C1,C13 nonbonded distances of 3.16 and 3.82 Å are significantly shorter than the 4.2 Å suggested by the Schmidt rule for topochemical solid-state photodimerizations,[10] and the two double bonds are nearly parallel as indicated by a C1−C2−C12−C13 dihedral of only 30.1°. Analysis of the packing structure of **2** revealed that double bonds of neighboring molecules have distances that range from 5.36 to 3.72 Å and are not parallel, making the intermolecular 2 + 2 reactions topochemically forbidden. Other structural features in the packing structure of **2** include parallel layers of molecules in a two-dimensional hydrogen-bonding network made up of horizontal chains of alternating ketone enantiomers (in blue and purple in Figure 1) linked by S1(O)=O1···H−C3 bonds of neighboring thiophene dioxides. Parallel chains in the vertical direction interact by means of ketone and thiophene oxide C=O3···H−C4 hydrogen bonds. Additional close contacts, not shown in Figure 2, occur between the sulfone oxygen and a methyl group hydrogen [S1(O)=O1···H−C6] and between a sulfide C−H bond and another methyl group hydrogen [C14−H···H−C10].

Crystals of the tetracyclic cyclopentanone **5**[11] were obtained by slow evaporation from diethyl ether, and their structure was solved in the space group $P2_1/n$ with one molecule per asymmetric unit. Interesting features of this structure are the close contacts between O2−S2 (3.16 Å) and the staggered conformation of the carbonyl and methyl groups that results

(8) Crystal data for **7** at 298(2) K: $C_{15}H_{18}O_5S_2$, FW 342.41, monoclinic, space group *Cc*, $a = 8.7070(7)$ Å, $b = 26.568(2)$ Å, $c = 7.4528(6)$ Å, $\alpha = 90°$, $\beta = 116.5060(10)°$, $\gamma = 90°$, $V = 1542.8(2)$ Å^3, $Z = 4$, $\rho_{calcd} = 1.474$ mg/m^3, $F(000) = 720$, $\lambda = 0.71073$ Å, μ (Mo Kα) = 0.350 mm^{-1}, crystal size = 0.40 × 0.20 × 0.20 mm^3; of the 6572 reflections collected, 3320 [*R*(int) = 0.0156] were independent reflections; max/min residual electron density 0.9305 and 0.8320 e·Å^{-3}, $R1 = 0.0244$ ($I > 2\sigma(I)$) and $wR2 = 0.0676$.

(9) Crystal data for **2** at 298(2) K: $C_{15}H_{18}O_3S_2$, FW 310.41, monoclinic, space group *Cc*, $a = 8.1368(9)$ Å, $b = 15.1887(17)$ Å, $c = 11.840(5)$ Å, $\alpha = 90°$, $\beta = 103.075(2)°$, $\gamma = 90°$, $V = 1537.9(3)$ Å^3, $Z = 4$, $\rho_{calcd} = 1.341$ mg/m^3, $F(000) = 656$, $\lambda = 0.71073$ Å, μ (Mo Kα) = 0.350 mm^{-1}, crystal size = 0.40 × 0.30 × 0.20 mm^3; of the 6483 reflections collected, 3307 [*R*(int) = 0.0189] were independent reflections; max/min residual electron density 0.261 and −0.209 e·Å^{-3}, $R1 = 0.0370$ ($I > 2\sigma(I)$) and $wR2 = 0.0997$.

(10) Schmidt, G. M. J. *Pure Appl. Chem.* **1971**, *27*, 647.

