X-Ray crystallographic analysis and photochemical reaction of asymmetrically substituted α,β-unsaturated thioamides

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Photochemical reaction of asymmetrically substituted *N*-benzyl-*N*-isopropyl-α,β-unsaturated thioamides both in solution and in the solid state was investigated. All thioamides exist in an equilibrium between two rotamers owing to the rotation of the C(=S)–N bond. The free energy of activation for the bond rotation was estimated by temperature-dependent ^{1}H NMR spectroscopy. The free energy of activation lies in a range 18.4–19.5 kcal mol^{-1}. Irradiation in benzene solution proceeded to give hydrogen abstraction by alkenyl carbon from both benzyl and isopropyl groups, leading to β-thiolactam and 1,3,5-dithiazinane products, respectively. Hydrogen abstraction from only the isopropyl group took place in the solid-state photolysis, giving an isomeric β-thiolactam product.

Introduction

Solid state photoreaction provides product- and stereoselectivity compared with reactions that occur in solution, due to restriction of molecular movement imposed by the environment.[1–3] To investigate geometrical aspects of thioamides and differences between photochemical reactivity with the reaction media, photochemical reaction of asymmetrically substituted *N*-benzyl-*N*-isopropyl-α,β-unsaturated thioamides were examined. It is well known that an alkenyl double bond abstracts hydrogen inter- or intra-molecularly as well as do carbonyl compounds;[4] however, the reaction profile substantially differs from that of carbonyls in terms of the electronic configuration of the reactive excited state.[5–8] Recently we reported solid-state photochemistry of *N*,*N*-dibenzylcyclohexenecarbothioamides in which hydrogen abstraction by alkenyl carbon leads to β-thiolactams.[9] We have now found a unique product selectivity in the photochemical reaction which depends on both the substituents on the nitrogen atom and the reaction media.

Molecular conformation in solution

The thioamides **1a**–**c** were conveniently prepared by thionation of the corresponding *N*-benzyl-*N*-isopropyl-α,β-unsaturated amides with Lawesson's reagent (Table 1).[10,11]

Asymmetrically substituted amides exist in two possible conformations by the rotation of their C(=O)–N bond because of the high free energy of activation (17–25 kcal mol^{-1}).[12] † The thioamides **1a**–**c** similarly exist in equilibrium between rotamers **1-A** and **1-B**. This conformational isomerization was observed by ^{1}H NMR spectroscopy, in which their distributions were quantified in deuterated DMSO at 30 °C. Table 1 shows the ratio of **1-A**:**1-B**, and all thioamides **1a**–**c** favor the conformation **1-A** where a benzyl group was placed close to the thiocarbonyl group on account of steric demands.

Fig. 1 shows the temperature-dependent ^{1}H NMR spectra of compound **1a** in [^{2}H$_6$]DMSO. The CH_2 hydrogens of the benzyl group derived from both rotational isomers are not equivalent at 30 °C, and distinct peaks appeared at δ 4.90 (minor) and δ 5.25 (major). The assignment was performed by COSY techniques. On raising the temperature, the methylene hydrogens of the benzyl group became equivalent. The free energy of activation of the rotation of the C(=S)–N bond could be estimated from the temperature of the coalescence point (T_c) and the difference in the chemical shifts of the signals of the two conformers ($\Delta\nu$).[13–15] The estimated free energies of activation lie in the range 18.4–19.5 kcal mol^{-1} as shown in Table 1. The assignment of stereochemistry (**1-A** or **1-B**) was achieved on the basis of the chemical shift in the ^{1}H NMR spectra. The peaks due to the protons close to the thiocarbonyl sulfur atom appeared at lower magnetic field because of the deshielding effect of the thiocarbonyl group.

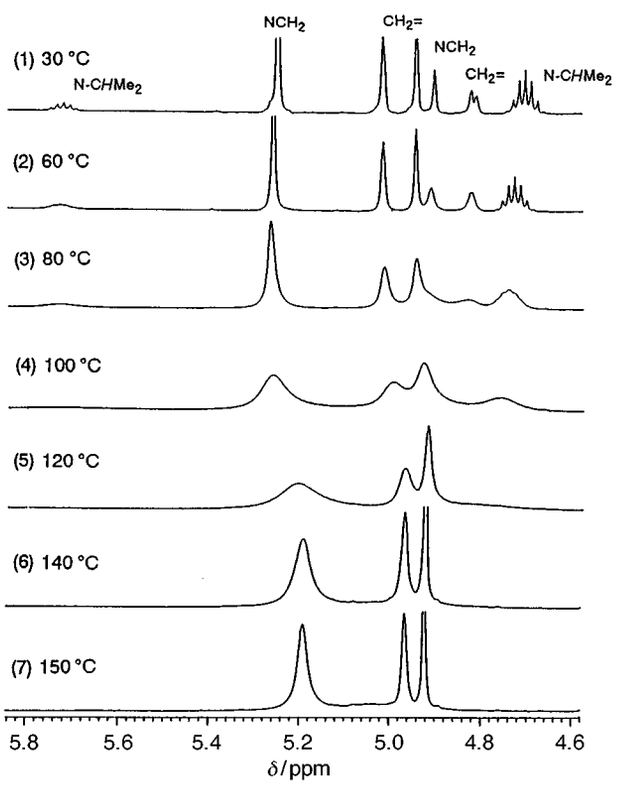
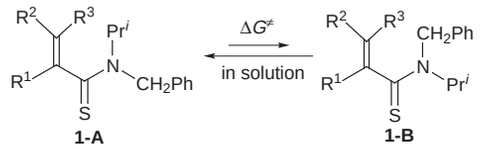


Fig. 1 ^{1}H NMR spectra of compound **1a** in [^{2}H$_6$]DMSO at various temperatures from 30 to 150 °C.

