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The Reactions of O_2 ($^1\Delta_g$) with Anancomeric 1,3-Dithianes. The First Experimental Evidence in Support of a Hydroperoxy Sulfonium Ylide as a Precursor to Sulfoxide on the Sulfide Singlet Oxygen Reaction Surface

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The kinetic isotope effects for the formation of anancomeric 1,3-dithiane-1-oxides in the reactions of singlet oxygen with the parent 1,3-dithianes have been determined for a series of 2-protio and 2-deuterio analogues. The substantial isotope effects are used to argue for formation of a hydroperoxysulfonium ylide as a key intermediate in sulfoxide formation. These results confirm an earlier theoretical prediction and force a change in the currently accepted mechanism for this important reaction. The first experimental demonstration of a novel singlet oxygen-induced epimerization of a 1,3-dithiane and a novel intramolecular electron transfer within a hydroperoxysulfonium ylide are also reported.

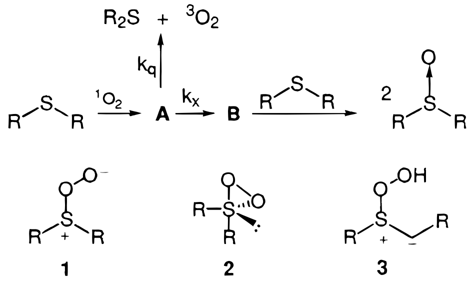
Introduction

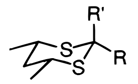
The photooxidations of organic sulfides were first described by Schenck and Krauch in 1962.[1] Foote and co-workers[2] later provided experimental evidence for the sequential formation of two intermediates on the $O_2(^1\Delta g)$/sulfide reaction surface in aprotic solvents (Scheme 1). However, all attempts to spectroscopically identify these intermediates under normal reaction conditions have failed.[3,4] Nevertheless, a persulfoxide, **1**, and a thiadioxirane, **2**, are often invoked as intermediates **A** and **B**, respectively. These assignments, especially for the persulfoxide, are supported by a substantial body of experimental work. In contrast, ab initio calculations are inconsistent with this mechanism revealing an energetically inaccessible barrier of 20 kcal/mol separating the persulfoxide and thiadioxirane.[5,6] Consequently, Jensen and co-workers[7] recently proposed a revised mechanism using ab initio calculations to argue that intermediate **B** is better described as a *S*-hydroperoxysulfonium ylide, **3**. We now present kinetic isotope effect data that provide the first experimental verification of this new mechanism.

Results

Product Studies. The readily available anancomeric[8] 1,3-dithianes **4a−g** were chosen as substrates for these studies. A molecular mechanics examination reveals that **4a**, **4c**, and **4f** adopt chair conformations (C) with the 2-substituents and the 4,6-methyl groups occupying equatorial positions. 1,3-Dithiane **4d** also adopts a chair conformation but with the 2-substituent in the axial position trans to the 4,6-methyl groups. In all of the 1,3-dithianes **4a−g**, the chair−twist-boat (TB) energy difference is greater than 3.0 kcal/mol with the sole exceptions of **4b** and **4g** where the twist-boat is substantially populated (ΔH_{C-TB}(**4b**) = −2.58 kcal/mol; ΔH_{C-TB}(**4g**) = −0.34 kcal/mol).[9]

Scheme 1





4a R = CH_3 ; R' = H
4b R = H ; R' = CH_3
4c R = CO_2CH_3 ; R' = H
4d R = H ; R' = CO_2CH_3
4e R = R' = H
4f R = Ph ; R' =H
4g R = H ; R' = Ph

Singlet oxygen generated either photochemically (C_6D_6, 10^{-4} M tetraphenylporphyrin, O_2, *hν*) or chemically by decomposition of 1,4-dimethylnaphthalene-1,4-endoper-

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[8] "Fixed in a single conformation either by geometric constraints, as (axial) 2*β*-chloro-*trans*-decalin, or because of an overwhelming one-sided conformational equilibrium, as *cis*-4-*tert*-butylcyclohexanol." Eliel, E. L.; Wilen, S. H. *Stereochemistry of Organic Compounds*; John Wiley & Sons: New York, NY, 1994.

[9] PCModel, Serena Software, Bloomington IN. Heats of formation chair (C) and twist-boat in kcal/mol (TB): **4a** C −34.73, TB −28.53; **4b** C −33.78, TB −31.20; **4c** C −114.56, TB −111.09; **4d** C −113.63, TB −110.08; **4e** C −28.15, TB −24.58; **4f** C −2.58, TB +3.63; **4g** C +0.66, TB +1.00.

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Scheme 2

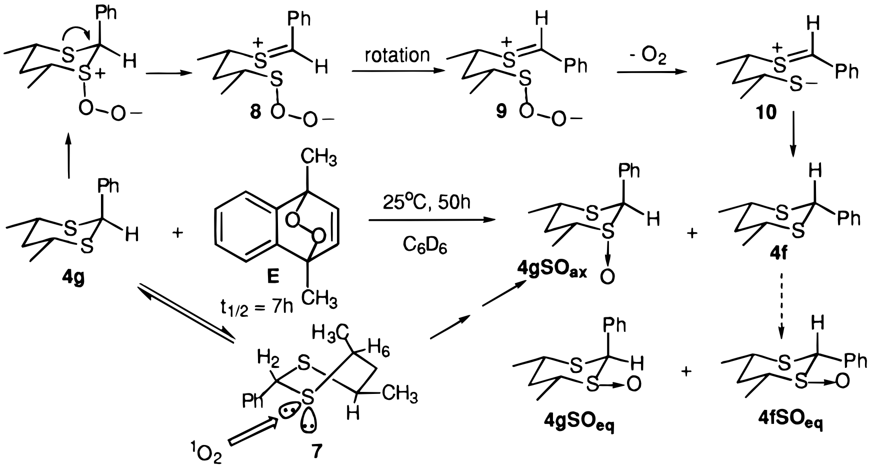


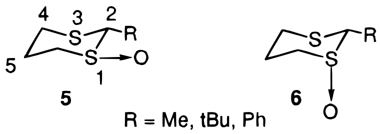
Table 1. Comparison of the ^{13}C Chemical Shifts of 1,3-Dithiane 1-Oxides and Their 1,3-Dithiane Parent[a]

