Pergamon

TETRAHEDRON

Tetrahedron 57 (2001) 6713–6719

# Absolute asymmetric β-lactam synthesis via the solid-state photoreaction of acyclic monothioimides and the reaction trajectory in the chiral crystalline environment

Masami Sakamoto,* Masaki Takahashi, Takashi Mino and Tsutomu Fujita

*Department of Materials Technology, Faculty of Engineering, Chiba University, Yayoi-cho, Inage-ku, Chiba 263-8522, Japan*

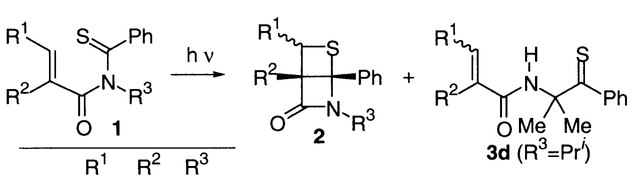
Received 13 April 2001; accepted 6 June 2001

**Abstract**—Achiral *N*-methacryloylthiobenzanilide formed (*Z,E*)-conformation of the imide moiety and crystallized in a chiral fashion. The solid-state photoreaction gave optically active β-lactam. The dynamic molecular rearrangement for cyclization was elucidated on the basis of direct comparison of the absolute configuration of both the starting material and the photoproduct. Crystal-to-crystal transformation was observed in the photoreaction of the (*E,E*)-conformation of *N*-isopropyl-*N*-tigloylthiobenzamide, which needs small atomic rearrangement for the cyclization and gave thietane stereo- and chemo-selectively. © 2001 Elsevier Science Ltd. All rights reserved.

Absolute asymmetric transformations in the crystalline state are of wide interest since they occur spontaneously in the absence of any outside chiral influence and are relevant to theories concerning the prebiotic origin of natural chirality.[1,2] Furthermore, the development of photoreaction using chiral crystals also has potential for the synthesis of optically active compounds that are difficult to prepare in other ways from the viewpoint of chemo-, regio-, and enantioselectivity.[3–13] We have reported one example involving the solid-state photoreaction of *N*-(α,β-unsaturated carbonyl)thiobenzanilide **1a** leading to optically active thietane-fused β-lactam **2a** (Scheme 1).[12] Now we have examined the details of the reaction mechanism on the basis of the correlation of the absolute–absolute configuration of both the starting materials and the photoproduct,[14] and the reaction mechanism for the 2+2 thietane formation in the solid-state.

All monothioimides except **1b**, which did not give available crystals, were subjected to X-ray single crystal analysis. Table 1 summarizes the crystal data and Fig. 1 shows the Ortep drawing of **1a** (Fig. 1a), **1c** (Fig. 1b) and **1d** (Fig. 1c). We already reported the X-ray crystal data for **1a** in a preliminary report;[12] however, the crystal was analyzed again to determine the absolute configuration.

The crystal of **1a** showed an orthorhombic crystal system and other crystals, **1c** and **1d**, were monoclinic. For the achievement of absolute asymmetric synthesis, achiral materials must crystallize in a chiral space group. Only



| | $R^1$ | $R^2$ | $R^3$ |
|---|---|---|---|
| a | H | Me | Ph |
| b | H | Me | $Pr^i$ |
| c | Me | Me | Ph |
| d | Me | Me | $Pr^i$ |