The conformational distribution was also supported by computational calculations using the PM3 method with MacSpartan. The energetically more favorable conformer of **1a-A** (Fig. 2) is 1.3 kcal mol^{-1} more stable than conformer **1a-B**.[16]

† 1 cal = 4.184 J.

Table 1 Free energy of activation energies for bond rotation and the conformational distribution of thioamides **1** in solution



Thioamide	R^1	R^2	R^3	$\Delta\nu^a$ (Hz)	Coalescence[a] temp. T_c (°C)	$\Delta G^{\ddagger}$ (kcal mol^{-1})	**1-A**:**1-B**[b]
1a	Me	H	H	173	140	19.5	86:14
1b	Me	H	Me	220	140	19.3	82:18
1c	-$(CH_2)_4$-		H	193	120	18.4	70:30

[a] Thioamide **1** was dissolved in [$^2H_6$]DMSO and the ^{1}H NMR spectra were measured at various temperatures from 30 to 150 °C. The free energy of activation of the rotation of the C(=S)–N bond ($\Delta G^{\ddagger}$) could be estimated from the coalescence temperature (T_c) and the difference in chemical shifts ($\Delta\nu$) derived from benzyl protons of the two conformers. [b] This ratio was determined in [$^2H_6$]DMSO at 30 °C.

Table 2 Crystal data for α,β-unsaturated thioamides **1a**–**c**

Entry	**1a**	**1b**	**1c**
Formula	$C_{14}H_{19}NS$	$C_{15}H_{21}NS$	$C_{17}H_{23}NS$
Mol. weight	233.37	247.40	373.44
Crystal system	monoclinic	monoclinic	monoclinic
Space group	$P2_1/n$	Cc	$P2_1/c$
Z	4	4	4
a/Å	7.2417(8)	10.585(2)	7.239(1)
b/Å	9.6640(6)	10.571(1)	11.218(1)
c/Å	20.140(2)	13.431(2)	19.388(1)
β/deg	90.565(8)	102.70(1)	90.725(9)
V/Å^3	1409.4(2)	1466.1(3)	1574.3(3)
ρ_{calc}/g cm^{-3}	1.100	1.121	1.154
μ(Cu-Kα)/cm^{-1}	18.19	17.74	16.98
F(000)	504	536	592
Crystal size/mm	0.45 × 0.12 × 0.50	0.25 × 0.20 × 0.40	0.32 × 0.30 × 0.35
Reflections used	2928	1234	3229
R	0.068	0.067	0.066
R_w	0.072	0.063	0.070
Torsion angle of C=S (°)[a]	5.4	7.0	3.0
Torsion angle of alkenyl group (°)[b]	87.9	100.5	89.5

[a] The torsional angle ω is defined as $\omega = 1/2(\omega 1 + \omega 2)$, where $\omega 1$ is a torsional angle of C(isopropyl α carbon)–N–C–S and $\omega 2$ is that of C(benzyl methylene carbon)–N–C(carbonyl carbon)–C(α carbon). [b] The torsion angle is defined as S=C–C=C.

Crystal and molecular structure of thioamides 1a–c in the crystalline state

Recrystallization of thioamides **1a**–**c** from chloroform–hexane solution gave colorless or slightly yellow prismatic crystals. All thioamides were subjected to X-ray single-crystal analysis.‡ The crystal and structural data are summarized in Table 2. Fig. 3 shows an ORTEP diagram of the thioamides **1a**–**c**.

All thioamides showed one conformation **1-A** in which a benzyl group was placed close to the thiocarbonyl group, similarly to the major isomer in solution. The thioamide chromophore maintains an almost planar conformation, the torsional angle of the thiocarbonyls are within 7.0° (Table 2). The alkenyl double bonds are perpendicular to the thioamide group, and twist in the range 87.9–100.5°.

Photochemical reaction of α,β-unsaturated thioamides 1a–c in solution and in the solid state

When the thioamide **1a** was irradiated in benzene with a high pressure mercury lamp under argon, *N*-isopropyl-β-thiolactam **2a** and 1,3,5-dithiazinane **4a** were obtained in 31 and 69% yield, respectively (Table 3, entry 1). The structure of compound **2a** was determined on the basis of its spectral data. The ^{1}H NMR spectrum showed signals at δ 0.83 (s, 3H, 3-Me), 1.36 (s, 3H, 3-Me) and 4.84 (s, 1H, 4-CH) in addition to the peaks derived from the isopropyl and phenyl groups. In the ^{13}C NMR spectrum, the peaks derived from the alkenyl group and the benzyl carbon disappeared and new singlet and doublet peaks were shown at δ_C 58.6 (s) and 74.4 (d) assignable to 3-C and 4-C, respectively. The structure of product **4a** was also determined by its spectral data. The mass spectrum (FAB) showed a molecular-ion peak at m/z 320 (MH^+) which indicated the molecule was formed from compound **1a** and a dimethyl(thio)ketene fragment. The ^{1}H NMR spectrum exhibited six methyl singlets,