compd	$\Delta^{13}C_2$	$\Delta^{13}C_4$	$\Delta^{13}C_5$	$\Delta^{13}C_6$	$\Delta^{13}C_{Me4}$	$\Delta^{13}C_{Me6}$
4aSO$_{eq}$	16.17	−0.73	2.75	18.81	−1.54	−4.65
4bSO$_{eq}$	11.43	−1.79	1.38	16.91	−1.97	−5.03
4bSO$_{ax}$	15.25	−1.10	−12.45	12.99	−0.66	−4.73
4cSO$_{eq}$	15.42	−0.38	2.32	20.65	−1.66	−4.64
4eSO$_{eq}$	16.62	−0.83	0.81	20.95	−1.99	−5.15
4fSO$_{eq}$	15.39	−0.81	2.64	19.71	−1.63	−4.43
4gSO$_{eq}$	11.6	0.30	1.75	15.30	−1.16	−5.39
4gSO$_{ax}$	17.11	−0.12	−12.82	11.53	−0.30	−3.95
5 (R = Me)[b]	17.6	−1.6	4.3	22.3		
(R = Ph)	17.9	−2.7	6.0	22.5		
(R = tBu)	15.0	−1.4	4.2	24.2		
6 (R = Me)[b]	10.1	−6.3	−4.3	14		
(R = Ph)	12.6	−2.4	−11.8	14.9		
(R = tBu)	12.0	−1.5	−11.6	16.5		

[a] $\Delta^{13}C_N = \delta^{13}C_N$(*S*-oxide) − $\delta^{13}C_N$(parent dithiane). [b] Reference 15.

oxide, **E**,[10] (Scheme 2) reacted with 1,3-dithianes **4a**, **4c**, **4e**, and **4f** to give exclusively (>98%) the equatorial rather than the axial sulfoxides, with no epimerization at C-2. This preference for equatorial oxidation is similar to that observed for a variety of oxidants including periodate,[11] *m*-CPBA,[12,13] and H_2O_2/SeO_2.[14] Axial oxidation suffers from destabilizing steric and electronic interactions between the oxidant and the axial hydrogen on C_5 and with the axial lone pair on the remote sulfur atom, respectively. Axial oxidation, however, is observed in the reaction of $^1O_2$ with 1,3-dithianes **4b** and **4g**. In these cases, least hindered addition of $^1O_2$ to sulfur in the energetically accessible twist-boat conformations led to the axial sulfoxides (e.g., **7** in Scheme 2).

The stereochemistries of the sulfoxide oxygens were determined by comparing the ^{13}C chemical shifts of the sulfoxide to its parent 1,3-dithiane ($\Delta^{13}C_N = \delta^{13}C_N$(*S*-oxide) − $\delta^{13}C_N$(parent dithiane)). The $\Delta^{13}C_N$ value (Table 1) of carbon 5 is diagnostic of the sulfoxide stereochemistry. An axial oxygen is known to produce a significant shielding effect on synclinal carbons, and as a consequence, carbon 5 is expected to have a dramatic upfield shift in the axial but not in the equatorial sulfoxide.[15] The remarkable similarity of the $\Delta^{13}C_N$ values in Table 1 to those reported for **5** and **6** provide compelling evidence for the assigned structures.



5 **6**

R = Me, tBu, Ph

At approximately 50% conversion of **4g** the axial oxidation product (**4gSO$_{ax}$**; Scheme 2) represents only 12% of the reaction mixture. Examination of the reaction mixture as a function of time reveals that epimerized starting material, **4f**, is the exclusive oxidation product at very low conversions but is only 3% of the reaction mixture at 50% conversion. The major product (25%) at 50% conversion is **4fSO$_{eq}$**. 1,3-Dithiane sulfoxide **4gSO$_{eq}$** is a minor product (0−3.5%) throughout the course of the reaction.

We suggest that the epimerization occurs by assisted opening of the persulfoxide by the remote sulfur, rotation about the sulfur carbocation bond followed by loss of oxygen (or visa versa), and reclosure to form the epimerized starting material, **4f**[16] (Scheme 2). This suggestion is supported by the formation of small amounts of benzaldehyde, which increased with the addition of water, consistent with hydrolysis of zwitterions **8**, **9**, or **10** (Scheme 2). The absence of starting material epimerization in the reactions of **4b** and **4d**, which have less effective carbocation stabilizing groups in the 2-axial position, is also consistent with this suggestion. In addition, thermodynamically favorable loss of oxygen from peroxypersulfenate ester, **9**, has been suggested as a key step in molecular oxidations of thiols.[17] An alternative mechanism involving removal of the equatorial hydrogen at C_2 to form the hydroperoxy sulfonium ylide followed by reprotonation from the axial direction and loss of oxygen is inconsistent with the experimental

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Table 2. 2,6-Di-*tert*-butyl-4-methylphenol Inhibition of the Product Distribution in the Reaction of 4c with $^1O_2$[a]

[inhibitor][b]	% conversion	radical yield as % of conversion[c]	[**4cSO$_{eq}$**]
0	80.3	56	44
0.011	72.8	44	56
0.05	46	28	72
0.105	40	30	70

[a] Reaction of 0.18 M **4c** at 24 °C in C_6D_6 with 0.35 mol/L 1,4-dimethylnaphthalene-1,4-endoperoxide for 50 h. [b] 2,6-Di-*tert*-butyl-4-methylphenol. [c] Sum of **11**, **12**, **13a**, and **13b**.