**Scheme 1.**

**Table 1.** Crystal data for monothioamides **1a**, **1c** and **1d**

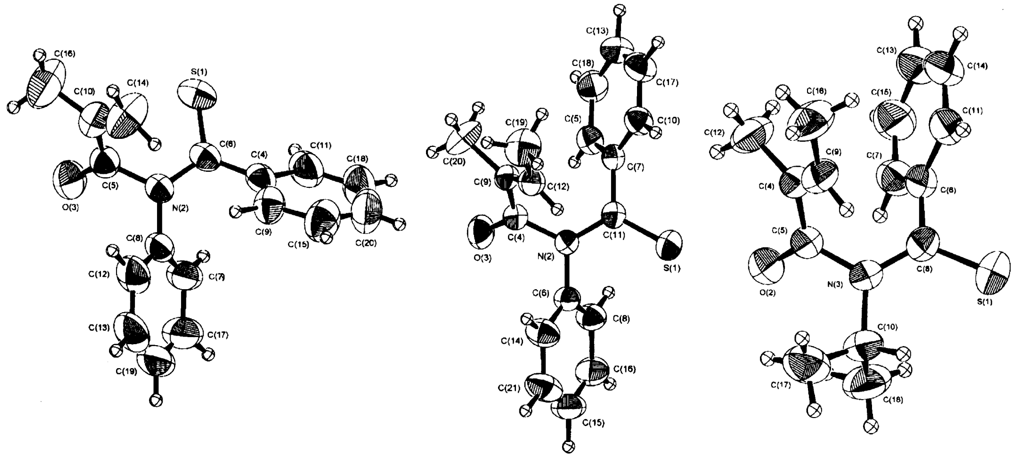
| | **1a** | **1c** | **1d** |
|---|---|---|---|
| Formula | $C_{17}H_{15}NOS$ | $C_{18}H_{17}NOS$ | $C_{15}H_{19}NOS$ |
| Mol. weight | 281.40 | 295.40 | 261.39 |
| Crystal system | Orthorhombic | Monoclinic | Monoclinic |
| Space group | $P2_12_12_1$ | $P2_1/n$ | $P2_1/c$ |
| $Z$ | 4 | 4 | 4 |
| $a$ (Å) | 9.799 (4) | 11.439 (3) | 11.081 (3) |
| $b$ (Å) | 16.439 (4) | 13.373 (4) | 9.091 (2) |
| $c$ (Å) | 9.542 (3) | 10.932 (3) | 15.051 (3) |
| $\beta$ (deg) | 90.00 (0) | 103.64 (2) | 90.85 (2) |
| $V$ (Å$^3$) | 1537.1 (9) | 1625.0 (8) | 1516.0 (7) |
| $\rho_{calc}$ (g cm$^{-3}$) | 1.216 | 1.207 | 1.15 |
| $\mu$ (Cu Kα) (cm$^{-1}$) | 17.8 | 17.4 | 18.0 |
| $F$ (000) | 592 | 624 | 560 |
| Crystal size (mm) | 0.40×0.40×0.30 | 0.30×0.20×0.20 | 0.50×0.30×0.20 |
| Used reflections | 1756 | 2996 | 2882 |
| $R$ | 0.039 | 0.044 | 0.043 |
| $R_w$ | 0.040 | 0.051 | 0.049 |

---

*Keywords*: absolute asymmetric synthesis; solid-state; photochemical reaction; chiral crystal; β-lactam.

* Corresponding author. Tel.: +81-43-290-3387; fax: +81-43-290-3401; e-mail: saka@tc.chiba-u.ac.jp

PII: S0040-4020(01)00619-6



(a) Ortep view of the absolute structure of (-)-**1a**

(b) Ortep view of **1c**

(c) Ortep view of **1d**

**Figure 1.** Ortep drawing of (−)-**1a**, **1c** and **1d**.

monothioimide **1a** was given in a chiral fashion and others crystallized in a racemic space group.[7] Each single crystal of **1a** is chiral and all molecules in one crystal are optically active, offering the same chiral configuration. A large amount of single crystals with the same chirality could be selectively prepared by seeding the desired crystals through recrystallization.

Fig. 2 shows the reflected UV and the CD spectra of the two enantiomorphic crystals of **1a** (Fig. 1a) in KBr pellets, which were independently obtained by spontaneous crystallization. These crystals gave specific curves in the region between 300 and 600 nm, which were mirror images designated as (+) and (−) at the wavelength of 470 nm. The monothioimide **1a** has no chiral center; however, the absolute structure of the chiral conformation in the chiral crystal could be established by the X-ray anomalous scattering method for the refinement of Roger's parameter (the final $\eta$ value was 0.943).[15] The Ortep diagram (Fig. 1a) exhibits the absolute structure of the chiral conformation of (−)-**1a**, which corresponds to (−)-crystal in the solid-state CD spectra (Fig. 2).

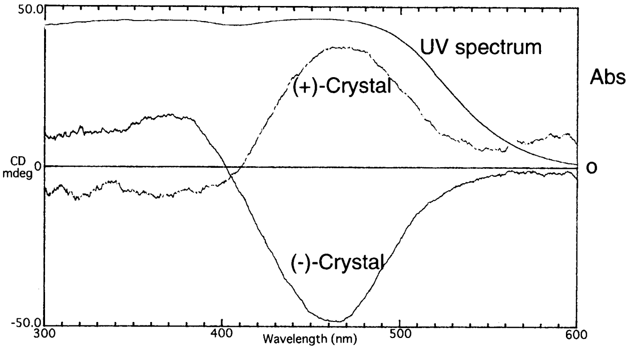


**Figure 2.** Refelected UV and solid-state CD spectra of enantiomeric crystals of both antipodes of **1a** in KBr.

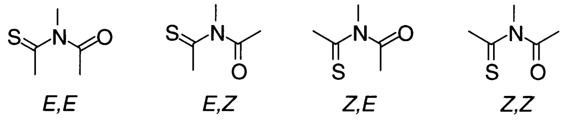
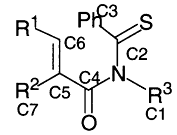


**Figure 3.** Conformation of acyclic monothioimide.

One important factor determining the reactivity involves the distribution of the stable conformation of the imides. Conformations of monothioimides are described as (*E*,*E*), (*E*,*Z*), (*Z*,*E*) and (*Z*,*Z*) based on the planar sp$^2$ nitrogen atom as shown in Fig. 3.[16] In homogeneous conditions, the conformational interconversion occurs freely, and the photochemical reaction proceeds from the preferable conformation. However, the conformational factors may play a more important role in the photochemical reactivity in the crystalline state.