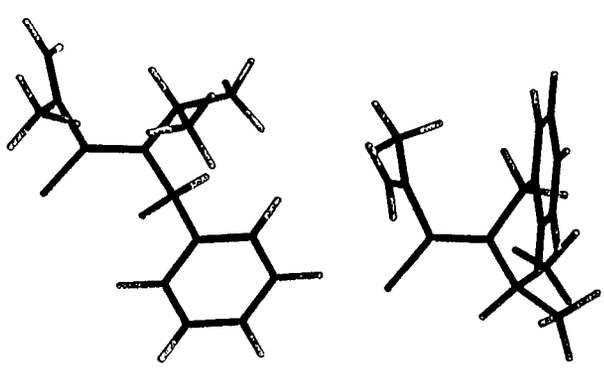
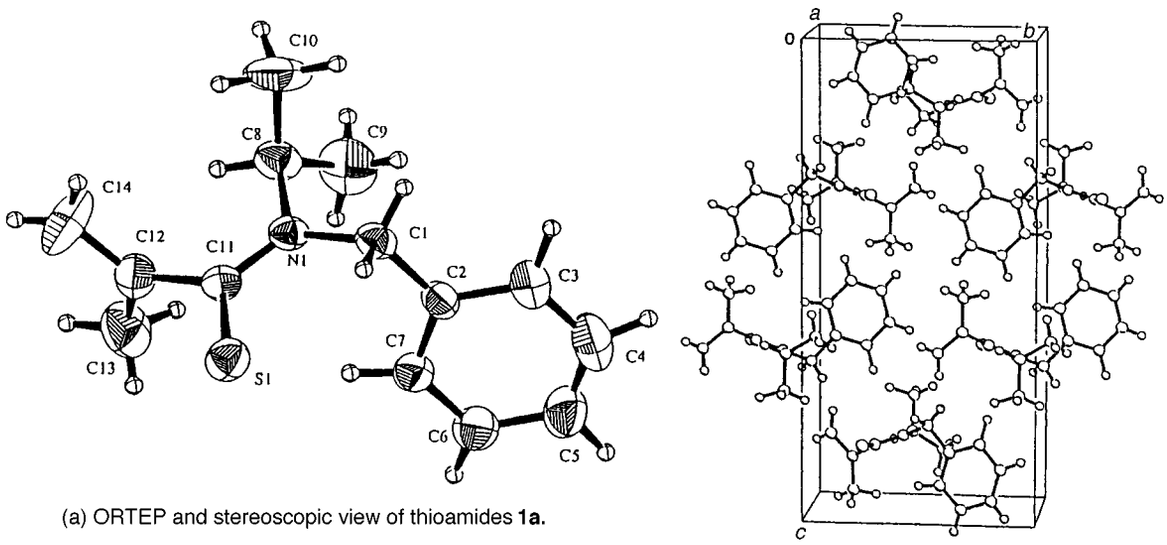
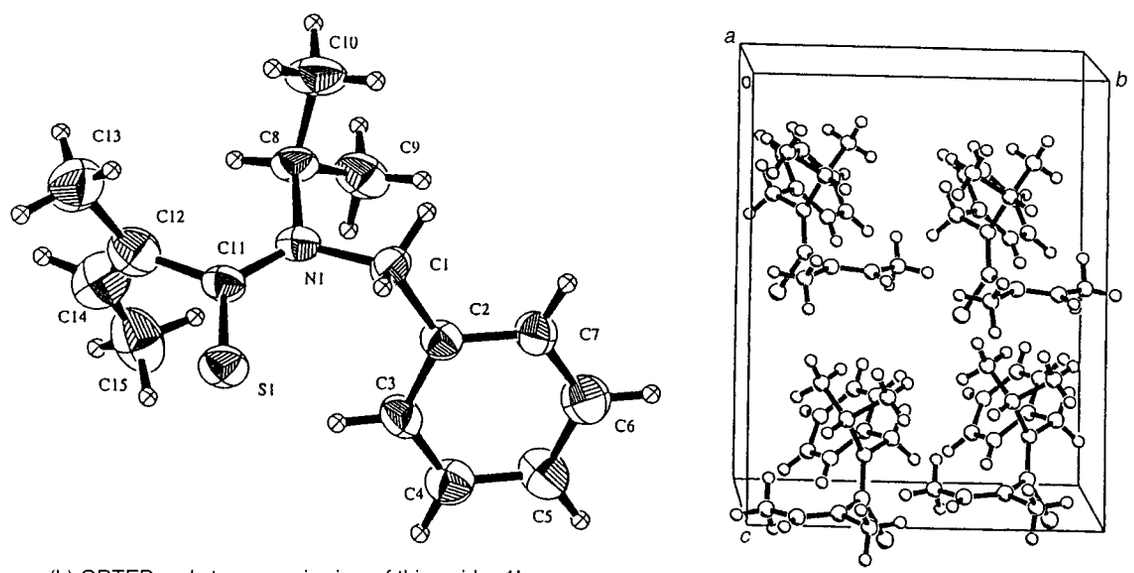


Fig. 2 Left. energetically minimum conformationof *anti* conformation (ΔH = 52.187 kcal mol^{-1}). Right. energetically minimum conformation of *syn* conformation (ΔH = 53.512 kcal mol^{-1}).

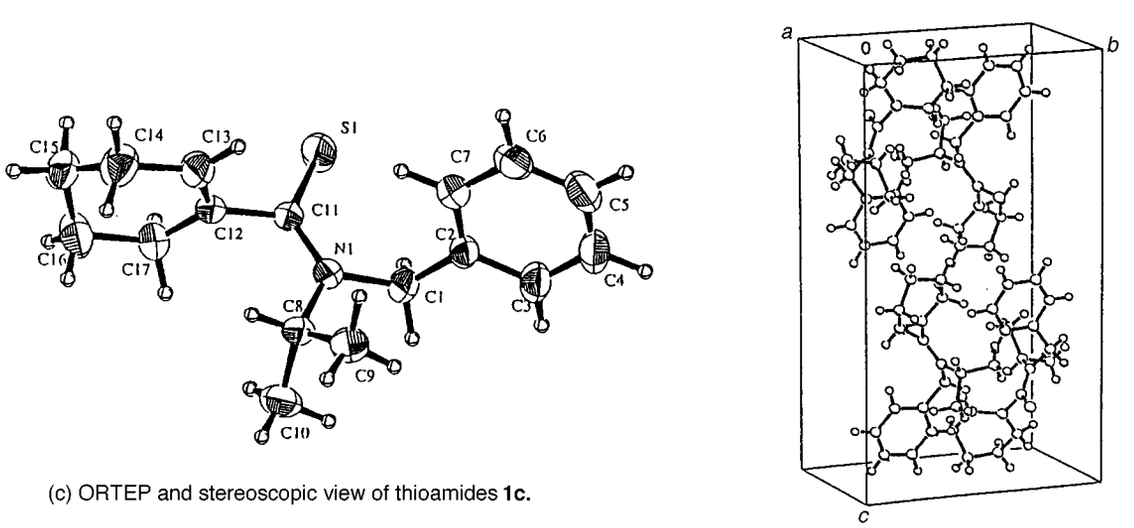
‡ Full crystallographic details, excluding structure factor tables, have been deposited at the Cambridge Crystallographic Data Centre (CCDC). For details of the deposition scheme, see 'Instructions for Authors', *J. Chem. Soc., Perkin Trans. 1*, available *via* the RSC Web page (http://www.rsc.org/authors). Any request to the CCDC for this material should quote the full literature citation and the reference number 207/274.



