the necessity for reporting homogeneity or nonhomogeneity in such reaction mixtures. These findings introduce an added caution in the application of such systems for stereochemical correlations and in the proposal of precise transition-state stereochemistries to explain such results until extensive studies on the system have been completed. We are currently engaged in exploring the many variables involved in this and related systems.

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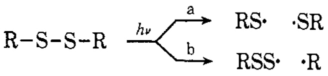
Photo-CIDNP from Carbon–Sulfur Cleavage of Alkyl Disulfides

Sir:

The literature on the photolysis of simple disulfides, which serve as a model for studying the photoreactions of sulfur-containing proteins, is sparse but identifies two distinct photochemical processes (Scheme I).

Scheme I



Sulfur–sulfur photocleavage[1] (path a), both direct and sensitized, to yield thiyl radicals is well known in both gas[2] and liquid[3] phases. Carbon–sulfur cleavage (path b) during photolysis has been observed[4] and shown to be a sensitized process for certain disulfides in the liquid phase.[5] Important mechanistic details, such as the nature of the excited state, the mode of its deactivation, and the relationship between the sensitized and unsensitized photolyses, remain to be elucidated, however, before the role of this process in the photodynamic inactivation of enzymes can be evaluated.

We wish to report photo-CIDNP evidence which provides additional insight into the mechanism of C–S cleavage in solution. The spectrum in Figure 1 was recorded[6] during photolysis of 0.08 *M* *tert*-butyl disulfide **1** in benzene solution inside the modified probe of an HA-60 spectrometer, using the unfiltered beam of a 1000-W high-pressure mercury arc lamp. Photolysis in the presence of either acetophenone or benzophenone yielded similar but more strongly enhanced signals. The polarized products are isobutylene (**3**, CH_3 and vinyl protons emission) and isobutane (**4a**, CH_3 protons enhanced absorption). Application of the simple rules based on the radical pair model of CIDNP[7] suggests a cage disproportionation between *tert*-butyl[8] and *tert*-butylperthiyl[9] radicals proceeding from a *triplet* excited state of the disulfide as the source of the isobutylene polarization. Cage escape by *tert*-butyl radical to yield polarized isobutane (possibly by hydrogen abstraction from starting material[10]) is also consistent with this mechanism (Scheme II).

Figure 1. Photo-CIDNP spectrum recorded during irradiation of 0.08 *M* *tert*-butyl disulfide in benzene. The peak at δ 1.25 (s) is starting material, the peaks at δ 1.63 and 4.75 are isobutylene, and the peak at δ 0.90 (d) is isobutane. When irradiation is interrupted, only the peak at δ 1.25 remains.

Diffusive encounters of *tert*-butyl and *tert*-butylperthiyl radicals are an additional source of the polarized products, but one which can be diminished by the use of scavengers. The addition of 0.025 *M* *n*-butanethiol decreased the polarization of **3**, most probably because *tert*-butyl radicals are scavenged efficiently. Indeed, the polarization of **4a** was slightly increased, presumably because the shorter lifetime of the *tert*-butyl radical allowed less proton relaxation in the radicals escaping from a geminate encounter. The addition of higher concentrations of the mercaptan (up to 0.3 *M*), however, caused no further change in the intensity of the isobutylene lines. This residual polarization must result from a triplet–geminate pair interaction which is not disturbed by moderate scavenger concen-

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(1) E. Block, *Quart. Rep. Sulfur Chem.*, **4**, 283 (1969).

(2) P. M. Rao, J. A. Copeck, and A. R. Knight, *Can. J. Chem.*, **45**, 1369 (1967).

(3) C. Walling and R. Rabinowitz, *J. Amer. Chem. Soc.*, **81**, 1137 (1959).

(4) A. B. Callear and D. R. Dickson, *Trans. Faraday Soc.*, **66**, 1987 (1970).

(5) (a) G. W. Byers, H. Gruen, H. G. Giles, H. N. Schott, and J. A. Kampmeier, *J. Amer. Chem. Soc.*, **94**, 1016 (1972); (b) H. Gruen, H. N. Schott, G. W. Byers, H. G. Giles, and J. A. Kampmeier, *Tetrahedron Lett.*, 3925 (1972).

(6) This photolysis apparently is not solvent sensitized since similar spectra (isobutylene, methylene) are obtained in carbon tetrachloride and in cyclohexane. It also seems unlikely that the polarization observed is due to the presence of an impurity capable of sensitizing this reaction since the polarization from **3** during photolysis of **1** is not smaller in more highly purified samples. Secondary photolysis of products was not occurring since the spectra reported were obtained immediately after irradiation was started and remained unchanged for several minutes afterward. Deoxygenation of the samples by nitrogen bubbling produced no change in the observed spectra.

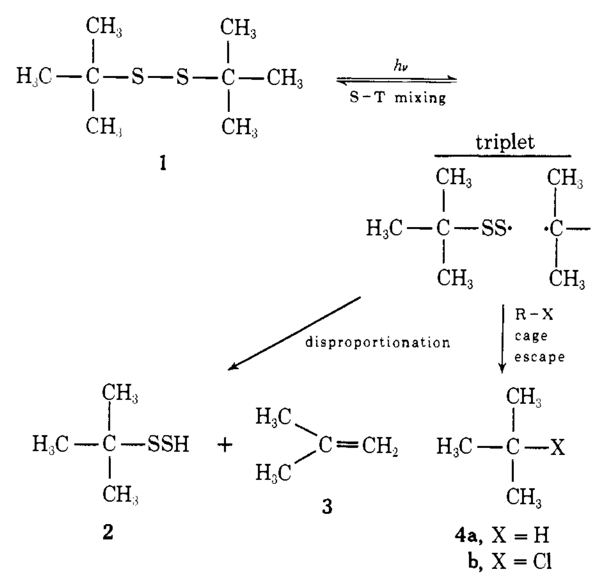
(7) H. R. Ward, *Accounts Chem. Res.*, **5**, 18 (1972); R. G. Lawler, *ibid.*, **5**, 25 (1972).

