Novel Palladium(II)-Catalyzed Cyclization of Aziridines and Sulfur Diimides

Jin-Ook Baeg and Howard Alper*

Contribution from the Department of Chemistry, University of Ottawa, 10 Marie Curie, Ottawa, Ontario, Canada K1N 6N5

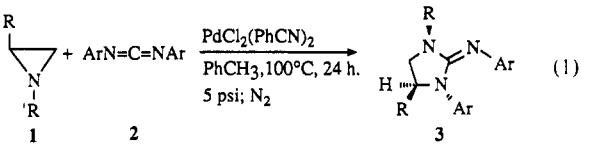
*Received September 23, 1993**

Abstract: Bis(benzonitrile)palladium dichloride is an effective catalyst for the cyclization reaction of aziridines and sulfur diimides, in toluene, affording imidazolidinethiones in 52–70% yield. Reaction of an aziridine, labeled with ^{13}C at one of the ring carbons, with a sulfur diimide resulted in incorporation of the label at the 2- and 5-positions of the imidazolidinethione. Thiazolidinimine formation results from the palladium(II)-catalyzed reaction of an aziridine with phenyl isothiocyanate.

The cycloaddition of three-membered-ring heterocycles with heterocumulenes is a useful method for the formation of five-membered-ring heterocycles. For example, succinimides were synthesized from aziridinones and diphenylketene,[1] and oxadiazolidinones were obtained from oxaziridines and phenylisocyanate.[2] Better yields and regioselectivities resulted using halides as catalysts. For instance, lithium bromide is capable of catalyzing the cycloaddition of oxiranes with isocyanates,[3] while organotin and organoantimony halides promote the cycloaddition of azidridines and oxiranes with heterocumulenes.[4-7] In recent years, significant improvement in regioselectivity and stereoselectivity was achieved by the use of transition metal complexes as catalysts (e.g., Pd(O),[8-10] Pd(II)[11]).

The synthesis and reactivity of sulfur diimides have been widely studied, particularly for Diels–Alder cycloaddition reactions.[12-14] Various electron-deficient sulfur diimides (employed as the heterodienophile) such as bis(arylsulfonyl)-,[15,16] bis(alkoxycarbonyl)-,[17] or bis(*p*-nitrobenzoyl)sulfur diimide[18] readily react with dienes to form thiazines. Unlike other heterocumulenes, sulfur diimides have rarely been used in cycloaddition reactions with heterocycles.[19]

We recently found that bis(benzonitrile)palladium dichloride catalyzes the cycloaddition of aziridines and carbodiimides to form imidazolidinimines **3** in fine yields (eq 1).[11]



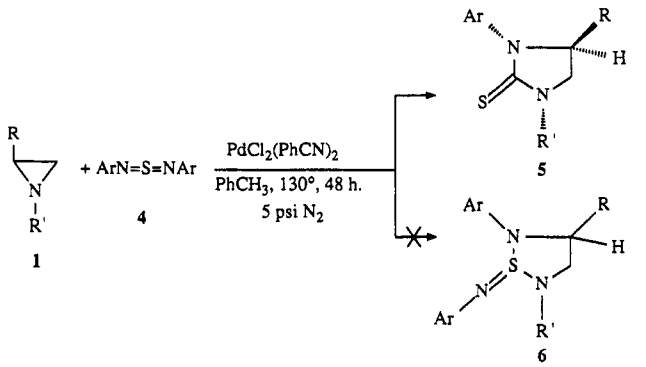
(1)

We now wish to report the bis(benzonitrile)palladium dichloride catalyzed cycloaddition of aziridines with sulfur diimides affording imidazolidinethiones in good yields. In this novel reaction, both the thiocarbonyl carbon and the methylene group of the product arise from the methylene unit of the aziridine reactant.

Results and Discussion

It was anticipated that replacement of the heterocumulene carbon of **2** by a sulfur atom (i.e., sulfur diimide **4**) in the palladium-catalyzed reaction would result in the formation of a thiadiazolidenimine (**6**, Scheme 1). The latter compound was not obtained in the reaction. A unique cyclization process occurred instead. Specifically, treatment of 1-*tert*-butyl-2-phenylaziridine (**1**, R = Ph, R′ = $C(CH_3)_3$) with di-*p*-tolylsulfur diimide (**4**, Ar = *p*-$CH_3(C_6H_4)$) in toluene at 130 °C, using bis(benzonitrile)-palladium dichloride as the catalyst, afforded the imidazolidinethione **5** (Ar = *p*-$CH_3C_6H_4$, R = Ph, R′ = $(CCH_3)_3$) in 53% yield of pure material.

Scheme 1



The ratio of aziridine to sulfur diimide to palladium catalyst used was 20:10:1.0. The reaction is sensitive to the ratio of aziridine **1** and sulfur diimide **4**. When the ratio of aziridine **1**

* Abstract published in *Advance ACS Abstracts,* January 1, 1994.