Table 3. Kinetic Data for Reactions of $^1O_2$ with 4a–g and Their 2-Deuterated Analogues[a,b]

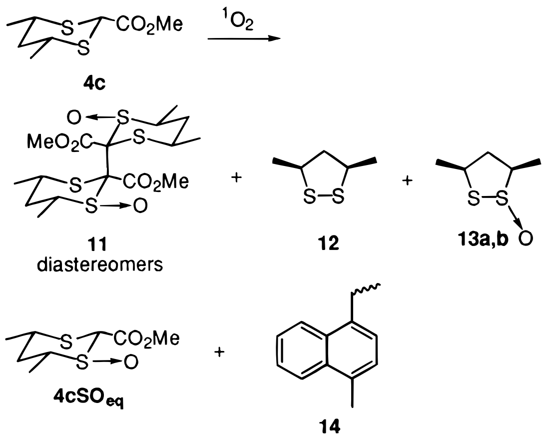
compd	$k_T \times 10^{-5}$ $M^{-1}\,s^{-1}$	$k_r \times 10^{-5}$ $M^{-1}\,s^{-1}$	compd	$k_T \times 10^{-5}$ $M^{-1}\,s^{-1}$	$k_r \times 10^{-5}$ $M^{-1}\,s^{-1}$
4a		2.02[c]	**4d**	0.88 (1.0)	<0.2
4a-*d*		1.30	**4e**		1.01
4b		3.74	**4e**-*d*$_2$		0.771
4b-*d*		2.42	**4f**	118.6 (134)	1.03
4c	15.0 (17)	9.94[c] (10.04)[d]	**4g**	7.88 (8.95)	12.59
4c-*d*		6.18			

[a] k_T measured in benzene. [b] The errors in k_T are less than ±10%, and the errors in k_r are less than ±8%. [c] Absolute rate constants measured by the method of Higgin, Foote, and Cheng.[24] For **4c** relative to k_r (1.84×10^6 M^{-1} s^{-1}) for octalin (Greer, A. Ph.D. dissertation, University of Wyoming) and for **4a** relative to k_r for 1-methylcyclohexene ($k_r = 7.52 \times 10^4$ M^{-1} s^{-1} in C_6H_6 at 22 °C. [d] Relative to directly measured k_r for **4a**.

results. This alternative mechanism would require that **4g** interact to a large extent with $^1O_2$ by a nonproductive physical quenching pathway that is not observed (Table 3).

Electron transfer and S_N2 reactions of thiols,[18] dialkyl sulfides,[19] and diarylsulfides[20] with peroxides have all been reported. In general, in these reactions, the more easily reduced diacylperoxides, peroxy esters, and dioxetanes are more reactive than dialkyl peroxides. For example, diphenylsulfide reacts rapidly with several dioxetanes but is completly unreactive toward 9, 10-diphenylanthracene peroxide, ascaridole, and 1,4-dimethylnaphthalene-1,4-endoperoxide.[20] Pryor and Hendrickson[19] have reported that the decomposition of *tert*-butyl peroxybenzoate is accelerated by a factor of 17 in the presence of 1.0 M Me_2S. In contrast, we find that the decompositions of 1,4-dimethylnaphthalene-1,4-endoperoxide, **E**, are first order and that the rate constants are experimentally identical in the absence ($k = (2.64 \pm 0.11) \times 10^{-5}$ s^{-1}) and in the presence of 1,3-dithiane **4g** ($k = (2.87 \pm 0.11) \times 10^{-5}$ s^{-1}). Consequently, endoperoxide **E** acts only as a source of singlet oxygen, and any direct reactions with the dithianes leading to oxidation or epimerization (**4g**) can be precluded.

Careful monitoring of the photooxidation of the ester **4c** reveals formation of several products in addition to the anticipated **4cSO$_{eq}$**. Analysis of the reaction mixtures by GC/MS suggested formation of dimers **11**, dithiolane **12**, and dithiolane-1-oxides **13a,b**, which were subsequently isolated and conclusively identified. In addition, when 1,4-dimethylnaphthalene-1,4-endoperoxide is used as a source of singlet oxygen, several minor products containing the naphthyl fragment, **14**, also form in the reaction. Addition of 2,6-di-*tert*-butyl-4-methylphenol (BHT) resulted in a decrease in the percent conversion of **4c**, an increase in the yield of **4cSO$_{eq}$** as a function of percent conversion, and complete inhibition of the formation of dimers **11** (Table 2).



Kinetic Studies. The rate constants for substrate-induced removal of singlet oxygen from solution, k_T (Table 3), were measured for 1,3-dithianes **4c**, **4d**, **4f**, and **4g** in benzene by monitoring their ability to quench the time-resolved emission of $^1O_2$ at 1270 nm.[21,22] The 1,3-dithianes with all equatorial substituents, **4c** and **4f**, react more than 1 order of magnitude faster than their axial epimers. The rate constant ratios ([k_T(**4f**)]/[k_T(**4g**)]) = 15 and ([k_T(**4c**)]/[k_T(**4d**)]) = 17 are even larger than that for the oxidations of **4f** and **4g** with H_2O_2/SeO_2 ([k(**4f**)]/[k(**4g**)]) = 7.7, reflecting the well-known sensitivity of $^1O_2$ to steric and electronic effects.[23]

The relative rate constants for product formation, k_r(rel), were measured by comparing the percent conversions of 0.18 M solutions of the 1,3-dithianes and several 2-deuterated analogues with a fixed amount of $^1O_2$ generated by decomposition of 1,4-dimethylnaphthalene-1,4-endoperoxide. The relative rate constants for **4c** and **4c**,**d** were measured in the presence of 0.05 M BHT in order to inhibit the contribution of the free-radical process to their disappearance (vide supra). These relative rate constants were converted to absolute rate constants (Table 3) using the k_r value measured for **4a**.[24]

Discussion

Several pieces of experimental data collected in this study argue that a hydroperoxy sulfonium ylide-like intermediate similar to **3**, with significant interaction between the terminal peroxy oxygen and the α-hydrogen atom, is intermediate **B** in the Foote reaction mechanism (Scheme 1). These include the following:

(1) The magnitude of k_r for the axial epimer in the 2-methyl- and 2-phenyl-substituted 1,3-dithianes are larger than for the equatorial epimer. This is consistent with a greater kinetic acidity of the 2-equatorial in