**Table 2.** Geometrical data of monothioimides **1** obtained by X-ray crystallographic analysis



| Thioamide **1** | **1a** | **1c** | **1d** |
|---|---|---|---|
| Configuration of imide | *Z*,*E* | *E*,*E* | *E*,*E* |
| Twist angle of C=S[a] | 22.7 | 24.7 | 16.8 |
| Twist angle of C=O[b] | 55.7 | 38.7 | 47.3 |
| Twist angle of C=C[c] | 20.1 | 30.1 | 32.1 |
| Distance S2–C6[d] | 3.59 | 4.13 | 4.32 |
| Distance C2–C5[e] | 3.11 | 3.00 | 3.01 |

[a] Twist angle of C=S is defined as follows: $\tau=1/2(\omega1+\omega2)$, where $\omega1$ and $\omega2$ are torsion angles of C1–N–C2–C3 and C4–N–C2–S, respectively.

[b] Twist angle of C=O is defined as follows: $\tau=1/2(\omega1+\omega2)$, where $\omega1$ and $\omega2$ are torision angle of C1–N–C4–C5 and C2–N–C4–O, respectively.

[c] Twist angle of C=C is defined as follows: $\tau=1/2(\omega1+\omega2)$, where $\omega1$ and $\omega2$ are torsion angles of N–C4–C5–C7 and O–C4–C5–C6, respectively.

[d] Distance of S–C6 is the distance between the S and C6 atoms. A new bond will be formed between these two atoms.

[e] Distance of C2–C5 is the distance between the C2 and C5 atoms.

**Table 3.** Photochemical reaction of *N*-(α,β-unsaturated carbonyl)thiobenzamides **1a–d** under various conditions

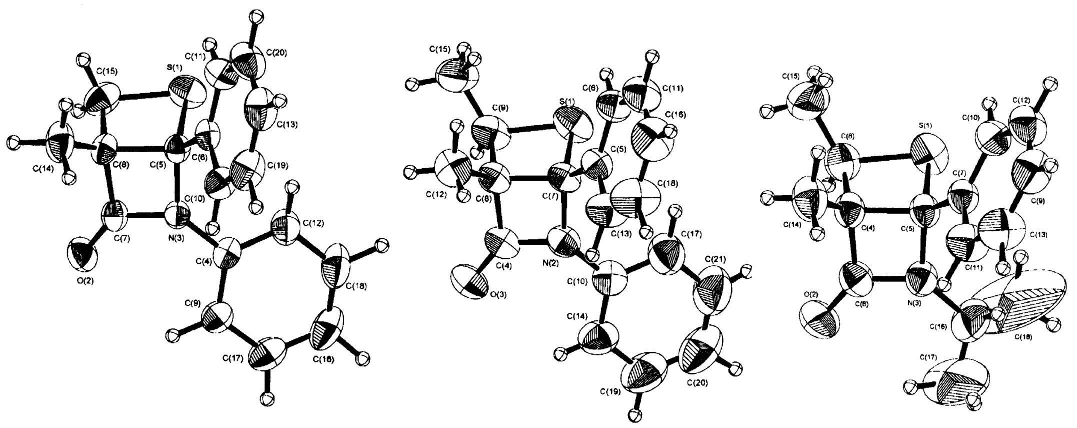
| Entry | Thiomide | Condns | Temp. (°C) | Yield of **2**[a,b] | *Syn*/*Anti* | ee (%) |
|---|---|---|---|---|---|---|
| 1 | **1a** | Benzene[c] | 15 | 77 | – | 0 |
| 2 | **1a** | Solid | 0 | 75 | – | 10 |
| 3 | **1a** | Solid | −45 | 70[d] | – | 40 |
| 4 | **1b** | Benzene[c] | 15 | 73 | – | 0 |
| 5 | **1b** | Solid | 0 | 93 | – | 0 |
| 6 | **1c** | Benzene[c] | 15 | 80 | 0.8 | 0 |
| 7 | **1c** | Solid | 0 | 92 | 10 | 0 |
| 8 | **1d** | Benzene[c] | 15 | 80 (17)[e] | 0.7 | 0 |
| 9 | **1d** | Solid | 0 | 95 | 22 | 0 |