(a) ORTEP and stereoscopic view of thioamides **1a.**



(b) ORTEP and stereoscopic view of thioamides **1b.**



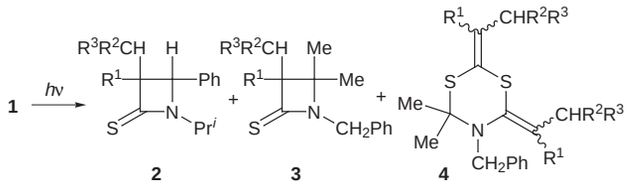
(c) ORTEP and stereoscopic view of thioamides **1c.**

Fig. 3 ORTEP diagram of thioamides **1a**–**c**.

one benzyl singlet, aromatic protons and the absence of the isopropyl septet. The ^{13}C NMR spectrum also strongly supported the six-membered 1,3,5-dithiazinane structure. Photolysis of other thioamides **1b**,**c** in benzene solution also gave the corresponding β-thiolactam **2** and 1,3,5-dithiazinane **4** as shown in Table 3, entries 3, 5.

Considerably different photochemical behavior was observed in the solid-state photolysis of thioamides **1a**–**c**. Powdered

Table 3 Photoreaction of thioamides **1** in both solution and the solid state

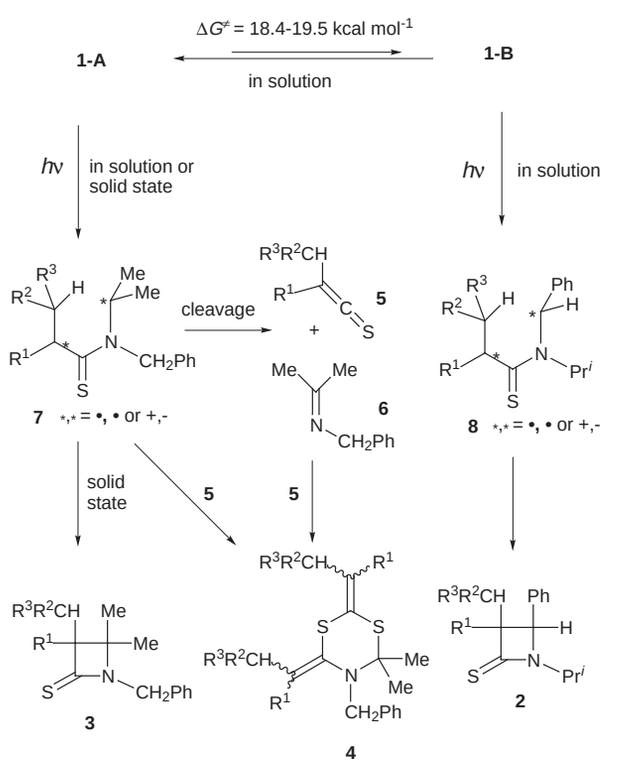


Entry	Thioamide	Conditions	Conversion (%)	Yield (%)[a] 2	3	4
1	**1a**	benzene	76	31	0	69
2	**1a**	solid state	19	0	0	100
3	**1b**	benzene	46	29	0	71
4	**1b**	solid state	57[b]	0	88	12
5	**1c**	benzene	53	22	0	78
6	**1c**	solid state	100	0	56	44

[a] Chemical yields are determined on the basis of consumed thioamides. [b] *E*/*Z* isomerisation also took place.

thioamide **1a** was irradiated in the solid state at 0 °C until 19% conversion yield, because the solid changed to an amorphous substrate at around 20% conversion.[17] In this case, dithiazinane **4a** was obtained as the sole photoproduct (entry 2). On the other hand, photolysis of thioamide **1b** gave a new type of β-lactam, **3b**, as a main product in 88% yield in addition to dithiazinane **4b** (12%); the β-lactam **2b** was not detected (entry 4). Photochemical *E*,*Z* isomerization of (*Z*)-**1b** was also observed in the early stage of the reaction, where the quotient of the photostationary state was *Z*/*E* = 1.9 as determined by ^{1}H NMR analysis.[18] In the case of thioamide **1c**, β-thiolactam **3c** was obtained as a main product in 56% yield accompanied by the dithiazinane **4c**; the structural isomer **2c**, which was isolated in solution photochemistry, was not observed (entry 6). Irradiation with longer-wavelength light (365 nm) using a uranil glass filter did not give any significant difference in the product ratio.