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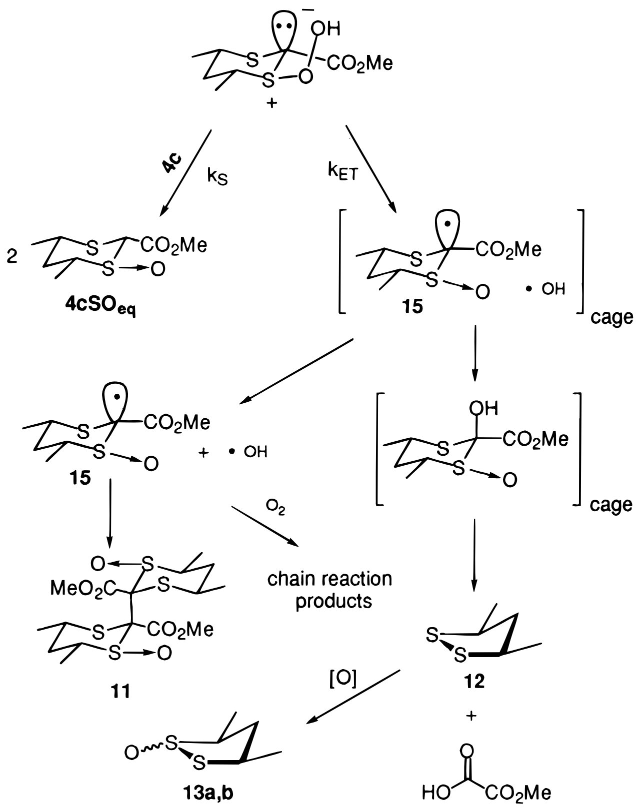
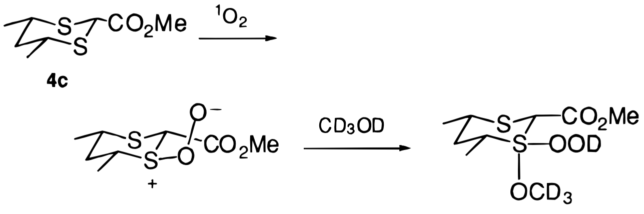
Scheme 3



comparison to the 2-axial hydrogen in the persulfoxide and more rapid formation of the hydroperoxy sulfonium ylide-like intermediate[25] (k_X in Scheme 1). The lack of chemical reactivity, k_r, and very small k_T exhibited by **4d** is surprising but perhaps reflects a destabilizing electronic and/or steric interaction between the incipient terminal oxygen in the developing persulfoxide and the carbomethoxy group.

(2) The formation of dimers **11** and the ability of BHT to inhibit their formation strongly implicate the captodatively stabilized radical **15** as an intermediate (Scheme 3). This radical can most reasonably be formed by intramolecular electron transfer from the carbon-centered anion to the peroxy linkage in the hydroperoxy sulfonium ylide. Increasing concentrations of **4c** favor formation of **4cSO$_{\rm eq}$** at the expense of the radical products, exactly as predicted by Scheme 3.

(3) Perhaps the most convincing evidence that a hydroperoxy sulfonium ylide-like species[26] is intermediate **B** are the isotope effects, k_H/k_D, for product formation [(**4a**/**4a−d**) = 1.55 ± 0.06; (**4b**/**4b−d**) = 1.54 ± 0.16; (**4c**/**4c−d**) = 1.62 ± 0.11; and (**4e**/**4e−d$_2$**) = 1.31 ± 0.05], which are calculated using the data in Table 3. These isotope effects are consistent with the partitioning of persulfoxide **1** (intermediate A in Scheme 1) along a physical quenching pathway (k_q in Scheme 1) leading to substrate and $^3O_2$ or along the reaction coordinate to the hydroperoxy sulfonium ylide-like intermediate. In CD_3OD, the isotope effect (k_H/k_D) = (**4c**/**4c**,**d**) is only 0.95, the electron-transfer products were suppressed, and no deuterium was washed into either the starting materials or products. The much reduced isotope effect is consistent with competitive inhibition of hydroperoxy sulfonium ylide formation by addition of CD_3OD to the persulfoxide to form sulfurane **16**.



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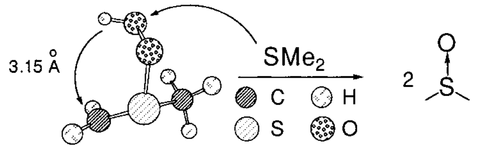
Conclusion

The successful formation of the hydroperoxysulfonium ylide-like intermediate is likely to be governed by a variety of factors including accessibility, and acidity, of the α-hydrogen. As a consequence, formation of the hydroperoxysulfonium ylide-like species competes with variable degrees of success with unproductive physical quenching during sulfide photooxidations. The lowest energy conformer of dimethylhydroperoxysulfonium ylide, **17**, adopts a hydrogen-bonded structure with O−H- -α-carbon distance of 3.15 Å at the MP2/6-311+G(2df) computational level,[7] reminiscent of the structures suggested for α-hydroperoxy ethers and amines.[27] Reduction of **17** with the sulfide substrate would consequently deliver the hydroperoxy proton intramolecularly to the α-carbon. This mechanism provides a convenient explanation for the lack of deuterium incorporation when sulfide photooxidations are run in D_2O wet benzene.[28] This reduction (eq 1) can now take its place along with Pummerer rearrangements,[29−32] conversions to sulfones,[28] and epoxidations[33] as well-established reactions of hydroperoxysulfonium ylides. Additional experimental work to determine the generality of this mechanism is currently in progress and will be reported in due course.



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Experimental Section

General Aspects. An HP-5 (30 m × 0.25 mm × 0.25 μm (length × inside diameter × film thickness)) capillary column was used for GC/MS data collection and a 5% diphenyl−95%

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dimethylpolysiloxane (30 m × 0.32 mm × 1.0 μm (length × inside diameter × film thickness)) or an HP-1 cross-linked methylsilicon (30 m × 0.53 mm × 1.5 μm (length × inside diameter × film thickness)) fused silica columns were used for analytical GC data collection. ^{1}H and ^{13}C NMR spectra of 0.5% solutions of dithiane oxides in $CDCl_3$ or C_6D_6 were recorded at 400.13 MHz on a Bruker Avance DRX-400 spectrometer. The peaks corresponding to the residual protons of $CDCl_3$ (7.27 ppm) or C_6D_6 (7.16 ppm) were used as the internal reference. The triplet at 77.23 ($CDCl_3$) was used as the reference for the ^{13}C NMR spectra. Anhydrous diethyl ether and tetrahydrofuran were distilled from sodium benzophenone ketyl. The 1,3-dithianes were prepared by the methods of Eliel and co-workers.[25,34,35] The solid dithianes were purified by recrystallization from methanol and subsequently by sublimation in a vacuum (0.1 Torr) prior to the kinetic experiments. The dithianes that were liquids at room temperature were purified by recrystallization from methanol at −78 °C and subsequently by vacuum distillation. Oxidations of the dithianes by $SeO_2-H_2O_2$[36] gave the dithiane oxides in 80% yield. Dithiane-oxides were purified by chromatography on SiO_2 (Merck 60 PF_{254}) and recrystallization from acetone. The endoperoxide of 1,4-dimethylnaphthalene, **E**, was prepared by method of Wasserman and Larsen.[10]