(1) L'abbé, G.; Asch, A. V.; Toppet, S. *Bull. Soc. Chim. Belg.* **1978**, *87*, 929.
(2) Komatsu, M.; Ohshiro, Y.; Hoho, H.; Sato, M.; Toshio, A. *J. Org. Chem.* **1974**, *39*, 948.
(3) Herweh, J. E.; Kauffman, W. J. *Tetrahedron Lett.* **1971**, 809.
(4) Matsuda, H.; Ninagawa, A.; Hasegawa, H. *Bull. Chem. Soc. Jpn.* **1985**, *58*, 2717.
(5) Fujiwara, M.; Baba, A.; Matsuda, H. *J. Heterocycl. Chem.* **1988**, *25*, 1351.
(6) Baba, A.; Seki, K.; Matsuda, H. *J. Heterocycl. Chem.* **1990**, *27*, 1925.
(7) Nomura, R.; Nakano, T.; Nishio, Y.; Ogawa, S.; Ninagawa, A.; Matsuda, H. *Chem. Ber.* **1989**, *122*, 2409.
(8) Fujinami, T.; Suzuki, T.; Kamiya, M. *Chem. Lett.* **1985**, 199.
(9) Trost, B. M.; Sudhakar, A. R. *J. Am. Chem. Soc.* **1987**, *109*, 3792.
(10) Trost, B. M.; Sudhakar, A. R. *J. Am. Chem. Soc.* **1988**, *110*, 7933.
(11) Baeg, J. O.; Alper, H. *J. Org. Chem.* **1992**, *57*, 157.
(12) Bussas, R.; Kresze, G.; Münsterer, H.; Schwöbel, A. *Sulfur Rep.* **1983**, *2*, 215.
(13) Weinreb, S. M.; Staib, R. R. *Tetrahedron* **1982**, *38*, 3087.
(14) Boger, D. L.; Weinreb, S. M. *Hetero Diels–Alder Methodology in Organic Synthesis*; Academic Press: New York, 1987; p 16.
(15) Levchenko, E. S.; Bal'on, Y. G. *Zh. Org. Khim.* **1965**, *1*, 305.
(16) Levchenko, E. S.; Bal'on, Y. G. *Zh. Org. Khim.* **1965**, *1*, 150.
(17) Levchenko, E. S.; Bal'on, Y. G.; Kirsanov, A. V. *Zh. Org. Khim.* **1967**, *3*, 2068.
(18) Borovikova, G. S.; Levchenko, E. S.; Dorokhova, E. M. *Zh. Org. Khim.* **1979**, *15*, 479.
(19) Hänssgen, D.; Odenhausen, E. *J. Organomet. Chem.* **1977**, *124*, 143.

0002-7863/94/1516-1220$04.50/0

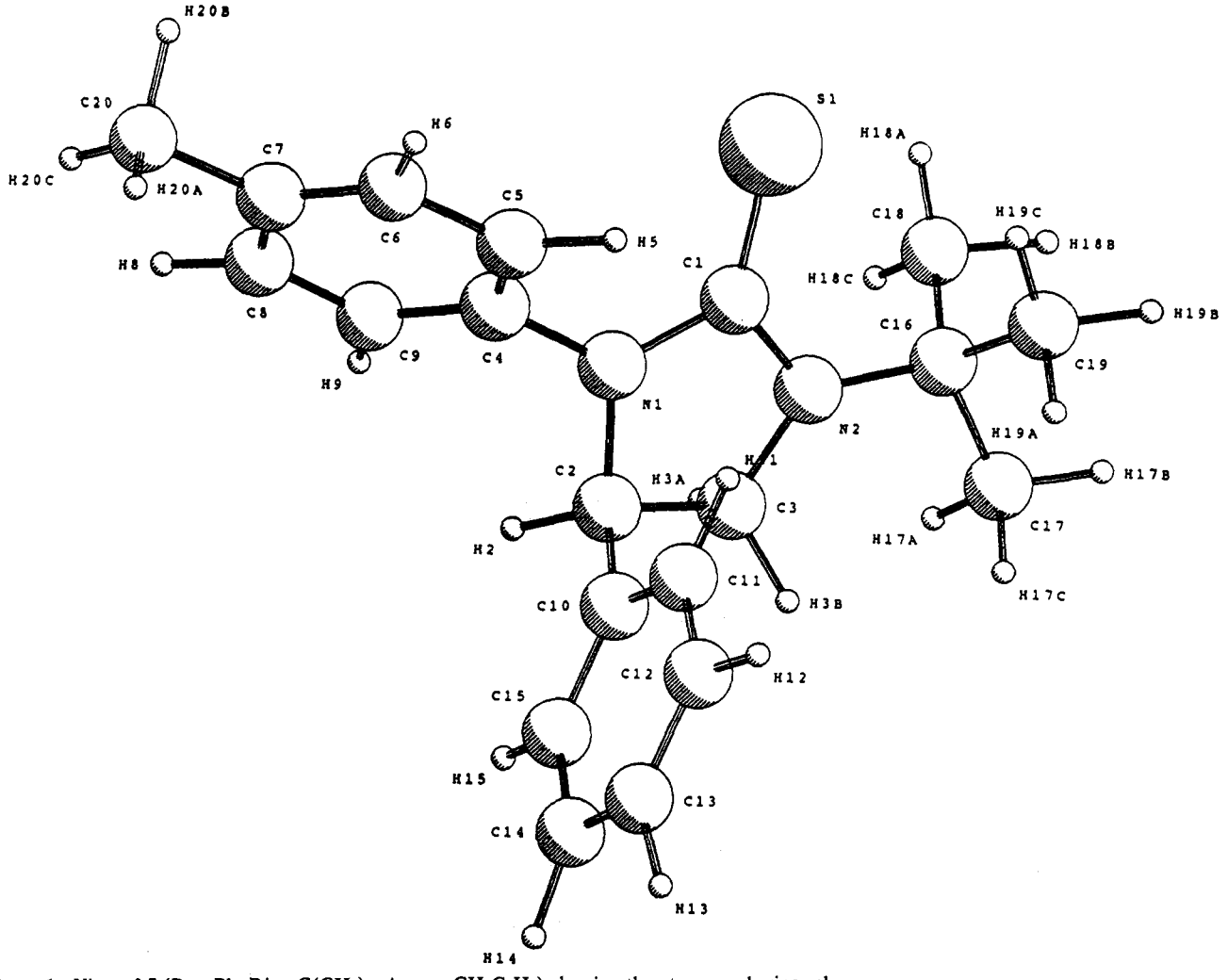
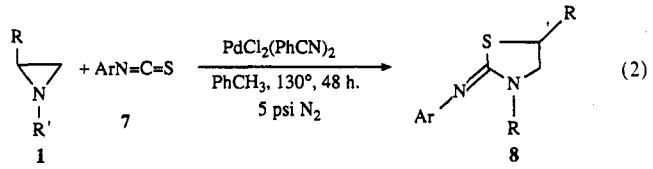


Figure 1. View of **5** (R = Ph, R′ = $C(CH_3)_3$, Ar = p-$CH_3C_6H_4$) showing the atom-numbering scheme.