[a] Chemical yields are isolated yeilds.
[b] The conversion yields of the reaction were 100% except entry 3.
[c] See Ref. 22.
[d] The reaction conversion was 30%, and the yield was determined on the basis of consumed **1a**.
[e] The number in the parentheses is the chemical yield of thioketone **3**, which was formed by β-hydrogen abstraction by the thiocarbonyl group.[23]

Monothioimides in (*E*,*E*)- and (*Z*,*E*)-conformation should be used for the photochemical cycloaddition leading to thietane. In these conformations it is expected that each reacting site, which will make a new bond, is placed closely. The X-ray crystallographic analyses revealed the molecular conformation in the crystal. It is notable that the conformation of the imide chromophore differs from each other in **1a–1d** owing to the alkenyl groups. The monothioimide **1a** forms (*Z*,*E*)-conformation, and tigloyl derivatives **1c** and **1d** are doped in (*E*,*E*)-conformation in the crystal. The imide plane is remarkably twisted from the ideal $sp^2$ nitrogen atom as shown in Table 2. Surprisingly, the imide chromophore slips out considerably from the ideal plane. The twist angle of C=O, which is defined as an average of the torsion angles of N–C4–C5–C7 and O–C4–C5–C6, is in the range of 38.7–55.7° and is much greater than that of the C=S moiety (16.8–22.7°).[12] This structure is consistent with the lone pair electrons of the nitrogen atom being conjugated through the thiocarbonyl rather than through a carbonyl group. The alkenyl group is slightly twisted to the amide carbonyl (20.1–32.1°). Fortunately, the direction of inclination is preferred to the cyclization with the thiocarbonyl group in all cases.

To investigate the relationship between the molecular conformation and the photochemical reactivity in the solid-state, geometrical data required for the mechanistic analyses are also collected in Table 2. With these points in mind, inspection of the geometrical data of **1** should provide further insight into the factors of lattice-controlled solid-state processes.

One of the most important parameters to determine the reactivity is the distance between the thiocarbonyl sulfur (S) and the alkenyl carbon atom (C6) in Table 2, because a new bond will be formed between these two atoms at the initial step of the photoprocess.[17,18] The actual distances of (*Z*,*E*)-conformation imide **1a** is 3.59 Å, which is closely placed and is almost the same as the sum of the van der Waals radii 3.50 Å. In the *E*,*E*-conformation, the atomic distances between (S) and (C6) are longer than that of **1a**, which are 4.13 Å for **1c** and 4.32 Å for **1d**, respectively. For the second step of cyclization, the atomic distance between the thiocarbonyl carbon (C2) and the alkenyl carbon (C5) is in the range from 3.00 to 3.11 Å, which is much smaller than the sum of the van der Waals radii 3.40 Å. From this geometrical consideration of the site of the new bond formation,



(a) Ortep drawing of the absolute structure of (+)-(1*S*,4*R*)-**2a**

(b) Ortep drawing of **2c**

(c) Ortep drawing of **2d**

**Figure 4.** Ortep drawing of β-lactams **2a**, **2c** and **2d**.

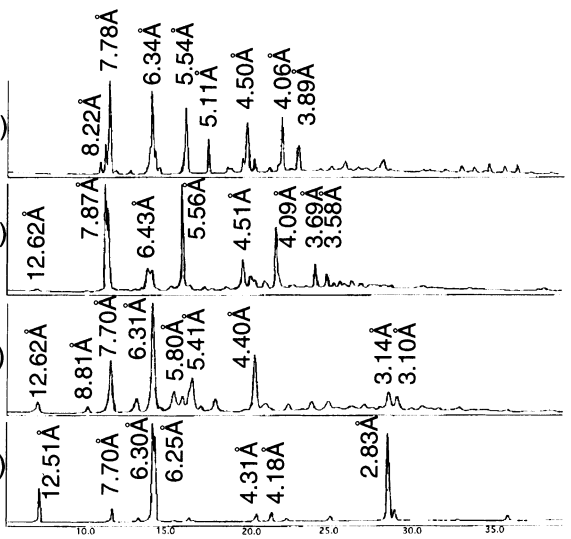
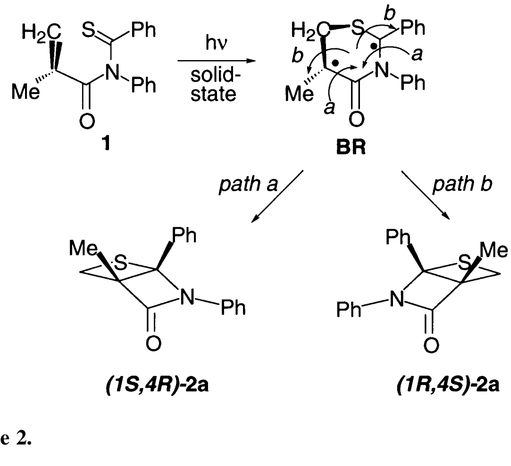