Scheme 1 shows a plausible mechanism for the formation of β-thiolactams **2**,**3** and dithiazinane **4**. Thioamide **1** is composed



Scheme 1

Table 4 Geometrical parameters of the X-ray structures of α,β-unsaturated thioamides **1a**–**c**

Thioamide	Conformation	*d*1 (Å)	*d*2 (Å)	ω_c (°)	Δ_c (°)	θ (°)
1a	**1a-A**	2.83	4.73	62	54	132
1b	**1b-A**	2.71	4.89	45	65	127
1c	**1c-A**	2.84	4.95	54	56	127
(alkene)	ideal	<2.90	<2.90	45	90	180

of two conformers **1-A** and **1-B** in solution, where the conformer **1-A** slightly predominates over conformer **1-B**. γ-Hydrogen abstraction by the alkenyl carbon from the isopropyl group in **1-A** resulted in the formation of a diradical (or a zwitterion) **7** which subsequently cleaves to a thioketene **5** and *N*-isopropylidenebenzylamine **6**. Cycloaddition of intermediate **7** with the thioketene **5** gives dithiazinane **4**. Previously we reported that the irradiation of *N*,*N*-dibenzylmethacrylthioamide led to the formation of β-thiolactams *via* a zwitterionic intermediate which was confirmed by a trapping experiment with amine.[10] In this case, intermediate **7** formed by hydrogen abstraction from the isopropyl group did not cyclize to a β-lactam in solution. On the other hand, conformer **1-B** abstracts a benzylic hydrogen atom, leading to intermediate **8**, and subsequently cyclization takes place to give a β-thiolactam **2**. It seems that intermediate **7** does not cyclize in solution because of the steric repulsion for C–C bond formation.

Participation of thioketene **5** in the formation of dithiazinane **4** is supported by the fact that the photolysis in methanol reduced the chemical yield of compound **4a** (13% yield). We infer that dimethyl(thio)ketene **5a** was consumed by methanol to give the corresponding thioester faster than addition with diradical or zwitterionic intermediate **7**. Another route to dithiazinane **4**, *via* the addition of imine **6** with bimolecular thioketene **5**, is also possible. A similar reaction is sometimes found in the reaction of ketene with imines to give 2:1 adducts.[19]

In the solid state, all crystals are composed of only conformer **1-A**, and the alkenyl β-carbon is placed close to a hydrogen atom of the isopropyl group. In the crystal, conformational factors become more important because interconversion involving dramatic movements of the substituents cannot usually occur. Hydrogen abstraction from the isopropyl group by alkenyl carbon can give a diradical intermediate **7**, which could cyclize to β-thiolactam **3** or cleave to products **5** and **6**. Hydrogen abstraction from the benzyl group is not favored, because the benzyl hydrogen is far from the alkenyl carbon atom. If hydrogen abstraction were to proceed, drastic conformational re-orientation for the cyclization to β-thiolactam **3** would be needed, which is improbable in the solid state.

It seems that the principal parameters, *viz.* distance and the dihedral angle, between the reacting hydrogen and the alkenyl double bonds are the most critical for determining the photochemical reactivity of hydrogen abstraction. All geometrical and crystallographic data required for the mechanistic analyses are collected in Tables 2 and 4.

According to X-ray crystal structural analyses of thioamides **1a**–**c**, the conformations in the crystal lattices have a strong tendency to be of type **1-A**. Alkenyl groups are nearly orthogonal to the thioamide plane, the torsional angles are between 87.9° and 100.5° (Table 2). Table 4 shows that the distances between the isopropyl α-hydrogen and alkenyl β-carbon (represented by *d*1) are in the range 2.71–2.84 Å, which is much shorter than the sum of the van der Waals radii of the two atoms (2.90 Å). The *d*2 value is the distance between the nearest benzyl hydrogen and the alkenyl β-carbon, which are separated in the range 4.73–4.95 Å. Too long a distance value also indicates the difficulty of hydrogen abstraction from a benzyl group. The term ω_c means an angle formed between the C–H vector and its projection on the mean plane of the alkenyl group, and the value 45–62° are not far from ideal (45°).

The value Δ_c means the angle C=C---H, which is the range 54–65° (ideal is 90°), and θ is the C---H–C angle (ideal is 180°).[1]

These facts support our contention that the hydrogen abstraction of thioamides is permitted from the standpoint of molecular conformation and geometry, which means the photochemical reaction is topochemically allowed.

We previously reported that the photochemical hydrogen abstraction of *N*,*N*-dibenzyl-α,β-unsaturated thioamides proceeded from the singlet excited state on the basis of sensitization and quenching experiments. The excited state of the orthogonally twisted unsaturated thioamide chromophore of structure **1-A** could generate diradical intermediate **7**, which could cyclize with a minimum amount of molecular movement affected by steric repulsion of neighboring molecules.

On the other hand, 1,3-dithiazinanes **4a**–**c** were also formed in the crystalline state. X-Ray analyses of thioamides **1** reveals that there is no molecule for intermolecular addition of diradical at an available distance. Therefore, it is inferred that the lattice is disrupted by the initial photolysis, or just possibly that reactive intermediates are trapped in the lattice and do not react until the crystals are dissolved.

Conclusion

Photolysis of unsymmetrically substituted α,β-unsaturated thioamides affords a mixture of two rotational isomers owing to the rotation of the C–N bond under homogeneous conditions. On the other hand, the crystals were composed of only one conformer. The molecular structure was reflected in the photochemical results, and considerable differences were shown between the photoproducts depending on the reaction medium.

Experimental

General

NMR spectra were recorded on $CDCl_3$ solutions in a JEOL GSX-400 or 500 spectrometer operating at 400 or 500 MHz, respectively, for ^1H and ^{13}C NMR spectroscopy. Chemical shifts are reported in parts per million (ppm) relative to $SiMe_4$ as internal standard and *J*-values are given in Hz. Elemental analyses were made using a Perkin-Elmer-240 instrument. UV spectra were measured with a JASCO model V-570 UV–VIS–NIR spectrophotometer; ε-values are given in l mol^{-1} cm^{-1}. IR spectra were recorded on a JASCO FT/IR-230 spectrometer for samples as KBr disks, unless otherwise noted.