(11) Crystal data for **5** at 298(2) K: $C_{15}H_{18}O_3S_2$, FW 310.41, monoclinic, space group $P2_1/n$, $a = 8.253(3)$ Å, $b = 13.319(5)$ Å, $c = 13.795(5)$ Å, $\alpha = 90°$, $\beta = 91.666(6)°$, $\gamma = 90°$, $V = 1515.7(10)$ Å^3, $Z = 4$, $\rho_{calcd} = 1.360$ mg/m^3, $F(000) = 656$, $\lambda = 0.71073$ Å, μ (Mo Kα) = 0.355 mm^{-1}, crystal size = 0.40 × 0.10 × 0.10 mm^3; of the 8231 reflections collected, 3108 [*R*(int) = 0.0769] were independent reflections; max/min residual electron density 0.392 and −0.317 e·Å^{-3}, $R1 = 0.0700$ ($I > 2\sigma(I)$) and $wR2 = 0.1702$.
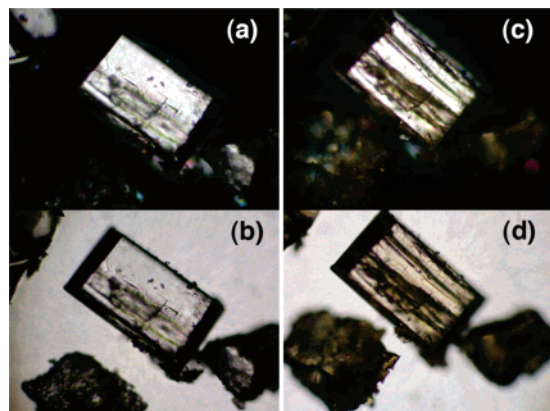
FIGURE 3. Crystals of ketosulfone **2** under cross (a and c) and parallel (b and d) polarizers before (a and b) and after (c and d) 9 h of UV irradiation. Although crystals retain their shape, translucency, and some birefringence even after 100% conversion to tetracyclic cylopentanone **5**, both single-crystal and X-ray powder diffraction indicate a severe loss of long-range order.
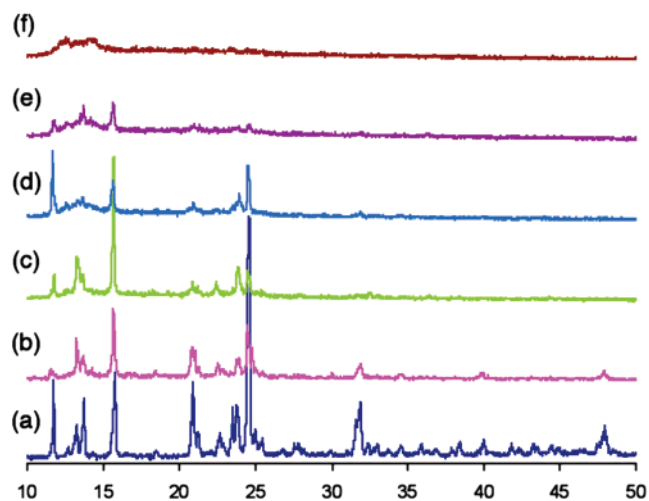

FIGURE 4. XRPD experiments on the solid-state photochemical transformation of **2** to **5** as a function of time recorded at 0, 15, 40, 75, 140, and 520 min of irradiation (bottom to top), the corresponding yields are 0, 28, 38, 50, 60, and 85% respectively.

from the highly rigid tetracyclic structure. The bond distances and bond angles are within the expected values, and the packing structure is characterized by a three-dimensional network of C=O···HC, SO···HC, and S···HC short contacts. From a total of 12 short contacts per molecule, six correspond to weak hydrogen-bond donor sites (C—H) and six to hydrogen-bond acceptor sites [C=O and S(O)=O]. The packing structure may be described as possessing two sets of dimeric and complementary hydrogen-bonding motifs (Figure 2). One involves the sulfone oxygen [S1(O2)=O1] from one molecule and a tertiary cyclobutane hydrogen (H5) from another. The other involves the second sulfone oxygen [S1(O1)=O2] and a vinylic hydrogen (H8). As expected from the acidity of C—H bonds involved in these interactions, the S1(O1)=O2···H(8)—C distance of 2.498 Å, involving a vinylic hydrogen, is slightly shorter than that of the S1(O2)=O1···H(5)—C interaction, involving an aliphatic hydrogen, which is measured at 2.507 Å. Other interactions include a weak C—H···O=C hydrogen bond involving the carbonyl oxygen and additional short contacts between the carbonyl oxygen and the thiophene sulfur with methyl group hydrogens from neighboring molecules.

Analysis of the Solid-to-Solid Photoreaction. Our initial observations with crystals of monosulfone **2** indicated a very clean reaction with a remarkably high photochemical efficiency. To our surprise, visual analysis of single crystals before, during, and after complete reaction to cage product **5** appeared to undergo no major changes in optical properties. As this observation was corroborated by optical microscopy under cross polarizers (Figure 3), we were encouraged to explore the possibility of a single crystal-to-single crystal or topotactical transformation.[12] While a molecular conformation with the proper spatial disposition of the two double bonds[13] was previously confirmed from the X-ray structure of **2** (Figure 1), it is well-known single crystal-to-single crystal reactions demand a great deal of geometric congruence between the molecular and crystal structures of both reactant and product.[14−16] That the solid-state reaction does not lead to the crystal phase of the