(8) $g = 2.0025$: R. W. Fessenden and R. H. Schuler, *J. Chem. Phys.*, **39**, 2147 (1963).

(9) $g = 2.01$ by analogy to ethyl thiyl radical: A. Torikai, S. Sawada, F. Fueki, and Z. Kuri, *Bull. Chem. Soc. Jap.*, **43**, 1617 (1970).

(10) Stronger isobutane polarization is observed in the presence of greater amounts of starting compound despite the unchanging isobutylene polarization, indicating more rapid scavenging of *tert*-butyl radicals by **1** or a minor impurity such as *tert*-butylthiol.

Scheme II



trations. Also, the intensity of the vinyl protons of **3** exhibits an unusual time dependence (first quite intense, rapidly diminishing to half the original value), which may well result from the formation of an efficient *tert*-butyl radical scavenger, *e.g.*, *tert*-butyl mercaptan, as a reaction product. (No information on the fate of the perthiyl fragment[11] is obtained in the nmr experiments both because the unpaired electron in the perthiyl radical is too weakly coupled to the CH$_3$ protons and because the S–H proton signal in **2** is probably broadened.)

The photolysis of **1** in carbon tetrachloride (sensitized or direct) shows **3** again in emission, a much weaker absorption signal from **4a**, and an enhanced absorption for *tert*-butyl chloride (**4b**). The absence of CIDNP in the starting disulfide itself is relevant to the reported[5] quantum yield of 0.34 for the formation of **4b** in the benzophenone-sensitized photolysis of **1** in carbon tetrachloride. One of the possibilities suggested to explain the low quantum yield was that recombination of the geminate radical pair might serve as an effective route for radiationless return of the excited triplet state to the ground-state singlet. Comparison of the integrated intensities of the methyl protons of starting material and isobutylene during benzophenone-sensitized photolysis of **1** in benzene yields a minimum ratio of disproportionation to recombination of 34:1, provided that the spin–lattice relaxation times of the protons in the two compounds are the same.[12] This indicates that recombination of *tert*-butyl and perthiyl radicals is at most a minor pathway for deactivation of the triplet state of **1**, although recombination of two *tert*-butyl mercapto radicals would have been undetected and could still be important. Direct and acetophenone- or benzophenone-sensitized photolysis of benzyl disulfide in benzene produces enhanced absorption in the starting material (methylenes), however, consistent with cage recombination proceeding from C–S cleavage of a triplet excited state.

Weak emission signals from **3** and enhanced absorption from **4a** and **4b** are also observed during the direct- and benzophenone-sensitized photolysis of *tert*-butyl sulfide in carbon tetrachloride, supporting other reports of C–S bond cleavage as a primary photochemical process in photolysis of simple sulfides.[13]

Since it is known that cystine residues are generally the site of enzyme photoinactivation[14] and that in solutions of pH >5 C–S cleavage in cystine is far more important than S–S cleavage,[15] several attempts were made to observe CIDNP signals during the direct and sensitized photolysis of aqueous solutions of cystine. The absence of polarization may well be due to a low quantum yield for this process.

It is somewhat surprising that for the sulfide and the two disulfides discussed here, the unsensitized photolysis produces a radical pair from a triplet state. Apparently, the rate of intersystem crossing is competitive with dissociation occurring from the photoexcited singlet. Further, it has previously been suggested that both **3** and **4a** may be produced in the photolysis of **1** from *tert*-butyl radicals which escape the geminate cage.[5a] Our results, however, support geminate disproportionation as at least a contributing process in the formation of **3**.

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[14] K. C. Smith and P. C. Hanawalt in "Molecular Photobiology," K. C. Smith and P. C. Hanawalt, Ed., Academic Press, New York, N. Y., 1969, p 85.

[15] W. Forbes and W. Savige, *Photochem. Photobiol.*, 1, 1 (1962).

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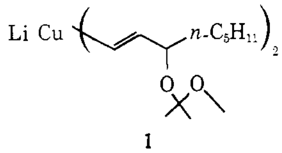
Synthesis of 13-*cis*-Prostaglandins *via* a Highly Stereoselective Conjugate Addition with a Functionalized Organocopper Reagent[1]

Sir:

We recently reported a synthesis of (−)-PGE$_1$ which had as its key step a conjugate addition with the *trans*-divinyl cuprate **1**[2] to the unsaturated ketone **7b**. We now report results from the conjugate addition of the *cis*-divinyl cuprate **2** which, in contrast to the *trans*-divinyl cuprate **1**, affords 1,4 adducts in high yields and, more importantly, with a very high degree of stereoselectivity.



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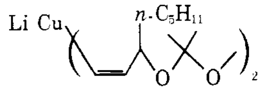

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[1] Publication No. 424 from the Institute of Organic Chemistry. Studies in Prostaglandins. XI. For the previous paper in this series see ref 2.

[2] A. F. Kluge, K. G. Untch, and J. H. Fried, *J. Amer. Chem. Soc.*, **94**, 7827 (1972). See also: C. J. Sih, P. Price, R. Sood, R. G. Salomon, G. Peruzotti, and M. Casey, *ibid.*, **94**, 3643 (1972).