(R = Ph, R′ = $C(CH_3)_3$) and sulfur diimide **4** (Ar = p-tolyl) was 1:1, the yield decreased to 36%.

The bis(benzonitrile)palladium dichloride analyzed cycloaddition reaction was effected using different aziridines and either diphenyl or di-p-tolylsulfur diimide, affording imidazolidinethiones **5** in 52–70% yields. In all of these reactions the aziridine experiences cleavage of the more substituted ring carbon–nitrogen bond. The imidazolidinethione **5** was identified by means of spectral data (see Experimental Section) as well as an X-ray analysis of **5** (R = Ph, R′ = $C(CH_3)_3$, Ar = p-$CH_3C_6H_4$). The thiocarbonyl stretching frequency of **5** occurred in the infrared spectrum at 1241–1251 cm^{-1},[20] and the thiocarbonyl carbon occurred at δ 182.00–183.16 in the ^{13}C-NMR spectrum.[21] Two doublets of doublets and a triplet (i.e., two overlapping doublets) were normally observed for the ring protons of **5** in the ^1H NMR. The mass spectra displayed molecular ion peaks in all cases. An X-ray structure determination revealed that the phenyl substituent of **5** (R = Ph, R′ = $C(CH_3)_3$, Ar = p-$CH_3C_6H_4$) was trans to both of the substituents (p-$CH_3C_6H_4$, $C(CH_3)_3$) attached to the nitrogen atoms. An ORTEP drawing is presented in Figure 1.

One can consider the formation of **5** by a formal [3 + 2] cycloaddition of an aryl isothiocyanate **7** and aziridine **1**. However, treatment of 1-(1-adamantyl)-2-phenylaziridine (**1**, R = Ph, R′ = 1-adamantyl) with phenyl isothiocyanate (**7**, Ar = Ph) under the same reaction conditions as in Scheme 1 gave the thiazolidinimine **8** in 85% isolated yield, and no imidazolidinethione **5** was detected in the reaction (eq 2).



(2)

(R=Ph,R'=1=adamantyl, Ar=Ph)

This result is analogous to the organoantimony halide catalyzed cycloaddition of aziridines with phenyl isothiocyanate.[7] Therefore, the imidazolidinethiones **5** do *not* originate from the cycloaddition reaction of aziridines and *in situ* generated aryl isothiocyanates.

Several experiments were then undertaken to probe the source of the carbon in the thiocarbonyl group of **5**. The benzonitrile ligand is an unlikely source of the thiocarbonyl carbon, since use of excess benzonitrile (equimolar with respect to **1**) in the reaction of **1** and **4** resulted in a lower yield of **5** [e.g., **1**, R = Ph, R′ = $C(CH_3)_3$, reacted with **4**, Ar = p-$CH_3C_6H_4$, to give **5** in 5% yield]. The methyl group of the solvent, toluene, is not incorporated in the product, since similar product yields were obtained in benzene or toluene, using the conditions described above. It seemed conceivable that the thiocarbonyl carbon of **5** derived from a second molecule of the reactant aziridine **1**, with the ring carbons (i.e., at the 2- or 3-position) being the likely candidates. In order to address this possibility, 1-*tert*-butyl-2-

(20) Pretsch, E.; Seibl, J.; Simon, W.; Clerc, T. *Tables of Spectral Data for Structure Determination of Organic Compounds*; Springer-Verlag: New York, 1983; p I220.

(21) Asset, G.; Kister, J.; Metzger, J. *Tetrahedron Lett.* **1976**, 3313.

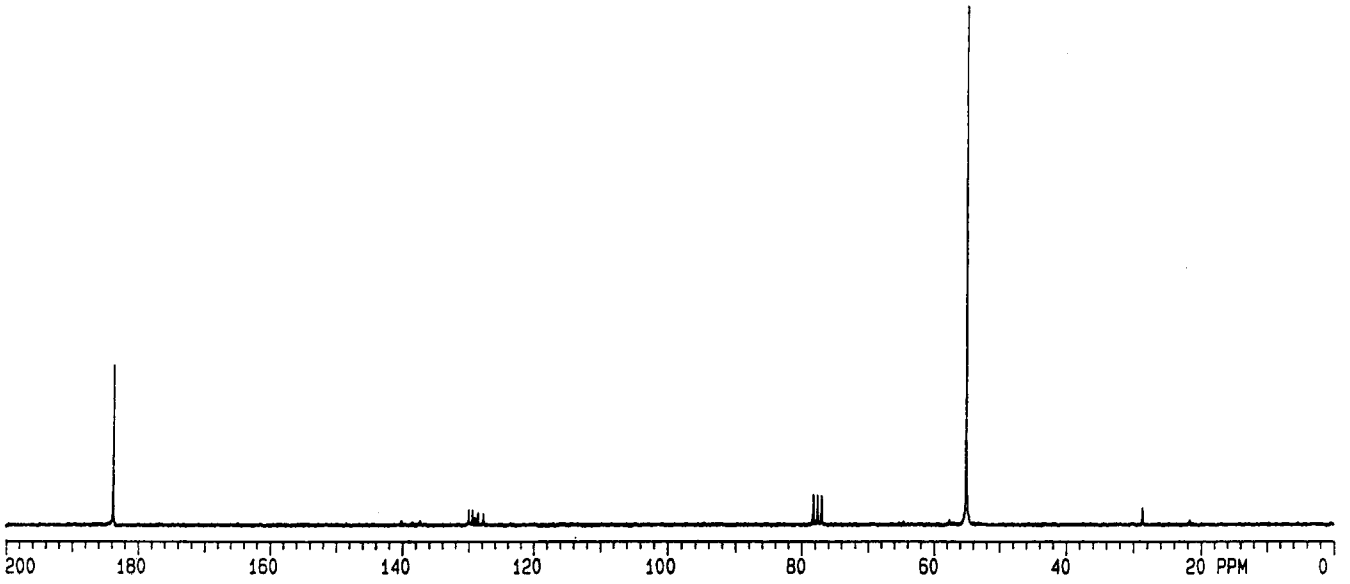
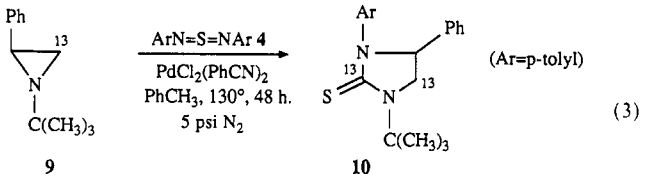