General procedure for the preparation of *N*-benzyl-*N*-isopropyl-α,β-unsaturated thioamides 1a–c

All α,β-unsaturated thioamides **1a**–**c** were prepared by treatment of the corresponding α,β-unsaturated amides with Lawesson's reagent. The requisite α,β-unsaturated amides can be easily prepared by condensation of the corresponding acid chlorides and amines in the presence of triethylamine. A synthesis of thioamide **1a** is exemplified as follows. To a benzene solution containing 5.0 g (23 mmol) of *N*-benzyl-*N*-isopropylmethacrylamide was added 3.5 g (15 mmol) of Lawesson's reagent at rt. The reaction mixture was refluxed for 3 h and then cooled to rt. Benzene was evaporated off *in vacuo*, the residual mixture was subjected to chromatography on silica gel, and the crystalline thioamide **1a** was recrystallized from a $CHCl_3$–hexane mixture to afford slightly yellow prisms with mp 78–79 °C. The structures of thioamides **1a**–**c** were determined on the basis of spectral data, elemental analysis, mass spectroscopy, and unequivocally by X-ray crystallographic analysis.

***N*-Benzyl-*N*-isopropylmethacrylthioamide 1a.** This was obtained as slightly yellow prismatic crystals from hexane–chloroform (62%), mp 78–79 °C; ν_{max}/cm^{-1} 1344 and 1448; $\lambda_{max}(C_6H_{12})$/nm 285 (ε 14 300) and 385 (140); $\delta_H(CDCl_3)$ 1.18 and 1.19 (each d, *J* 6.6, total 6H), 1.90 and 2.16 (each s, total 3H), 4.72 and 5.82 (each septet, *J* 6.6, total 1H), 4.9–5.0 (m, total 2H), 4.82 and 5.23 (each s, total 2H), 7.1–7.4 (m, 5H); $\delta_C(CDCl_3)$ 19.9 and 21.3 (each q), 22.9 (q), 48.4 and 50.9 (each t), 52.4 and 55.2 (each d), 111.5 and 111.8 (each t), 126.5 (d), 127.5 (d), 126.8 (d), 127.5 (d), 128.4 (d), 128.6 (d), 136.8 and 137.4 (each s), 147.5 (s) and 204.5 (s) (Found: C, 72.0; H, 8.35; N, 6.0. Calc. for $C_{14}H_{19}NS$: C, 72.05; H, 8.21; N, 6.00%).

(*E*)-*N*-Benzyl-*N*-isopropylbut-2-enethioamide 1b. This was obtained as prismatic crystals from hexane–chloroform (74%), mp 111–112 °C; ν_{max}/cm^{-1} 1650; $\lambda_{max}(C_6H_{12})$/nm 285 (ε 12 000) and 387 (100); $\delta_H(CDCl_3)$ 1.16 and 1.30 (each d, *J* 6.9, total 6H), 1.57 and 1.71 (each dq, *J* 1.7 and 6.9, total 3H), 1.76 and 2.05 (each m, total 3H), 4.68 and 5.93 (each septet, *J* 6.9, total 1H), 4.59 and 4.95 (ABq, *J* 8.1, total 2H), 5.27 (s, 2H), 5.27 (m, 1H) and 7.1–7.4 (m, 5H); $\delta_C(CDCl_3)$ 14.9 and 15.5 (each q), 20.5 and 22.1 (each q), 23.5 and 23.7 (each q), 49.1 and 50.9 (each t), 52.7 and 55.5 (each d), 119.6 and 120.3 (each t), 127.3 (d), 127.5 (d) 128.8 (d), 129.0 (d), 137.7 (s), 139.5 (s), 204.3 and 204.7 (each s) (Found: C, 72.8; H, 8.7; N, 5.8. Calc. for $C_{15}H_{21}NS$: C, 72.82; H, 8.56; N, 5.66%).

***N*-Benzyl-*N*-isopropylcyclohex-1-enecarbothioamide 1c.** This was obtained as prismatic crystals from hexane–chloroform (73%), mp 105–106 °C; ν_{max}/cm^{-1} 1209, 1336 and 1447; $\lambda_{max}(C_6H_{12})$/nm 285 (ε 10 900) and 388 (150); $\delta_H(CDCl_3)$ 1.17 and 1.22 (each d, *J* 6.6, total 6H), 1.4–2.6 (m, 8H), 4.74 and 5.86 (each septet, *J* 6.6, total 1H), 4.77 and 5.23 (each s, total 2H), 5.54 and 5.69 (each s, total 1H) and 7.1–7.4 (m, 5H); $\delta_C(CDCl_3)$ 21.1 and 21.3 (each q), 21.4 (t), 22.4 (t), 24.5 (t), 28.4 (t), 48.4 and 55.1 (each t), 54.9 (d), 126.4 (d), 126.7 (d), 128.2 (d), 128.3 (d), 137.0 (s), 146.8 (s) and 205.4 (s) (Found: C, 74.55; H, 8.65; N, 5.2. Calc. for $C_{17}H_{23}NS$: C, 74.67; H, 8.48; N, 5.12%).

X-Ray crystallographic analysis of *N*-benzyl-*N*-isopropyl-α,β-unsaturated thioamides 1a–c

A crystal was mounted on a glass fiber. All measurements were made on a Rigaku AFC5S diffractometer with graphite-monochromated Cu-Kα radiation. The data were collected at a temperature of 23 ± 1 °C using the ω–2θ scan technique to a maximum 2θ-value of 135.1° for **1a**, 120.2° for **1b** and 135.2° for **1c**. Omega scans of several intense reflections, made prior to data collection, had an average width at half-height of 0.17° for **1a**,**b** and 0.15° for **1c** with a take-off angle of 6.0°. The structures were solved by direct methods and expanded using Fourier techniques. The non-hydrogen atoms were refined anisotropically. Hydrogen atoms were refined isotropically. The crystal data and the unweighted and weighted agreement factors are summarized in Table 2.