product obtained by recrystallization from solution was evident by comparing the single-crystal X-ray structure of **2** with that of **5**. Not only do the two structures have different space groups (*Cc* and *P*2₁/*n*, respectively) but they also have completely different packing arrangements as illustrated in Figures 1 and 2. Considering the unusual optical properties of **2**, we decided to investigate the occurrence of a single crystal-to-single crystal transformation into a different crystal phase of the photoproduct, either a stable polymorph or a metastable phase. To explore this possibility, we set out to analyze the effects of reaction progress on a powder sample of **2** by following changes in the X-ray powder diffraction pattern (XRPD). The results in Figure 4 show that the reaction is not topotactic. A set of peaks corresponding to the pure reactant (Figure 4a) slowly broaden and decrease in intensity, until ca. 30% conversion (Figure 4b). Upon further reaction, peaks corresponding to the reactant phase are displaced by a second set, suggesting a reconstructive phase transition (Figure 4c,d). Extended irradiation and increased conversion led to the subsequent broadening of the second set of peaks (Figure 4e) until the sample loses much of its crystallinity (Figure 4f), suggesting a crystalline to amorphous transformation.[17] The observations made by XRPD were confirmed by differential scanning calorimetry. The thermograms showed (1) a decrease of the melting point of the reactant, which was originally at 122 °C, (2) the appearance of a eutectic transition at 50−52 °C, and (3) the eventual disappearance of the two signals at conversion values above ca. 65%. Also evident in the thermogram of pure **2** is an exothermic transition immediately following melting (Figure 5). The former was shown to correspond to the intramolecular Diels−Alder reaction by subsequent characterization of the previously observed product **6**. A small amount of a byproduct also formed in this reaction was tentatively assigned by ¹H NMR analysis to the

(12) Friščić, T.; MacGillivray, L. R. *Kristallogr.* **2005**, *220*, 351.

(13) Schmidt, G. M. J. *J. Chem. Soc.* **1964**, 2014.

(14) Keating, A. E.; Garcia-Garibay, M. A. In *Organic and Inorganic Photochemistry*; Ramamurthy, V., Schanze, K., Eds.; Marcel Dekker: New York, 1998; Vol. 2; pp 195−248 and references therein.

(15) (a) Nakanishi, H.; Jones, W.; Thomas, J. M. *Chem. Phys. Lett.* **1980**, *71*, 44. (b) Nakanishi, H.; Jones, W.; Thomas, J. M. *J. Phys. Chem.* **1981**, *85*, 3636.

(16) (a) Gnanaguru, K.; Ramasubbu, N.; Venkatesan, K.; Ramamurthy, V. *J. Org. Chem.* **1985**, *50*, 2337. (b) Ramamurthy, V.; Venkatesan, K. *Chem. Rev.* **1987**, *87*, 433.

(17) Suzuki, T.; Fukushima, T.; Yamashita, Y.; Miyashi, T. *J. Am. Chem. Soc.* **1994**, *116*, 2793.
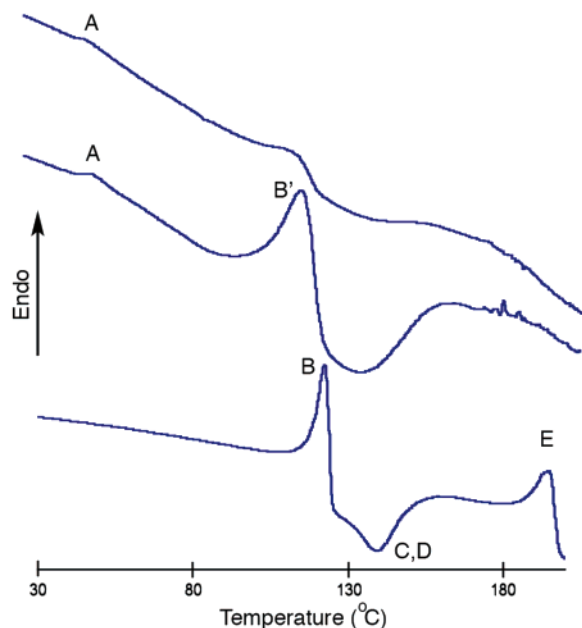
FIGURE 5. (Bottom) DSC trace of pure crystals of **2**; (middle) DSC after 40 min irradiation to give 38% of **5**; and (top) after 140 min irradiation and 58% conversion to **5**. The bottom trace shows an endothermic melting transition at 122.6° (B) followed by an exotherm assigned to the Diels−Alder reaction and crystallization of Diels−Alder adducts **6** and **8** (C and D, not resolved). The final endotherm at 195.1 °C corresponds to reduced and broadened melting of Diels−Alder adduct **6**, contaminated with a very small amount of a second product, which we tentatively identify as stereoisomer **8**. The middle and top traces feature the appearance of a eutectic endotherm (A) at 49−52 °C and show the depression and broadening of the melting transition (B′). There are no observable transitions in DSC traces obtained at higher conversion values, suggesting a transformation into an amorphous solid.
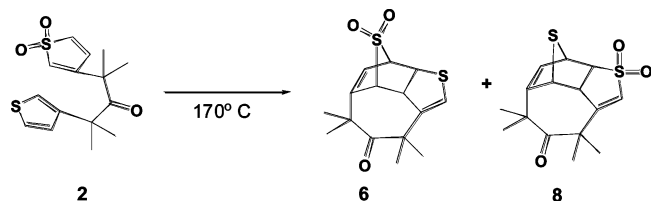