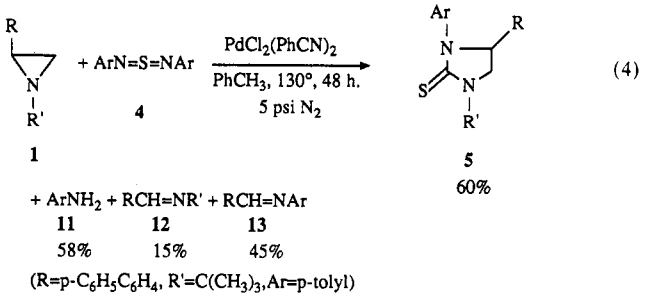
Figure 2. ^{13}C-NMR spectrum of **10**.

phenyl[3-^{13}C]aziridine (**9**) was prepared from [^{13}C]iodomethane. Treatment of [^{13}C]iodomethane with triphenylphosphine afforded labeled methyltriphenylphosphonium iodide in 96% yield.[22] Reaction of the latter with 5 N aqueous sodium hydroxide in benzene gave the labeled styrene ($PhCH{=}^{13}CH_2$) in 42% GC yield.[23] The benzene solution, containing Ph_3PO as a byproduct, was reacted *in situ* with *m*-chloroperbenzoic acid to give 2-phenyl-[3-^{13}C]oxirane in 52% isolated yield.[24] Subsequent reaction of the labeled oxirane with *tert*-butylamine, followed by treatment with bromine/PPh_3 and Et_3N in acetonitrile, gave **9** in 66% yield.[25] When **9** was treated with di-*p*-tolylsulfur diimide (**4**, Ar = *p*-$CH_3C_6H_4$) using conditions identical to those for the unlabeled reaction [$PdCl_2(PhCN)_2$, $PhCH_3$, 130 °C, 48 h], the ^{13}C-labeled imidazolidinethione **10** was obtained in 52% yield (eq 3).

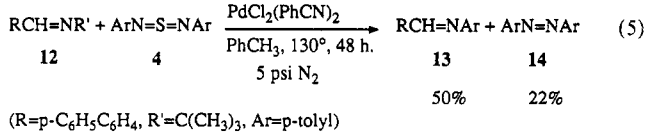


The ^{13}C-NMR spectrum of **10** clearly shows that the product contains ^{13}C at the 2- and 5-positions (δ 183.17 ($^{13}C{=}S$) and δ 54.46 ($^{13}CH_2$), respectively) (Figure 2). The mass spectrum gave an intense molecular ion peak at *m/e* 326. Therefore, the ^{13}C-labeling experiment demonstrated that the source of the new carbon atom in **5** is the CH_2 group of the reactant aziridine **1**.

Some additional information relevant to the reaction was obtained by analysis of the products accompanying the cycloaddition of **1** and **4** (eq 4). The primary arylamine **11** and two imines **12** and **13** were also isolated when **1** (R = *p*-$C_6H_5C_6H_4$, R′ = $C(CH_3)_3$) was treated with **4** (Ar = *p*-tolyl) to give **5** under the standard conditions. The yield of amine **11** (originally part of the sulfur diimide **4**) was almost the same as that of the imidazolidinethione **5**. The yield of the imine **12**, which results from formal loss of methylene from the aziridine **1**, was 15%. Imine **13**, isolated in 45% yield, may arise from an exchange reaction between **12** and **4**. Some evidence for the latter reaction



was obtained by treating the amine **12** with the sulfur diimide **4** in the presence of $PdCl_2(PhCN)_2$, which afforded a mixture of imine **13** (50%) and azoarene **14** (22% yield) (eq 5). Any azoarene



14, formed by treatment of **1** with **4** (eq 4), could react with an palladoazacyclobutane, to give **11** and **13**. This would explain the generation of only traces of **14** in the reaction leading to **5** (eq 4). This rationale assumes occurrence of a metathesis pathway for the production of the imidazolidinethione.

In conclusion, $(PhCN)_2PdCl_2$ is an effective catalyst for the reaction of aziridines with sulfur diimides to form imidazolidinethiones.

Experimental Section

General Methods. A Fisher-Johns apparatus was used for melting point determinations. The following spectrometers were used to obtain spectral data: Bomem MB 100-C15 (FT-IR); Bruker AMX 500, Varian XL-300, and Gemini 200 (NMR); VG 7070 E (MS). The aziridines, sulfur diimides, and palladium catalyst were prepared according to literature procedures.[25-28] The organic solvents were dried and distilled prior to use. Elemental analyses were carried out by MHW Laboratories, Phoenix, AZ. All reactions were conducted under a dry nitrogen atmosphere.