General procedure for the photochemical reaction in benzene

A benzene solution of an amide **1a**–**c** (0.02 mol) was purged with deoxygenated, dried argon for 15 min prior to the photolysis and was irradiated with a 500 W high-pressure mercury lamp through a Pyrex filter. After irradiation, the photolysate was chromatographed on silica gel (Merck Kieselgel 60) with benzene as eluent.

General procedure for the photochemical reaction in the solid state

Solid samples were irradiated as a powder sandwiched between Pyrex glass slides on the inside of a polyethylene bag which was fixed on the outside of an immersion-well apparatus, and cooled during the photolysis in an ice–water-bath (at 0 °C). After irradiation, the photolysate was treated in the same manner as that used in the solution photochemistry.

1-Isopropyl-3,3-dimethyl-4-phenylazetidine-2-thione 2a. This was obtained as an oil; bp 48–53 °C (2 mmHg); $\nu_{max}(CHCl_3)$/cm^{-1} ($CHCl_3$) 1695; $\lambda_{max}(C_6H_{12})$/nm 242 (ε 7300) and 267 (13 300); $\delta_H(CDCl_3)$ 0.83 (s, 3H), 1.23 (d, *J* 6.6, 3H) 1.30 (d, *J* 6.6, 3H), 1.36 (s, 3H), 4.39 (septet, *J* 6.6, 1H), 4.84 (s, 1H) and 7.2–7.4 (m, 5H); $\delta_C(CDCl_3)$ 19.1 (q), 20.6 (q), 24.5 (q), 47.5 (d), 58.6 (s), 74.4 (d), 126.0 (d), 127.2 (d), 128.4 (d), 136.0 (s) and 211.3 (s) (Found: C, 71.85; H, 8.3; N, 6.0. Calc. for $C_{14}H_{19}NS$: C, 72.05; H, 8.21; N, 6.00%).

5-Benzyl-2,4-diisopropylidene-6,6-dimethyl-1,3,5-dithiazinane 4a. This was obtained as an oil; bp 95–100 °C (2 mmHg); $\nu_{max}(CHCl_3)$/cm^{-1} 1365, 1453 and 2904; $\lambda_{max}(C_6H_{12})$/nm 260 (ε 10 700); $\delta_H(CDCl_3)$ 1.25 (s, 3H), 1.46 (s, 3H), 1.63 (s, 3H), 1.67 (s, 3H), 1.89 (s, 3H), 1.99 (s, 3H), 4.09 (s, 2H) and 7.2–7.3 (m, 5H); $\delta_C(CDCl_3)$ 19.7 (q), 20.3 (q), 21.6 (q), 21.7 (q), 29.1 (q), 31.2 (q), 52.2 (t), 69.9 (s), 119.0 (s), 126.7 (d), 127.6 (d), 130.1 (d), 131.0 (s), 134.9 (s), 135.3 (s) and 135.8 (s); LRMS (FAB) Calc. for $C_{18}H_{26}NS_2$: *m*/*z* 320 (MH^+) (Found: C, 67.4; H, 7.7; N, 4.35. Calc. for $C_{18}H_{25}NS_2$: C, 67.69; H, 7.89; N, 4.39%).

(*E*)-*N*-Benzyl-*N*-isopropylbut-2-enethioamide 1b. This was analyzed by ^1H and ^{13}C NMR spectroscopy as a crude reaction mixture: $\delta_H(CDCl_3)$ 1.16 and 1.30 (each d, *J* 6.9, total 6H), 1.57 and 1.71 (each dq, *J* 1.7 and 6.9, total 3H), 1.76 and 2.01 (each m, total 3H), 4.68 and 5.93 (each septet, *J* 6.9, total 1H), 4.59 and 4.95 (ABq, *J* 8.1), and 5.27 (s, total 2H), 5.27 (m, 1H) and 7.1–7.4 (m, 5H); $\delta_C(CDCl_3)$ 14.9 and 15.5 (each q), 20.5 and 22.1 (each q), 23.5 and 23.7 (each q), 49.1 and 50.9 (each t), 52.7 and 55.5 (each d), 119.6 and 120.3 (each t), 127.3 (d), 127.5 (d) 128.8 (d), 129.0 (d), 137.7 (s), 138.9 (s) and 206.3 (s).

3-Ethyl-3-methyl-1-isopropyl-4-phenylazetidine-2-thione 2b. This was obtained as an oil; bp 65–70 °C (3 mmHg); $\nu_{max}(CHCl_3)$/cm^{-1} 1695; $\lambda_{max}(C_6H_{12})$/nm 244 (ε 6200) and 268 (10 500); $\delta_H(CDCl_3)$ 0.52 (t, *J* 7.4, 3H), 1.21 (d, *J* 6.9, 3H), 1.28 (d, *J* 6.9, 3H), 1.35 (s, 3H), 1.5–1.6 (m, 1H), 4.38 (septet, *J* 6.9, 1H), 4.79 (s, 1H) and 7.2–7.4 (m, 5H); $\delta_C(CDCl_3)$ 7.5 (q), 18.9 (q), 20.5 (q), 20.7 (q), 25.1 (t), 47.6 (d), 58.5 (s), 74.2 (d), 127.4 (d), 128.3 (d), 128.4 (d), 135.9 (s) and 211.2 (s) (Found: C, 72.65; H, 8.4; N, 5.6. Calc. for $C_{15}H_{21}NS$: C, 72.82; H, 8.56; N, 5.66%).