FIGURE 6. Samples of **2** heated to 170 °C provided a mixture of the isomers **6** and **8** in a 9:1 ratio.

inverse demand Diels−Alder adduct **8**. Overlapping with the reaction exotherm was another one corresponding to crystallization of a mixture of the aforementioned regular and inverse demand Diels−Alder adducts **6** and **8** (Figure 6).[18] Notably, crystalline specimens of **2** analyzed under the polarizing microscope before, during, and after the photochemical reaction retained a significant amount of birefringence and remained remarkably translucent (Figure 3).[19] While the reason for these unusual optical properties is not known at this time, the potential availability of materials that preserve their index of refraction and polarization during a chemical transformation is intriguing and potentially useful.

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(18) The NMR including the assignment of both **6** and **8**, which were obtained by heating a sample of **2** to 170 °C, is included in the Supporting Information along with the corresponding DSC trace.

(19) Similar observations were reported in: Kaupp, G.; Schmeyers, J.; Kato, M.; Tanaka, K.; Harata, N.; Toda, F. *J. Phys. Org. Chem.* **2001**, *14*, 444−452.

Conclusions

While the remarkably efficient 2 + 2 cyclization of compound **2** prevents us from drawing any conclusions on the effects of thiophene oxides on the photodecarbonylation reaction, the previously reported solid-state reactivity of dithiophenyl ketone **1** highlights the potential of the solid-state reaction for the preparation of sulfur-containing heterocycles. While controlled oxidation of one of the thiophene rings in ketone **1** to the corresponding 1,1-dioxide **2** was possible, oxidation of the two thiophenyl groups was not possible due to the dominant intramolecular Diels−Alder reactions that take place under the oxidation conditions. To our surprise, UV irradiation of 1,1-dioxide **2** led to the intramolecular 2 + 2 cycloadduct **5** in quantitative yields both in solution and in the solid state. X-ray powder diffraction and DSC analysis as a function of conversion suggested that the solid-state reaction of **2** to **5** involves a reconstructive crystal-to-crystal transition followed by a crystal-to-amorphous transformation. However, microscopic analysis revealed that single crystals preserved a high degree of translucency and birefringence, the latter suggesting some residual molecular alignment. The results with crystals of **1** highlight the fact that competing reactions, such as the intramolecular 2 + 2 dimerization of the thiophene and thiophene-*S*,*S*-dioxo moieties, can overtake what may otherwise be favorable photochemical processes.

Experimental Section

General Methods. Reagents and solvents, workup procedures, and analyses were performed in general as described in the Supporting Information.

Photoproduct Analyses. The photochemical transformation of acetone **2** going to the 2 + 2 adduct **5** was achieved in high conversions (100%) in four different manners: (1) polycrystalline powders of crystals of **2** (50−150 mg) were placed in a petri dish and irradiated with a medium-pressure Hg Hanovia lamp using a Pyrex filter ($\lambda > 290$ nm) to give **5** as the only product in the form of a powder; (2) 50 mg scale reactions of crystals of **2** were photolyzed at UCLA when the UV index was greater than 9 (UVA and UVB cover wavelength ranges of ~290−320 and 320−400 nm, respectively, which are efficient at causing decarbonylation; UV indexes may vary throughout the photolysis period: (a) http://www.weather.com, (b) http://www.epa.gov/sunwise/uvcalc.html, (c) http://www.theozonehole.com); (3) in dilute solutions as described below (synthesis of **5**); (4) using single crystals as described below (synthesis of **5**).

