

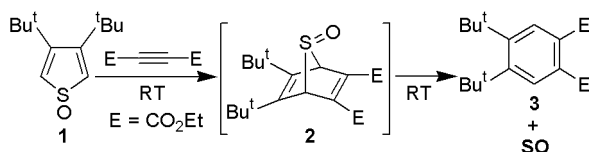
[1 + 2] Cycloadditions of Sulfur Monoxide (SO) to Alkenes and Alkynes and [1 + 4] Cycloadditions to Dienes (Polyenes). Generation and Reactions of Singlet SO?

Juzo Nakayama,* Yumi Tajima, Piao Xue-hua, and Yoshiaki Sugihara

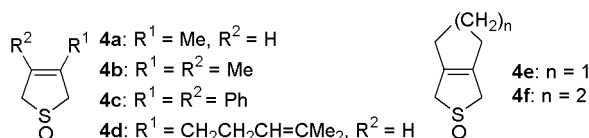
Department of Chemistry, Graduate School of Science and Engineering, Saitama University, Urawa-ku, Saitama, Saitama 338-8570, Japan

Received March 23, 2007; E-mail: nakaj@post.saitama-u.ac.jp

Recently, we reported that the Diels–Alder reaction of 3,4-di-*tert*-butylthiophene 1-oxide (**1**) with dimethyl acetylenedicarboxylate (DMAD) at room temperature affords dimethyl 4,5-di-*tert*-butylphthalate (**3**) in high yield probably through extrusion of sulfur monoxide (SO) from the initial adduct **2**.¹ The SO, generated here, would be singlet if the SO extrusion from **2** takes place and is concerted. We have thus examined a range of chemical trapping experiments of the SO to characterize its reactivities and to compare them with those of SO generated from other organic sources.^{2,3}

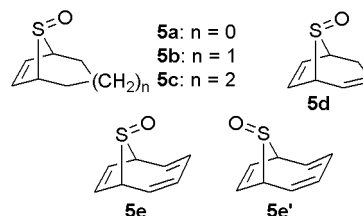


Thus, the reaction of **1** with an equimolar amount of DMAD was examined at room temperature in the presence of excess diene.⁴ 2-Methyl-1,3-butadiene, 2,3-dimethyl-1,3-butadiene, 2,3-diphenyl-1,3-butadiene, myrcene, 1,2-dimethylenecyclopentane, and 1,2-dimethylenecyclohexane successfully trapped the SO to give the [1 + 4] cycloadducts **4a**^{2f} (49%), **4b**^{2a} (74%), **4c**^{2a} (28%), **4d**^{2k} (27%), **4e** (76%), and **4f** (44%), respectively; the phthalate **3** was isolated in good yield in all cases. Reportedly, SO, generated by thermolysis of thiirane oxide in refluxing toluene, added to each of the three 2,4-hexadiene isomers to provide [1 + 4] adducts, in which the stereochemistry of the dienes was not retained.^{2f,g} The authors thus concluded that triplet SO was generated⁵ and the addition took place through a radical intermediate. By contrast, the SO generated from **2** failed to add to these dienes, and thus we could not determine the stereochemistry of the addition.



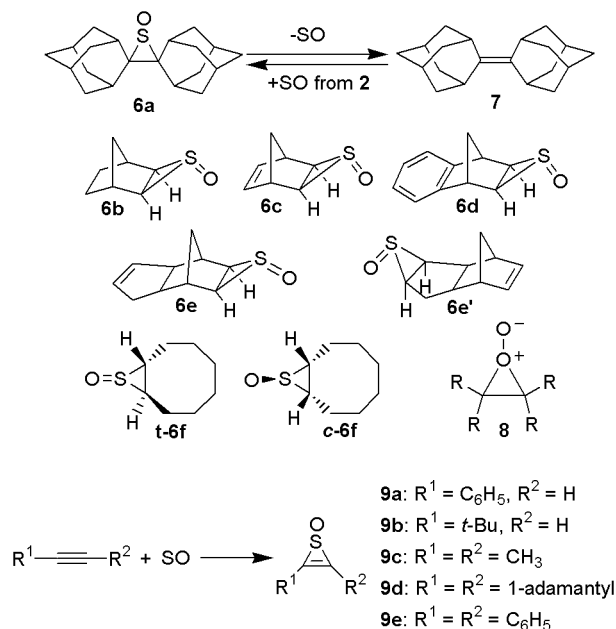
The SO was also trapped by cyclic dienes (polyenes) such as 1,3-cyclohexadiene, 1,3-cycloheptadiene, 1,3-cyclooctadiene, cycloheptatriene, and cyclooctatetraene to give **5a** (68%), **5b** (27%), **5c**^{2f} (2%), **5d** (26%), and **5e**²ⁱ (39%), respectively, although cyclopentadiene failed to give the corresponding adduct. Reportedly, the SO, generated from thiirane oxide in refluxing toluene, gave a mixture of **5e** (23.6%) and **5e'** (4.5%) on reaction with cyclooctatetraene,²ⁱ whereas in our case, **5e** is the sole adduct. **5e** isomerized to **5e'**, when heated in refluxing toluene, to produce a 9:1 equilibrium mixture of **5e** and **5e'**.^{6,7} The other adducts **5a–5d** did not undergo such isomerization under the same conditions. Thus, the present [1 + 4] addition is kinetically controlled and results in the