Photooxidation of 1,3-Dithianes. Samples of 1,3-dithiane (0.09−0.18 mmol), TPP (0.0001 mmol), and internal standard (hexamethyldisiloxane or fluorene) were dissolved in 1.0 of deuteriobenzene. A slow stream of oxygen (0.5−1.0 mL/min) was passed through solution until saturation was completed (usually 20−30 min). Then, the solution was irradiated with a 600 W tungsten lamp equipped through 1 cm of a 12 M $NaNO_2-H_2O$ filter solution for a given time interval. The reaction mixture was analyzed for products formed by NMR and GC-MS methods.

Relative k_r Determinations. Samples of 1,3-dithiane (0.09 mmol), 1,4-dimethylnaphthalene-1,4-endoperoxide (0.175 mmol), and internal standard (hexamethyldisiloxane or fluorene) were dissolved in 0.50 mL of deuteriobenzene. A 0.05 mL aliquot of this solution was removed and immediately analyzed by NMR to give the concentration of dithiane at time = 0 (C^0_{dithiane}). The remaining sample was allowed to sit at room temperature for 50 h and then analyzed by NMR to give the concentration of dithiane at time = t (C^t_{dithiane}). The experiment is repeated several times and the average value of $C^0_{\mathrm{dithiane}}/C^t_{\mathrm{dithiane}}$ was used for the k_r calculations. The k_r(rel) values were calculated as [k_r(1,3-dithiane)/ k_r(2-carbomethoxy-1,3-dithiane)] = [$\ln(C^t_{\mathrm{dithiane}}/C^0_{\mathrm{dithiane}})/\ln(C^t_{\mathrm{reference-dithiane}}/C^0_{\mathrm{reference-dithiane}})$].

Absolute k_r Determinations. The absolute values of k_r for **4a** and **4c** were measured by the method of Higgins, Foote, and Cheng,[24] and k_r(**4a**) was used to convert the other k_r(rel) values to absolute rate constants. Kinetic samples consisted of 1 mL benzene-d_6 solutions that were 10^{-4} M in TPP, 0.052 M in 1,3-dithiane, 0.099 M in 1-methylcyclohexene (1-MCH) for **4a** or octalin for **4c**, and 0.073 in diphenylmethane as internal standard. Aliquots (0.2 mL) were removed from these samples and analyzed by GC to give the concentration of **4c** at time = 0 ($C^0_{\mathbf{4c}}$). The rest of the sample was saturated with oxygen and irradiated with a 600 W tungsten lamp under a continuous flow of oxygen. At various time intervals 0.2 mL of the reaction mixture was removed and mixed with 0.2 mL of benzene 0.3 M in Ph_3P and stored at room temperature for 12 h. These samples were then analyzed by GC.

Endoperoxide, E, Kinetic Decomposition Determination. Decomposition of 0.24 M 1,4-dimethylnaphthalene-1,4-endoperoxide in C_6D_6 was followed by disappearance of the vinyl peak in the proton NMR spectra of the endoperoxide in the absence and in the presence of 0.19 M **4g**. The kinetic solutions contained fluorene (0.06 M) as an internal standard and 2 × 10^{-3} M DABCO as a singlet oxygen quencher ($k = 2.6 \times 10^8$ M^{-1} s^{-1})[37] in order to prevent the back reaction of singlet oxygen with the 1,4-dimethylnaphthalene product. Plots of time versus $\ln([E]_0/[E]_t)$ were linear over 3 half-lives, and the rate constants were extracted from the experimental data by least-squares analysis.

Error Analysis. The errors on the kinetic isotope effects were calculated using eq 2.[38] This equation describes the error on a nonlinear combination of quantities each subject to its own error.

$$\sigma_z{}^2 = \left(\frac{\partial z}{\partial x}\right)^2 \sigma_x{}^2 + \left(\frac{\partial z}{\partial y}\right)^2 \sigma_y{}^2 + 2\frac{\partial z}{\partial x}\frac{\partial z}{\partial y}(\mathrm{COV})_{xy} \qquad (2)$$

The two k_r's were measured independently, and as a consequence the covariance $(\mathrm{COV})_{xy} = 0$. If one sets $(k_X/k_Y) = z = (\ln x)/(\ln y)$ and defines $\Delta x = \sigma_x$, $\Delta y = \sigma_y$, $\Delta z = \sigma_z$ as the errors in X, Y, and Z, respectively, where $X = C^t_{\mathrm{dithiane,X}}/C^0_{\mathrm{dithiane,X}}$, and $Y = C^t_{\mathrm{dithiane,Y}}/C^0_{\mathrm{dithiane,Y}}$ one can derive the error propagation formula given in eq 3 and use it to calculate the errors for the kinetic isotope effects.

$$\Delta Z = \left(\frac{\Delta X^2}{(X \ln Y)^2} + \frac{\Delta Y^2 \ln^2 X}{Y^2 \ln^4 Y}\right) \qquad (3)$$