1-Benzyl-3-ethyl-3,4,4-trimethylazetidine-2-thione 3b. This was obtained as an oil; bp 65–70 °C (3 mmHg); ν_{max}/cm^{-1} 1499; $\lambda_{max}(C_6H_{12})$/nm 262 (ε 7800) and 268 (8000); $\delta_H(CDCl_3)$ 0.98 (t, *J* 7.4, 3H), 1.16 (s, 3H), 1.22 (s, 6H), 1.28 and 1.74 (each m, 2H), 4.63 (s, 2H) and 7.2–7.4 (m, 5H); $\delta_C(CDCl_3)$ 9.0 (q), 16.8 (q), 21.7 (q), 22.5 (q), 26.6 (t), 44.8 (t), 59.8 (s), 72.4 (s), 127.7 (d), 128.4 (d), 128.6 (d), 136.1 (s) and 209.0 (s); HRMS (FAB) *m*/*z* 248.1475 ($C_{15}H_{22}NS$ requires *m*/*z* 248.1473) (Found: C, 72.6; H, 8.5; N, 5.6. Calc. for $C_{15}H_{21}NS$: C, 72.82; H, 8.56; N, 5.66%).

5-Benzyl-2,4-di(*sec*-butylidene)-6,6-dimethyl-1,3,5-dithiazinane 4b. This was obtained as an oil; bp 100–105 °C (2 mmHg); ν_{max}/cm^{-1} 1454 and 1635; $\lambda_{max}(C_6H_{12})$/nm 260 (ε 9550); $\delta_H(CDCl_3)$ 0.38 (t, *J* 7.4, 3H), 1.00 (m, 3H), 1.46 (s, 3H), 1.62 (s, 3H), 1.88 (s, 3H), 1.98 (s, 3H), 2.40 (m, 2H), 3.55 (q, *J* 6.2, 2H), 4.12 (s, 2H) and 7.2–7.5 (m, 5H); $\delta_C(CDCl_3)$ 11.4 (q), 12.0 (q), 16.6 (q), 21.7 (q), 26.4 (t), 29.0 (t), 29.3 (q), 31.5 (q), 52.56 (t), 69.8 (s), 117.5 (s), 118.9 (s), 127.7 (d), 128.6 (d), 129.9 (d), 138.9 (s), 140.3 (s) and 141.2 (s); HRMS (FAB) *m*/*z* 348.1808 ($C_{20}H_{30}NS_2$ requires *m*/*z* 348.1820) (Found: C, 68.9; H, 8.35; N, 4.0. Calc. for $C_{20}H_{29}NS_2$: C, 69.13; H, 8.41; N, 4.03%).

1-Isopropyl-4-phenylazetidine-3-spiro-1′-cyclohexane-2-thione 2c. This was obtained as an oil; bp 73–74 °C (4 mmHg); $\nu_{max}(CHCl_3)$/cm^{-1} 1700; $\lambda_{max}(C_6H_{12})$/nm 244 (ε 2100) and 268 (3800); $\delta_H(CDCl_3)$ 1.16 (d, *J* 6.8, 3H), 1.27 (d, *J* 6.8, 3H), 1.2–1.9 (m, 10H), 4.39 (septet, *J* 6.8, 1H), 4.84 (s, 1H) and 7.2–7.4 (m, 5H); $\delta_C(CDCl_3)$ 7.5 (q), 19.0 (q), 20.6 (q), 21.2 (t), 23.1 (t), 24.8 (t), 27.6 (t), 34.9 (t), 47.5 (d), 59.6 (s), 74.1 (d), 127.6 (d), 128.3 (d), 128.4 (d), 136.0 (s) and 210.6 (s) (Found: C, 74.45; H, 8.45; N, 5.0. Calc. for $C_{17}H_{23}NS$: C, 74.67; H, 8.48; N, 5.12%).

1-Benzyl-4,4-dimethylazetidine-3-spiro-1′-cyclohexane-2-thione 3c. This formed prismatic crystals from hexane–chloroform, mp 84–85 °C; ν_{max}/cm^{-1} 1262 and 1504; $\lambda_{max}(C_6H_{12})$/nm 268 (6400); $\delta_H(CDCl_3)$ 1.1–1.9 (m, 10H), 1.21 (s, 6H), 4.64 (s, 2H) and 7.2–7.4 (m, 5H); $\delta_C(CDCl_3)$ 21.8 (q), 23.2 (t), 25.3 (t), 30.0 (t), 44.6 (t), 60.1 (s), 72.5 (s), 127.7 (d), 127.9 (d), 128.4 (d), 128.6 (d), 128.8 (d), 136.3 (s) and 208.3 (s); HRMS (FAB) *m*/*z* 274.1620 ($C_{17}H_{24}NS$ requires *m*/*z*, 274.1629) (Found: C, 74.6; H, 8.4; N, 5.0. Calc. for $C_{17}H_{23}NS$: C, 74.67; H, 8.48; N, 5.12%).

5-Benzyl-2,4-dicyclohexylidene-6,6-dimethyl-1,3,5-dithiazinane 4c. This was obtained as an oil; bp 120–125 °C (1 mmHg); $\nu_{max}(CHCl_3)$/cm^{-1} 1445 and 2930; $\lambda_{max}(C_6H_{12})$/nm 259 (ε 11 900); $\delta_H(CDCl_3)$ 1.2–1.7 (m, 20H), 1.49 (s, 3H), 1.63 (s, 3H), 4.06 and 4.21 (ABq, *J* 13.0, 2H) and 7.2–7.3 (m, 5H); $\delta_C(CDCl_3)$ 26.5 (t), 26.6 (t), 26.8 (t), 27.1 (t), 27.7 (t), 29.0 (q), 30.2 (t), 30.4 (t), 31.3 (q), 32.0 (t), 51.8 (t), 69.9 (s), 116.8 (s), 126.7 (d), 127.7 (d), 128.7 (s), 130.3 (d), 138.7 (s), 143.3 (s) and 145.1 (s); HRMS (FAB) *m*/*z* 400.2122 ($C_{24}H_{34}NS_2$ requires *m*/*z*, 400.2133) (Found: C, 71.9; H, 8.2; N, 3.35. Calc. for $C_{24}H_{33}NS_2$: C, 72.15; H, 8.33; N, 3.51%).

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