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Reaction of Organic Sulfides with Singlet Oxygen. A Revised Mechanism

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Abstract: On the basis of ab initio calculations we propose a revised mechanism for the reaction of organic sulfides with singlet oxygen, which is more consistent with experimental evidence than previous schemes. In aprotic solvents the reagents initially form a weakly bound peroxysulfoxide, with a small barrier due to entropy. The peroxysulfoxide may decay back to ground state (triplet) oxygen, be trapped by sulfoxides, or rearrange to a *S*-hydroperoxysulfonium ylide with a barrier of ∼6 kcal/mol. The latter is ∼6 kcal/mol more stable than the peroxysulfoxide, and can be trapped by sulfides or rearrange to a sulfone. In some cases, like five-membered rings or benzylic sulfides, the *S*-hydroperoxysulfonium ylide may undergo a 1,2-OOH shift to an α-hydroperoxysulfide, which eventually leads to cleavage products. In protic solvents the peroxysulfoxide is rapidly converted to a sulfurane by solvent.

Introduction

The photooxidation of organic sulfides (R_2S) was originally reported by Schenck and Krauch in 1962.[1] It is now generally accepted that the reaction proceeds via the lowest excited singlet state of molecular oxygen, commonly referred to as singlet oxygen. The major reaction product is the sulfoxide (R_2SO), with varying amounts of sulfone (R_2SO_2) depending on the substrate and reaction conditions. Some substrates, like benzylic sulfides, also give products corresponding to oxidation of the carbon framework.

The reaction mechanism has proven to be very complex.[2−6] Both the reaction efficiency and kinetic behavior depend on substrate, temperature, and solvent. Kinetic and trapping experiments suggest that there are at least two distinct intermediates present in aprotic solvent, while a single intermediate is sufficient for explaining the experimental data in protic solvents.[2] It has not been possible to detect any of these intermediates spectroscopically under normal reaction conditions. Low-temperature matrix isolation studies have obtained IR bands of an unstable species,[7] but the nature of this species is not clear.[8]

We have previously performed ab initio calculations with the aim of evaluating the viability of various proposed intermediates, and to describe the detailed pathways for their formations.[9,10] These calculations suggested that the energetics of the proposed mechanism were inconsistent with experimental facts.

None of the previous mechanisms have been able to explain all available experimental facts. We here wish to report new calculations which suggest a revised reaction scheme. The central feature is the presence of a new intermediate, a *S*-hydroperoxysulfonium ylide.[11] After a brief review of key experimental observations, the results of our calculations are presented, and it is shown how the experimental facts fit the new reaction scheme.

During the course of this work Ishiguro et al. reported semiempirical calculations, which also suggest a *S*-hydroperoxysulfonium ylide intermediate.[12] Just prior to completion of this work we learned that Prof. McKee had performed similar type calculations for dimethyl sulfide using DFT methods for structural features and QCISD(T) calculations for energetics.[13] With a single exception (discussed below), we find very good agreement with these results.

Computational Details

All calculations have been performed with the Gaussian-94[14] and ACES II[15] program packages, using standard basis sets.[16,17] Singlet oxygen is a delta state, which requires a complex wave function within a single determinant framework. At the MP2 level the experimental singlet−triplet energy difference of 22.5 kcal/mol[18] is reproduced to

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(8) Previous calculations at the MP2/6-31G(d) level did not provide a good match for the observed frequencies (ref 9). We have improved the theoretical level to MP2/6-311+G(2df), with only minor changes in calculated frequencies and isotopic shifts. Frequencies for the *S*-hydroperoxysulfonium ylide **4** have also been calculated, but these do not agree with experimental values either.

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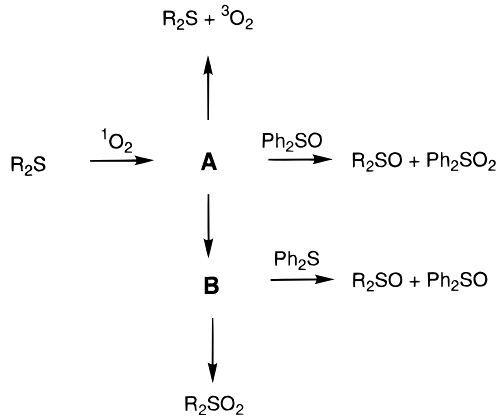
within 1 kcal/mol. We have consistently estimated the energy of $^1O_2$ by adding the experimental singlet−triplet gap to calculated values for $^3O_2$.