Synthesis of 2,4-Dimethyl-2-*S*,*S*-(thiophen-3-yl)oxide-4-(thiophen-3-yl)pentan-3-one (2). A 250 mL round-bottom flask was charged with ketone **1**[4a] (1.5 g, 5.39 mmol) and 3-chloroperoxybenzoic acid (2.79 g, 16.17 mmol); 180 mL of dry CH_2Cl_2 was added and stirred for 24 h at room temperature, then washed with aqueous NaOH, and the organic layer was dried over $MgSO_4$. Purification of the residue by column chromatography (silica, $CH_3COOC_2H_5$/hexanes = 15:85) resulted in 0.53 g (1.71 mmol, 32% yield) of **2** as a white crystalline powder, mp = 123 °C, along with 1.02 g (68%) recovered as the starting material **1**: λ_{max} (MeCN) 237; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.19 (dd, $J = 5.1$ Hz, 1H), 6.96 (dd, $J = 5.1$ Hz, 1H), 6.87 (dd, $J = 3.54$ Hz, 1H), 6.67 (dd, $J = 6.9$ Hz, 1H), 6.46 (dd, $J = 6.9$ Hz, 1H), 6.1 (dd, $J = 4.5$ Hz, 1H), 1.68 (s, 6H), 1.49 (s, 6H) ppm; ^{13}C NMR (125 MHz, $CDCl_3$) δ 207.9, 149.1, 147, 129.6, 128.6, 127, 124.5, 124.1, 123, 51.3, 50.4, 28.9, 25.8 ppm; IR (neat) ν_{max} 1686, 1469, 1389, 1369, 1287, 1144, 1121 cm^{−1}; MS (EI) *m/z* calcd for $C_{15}H_{18}O_3S_2$ 310.1, found 328.0 (M + NH_3^+), 125.0, 97.0; HRMS (EI) *m/z* calcd for $C_{15}H_{18}O_3S_2$ + H_2O 328.0803, found 328.000. Anal. Calcd for $C_{15}H_{18}O_3S_2$: C, 58.04; H, 5.84. Found: C, 58.55; H, 5.88. The

structure of compound **2** was confirmed by X-ray diffraction (please see Supporting Information for cif file).

Cyclobutano[4,5]thieno[3′,4′]-(2′,2″,5′5″-tetramethyl)-cyclopentanone[4‴,5‴]1‴,1‴dioxothiophene (5). Ketone **5** was obtained by photolysis of polycrystalline powders or single crystals (2 × 2 × 2 mm) of **2** (as previously described) to yield a brown-orange powder or single crystals shown by ^{1}H NMR to have proceeded to 100% conversion; alternatively, dilute solutions of **2** (3 mg, 0.009 mmol in 3 mL) in C_6D_6, $(CD_3)_2CO$, or cyclohexane provided **5** as the only product: λ_{max} (MeCN) 248; ^{1}H NMR (500 MHz, CDCl3) δ 6.97 (d, $J = 6.7$ Hz, 1H), 6.93 (d, $J = 6.7$ Hz, 1H), 6.43 (d, $J = 6.05$ Hz, 1H), 5.1 (d, $J = 6.05$ Hz, 1H), 4.56 (d, $J = 8.1$ Hz, 1H), 3.7 (d, $J = 8.1$ Hz, 1H), 1.32 (s, 3H), 1.28 (s, 3H), 1.22 (s, 3H), 1.09(s, 3H) ppm; ^{13}C NMR (125 MHz, CDCl3) δ 221.9, 138.5, 137.3, 134.8, 118.2, 71.4, 67.3, 57.5, 50.3, 48.5, 46.5, 27.1, 24.4, 22.5, 18.6 ppm; IR (neat) ν_{max} 1737, 1468, 1391, 1370, 1292, 1142 cm^{-1}; HRMS (MALDI-TOF) m/z calcd for $C_{15}H_{18}O_3S_2$ + Na 333.0595, found 333.0560. Anal. Calcd for $C_{15}H_{18}O_3S_2$: C, 58.04; H, 5.84. Found: C, 58.42; H, 6.17. The structure of compound **5** was confirmed by X-ray diffraction (please see Supporting Information for cif file).