General Procedure for the Palladium-Catalyzed Cycloaddition Reaction of Aziridines and Sulfur Diimides. A mixture of aziridine (2.0 mmol), sulfur diimide (1.0 mmol), and bis(benzonitrile)palladium dichloride

(22) Wittig, G.; Schoellkopf, U. *Organic Syntheses*; Wiley: New York, 1973; Collect. Vol. V, p 751.
(23) Tagaki, W.; Inoue, I.; Yano, Y.; Okonogi, T. *Tetrahedron Lett.* **1974**, 2587.
(24) Hibbert, H.; Burt, P. *Organic Syntheses*; Wiley: New York, 1941; *Collect.* Vol. 1, p 494.
(25) Okada, I.; Ichimura, K.; Sudo, R. *Bull. Chem. Soc. Jpn.* **1970**, *43*, 1185.
(26) Levchenko, E. S.; Kirsanov, A. V. *Zh. Obshch. Khim.* **1961**, *31*, 1968.
(27) Levchenko, E. S.; Korsonov, A. V. *Zh. Org. Khim.* **1965**, *1*, 300.
(28) Doyle, J. R.; Slade, P. E.; Johassen, H. B. *Inorg. Synth.* **1960**, *6*, 218.

(0.038 g, 0.10 mmol) in toluene (3.0 mL) was heated with stirring in a glass autoclave for 48 h at 130 °C (oil bath temperature) under a slight pressure of nitrogen (5 psi). After being cooled to room temperature, the autoclave was opened and the red-brown homogeneous solution was filtered through Celite. The filtrate was concentrated by rotary evaporation, and the crude product was purified by silica gel thin-layer chromatography using 10:1 toluene/acetonitrile as the developer.

Yields (based on sulfur diimide), melting points, IR, NMR, MS, and either high-resolution mass spectra (HRMS) determinations or analytical data for **5** are as follows:

(a) R = Ph, R′ = $C(CH)_3$, Ar = *p*-tolyl: 53% yield; mp 203–204 °C; IR ν(C=S) 1242 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.52 (s, 9H, $C(CH_3)_3$), 2.22 (s, 3H, CH_3), 3.66 (dd, 1H, J = 8.4 and 9.9 Hz), 4.17 (t, 1H, J = 9.9 Hz), 4.95 (dd, 1H, J = 8.4 and 9.9 Hz), 7.01–7.26 (m, 9H, aromatic protons); ^{13}C NMR ($CDCl_3$) δ 21.26 (*p*-$CH_3C_6H_4$), 28.05 (CH_3), 54.48 (CH_2), 57.07 ($C(CH_3)_3$), 64.36 (CHAr), 127.23, 128.03, 128.48, 128.85, 129.40 (CH-aromatic), 136.70, 137.79, 139.52 (quaternary aromatic carbons), 183 (C=S); MS (*m/e*) 324 $[M]^+$; HRMS (*m/e*) 324.1643 (calcd for $C_{20}H_{24}N_2S$, 324.1660).

(b) R = Ph, R′ = *n*-C_4H_9, Ar = *p*-tolyl: 52% yield; mp 109–110 °C; IR ν (C=S) 1251 cm^{-1}; ^1H NMR ($CDCl_3$) δ 0.95 (t, 3H, CH_3), 1.38 (q, 2H, CH_2CH_3), 1.63 (m, 2H, $CH_2CH_2CH_3$), 2.22 (s, 3H, CH_3), 3.71 (m, 3H, NCH_2 and 1H of CH_2 ring), 4.08 (t, 1H, CH_2 ring, J = 10.0 Hz), 5.11 (dd, 1H, CHPh, J = 7.6 and 10.0 Hz), 6.99–7.30 (m, 9H, aromatic); ^{13}C NMR ($CDCl_3$) δ 14.03 (CH_3), 20.10, 29.25 (CH_3CH_2-CH_2), 21.12 (CH_3), 47.62 (NCH_2), 55.58 (CH_2 ring), 64.61 (CHPh), 127.17, 128.54, 128.59, 129.01, 129.40 (CH-aromatic), 136.57, 137.46, 139.66 (quaternary carbons of aromatic group), 182.60 (C=S); MS (*m/e*) 324 $[M]^+$. Anal. Calcd for $C_{20}H_{24}N_2S$: C, 73.03; H, 7.45; N, 8.63. Found: C, 73.86; H, 7.36; N, 8.58.

(c) R = Ph, R′ = 1-adamantyl, Ar = Ph: 52% yield; mp 215–216 °C; IR ν (C=S) 1244 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.61–2.60 (m, 15H, adamantyl protons), 3.68 (dd, 1H, J = 8.2 and 10.0 Hz), 4.18 (t, 1H, J = 10.0 Hz), 4.60 (dd, 1H, J = 8.2 and 10.0 Hz), 7.10–7.25 (m, 10H, aromatic ring protons); ^{13}C NMR ($CDCl_3$) δ 29.93, 36.27, 39.34 (secondary and tertiary adamantyl carbons), 53.52 (CH_2), 58.34 (quaternary carbon of adamantyl group), 64.27 (CHPh), 126.80, 127.14, 128.21, 128.43, 128.53, 128.83 (CH-aromatic), 139.50, 140.26 (quaternary carbons of Ph), 182.01 (C=S); MS (*m/e*) 388 $[M]^+$. Anal. Calcd for $C_{25}H_{28}N_2S$: C, 77.28; H, 7.26; N, 7.21. Found: C, 77.08; H, 7.19; N, 7.14.