***r*-2-Phenyl-*trans*-4,*trans*-6-dimethyl-1,3-dithiane *trans*-oxide (4gSO$_{ax}$):** white crystals; mp 145−146.5 °C; ^{1}H NMR (400.13 MHz, $CDCl_3$) δ 1.25 (d, $^3J_{H-H} = 7.1$ Hz, 3H, CH_3CS), 1.35 (d, $^3J_{H-H} = 6.7$ Hz, 3H, CH_3CSO), 1.50 (ddd, $^2J_{H-H} = 14.6$ Hz, $^3J_{H-H} = 2.2$, 2.9 Hz, 1H, $H(5)_{eq}$), 2.12 (dt, $^2J_{H-H} = 14.6$ Hz, $^3J_{H-H} = 11.8$ Hz, 1H, $H(5)_{ax}$), 2.32 (dqd, $^3J_{H-H} = 11.8$, 7.1 Hz, $^3J_{H-H} = 2.1$ Hz, 1H, $CHCH_3S$), 3.20 (dqd, $^3J_{H-H} = 11.8$, 6.7, 2.9 Hz, 1H, $CHCH_3SO$), 5.06 (s, 1H, CHPh), 7.30−7.70 (m, 5H, C_6H_5); MS (70 eV) *m/e* (relative intensity) 240 (37, $M^{\cdot+}$), 69 (100, $C_5H_9{}^+$). Anal. Calcd for $C_{12}H_{16}S_2O$: C, 59.96; H, 6.71; S, 26.68. Found: C, 59.95; H, 6.80; S, 26.65.

***r*-2-Phenyl-*trans*-4,*trans*-6-dimethyl-1,3-dithiane *cis*-oxide (4gSO$_{eq}$):** colorless prisms; mp 104−105.5 °C; ^{1}H NMR (400.13 MHz, C_6D_6) δ 0.74 (d, $^3J_{H-H} = 6.8$ Hz, 3H, CH_3CS), 0.94 (d, $^3J_{H-H} = 6.8$ Hz, 3H, CH_3CSO), 1.19 (dt, $^2J_{H-H} = 14.5$ Hz, $^3J_{H-H} = 2.6$ Hz, 1H, $H(5)_{eq}$), 1.45 (dt, $^2J_{H-H} = 14.5$ Hz, $^3J_{H-H} = 11.9$ Hz, 1H, $H(5)_{ax}$), 2.34 (dqd, $^3J_{H-H} = 11.9$, 6.8, 2.6 Hz, 1H, $CHCH_3S$), 2.83 (dqd, $^3J_{H-H} = 11.9$, 6.8, 2.6 Hz, 1H, $CHCH_3SO$), 4.45 (s, 1H, CHPh), 7.13−7.86 (m, 5H, C_6H_5); MS (70 eV) *m/e* (relative intensity) 240 (19, M^+), 69(100, $C_5H_9{}^+$). Anal. Calcd for $C_{12}H_{16}S_2O$: C, 59.96; H, 6.71; S, 26.68. Found: C, 60.01; H, 6.80; S, 26.81.

***r*-2-Phenyl-*cis*-4,*cis*-6-dimethyl-1,3-dithiane *trans*-oxide (4fSO$_{eq}$):** white crystals; mp 115−117 °C; ^{1}H NMR (400.13 MHz, $CDCl_3$) δ 1.27 (d, $^3J_{H-H} = 6.8$ Hz, 3H, CH_3CS), 1.52 (d, $^3J_{H-H} = 6.8$ Hz, 3H, CH_3CSO), 2.08 (dt, $^2J_{H-H} = 15.0$ Hz, $^3J_{H-H} = 11.9$ Hz, 1H, $H(5)_{ax}$), 2.35 (dt, $^2J_{H-H} = 15.0$ Hz, $^3J_{H-H} = 2.4$ Hz, 1H, $H(5)_{eq}$), 2.90 (dqd, $^3J_{H-H} = 11.9$, 6.8, 2.4 Hz, 1H, $CHCH_3S$), 3.29 (dqd, $^3J_{H-H} = 11.9$, 6.8, 2.4 Hz, 1H, $CHCH_3SO$), 4.74 (s, 1H, CHPh), 7.36−7.52 (m, 5H, C_6H_5); MS (70 eV) *m/e* (relative intensity) 240 (25, M^+), 224 (2), 69 (100, $C_5H_9{}^+$). Anal. Calcd for $C_{12}H_{16}S_2O$: C, 59.96; H, 6.71; S, 26.68. Found: C, 59.99; H, 6.75; S, 26.81.

***r*-2-Carbomethoxy-*cis*-4,*cis*-6-dimethyl-1,3-dithiane *trans*-oxide (4cSO$_{eq}$):** white crystals; mp 131−132 °C; ^{1}H NMR (400.13 MHz, C_6D_6) δ 0.63 (d, $^3J_{H-H} = 6.8$ Hz, 3H, CH_3CS), 1.08 (d, $^3J_{H-H} = 6.8$ Hz, 3H, CH_3CSO), 1.17 (dt, $^2J_{H-H} = 14.9$ Hz, $^3J_{H-H} = 2.7$ Hz, 1H, $H(5)_{eq}$), 1.29 (dt, $^2J_{H-H} = 14.9$ Hz, $^3J_{H-H} = 11.7$ Hz, 1H, $H(5)_{ax}$), 2.17−2.27 (m, 2H, $CHCH_3S$, $CHCH_3SO$), 3.26 (s, 3H, CH_3O), 4.47 (s, 1H, $CHCO_2CH_3$); MS (70 eV) *m/e* (relative intensity) 222(1, $M^{\cdot+}$), 69 (100, $C_5H_9{}^+$). Anal. Calcd for $C_8H_{14}S_2O_3$: C, 43.22; H, 6.35; S, 28.84. Found: C, 43.40; H, 6.46; S, 28.95.

***r*-2,*cis*-4,*cis*-6-Trimethyl-1,3-dithiane *trans*-oxide (4a-SO$_{eq}$):** white crystals; mp 93−94 °C; ^{1}H NMR (400.13 MHz,

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C_6D_6) δ 0.72 (d, $^3J_{H-H}$ = 6.8 Hz, 3H, C*H*$_3$CS), 1.17 (d, $^3J_{H-H}$ = 6.8 Hz, 3H, C*H*$_3$CSO), 1.31 (dt, $^2J_{H-H}$ = 14.8 Hz, $^3J_{H-H}$ = 2.8 Hz, 1H, H(5)$_{eq}$), 1.41 (dt, $^2J_{H-H}$ = 14.8 Hz, $^3J_{H-H}$ = 11.5 Hz, 1H, H(5)$_{ax}$), 1.48 (d, $^3J_{H-H}$ = 7.0 Hz, 3H, CH$_3$C), 2.17 (dqd, $^3J_{H-H}$ = 11.5, 6.8, 2.8 Hz, 1H, C*H*CH$_3$S), 2.34 (dqd, $^3J_{H-H}$ = 11.5, 6.8, 2.8 Hz, 1H, C*H*CH$_3$SO), 3.37 (q,$^3J_{H-H}$ = 7.0 Hz, 1H, C*H*CH$_3$); MS (70 eV) *m*/*e* (relative intensity) 178 (19, M$^+$), 69 (100, $C_5H_9^+$). Anal. Calcd for $C_7H_{14}S_2O$: C, 47.15; H, 7.91; S, 35.96. Found: C, 46.90; H, 7.87; S, 35.72.