**Figure 5.** X-Ray diffraction patterns for the transformation of **1d** to **2d**, and the number on the spectra indicates interplanar spacing. (a) Starting material **1d**; (b) transition pattern (irradiated 15 min, 15% conversion); (c) irradiated crystal for 1.5 h, 100% conversion; (d) recrystallized **2d** from $CHCl_3$–hexane mixture.

it is expected that the reaction leading to thietane will smoothly progress.[19,20]

Recently, we reported the solution photochemistry for **1a**–**1d**, which gave the corresponding thietane-fused β-lactam **2a**–**d** and thioketone **3d** as shown in Scheme 1 and Table 3.[21–23] For tigloyl derivative **1c** and **1d**, β-lactams were obtained as a mixture of two stereoisomers (Table 3, entries 6 and 8). The *anti* isomers were preferably formed, in ratios of 0.8 and 0.7, respectively.

Fig. 2 shows the reflected UV spectra of the crystals of monothioimides **1a**, which indicates that the molecule absorbs photons sufficiently in the solid-state beyond 290 nm (Pyrex filtered light). X-Ray crystallographic analysis revealed that the crystal of thioamide **1a** was chiral and the space group was $P2_12_12_1$. The absolute configuration of (−)-rotatory crystals of **1a** was determined by the X-ray anomalous scattering method as (−)-(*M*)-**1a** for the helicity. The (−)-rotatory crystals obtained by the seeding method were irradiated at 0°C until the reaction conversion reached 100% yield; it needed 4 h irradiation. As expected, the asymmetric induction in **2a** was realized by an observation of its optical rotation, the $[\alpha]^{20}_{D}$ value of which was +23° as shown in Table 3, entry 2. The enantiomeric excess was determined as 10% ee by HPLC with a chiral column cell OJ column (Daicel Ind.) and $^1H$ NMR spectroscopy using chiral shift reagent $Eu(hfc)_3$. By suppression of the reaction conversion to 30% and decrease of the reaction temperature to −45°C, the enantiomeric purity rose up to 40% ee as shown in Table 3, entry 3. We could determine the absolute configuration of (+)-**2a** as (1*S*,4*R*)-isomer by the X-ray anomalous scattering method for the refinement of Roger's parameter (the final $\eta$ value was 1.256) as shown in Fig. 4a, which was the major photoproduct obtained by the solid-state photoreaction of (−)-(*M*)-**1a**.[24]



**Scheme 2.**

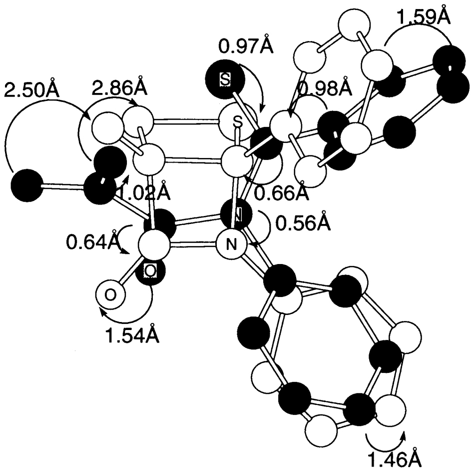


**Figure 6.** A front view of the superimposed structure of (−)-(*M*)-**1a** (black circle) and (+)-(1*S*,4*R*)-**2a** (empty circle) obtained by X-ray structural analysis using Overlay program in Chem3D.

In the solid-state photoreaction of **1b**, chemoselective reaction occurred, and the β-lactam **2b** was obtained in 93% yield (Table 3, entry 5). In the cases of **1c** and **1d**, *syn*-isomers of **2c** and **2d** were obtained stereospecifically, which were produced reflecting the stereochemistry of the tigloyl group of the starting monothioimides **1c** and **1d** (entries 7 and 9). The structure of **2c** and **2d** was established by X-ray structural analysis as shown in Fig. 4. Furthermore, chemoselective reaction was also observed in **1d**; the thioketone **3d** could not be isolated, but β-lactam **2d** was obtained exclusively (entry 9).