(d) R = Ph, R′ = 1-adamantyl, Ar = *p*-tolyl: 56% yield; mp 217–218 °C; IR ν(C=S) 1246 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.59–2.52 (m, 15H, adamantyl protons), 2.21 (s, 3H, CH_3), 3.67 (dd, 1H, J = 8.2 and 10.0 Hz), 4.16 (t, 1H, J = 10.0 Hz), 4.92 (dd, 1H, J = 8.2 and 10.0 Hz), 6.96–7.25 (m, 9H, aromatic ring protons); ^{13}C NMR ($CDCl_3$) δ 21.14 (*p*-$CH_3C_6H_4$), 29.94, 36.30, 39.36 (secondary and tertiary adamantyl carbons), 53.51 (CH_2), 58.27 (quaternary carbon of adamantyl group), 64.37 (CHPh), 127.20, 128.08, 128.40, 128.80, 129.33 (CH-aromatic), 136.58, 137.69, 139.65 (quaternary carbons of Ph), 182.22 (C=S); MS (*m/e*) 402 $[M]^+$. Anal. Calcd for $C_{26}H_{30}N_2S$: C, 77.57; H, 7.51; N, 6.96. Found: C, 77.73; H, 7.46; N, 6.90.

(e) R = *p*-BrC_6H_4, R′ = $C(CH_3)_3$, Ar = Ph: 60% yield; mp 153–154 °C; IR ν (C=S) 1246 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.67 (s, 9H, $C(CH_3)_3$), 3.60 (dd, 1H, J = 8.4 and 9.9 Hz), 4.17 (t, J = 9.9 Hz), 4.97 (dd, 1H, J = 8.4 and 9.9 Hz), 7.09–7.43 (m, 10H, aromatic protons); ^{13}C NMR ($CDCl_3$) δ 28.02 (CH_3), 54.27 (CH_2), 57.21 ($C(CH_3)_3$), 63.58 (CHAr), 127.01, 128.03, 128.72, 128.85, 132.06 (aromatic carbons), 122.45, 138.45, 140.16 (quaternary aromatic carbons), 182.86 (C=S); MS (*m/e*) 389 $[M]^+$ and 391 $[M + 2]^+$. Anal. Calcd for $C_{19}H_{21}BrN_2S$: C, 58.61; H, 5.44; N, 7.20. Found: C, 58.86; H, 6.01; N, 6.65.

(f) R = *p*-BrC_6H_4, R′ = $C(CH_3)_3$, Ar = *p*-tolyl: 58% yield; mp 175–176 °C; IR ν (C=S) 1241 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.66 (s, 9H, $C(CH_3)_3$), 2.22 (s, 3H, CH_3), 3.58 (dd, 1H, J = 8.2 and 10.0 Hz), 4.15 (t, 1H, J = 10.0 Hz), 4.92 (dd, 1H, J = 8.2 and 10.0 Hz), 7.01–7.41 (m, 8H, aromatic protons); ^{13}C NMR ($CDCl_3$) δ 21.15 (*p*-$CH_3C_6H_4$), 28.03 (CH_3), 54.23 (CH_2), 57.13 ($C(CH_3)_3$), 63.67 (CHAr), 127.88, 128.90, 129.47, 132.01 (aromatic carbons), 122.39, 136.79, 137.59, 138.59 (quaternary aromatic carbons), 183.07 (C=S); MS (*m/e*) 403 $[M]^+$ and 405 $[M + 2]^+$. Anal. Calcd for $C_{20}H_{23}BrN_2S$: C, 59.55; H, 5.75; N, 6.94. Found: C, 59.21; H, 5.82; N, 6.81.

(g) r = *p*-PhC_6H_4, R′ = 1-adamantyl, Ar = Ph; 70% yield; mp 211–212 °C; IR ν (C=S) 1245 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.69–2.55 (m, 15H, adamantyl protons), 3.71 (dd, 1H, J = 8.4 and 10.0 Hz), 4.20 (t, 1H, J = 10.0 Hz), 5.02 (dd, 1H, J = 8.4 and 10.0 Hz), 7.14–7.71 (m, 14H, aromatic ring protons); ^{13}C NMR ($CDCl_3$) δ 30.04, 36.37, 39.41 (secondary and tertiary adamantyl carbons), 53.59 (CH_2), 58.41 (quaternary carbon of adamantyl group), 63.96 (CHPh), 127.03, 127.40, 127.55, 127.64, 128.26, 128.63, 128.89, 129.09 (CH-aromatic), 138.59, 140.28, 140.43, 141.24 (quaternary carbons of aromatic group), 182.02 (C=S); MS (*m/e*) 464 $[M]^+$. Anal. Calcd for $C_{31}H_{32}N_2S$: C, 80.13; H, 6.94; N, 6.03. Found: C, 80.06; H, 7.03; N, 5.82.

(h) R = *p*-PhC_6H_4, R′ = 1-adamantyl, Ar = *p*-tolyl: 68% yield; mp 142–143 °C; IR ν (C=S) 1245 cm^{-1}; ^1H NMR ($CDCl_3$) ν 1.69–2.62 (m, 15H, adamantyl protons), 2.23 (s, 3H, CH_3), 3.70 (dd, 1H, J = 8.4 and 9.8 Hz), 4.19 (t, 1H, J = 9.8 Hz), 4.98 (dd, 1H, J = 8.4 and 9.8 Hz), 7.04–7.97 (m, 13H, aromatic ring protons); ^{13}C NMR ($CDCl_3$) δ 21.21 (*p*-$CH_3C_6H_4$), 30.03, 36.37, 39.43 (secondary and tertiary adamantyl carbons), 53.57 (CH_2), 58.34 (quaternary carbon of adamantyl group), 64.10 (CHPh), 127.02, 127.52, 127.69, 128.14, 128.87, 129.09, 129.43 (CH-aromatic), 136.63, 137.81, 138.68, 140.30, 141.22 (quaternary carbons of aromatic group), 182.28 (C=S); MS (*m/e*) 478 $[M]^+$. Anal. Calcd for $C_{32}H_{34}N_2S$: C, 80.29; H, 7.16; N, 5.85. Found: C, 80.50; H, 7.85; N, 5.35.