3,6−2′,2′,7′,7′-Tetramethylcycloheptanone-4,7-epithiobenzo-[b]thiophene,3a,4,7,7a-tetrahydro-8,8-dioxide (6). Two separate procedures in the synthesis of **6** were found: The first involves stirring of compound **2** (0.050 g, 0.16 mmol) in 10 mL of CH_2Cl_2 for 48 h at room temperature. The solvent was evaporated under reduced pressure, and the residue was recrystallized from a 1:1 acetone/diethyl ether solution to give colorless crystals of **6**, mp 194 °C (95%): ^{1}H NMR (500 MHz, CDCl3) δ 6.41 (s, 1H), 5.88 (d, $J = 3.9$ Hz, 1H), 4.79 (dd, $J = 6.6$ Hz, 1H), 4.4 (d, $J = 6.3$ Hz, 1H), 4.37 (d, $J = 3.9$ Hz, 1H), 3.71 (d, $J = 4.4$ Hz, 1H), 1.37 (s, 3H), 1.36 (s, 3H), 1.30 (s, 3H), 1.29 (s, 3H) ppm; ^{13}C NMR (125 MHz, CDCl3) δ 210.1, 156.2, 144.3, 131.4, 117.2, 64, 63.9, 62.7, 53, 51.8, 47.3, 27.1, 24.8, 24.3, 23.1 ppm; IR (neat) ν_{max} 1708, 1608, 1307, 1202, 1135, 1100 cm^{-1}; MS (EI) m/z calcd for $C_{15}H_{18}O_3S_2$ 310.1, found 327.0 (M + H_2O^+), 246.0 ($-SO_2$). Anal.

Calcd for $C_{15}H_{18}O_3S_2$: C, 58.04; H, 5.84. Found: C, 58.41; H, 5.90.

3,6−2′,2′,7′,7′-Tetramethylcycloheptanone-4,7-epithiobenzo-[b]thiophene,3a,4,7,7a-tetrahydro-1,1,8,8-tetraoxide (7). Compound **7** was obtained from running the oxidation of **2** (above) over extended periods of time, typically from 24 to 72 h, and was obtained as a white crystalline solid in variable yields (5−20%): ^{1}H NMR (500 MHz, CDCl3) δ 7.25 (s, 1H), 6.21 (s, 1H), 4.99 (m, 1H), 4.94 (s, 1H), 4.45 (m, 1H), 4.34 (m, 1H), 1.27 (s, 3H), 1.23 (s, 3H), 1.19 (s, 3H), 1.17 (s, 3H) ppm; ^{13}C NMR (125 MHz, CDCl3) δ 211.1, 155.5, 146.6, 132.6, 119.5, 63.1, 61.8, 61.7, 53.1, 51.7, 45.6, 27.6, 24.7, 23.0, 22.5 ppm. Anal. Calcd for $C_{15}H_{18}O_3S_2$: C, 52.61; H, 5.30. Found: C, 53.00; H, 5.33. The structure of compound **7** was confirmed by X-ray diffraction (please see Supporting Information for cif file).

Intramolecular Diels−Alder Reaction upon Melting of Ketone 2. A sample of **2** (0.0062 g, 0.02 mmol) was heated in the differential scanning calorimeter to 170 °C at 10 °C/min, and then cooled to 25 °C to yield (by ^{1}H NMR) 91% of **6** and 9% of a second compound tentatively identified by ^{1}H NMR as isomer **8**.

3,6−2′,2′,7′,7′-Tetramethylcycloheptanone-4,7-epithiobenzo-[b]thiophene,3a,4,7,7a-tetrahydro-1,1-dioxide (8): ^{1}H NMR (500 MHz, CDCl3) δ 6.5 (d, $J = 3.7$ Hz, 1H), 5.93 (d, $J = 1.9$ Hz, 1H), 4.54 (d, $J = 2.9$ Hz, 1H), 4.1 (s, 1H), 3.9 (s, 1H), 3.8 (s, 1H), 1.37 (s, 3H), 1.36 (s, 3H), 1.32 (s, 3H), 1.31 (s, 3H) ppm.

Supporting Information Available: ^{13}C CPMAS NMR, XRPD, and DSC analyses of compound **2** and ^{1}H and ^{13}C NMR spectra of compounds **5**, **6**, and **7**. Crystallographic files (cif) for compounds **2**, **5**, and **7**. This material is available free of charge via the Internet at http://pubs.acs.org.

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