In the present work we have relied on three standard computational methods: MP2/6-31G(d), MP2/6-311+G(2df), and CCSD(T)/6-31G(d).[16] Structural features (geometry optimizations, vibrational frequencies, and IRCs) have been done at the MP2/6-31G(d) level, and the sensitivity of energy differences has been tested by MP2/6-311+G(2df) and CCSD(T)/6-31G(d) single point calculations. For **TS24** and **TS46** we have also used the B3LYP/6-31G(d) method for geometry optimization. In the spirit of the G2 method,[19] we have estimated CCSD(T)/6-311+G(2df) energies as CCSD(T)/6-31G(d) − MP2/6-31G(d) + MP2/6-311+G(2df), and added zero point energy correction based on MP2/6-31G(d) vibrational frequencies scaled by 0.967.[20] For the energy difference between the separated reagents and the peroxysulfoxide, which is found to be very basis set dependent, we have employed a more systematic sequence of theoretical methods using the cc-pVXZ basis sets.[17] Transition structures have been confirmed by frequency calculations, and in the majority of cases the corresponding two minima have been established by tracing the IRC. For the whole set of systems studied, it is impractical to employ CCSD(T)/6-31G(d) and MP2/6-311+G(2df) calculations for all stationary points, and we have instead focused on MP2/6-31G(d) energy differences relative to the reference dimethyl sulfide system.

Background

Alkyl sulfides react readily with singlet oxygen to form sulfoxides as the major product. The limiting quantum yield is two, i.e., one mole of singlet oxygen gives rise to two moles of sulfoxide.[21] In protic solvents (e.g. MeOH) the reaction is very efficient, essentially all the generated singlet oxygen ends up as product. In aprotic solvents (e.g., benzene, dichloromethane, acetone, and acetonitrile) the reaction is very inefficient, only a few percent of the generated singlet oxygen ends up as product.[2] The majority of the singlet oxygen is converted back to ground state (triplet) oxygen by physical quenching. The reaction efficiency can be increased by lowering the temperature,[3,22] i.e., the activation energy for product formation is negative. The rate of singlet oxygen disappearance, however, is essentially independent of temperature. In the case of thiacyclohexane, the activation parameters for product formation in acetone have been reported to be $\Delta H^\ddagger = -4$ kcal/mol and $\Delta S^\ddagger = -46$ eu,[23] while Watanabe et al. have reported an activation energy of −9.9 kcal/mol for sulfoxide formation alone.[24] It also appears that the reaction efficiency is increased by increasing the solvent polarity.[25]

Scheme 1



Aromatic sulfides, such as diphenyl sulfides, react only very slowly with singlet oxygen. The same is true for the sulfoxide products. Nevertheless, if diphenyl sulfide or diphenyl sulfoxide is present in the reaction mixture when a dialkyl sulfide is photooxidized, diphenyl sulfoxide and diphenyl sulfone, respectively, are produced.[2] This suggests that one or more intermediates are present during the reaction, and that the intermediates are stronger oxidants than singlet oxygen itself.

In aprotic solvents kinetic experiments have established that addition of diphenyl sulfoxide increases the reaction efficiency by competitively inhibiting the physical quenching step. Addition of diphenyl sulfide, however, does not compete with quenching, but still leads to formation of diphenyl sulfoxide as a product. These observations have been explained in terms of the reaction mechanism shown in Scheme 1.

The reaction initially forms an intermediate **A**, which can decay back to ground-state oxygen (quenching), be trapped by sulfoxides, or rearrange to a second intermediate **B**. The second intermediate reacts with sulfides, and is the major product-forming step in the absence of trapping agents. The use of para-substituted diphenyl sulfides and sulfoxides have established that **A** acts as a nucleophile ($\rho = 0.3$[26] or 1.4[27]) while **B** acts as an electrophile ($\rho = -1.4$[26] or −1.3[27]).

Since intermediate **A** can be trapped by sulfoxides to form sulfones, and sulfoxides are the products of trapping of intermediate **B**, it follows that the sulfone/sulfoxide product ratio increases as the reaction proceeds. Extrapolation of this ratio to zero conversion, however, indicates that there is also an intramolecular reaction path for sulfone formation. This has been suggested to arise from rearrangement of intermediate **B**. Consistent with this hypothesis is the observation that the sulfone/sulfoxide ratio increases with decreasing sulfide concentration.[21,22] The ratio also increases upon lowering the temperature,[21,22] while solvent polarity does not seem to play a role.[25]

It should be noted that Watanabe et al. have reported the exact opposite behavior for a series of sulfides in benzene. In particular, they reported that the sulfone/sulfoxide ratio decreases as a function of increasing conversion, is independent of the sulfide concentration, and decreases at low temperature.[24] Furthermore, they also reported that addition of diphenyl