In most cases, the solid gradually changed to amorphous according to progress of the photoreaction. However, the crystal-to-crystal transformation was observed in the photoreaction of **1d**. Orange prismatic crystals gradually decolorized upon irradiation; finally, colorless prisms were obtained. We tried the single crystal X-ray analysis for the colorless or half-reacted crystals; however, sufficient reflections were not obtained. The crystal-to-crystal reaction was certified by XRD spectra as shown in Fig. 5. Fig. 5(a) shows the spectrum of starting material **1d**; Fig. 5(b) was the

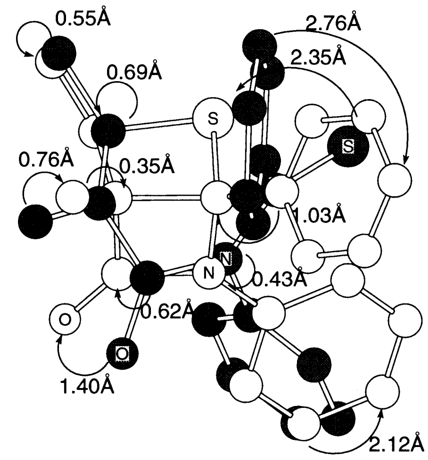


**Figure 7.** A front view of the superimposed structure of **1c** (black circle) and **2c** (empty circle) obtained by X-ray structural analysis using Overlay program in Chem3D.

pattern obtained after 15 min irradiation (15% conversion yield), in which new reflections were observed without phase separation. Fig. 5(c) exhibits the reflection pattern of 100% conversion yield, which needed 1.5 h of irradiation, and still shows sharp reflections. These crystals are in the metastable state because the reflection pattern, Fig. 5(d), derived from recrystallized **2d** shows different reflections from Fig. 5(c).

Scheme 2 shows the mechanism for the thietane formation, in which six-membered 1,4-biradical **BR** is appropriate.[17] There are two ways of cyclization to thietane **2**, and each pathway gives an enantiomeric structure of thietanes, (1*S*,4*R*)- or (1*R*,4*S*)-**2**, respectively. What atomic rearrangement is needed for the formation of thietane **2** in the crystal lattice? The answer was provided by a correlation study of the absolute structure before and after the reaction. The absolute structure of (−)-(*M*)-**1a** and the major isomer (+)-(1*S*,4*R*)-**2a** was determined by X-ray structural analysis using an anomalous scattering method (Figs. 1a and 4a). Fig. 6 shows the superimposed structure of both absolute structures which was drawn with the overlay program included in CSC Chem3D. Since the recrystallized crystals of **2a** were used for the X-ray crystallographic analysis, comparison of details is not appropriate. However, the photoproducts have an extremely rigid structure, and so we can argue on the molecular rearrangement for the fixed atoms and chromophores. The sulfur and the alkenyl carbon atoms are closely placed to make the C–S bond easily, and subsequent cyclization of biradical **BR** needs the rotation of the radical center like path a to yield (1*S*,4*R*)-**2a**. The molecular transformation from (−)-**1a** to (+)-**2a** needs considerable molecular rearrangement involving the rotation of the methacryl group. The dynamic structural changes in the crystal caused the relatively low enantiomeric excess of the products despite decreasing the temperature and suppressing the conversion (Table 3, entry 3). According to the cyclization the volume of the molecule was reduced, and this resulted in the formation of considerable spaces in the crystals. Furthermore, the molecular shift of the methacryl group resulted in making new defects in the crystal.

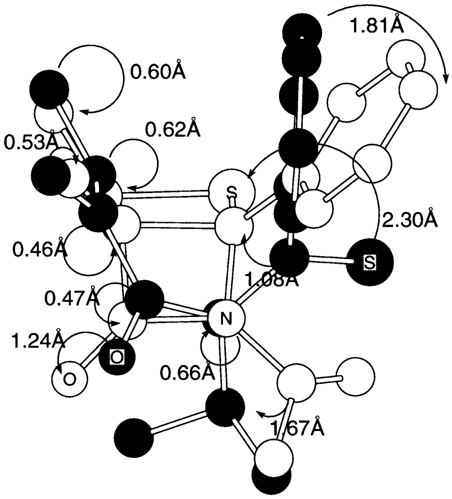


**Figure 8.** A front view of the superimposed structure of **1d** (black circle) and **2d** (empty circle) obtained by X-ray structural analysis using Overlay program in Chem3D.

Figs. 7 and 8 also show each overlay structure of the tigloyl derivatives **1c**–**2c** and **1d**–**2d,** in which all structures are determined by X-ray structural analyses. In all cases, recrystallized crystals **2c** and **2d** were used. The atom distance between the alkenyl carbon and the thiocarbonyl sulfur is longer than that of **1a** as shown in Table 2; however, the atomic shift subsequently followed by cyclization is comparatively small (Fig. 7). The thiocarbonyl carbon changed the angle according to the change in the hybrid orbital from $sp^2$ to $sp^3$ by the bond formation; nevertheless, less atomic shift is observed for other chromophores. In the case of **1d**, a further small atomic shift is observed in the solid-state photoreaction as shown in Fig. 8, in which a crystal-to-crystal transformation was maintained throughout the reaction without phase separation, and this fact resulted in the stereospecific formation of *syn*- **2c** and **2d**.