stereoselective formation of **5a–5e**, where the S=O group is *anti* to the resulting double bond. It was also reported that the SO, generated from thiirane oxide, did not add to cycloheptatriene to give **5d**, but gave 7,7'-dicycloheptatriene probably through hydrogen abstraction by SO.^{2b} Any sign of such reaction was not observed in the present case. In addition, throughout this study, [2 + 4] adducts of the SO with dienes never formed, in contrast with reactions of ¹O₂,⁸ diatomic sulfur (S₂),⁹ and sulfur dioxide¹⁰ which afford [2 + 4] cycloadducts.

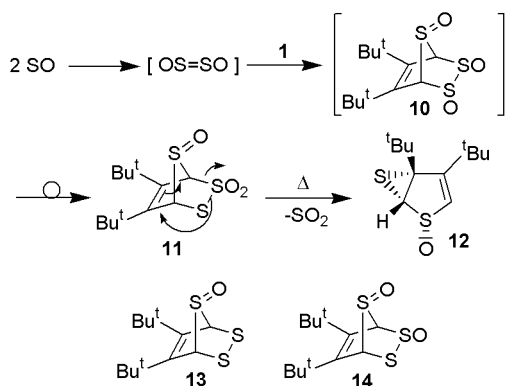


Thiirane oxide **6a** was reported to generate SO with formation of 2,2'-biadamantylidene (**7**).^{2j,k} We have now found that the reverse reaction does take place, that is, the SO, generated from **2**, added to **7** affording **6a** in 17% yield. Angle-strained alkenes, norbornene, norbornadiene, and benzonorbornadiene also reacted with the SO to produce **6b**¹¹ (2%), **6c**¹¹ (19%), and **6d** (4%), respectively, thus providing a new one-pot conversion of alkenes to thiirane oxides. Dicyclopentadiene gave **6e** (5%) and **6e'** (3%). The SO addition to *cis*- and *trans*-cyclooctene is stereospecific and gave **c-6f** (2%) and **t-6f** (17%) as the sole adduct, respectively, indicating that the addition may occur in a concerted manner.¹² However, more general information on the stereochemistry was not obtained because the SO did not add to *cis*- and *trans*-cyclodecenes and *cis*- and *trans*-3-hexenes. Incidentally, we should note the fact that thiirane oxides correspond to peroxides **8**, which were often postulated as the intermediates that lead to the formation of dioxetanes and other products for the reactions of ¹O₂ with alkenes.¹³

Synthetically most important is the addition of the SO to alkynes, which provided a simple synthesis of thiirene 1-oxides.¹⁴ Thus, the SO added to 2-phenylacetylene, 3,3-dimethyl-1-butyne, 2-butyne, di(1-adamantyl)acetylene, and diphenylacetylene to give thiirene 1-oxides **9a** (20%), **9b** (10%), **9c**¹⁵ (17%), **9d**^{14e-g} (7%), and **9e**^{14a,b} (5%), respectively. **9a** and **9b** are the first examples of monosubstituted thiirene 1-oxides. Even structurally simple thiirene 1-oxides such as **9a–c** are much more stable than expected and were satisfactorily purified by silica gel column chromatography, recrystallization, or distillation. In the ¹H NMR spectrum of **9a** and **9b**, the vinyl proton appeared at δ 8.69 and 8.20, respectively, values comparable to those of cyclopropenone (δ 9.0) and methylcyclopropenone (8.6).¹⁶