***r*-2,*trans*-4,*trans*-6-Trimethyl-1,3-dithiane *trans*-oxide (4bSO$_{ax}$):** white crystals; mp 81−82 °C; ^{1}H NMR (400.13 MHz, CDCl$_3$) δ 1.24 (d, $^3J_{H-H}$ = 6.9 Hz, 3H, C*H*$_3$CS), 1.33 (d, $^3J_{H-H}$ = 6.9 Hz, 3H, C*H*$_3$CSO), 1.55 (dt, $^2J_{H-H}$ = 14.6 Hz, $^3J_{H-H}$ = 2.6 Hz, 1H, H(5)$_{eq}$), 1.63 (d, $^3J_{H-H}$ = 7.5 Hz, 3H, CH$_3$C), 1.99 (dt, $^2J_{H-H}$ = 14.6 Hz, $^3J_{H-H}$ = 11.9 Hz, 1H, H(5)$_{ax}$), 2.54 (dqd, $^3J_{H-H}$ = 11.9, 6.9, 2.6 Hz, 1H, C*H*CH$_3$S), 3.04 (dqd, $^3J_{H-H}$ = 11.9, 6.9, 2.6 Hz, 1H, C*H*CH$_3$SO), 3.84 (q,$^3J_{H-H}$ = 7.5 Hz, 1H, C*H*CH$_3$); MS (70 eV) *m*/*e* (relative intensity) 178 (17, M$^+$), 69 (100, $C_5H_9^+$). Anal. Calcd for $C_7H_{14}S_2O$: C, 47.15; H, 7.91; S, 35.96. Found: C, 47.08; H, 7.84; S, 36.01.

***r*-2,*trans*-4,*trans*-6-Trimethyl-1,3-dithiane *cis*-oxide (4bSO$_{eq}$):** white crystals; mp 92−93 °C; ^{1}H NMR (400.13 MHz, CDCl$_3$) δ 1.17 (d, $^3J_{H-H}$ = 6.9 Hz, 3H, C*H*$_3$CS), 1.38 (d, $^3J_{H-H}$ = 6.9 Hz, 3H, C*H*$_3$CSO), 1.75 (d, $^3J_{H-H}$ = 7.1 Hz, 3H, CH$_3$C), 1.86 (dt, $^2J_{H-H}$ = 14.7 Hz, $^3J_{H-H}$ = 12.2 Hz, 1H, H(5)$_{ax}$), 2.18 (dt, $^2J_{H-H}$ = 14.7 Hz, $^3J_{H-H}$ = 2.5 Hz, 1H, H(5)$_{eq}$), 2.87 (dqd, $^3J_{H-H}$ = 12.2, 6.9, 2.5 Hz, 1H, C*H*CH$_3$S), 3.16 (dqd, $^3J_{H-H}$ = 12.2, 6.9, 2.50 Hz, 1H, C*H*CH$_3$SO), 3.91 (q,$^3J_{H-H}$ = 7.1 Hz, 1H, C*H*CH$_3$); MS (70 eV) *m*/*e* (relative intensity) 178 (18, M$^+$), 69 (100, $C_5H_9^+$). Anal. Calcd for $C_7H_{14}S_2O$: C, 47.15; H, 7.91; S, 35.96. Found: C, 46.95; H, 7.86; S, 35.69.

***r*-4,*cis*-6-Dimethyl-1,3-dithiane *trans*-oxide (4eSO$_{eq}$):** colorless needles; mp 155−157 °C; ^{1}H NMR (400.13 MHz, CDCl$_3$) δ 1.20 (d, $^3J_{H-H}$ = 6.8 Hz, 3H, C*H*$_3$CS), 1.43 (d, $^3J_{H-H}$ = 6.8 Hz, 3H, C*H*$_3$CSO), 1.91 (dt, $^2J_{H-H}$ = 15.0 Hz, $^3J_{H-H}$ = 11.8 Hz, 1H, H(5)$_{ax}$), 2.26 (dt, $^2J_{H-H}$ = 15.0 Hz, $^3J_{H-H}$ = 2.4 Hz, 1H, H(5)$_{eq}$), 2.67 (dqd, $^3J_{H-H}$ = 11.8, 6.8, 2.4 Hz, 1H, C*H*CH$_3$S), 3.04 (dqd, $^3J_{H-H}$ = 11.8, 6.82, 2.4 Hz, 1H, C*H*CH$_3$SO), 3.76 (d,$^2J_{H-H}$ = 12.7 Hz, 1H, H(2)$_{eq}$), 3.96 (d,$^2J_{H-H}$ = 12.7 Hz, 1H, H(2)$_{ax}$); MS (70 eV) *m*/*e* (relative intensity) 164 (15, M$^+$), 69 (100, $C_5H_9^+$). Anal. Calcd for $C_6H_{12}S_2O$: C, 43.87; H, 7.36; S, 39.04. Found: C, 43.60; H, 7.30; S, 39.25. Anal. Calcd for $C_6H_{12}S_2O$: C, 43.87; H, 7.36; S, 39.03. Found: C, 43.60; H, 7.30; S, 39.25.