In conclusion, the solid-state photoreaction of *N*-(α,β-unsaturated carbonyl)thioamides **1a**–**d** provided a stereo- and chemo-selective reaction rather than that in homogeneous conditions. The molecular conformation of the monothioimides depends on the alkenyl groups, and (*E*,*E*)- and (*Z*,*E*)- conformation is favorable for thietane formation. Achiral *N*-methacryloylthiobenzanilide **1a** gave chiral crystals by spontaneous crystallization, and absolute asymmetric synthesis was performed by the solid-state photoreaction leading to optically active thietane-fused β-thiolactam. The reaction mechanism for the cyclization was elucidated on the basis of the correlation between the absolute structures of both the prochiral starting monothioimide and the photoproduct. The solid-state photoreaction *N*-isopropyl-*N*-tigloylthioamide proceeded with crystal-to-crystal nature, and high stereoselectivity was observed.

## 1. Experimental

### 1.1. General

NMR spectra were recorded on $CDCl_3$ solutions on a JEOL

GSX-400 and 500 operating 400 and 500 MHz, respectively, for $^1$H- and $^{13}$C NMR spectroscopy. Chemical shifts are reported in parts per million (ppm) relative to TMS as internal standard. UV spectra were determined with a JASCO model V-570 UV/VIS/NIR spectrophotometer. Optical rotations were determined on a JASCO DIP-370 polarimeter operating at the sodium D line in $CHCl_3$ solution at the concentration of $c=1.0$.

### 1.2. General procedure for the preparation of *N*-(α,β-unsaturated carbonyl) thioamides (1a–1d)

All *N*-(α,β-unsaturated carbonyl)thiobenzamides **1a–1d** were prepared according to the literature.[12]

### 1.3. X-Ray crystallographic analysis of 1a–1d

The structure was solved by the direct method and refined by the method of full-matrix least-squares; all crystal data were summarized in Table 1.

### 1.4. General procedure for the photochemical reaction in benzene

A benzene solution of monothioimide **1a–1d** (0.02 M) was purged with deoxygenated and dried argon for 15 min prior to photolysis and was irradiated with a 500-W Eikosha high-pressure mercury lamp through a Pyrex filter. After irradiation, benzene was evaporated and the photolysate was chromatographed on silica gel (Merck Kieselgel 60) with ethyl acetate–hexane (10:1) as the eluent.

### 1.5. General procedure for the photochemical reaction in the solid-state

All of the solid-state photolyses were done under an atmosphere of deoxygenated and dried argon. The solid samples were sandwiched with Pyrex glasses and were irradiated in a polyethylene bag, a light source from a 500-W high-pressure mercury lamp was used. In the case of the low-temperature photolysis, powdered solid in the test tube was irradiated in a cooling apparatus and was irradiated. After irradiation, the photolysate was treated the same as that in solution photochemistry.

**Table 4.** Crystal data for β-lactams **2a**, **2c** and **2d** obtained by the solid-state photoreaction

| | **(+)-2a** | **2c** | **2d** |
|---|---|---|---|
| Formula | $C_{17}H_{15}NOS$ | $C_{18}H_{17}NOS$ | $C_{15}H_{19}NOS$ |
| Mol. weight | 281.40 | 295.40 | 261.39 |
| Crystal system | Orthorhomibic | Monoclinic | Monoclinic |
| Space group | $P2_12_12_1$ | $P2_1/c$ | $P2_1/c$ |
| $Z$ | 4 | 4 | 4 |
| $a$ (Å) | 9.503 (2) | 14.533 (3) | 12.697 (3) |
| $b$ (Å) | 25.385 (5) | 6.391 (2) | 6.530 (2) |
| $c$ (Å) | 6.155 (2) | 17.539 (4) | 17.693 (4) |
| $\beta$ (deg) | 90.00 (0) | 104.35 (2) | 98.15 (2) |
| $V$ (Å$^3$) | 1484.8 (6) | 1578.1 (6) | 1452.2 (6) |
| $\rho_{\text{calc}}$ (g cm$^{-3}$) | 1.259 | 1.24 | 1.20 |
| $\mu$ (Cu Kα) (cm$^{-1}$) | 18.39 | 17.9 | 18.8 |
| $F$ (000) | 592 | 624 | 560 |
| Crystal size (mm) | 0.40×0.40×0.30 | 0.40×0.20×0.20 | 0.50×0.35×0.15 |
| Used reflections | 1638 | 2835 | 3149 |
| $R$ | 0.040 | 0.037 | 0.084 |
| $R_W$ | 0.055 | 0.041 | 0.089 |

### 1.6. X-Ray crystallographic analysis of 2a–2d

The structure was solved by the direct method and refined by the method of full-matrix least-squares; all crystal data were summarized in Table 4.