As described above, the yields of the SO-trapping products are generally low to moderate, though the yield of **3** was more than 80%. The remaining SO is consumed to produce elemental sulfur, sulfur dioxide, and compound **11**. The formation of **11** can best be explained by dimerization of SO and the Diels–Alder reaction of the resulting disulfur dioxide ($OS=SO$)³ with **1** that produces *vic*-disulfide **10**,¹⁷ which undergoes a 1,2-rearrangement to give **11**. Thus, the reaction of DMAD with 2 molar equiv of **1** gave an increased yield of **11** (46%). **11** was alternatively obtained by oxidation of **13**¹⁸ through the known compound **14**¹⁸ and then **10**. **11** is thermally unstable and converted to **12** by extrusion of SO_2 .



Evidently the reactivities of the present SO differ from those of SO that was generated from thiirane oxides and other sources and considered to be triplet. Its capability of adding to alkenes and alkynes resembles singlet carbenes. Therefore, seemingly, the singlet SO was generated from **2** and directly involved in the trapping reactions without decay to the more stable triplet.^{19,20}

Acknowledgment. This work was supported by a Grant-in-Aid (#16350019) for Scientific Research the Ministry of Education, Culture, Sports, Science, and Technology, Japan.

Supporting Information Available: General procedure of the trapping experiments and spectroscopic data for new compounds and a few selected compounds. This material is available free of charge via the Internet at <http://pubs.acs.org>.