(i) R = *p*-PhC_6H_4, R′ = $C(CH_3)_3$, Ar = *p*-tolyl: 60% yield; mp 183–184 °C; IR ν (C=S) 1243 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.69 (s, 9H, $C(CH_3)_3$), 2.23 (s, 3H, CH_3), 3.68 (dd, 1H, J = 8.4 and 9.9 Hz), 4.19 (t, 1H, J = 9.9 Hz), 4.95 (dd, 1H, J = 8.4 and 9.9 Hz), 7.04–7.58 (m, 13H, aromatic protons); ^{13}C NMR ($CDCl_3$) δ 21.18 (*p*-$CH_3C_6H_4$), 28.09 (CH_3), 54.49 (CH_2), 57.13 ($C(CH_3)_3$), 64.08 (CHAr), 127.00, 127.53, 127.67, 128.05, 128.84, 129.46, 129.74 (CH-aromatic), 136.74, 137.87, 138.51, 140.26, 141.28 (quaternary aromatic carbons), 183.16 (C=S); MS (*m/e*) 400 $[M]^+$; HRMS (*m/e*) 400.19876 (calcd for $C_{26}H_{28}N_2S$, 400.19721).

Procedure for the Palladium-Catalyzed Cycloaddition Reaction of 1-Adamantyl-2-phenylaziridine and Phenyl Isothiocyanate. A mixture of aziridine (**1**, 1 mmol), phenyl isothiocyanate (**7**, 1 mmol), and bis(benzonitrile)palladium dichloride (0.038 g, 0.10 mmol) in toluene (3.0 mL) was heated with stirring in a glass autoclave, for 48 h at 130 °C (oil bath temperature) under a slight pressure of nitrogen (5 psi). The workup procedure was the same as that described in the general procedure for the palladium-catalyzed cycloaddition reaction of aziridines and sulfur diimides. The isolated yield of **8** was 0.33 g: 85% yield; mp 133–134 °C; IR ν (C=N) 1619 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.66–2.50 (m, 15H, adamantyl protons), 3.67 (dd, 1H, J = 8.2 and 9.7 Hz, CH_2), 4.01 (dd, 1H, J = 6.6 and 9.7 Hz, CH_2), 4.55 (m, 1H, CHPh), 6.95–7.46 (m, 10H, aromatic ring protons); ^{13}C NMR ($CDCl_3$) δ 30.73, 37.27, 40.29 (secondary and tertiary adamantyl carbons), 46.51 (CHPh), 56.57 (CH_2), 58.94 (quaternary carbon of adamantyl group), 122.53, 123.27, 128.17, 128.62, 129.37, 129.43 (CH-aromatic), 140.13, 153.26 (quaternary carbons of Ph), 156.75 (C=N); MS (*m/e*) 388 $[M]^+$. Anal. Calcd for $C_{25}H_{28}N_2S$: C, 77.23; H, 7.26; N, 7.21. Found: C, 77.08; H, 7.15; N, 7.50.

Synthesis of 1-*tert*-Butyl-2-phenyl[3-^{13}C]aziridine (9). (i) Methyl-[^{13}C]triphenylphosphonium Iodide. A solution containing 9.4 g (36.0 mmol) of triphenylphosphine dissolved in dry benzene (6.0 mL) was placed in a pressure bottle, the bottle was cooled in an ice bath, and 5.0 g (36.0 mmol) of [^{13}C]methyl iodide was added. The bottle was sealed, allowed to stand at room temperature for 2 days, and then reopened. The white solid was collected by filtration with the aid of about 100 mL of hot benzene and was dried in a vacuum at 100 °C over phosphorus pentoxide. The yield was 13.9 g (96%), mp 183–184 °C.

(ii) 2-Phenyl[3-^{13}C]oxirane. A heterogeneous mixture of benzaldehyde (1.83 g, 17.2 mmol), methyl[^{13}C]triphenylphosphonium iodide (13.9 g, 34.3 mmol), benzene (34 mL), and 5 N aqueous sodium hydroxide (102 mL) was stirred for 24 h at 40 °C. The reaction mixture was extracted with benzene (3 × 25 mL), the alkali was removed by washing with water, and the benzene solution was dried ($MgSO_4$) and filtered. The yield of 1-phenyl[2-^{13}C]ethene was 42% (GC yield, using *n*-undecane as internal standard). The benzene solution (also containing Ph_3PO as a byproduct) was used for the subsequent epoxidation.

To the benzene solution was added 7.6 g (22.0 mmol) of *m*-chloroperbenzoic acid (50%). The mixture was kept at 0 °C for 40 h and was shaken frequently during the first hour. The formed *m*-chloroperbenzoic acid was removed from the benzene solution by shaking with an excess of 10% aqueous sodium hydroxide, and the alkali was removed by washing with water. The benzene layer was dried ($MgSO_4$) and evaporated, and the residue was distilled *in vacuo* to give 0.91 g (52%) of oxirane: bp 38–40 °C/1 mmHg; ^1H NMR ($CDCl_3$) δ 2.78 (ddd, 1H, J = 2.5, 5.8, and 176.0 Hz, $^{13}CH_2$), 3.12 (ddd, 1H, J = 4.1, 5.8, and 178.0 Hz, $^{13}CH_2$), 3.83 (m, 1H, CHPh), 7.26–7.43 (m, 5H, Ph); MS (*m/e*) 121 $[M^+]$.