3,5-*cis*- Dimethyl-1,2-dithiolane (12) was synthesized by the method of Eliel[35] from *meso*-2,4-pentanediol ditosylate and sodium disulfide in DMF. It was purified by fractional distillation to give a yellow liquid: bp 68−69 °C (20 mm Hg); ^{1}H NMR (400.13 MHz, CDCl$_3$) δ 1.44(d, $^3J_{H-H}$ = 6.6 Hz, 6H, CH$_3$C), 1.47(dt, $^2J_{H-H}$ = 12.8 Hz, $^3J_{H-H}$ = 9.0 Hz, 1H, H(4)$_{ax}$), 2.67(dt, $^2J_{H-H}$ = 12.8 Hz, $^3J_{H-H}$ = 5.8 Hz, 1H, H(4)$_{eq}$), 3.69-(dqd, $^3J_{H-H}$ = 9.0, 6.6, 5.8 Hz, 2H, C*H*CH$_3$); ^{13}C NMR (100.61 MHz, CDCl$_3$) δ 51.64 (*C*CH$_3$), 51.43 (CH$_2$), 20.64 (CH$_3$). Anal. Calcd for $C_5H_{10}S_2$: C, 44.73; H, 7.51; S, 47.76. Found: C, 44.87; H, 7.48; S, 47.57.

***cis*-3,5-Dimethyl-1,2-dithiolane 1-oxides (13a and 13b)** were formed as a mixture in the oxidation of **12** with SeO$_2$−H$_2$O$_2$.[36] The mixture was separated by chromatography on SiO$_2$ to give pure samples of each diastereomer. ***cis*-3,5-dimethyl-1,2-dithiolane-*cis*-1-oxide (13a):** slightly yellow liquid; ^{1}H NMR (400.13 MHz, CDCl$_3$) δ 1.45 (d, $^3J_{H-H}$ = 6.7 Hz, 3H, CH$_3$C), 1.54 (d, $^3J_{H-H}$ = 6.7 Hz, 3H, CH$_3$C), 2.41 (td, $^2J_{H-H}$ = 13.7 Hz, 1H, $^3J_{H-H}$ = 11.4 Hz, H(4)ax), 2.63 (ddd, $^2J_{H-H}$ = 13.7 Hz, $^3J_{H-H}$ = 5.0, 4.2 Hz, 1H, H(4)eq), 3.26 (dqd, $^3J_{H-H}$ = 13.7, 6.7, 4.1 Hz, 1H, C*H*CH$_3$S), 3.96 (dqd, $^3J_{H-H}$ = 11.5, 6.7, 5.0 Hz, 1H, C*H*CH$_3$SO); ^{13}C δ NMR (100.61 MHz, CDCl$_3$) 68.88 (*C*CH$_3$SO), 50.83 (*C*CH$_3$), 43.76 (CH$_2$), 22.03 (CH$_3$), 12.12 (*C*H$_3$-CHSO). Anal. Calcd for $C_5H_{10}OS_2$: C, 39.97; H, 6.71; S, 42.68. Found: C, 39.75; H, 6.77; S, 42.87. ***cis*-3,5-dimethyl-1,2-dithiolane-*trans*-1-oxide (13b)**. Slightly yellow liquid. 1H NMR (400.13 MHz, CDCl$_3$) δ 1.45 (d, $^3J_{H-H}$ = 7.1 Hz, 3H, CH$_3$C), 1.48 (d, $^3J_{H-H}$ = 7.1 Hz, 3H, CH$_3$C), 1.88 (ddd, $^2J_{H-H}$ = 13.6 Hz, $^3J_{H-H}$ = 8.0 Hz, $^3J_{H-H}$ = 7.2 Hz, 1H, H(4)ax), 3.02 (dt, $^2J_{H-H}$ = 13.6 Hz, $^3J_{H-H}$ = 5.8 Hz, 1H, H(4)eq), 3.65 (dqd, $^3J_{H-H}$ = 8.0 Hz, $^3J_{H-H}$ = 7.2 Hz, $^3J_{H-H}$ = 5.8 Hz, 1H, C*H*CH$_3$S), 3.96 (dqd, $^3J_{H-H}$ = 7.2 Hz, $^3J_{H-H}$ = 7.1 Hz, $^3J_{H-H}$ = 5.8 Hz, 1H, C*H*CH$_3$SO). ^{13}C NMR (100.61 MHz, CDCl$_3$) δ 76.55 (*C*CH$_3$-SO), 50.96 (*C*CH$_3$), 46.60 (CH$_2$), 20.45 (CH$_3$), 16.20 (*C*H$_3$-CHSO). Anal. Calcd for $C_5H_{10}OS_2$: C, 39.97; H, 6.71; S, 42.68. Found: C, 40.06; H, 6.68; S, 42.61.

2, 2′-*R*,*S*-[(*r*-2-Carbomethoxy-*cis*-4,*cis*-6-dimethyl-1,3-dithianyl *trans*-oxide)-*r*-2′-carbomethoxy-*cis*-4′, *cis*-6′-dimethyl-1′,3′-dithiane *trans*-oxide] (11). Photooxidation of 4c gave a mixture of dimeric diastereomers of which **11** was the major component. The diastereomers were inseparable by thin-layer chromatography: ^{1}H NMR (400.13 MHz, C_6D_6) δ 1.10 (d, $^3J_{H-H}$ = 6.8 Hz, 6H, CH$_3$C), 1.11 (d, $^3J_{H-H}$ = 6.8 Hz, 6H, CH$_3$CSO), 1.20 (dt, $^2J_{H-H}$ = 14.2 Hz, $^3J_{H-H}$ = 2.7 Hz, 2H, H(5)eq), 1.40 (dt, $^2J_{H-H}$ = 14.2 Hz, $^3J_{H-H}$ = 12.1 Hz, 2H, H(5)-ax), 2.70−2.85 (m, 4H, SC*H*CH$_3$, C*H*CH$_3$SO), 3.23 (s, 6H, CH$_3$O); MS (70 eV) *m*/*e* (relative intesity) 442 (1, M$^+$), 69 (100, $C_5H_9^+$); HREI/MS (M$^+$) calcd 442.0612, obsd 442.0615.

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Supporting Information Available: ^{3}C NMR and MS data for 1,3-dithianes and oxides. Experimental data for k_r measurements and error analysis for isotope effects. Kinetic data for decomposition of 1,4-dimethylnaphthalene-1,4-endoperoxide. Proton NMR for dimer **11**. This material is available free of charge via the Internet at http://pubs.acs.org.

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