References

- (1) Otani, T.; Takayama, J.; Sugihara, Y.; Ishii, A.; Nakayama, J. *J. Am. Chem. Soc.* **2003**, *125*, 8255–8263.
- (2) (a) Dodson, R. M.; Sauer, R. F. *J. Chem. Soc., Chem. Commun.* **1967**, 1189–1190. (b) Dodson, R. M.; Nelson, J. P. *J. Chem. Soc., Chem. Commun.* **1969**, 1159–1160. (c) Chow, Y. L.; Tam, J. N. S.; Blier, J. E.; Szmant, H. H. *J. Chem. Soc., Chem. Commun.* **1970**, 1604–1605. (d) Baldwin, J. E.; Höfle, G.; Choi, S. C. *J. Am. Chem. Soc.* **1971**, *93*, 2810–2812. (e) Anastassiou, A. G.; Chao, B. Y.-H. *J. Chem. Soc.* **1971**, 979–980. (f) Chao, P.; Lemal, D. M. *J. Am. Chem. Soc.* **1973**, *95*, 920–922. (g) Lemal, D. M.; Chao, P. *J. Am. Chem. Soc.* **1973**, *95*, 922–924. (h) Aalbersberg, W. G. L.; Vollhardt, K. P. C. *J. Am. Chem. Soc.* **1977**, *99*, 2792–2794. (i) Quin, L. D.; Rao, N. S.; Szwedczyk, J. *Tetrahedron Lett.* **1985**, *26*, 6293–6296. (j) Abu-Yousef, I. A.; Harpp, D. N. *Tetrahedron Lett.* **1995**, *36*, 201–204. (k) Abu-Yousef, I. A.; Harpp, D. N. *J. Org. Chem.* **1997**, *62*, 8366–8371. (l) Huang, R.; Espenson, J. H. *J. Org. Chem.* **1999**, *64*, 6374–6379. (m) Grainger, R. S.; Procopio, A.; Steed, W. *Org. Lett.* **2001**, *3*, 3565–3568.
- (3) For generation of sulfur monoxide and its dimer by inorganic methods, see: Schenk, P. W.; Steudel, R. In *Inorganic Sulphur Chemistry*; Elsevier: Amsterdam, 1968; pp 367–418.
- (4) Trapping experiments were carried out by using an excess alkene, diene (polyene), or alkyne. Only for the trapping with *trans*-cyclooctene, **1**, DMAD, and the alkene were used in the 1:2:1 molar ratio; the use of the excess alkene caused the predominant formation of the Diels–Alder adduct of **1** and the alkene.
- (5) The formation of alkene from thiirane 1-oxide is not stereospecific.^{2d}
- (6) Anastassiou, A. G.; Wetzel, J. C.; Chao, B. Y.-H. *J. Am. Chem. Soc.* **1975**, *97*, 1124–1132.
- (7) DFT calculations (B3LYP/6-31+G(d)) showed that **5e** is more stable than **5e'** by 2.26 kcal/mol.
- (8) Wasserman, H. H.; Murray, R. W. *Singlet Oxygen*; Academic Press: New York, 1979.
- (9) For review, see: Abu-Yousef, I. A. *J. Sulf. Chem.* **2006**, *27*, 87–119.
- (10) Monnat, F.; Vogel, P.; Meana, R.; Sordo, J. A. *Angew. Chem., Int. Ed.* **2003**, *42*, 3924–3927.
- (11) Alexander, J. B.; Cooke, P. A.; Kendall, J. D.; Simpkins, N. S.; Westaway, S. M. *J. Chem. Soc., Perkin Trans. 1* **2000**, 153–163.
- (12) $Rh_2(OAc)_4$ -catalyzed SO transfer from *trans*-2,3-diphenylthiirane oxide to norbornene and norbornadiene was reported.⁹ The reaction is not stereoselective; for example, the transfer to norbornene gave a mixture of **6b** and its isomer in which the oxygen atom faces the methylene bridge.
- (13) For recent reviews on 1O_2 , see: (a) Stratakis, M.; Organopoulos, M. *Tetrahedron* **2000**, *56*, 1595–1615. (b) Clennan, E. L. *Tetrahedron* **2000**, *56*, 9151–9179. (c) Clennan, E. L.; Pace, A. *Tetrahedron* **2005**, *61*, 6665–6691.
- (14) (a) Carpino, L. A.; Chen, H.-W. *J. Am. Chem. Soc.* **1971**, *93*, 785–786. (b) Carpino, L. A.; Chen, H.-W. *J. Am. Chem. Soc.* **1979**, *101*, 390–394. (c) Ando, W.; Hanyu, Y.; Takata, T. *J. Am. Chem. Soc.* **1982**, *104*, 4981–4982. (d) Ando, W.; Hanyu, Y.; Takata, T.; Sakurai, T.; Kobayashi, K. *Tetrahedron Lett.* **1984**, *25*, 1483–1486. (e) Nakayama, J.; Takahashi, K.; Watanabe, T.; Sugihara, Y.; Ishii, A. *Tetrahedron Lett.* **2000**, *41*, 8349–8352. (f) Nakayama, J.; Takahashi, K.; Sugihara, Y.; Ishii, A. *Tetrahedron Lett.* **2001**, *42*, 4017–4019. (g) Nakayama, J.; Takahashi, K.; Ono, Y.; Morita, M.; Sugihara, Y.; Ishii, A. *Heteroat. Chem.* **2002**, *13*, 424–430.
- (15) It was claimed that singlet SO added to 2-butyne to give **9c** in a rare gas matrix at 12 K: Salama, F.; Frei, H. *J. Phys. Chem.* **1989**, *93*, 1285–1292. However, **9c** was not isolated, and its structural evidence only comes from IR spectrum.
- (16) Breslow, R.; Ryan, G. *J. Am. Chem. Soc.* **1967**, *89*, 3073.
- (17) Ishii, A.; Nakabayashi, M.; Nakayama, J. *J. Am. Chem. Soc.* **1999**, *121*, 7959–7960 and references cited therein.
- (18) Nakayama, J.; Aoki, S.; Takayama, J.; Sakamoto, A.; Sugihara, Y.; Ishii, A. *J. Am. Chem. Soc.* **2004**, *126*, 9085–9093.
- (19) The recent calculations showed that the triplet is more stable than the singlet by ca. 20 kcal/mol: Ishikawa, Y.; Gong, Y.; Weiner, B. R. *Phys. Chem. Chem. Phys.* **2000**, *2*, 869–876.
- (20) A bimolecular mechanism between **2** and a trapping agent would be least possible sterically. For example, the double bond of **7** is highly protected sterically, and also the S=O group of **2** is sterically protected by *tert*-butyl groups. Therefore, these two functional groups cannot come close enough to undergo the S=O transfer. This would be true for the reaction between **2** and di(1-adamantyl)acetylene.

JA072044E