## References

1. Green, B. S.; Lahav, M.; Rabinovich, D. *Acc. Chem. Res.* **1979**, *69*, 191.
2. Addadi, L.; Lahav, M. In *Origin of Optical Activity in Nature*; Walker, D. C., Ed.; Elsevier: New York, 1979; Chapter 14.
3. Hasegawa, M. *Chem. Rev.* **1983**, *83*, 507.
4. Ramamurthy, V. *Tetrahedron* **1986**, *42*, 5753.
5. Scheffer, J. R.; Garcia-Garibay, M.; Nalamasu, O. *Organic Photochemistry*; Padwa, A., Ed.; Marcel Dekker: New York, 1987; Vol. 8, p. 249.
6. Ramamurthy, V.; Venkatesan, K. *Chem. Rev.* **1987**, *87*, 433.
7. Sakamoto, M. *Chem. Eur. J.* **1997**, *3*, 684.
8. Ito, Y. *Synthesis* **1998**, 1.
9. Schmidt, G. M. J. *Pure Appl. Chem.* **1971**, *27*, 647.
10. Evans, S. V.; Garcia-Garibay, M.; Omkaram, N.; Scheffer, J. R.; Trotter, J.; Wireko, F. *J. Am. Chem. Soc.* **1986**, *108*, 5648.
11. Toda, F.; Yagi, M.; Soda, S. *J. Chem. Soc., Chem. Commun.* **1987**, 1413.
12. Sakamoto, M.; Hokari, N.; Takahashi, M.; Fujita, T.; Watanabe, S.; Iida, I.; Nishio, T. *J. Am. Chem. Soc.* **1993**, *115*, 818.
13. Takahashi, M.; Sekine, T.; Fujita, T.; Watanabe, S.; Yamaguchi, K.; Sakamoto, M. *J. Am. Chem. Soc.* **1998**, *120*, 12771.
14. Recently we reported examples of absolute configuration correlation studies before and after the solid-state photoreaction, see Ref. 13, and see: Sakamoto, M.; Takahashi, M.; Arai, W.; Mino, T.; Yamaguchi, K.; Watanabe, S.; Fujita, T. *Tetrahedron* **2000**, *56*, 6795.
15. For the $\eta$ value of (−)-**1a**, the parameter test favored only one chirality for (−)-(*M*)-**1a** with the final $R$ and $R_w$ being 0.039 and 0.040, which may guarantee the absolute helicity of the frozen molecules.
16. The conformation of imides has been studied; seeNoe, E. A.; Raban, N. *J. Am. Chem. Soc.* **1975**, *97*, 5811.
17. The initial C–S bond formation generally accepted for thietane formation via 2+2 photocycloaddition, because dithietanes or sulfides are obtained from the biradical intermediate in some cases. See Ref. 18. In the photoreaction of **1**, other reaction mechanism like a concerted process is excluded from consideration.
18. Photochemical thietane formation of thioamides and thioimides was reviewed; see: Nishio, T.; Sakamoto, M. *Rev. Heteroatom Chem.* **1995**, *12*, 23–52, see also pp 53–68.
19. It is known that the center-to-center distance should be less than 4.1 Å in an intermolecular 2+2 cyclobutane formation; (a) Cohen, M. D.; Schmidt, G. M. J. *J. Chem. Soc.* **1964**, 1969. (b) Bregman, J.; Osaki, K.; Schmidt, G. M. J.; Sonntag, F. I. *J. Chem. Soc.* **1964**, 2021.
20. Scheffer, J. R.; Garcia-Garibay, M.; Nalamasu, O. *Organic Photochemistry*; Padwa, A., Ed.; Marcel Dekker: New York, 1987; Vol. 8, pp. 249–338.
21. For the intramolecular oxetane formation in the solid-state, geometrical consideration was reported, see: Sakamoto, M.;

Takahashi, M.; Fujita, T.; Watanabe, S.; Nishio, T.; Iida, I.; Aoyama, H. *J. Org. Chem.* **1997**, *62*, 6298.

22. Sakamoto, M.; Yanase, T.; Fujita, T.; Watanabe, S.; Aoyama, H.; Omote, Y. *J. Chem. Soc., Perkin Trans. 1* **1991**, 406–407.
23. We already reported the formation of thioketone derivatives via the β-hydrogen abstraction by thiocarbonyl sulfur; see: Sakamoto, M.; Takahashi, M.; Shimizu, M.; Fujita, T.; Nishio, T.; Iida, I.; Yamaguchi, K.; Watanabe, S. *J. Org. Chem.* **1995**, *60*, 7088–7089.
24. For the $\eta$ value of (+)-**2a**, the parameter test favored only one chirality for (+)-(1*S*,4*R*)-**2a** with the final $R$ and $R_w$ being 0.040 and 0.055.