(iii) 1-Phenyl-2-(*tert*-butylamino)[2-^{13}C]1-ethanol. A mixture of 0.91 g (7.5 mmol) of 2-phenyl[3-^{13}C]oxirane and 2.74 g (37.5 mmol) of *tert*-butylamine was stirred in an autoclave for 60 h at 95 °C. After evaporation of excess *tert*-butylamine, the residual solid was crystallized from hexane to give 1.03 g (71%) of the white amino alcohol: mp 85–86 °C; IR ($CHCl_3$) $\nu_{OH,NH}$ 3600, 3400–3300 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.12 (s, 9H, $C(CH_3)_3$), 2.26–3.15 (m, 4H, $^{13}CH_2$, NH, OH), 4.55 (m, 1H, CHOH), 7.28 (m, 5H, Ph); MS (*m/e*) 194 [M$^+$].

(iv) 1-*tert*-Butyl-2-phenyl[3-^{13}C]aziridine (9). To an ice-cold solution of 1.40 g (5.3 mmol) of triphenylphosphine in 12 mL of acetonitrile (N_2 atmosphere) was added, drop-by-drop, an ice-cold solution of 0.85 g (5.3 mmol) of bromine in 3.5 mL of acetonitrile. To the resulting red solution was slowly added 1.03 g (5.3 mmol) of the β-amino alcohol, followed by drop-by-drop addition of 1.62 g (16.0 mmol) of distilled triethylamine in 3.5 mL of acetonitrile (all done at 0 °C). The reaction mixture was then stirred at ambient temperature for 20 min, triethylamine hydrobromide (2.24 g, 77%) was filtered, and the filtrate was concentrated by rotary evaporation. The residue was treated with hexane (6 × 15 mL), concentrated to 7 mL, and then filtered to remove triphenylphosphine oxide, and the filtrate was evaporated. The aziridine **9** was obtained in 66% yield by distillation at 40 °C (0.5 mmHg): ^{1}H NMR ($CDCl_3$) δ 1.06 (s, 9H, $C(CH_3)_3$), 1.66 (ddd, 1H, J = 0.8, 3.0, and $J_{^{13}C-^1H}$ = 176.0 Hz, $^{13}CH_2$), 1.91 (ddd, 1H, J = 0.8, 6.4, and $J_{^{13}C-^1H}$ = 162.0 Hz, $^{13}CH_2$), 2.64 (m, 1H, CHPh), 7.20–7.37 (m, 5H, Ph); ^{13}C NMR ($CDCl_3$) δ 27.20 (CH_3), 30.95 ($^{13}CH_2$, intense signal), 34.30 ($C(CH_3)_3$), 51.83 (CHPh), 127.20, 128.78 (CH-aromatic), 128.95 (quaternary aromatic (carbon); MS (*m/e*) 176 [M$^+$].

Procedure for the Palladium-Catalyzed Cycloaddition Reaction of 1-*tert*-Butyl-2-phenyl[3-^{13}C]aziridine and 1,3-Di-*p*-tolylsulfur Diimide. The reaction procedure was the same as that described in the general procedure for the palladium-catalyzed cycloaddition reaction of aziridines and sulfur diimides. The isolated yield of the pure product **10** was 52%: mp 203–204 °C; IR ν (^{13}C=S) 1214 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.69 (s, 9H, $C(CH_3)_3$), 2.23 (s, 3H, CH_3), 3.66 (doublet of multiplets, 1H, $J_{^{13}C-^1H}$ = 144.0 Hz, $^{13}CH_2$), 4.19 (doublet of multiplets, 1H, $J_{^{13}C-^1H}$ = 146.0 Hz, $^{13}CH_2$), 4.96 (m, 1H, CHPh), 7.02–7.35 (m, 9H, aromatic protons); ^{13}C NMR ($CDCl_3$) δ 21.16 (p-$CH_3C_6H_4$), 28.06 (CH_3), 54.46 ($^{13}CH_2$, intense signal), 57.07 ($C(CH_3)_3$), 64.23 (CHAr), 127.25, 128.04, 128.49, 128.87, 129.40 (CH-aromatic), 136.69, 137.85, 139.60 (quaternary aromatic carbons), 183.17 (^{13}C=S, intense signal); MS *m/e* 326 [M$^+$].

X-ray Analysis. A plate crystal of $C_{20}H_{24}N_2S$ was mounted on a glass capillary, and all measurements were made on a Rigaku diffractometer with Mo Kα radiation. Cell dimensions and the orientation matrix were obtained from least-squares refinement using the setting angles of 25 reflections in the range $40° < 2\theta < 47°$, corresponding to an orthorhombic cell with dimensions given in the supplementary material. For $Z = 4$ and FW = 324.48, the calculated density is 1.147 g/cm^3. The space group was determined to be $P2/2/2$. The data were collected at 21 °C using the $\omega - 2\theta$ scan technique to a maximum 2θ value of 47, and the data were corrected for Lorentz and polarization effects.[29]

The structure was solved by direct methods. All of the atoms with the exception of hydrogen were refined anisotropically. The final cycle of full-matrix least-squares refinement was based on 789 observed reflections ($I > 2.5\sigma(I)$) and 185 variable parameters. All calculations were performed using the NRC VAX crystallographiic software package.[30]

Acknowledgment. We are grateful to the Natural Sciences and Engineering Research Council for support of this research. We thank Dr. C. Bensimon for the X-ray determination of **5** (R = Ph, R′ = $C(CH_3)_3$, Ar = p-$CH_3C_6H_4$). We are indebted to Dr. L. S. Hegedus for his constructive comments concerning this manuscript.

Supplementary Material Available: Experimental details and tables of atomic parameters (x, y, z, and B_{iso}) and bond distances and angles for **5**, R = Ph, R′ = $C(CH_3)_3$, Ar = p-$CH_3C_6H_4$ (13 pages); tables of structure factors for **5** (9 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

(29) Grant, D. F.; Gabe, E. J. *J. Appl. Crystallogr.* **1978**, *11*, 114.
(30) Gabe, E. J.; Lee, A. L.; Lepage, Y. *J. Appl. Crystallogr.* **1989**, *22*, 384.