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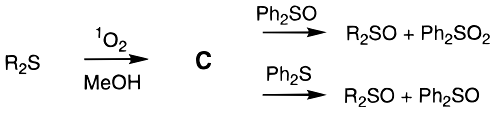
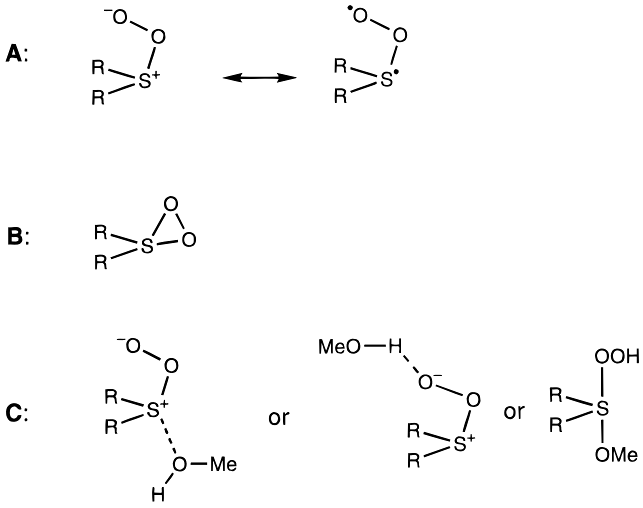
Scheme 2



Scheme 3



sulfoxide increases the yield of sulfoxide, but does not change the amount of sulfone formed.

In protic solvents such as MeOH, kinetic experiments are consistent with the formation of a single intermediate **C**, which can be trapped both by sulfides and sulfoxides (Scheme 2). Hammett substituent studies with diaryl sulfides demonstrate that intermediate **C** acts as an electrophile ($\rho = -0.6$).[28,29]

Intermediates **A** and **B** have been proposed to have structures corresponding to a peroxysulfoxide and thiadioxirane, respectively. The peroxysulfoxide can be written either in a dipolar or diradical form, and will in reality contain components of both resonance structures (Scheme 3). The chemistry, however, is consistent with dominance of the dipolar form (i.e. nucleophilic oxygen transfer, but not reactions corresponding to radical abstraction), as is the calculated wave function.[30]

The inhibition of physical quenching in MeOH has been explained in terms of a rapid conversion of initially formed **A** to **C** by solvent. **C** may either correspond to a solvent stabilized **A** or undergo actual addition to form a sulfurane (Scheme 3).

Relative to aprotic solvents, sulfone formation is inhibited in MeOH.[3,21,25] Substrates with intramolecular OH groups have been shown to give products corresponding to transfer of the alcohol oxygen to the sulfur in the sulfone, which strongly suggests that **C** has a sulfurane structure (Scheme 4).[31,32] This assignment is consistent with the electrophilic character displayed by the trapping experiments.

Small ring sulfides (Scheme 5) display reactivity differences relative to acyclic sulfides. In aprotic solvent thiirane gives the expected thiiraneoxide, but a solvent trapped sulfinic ester can be isolated in MeOH.[29,33] This presumably arises from ring opening by solvent in either the peroxysulfoxide or sulfurane intermediate. The four-membered ring sulfide, thietane, gives the expected sulfoxide product; however, in this case the reaction is quite efficient even in aprotic solvents. A detailed kinetic study indicated that this is due to a self-catalyzed mechanism, i.e., thietane itself apparently stabilizes the first formed intermediate, and thus competes with quenching.[27] Quenching is also substantially reduced in 1,5-dithiacyclooctane, which similarly has been explained by assuming that the second sulfur coordinates intramolecularly.[22,34]

In the reaction of thiazolidine with singlet oxygen Ando et al. have shown that an α-hydroperoxysulfide can be isolated, and they proposed a *S*-hydroperoxysulfonium ylide as an intermediate.[35−37] The parent five-membered-ring sulfide, thiolane, gives in addition to the normal sulfoxide and sulfone products a disulfide corresponding to oxidation of the α-carbon and ring opening.[35b,38] This aldehyde is presumably a result of decomposition of an initially formed α-hydroperoxysulfide. Benzylic sulfides give, in addition to the sulfoxide and sulfone, similar oxidation products, i.e., benzaldehyde.[39,40]

As mentioned above there appears to be both intra- and intermolecular pathways for sulfone formation, which can be distinguished by isotopic labeling experiments. If sulfides are oxidized by a mixture of ${}^{16}O_2$ and ${}^{18}O_2$ the intermolecular pathway will lead to isotopic scambling, while an intramolecular rearrangement gives sulfones with either both or neither of the oxygens labeled. Since the importance of the intermolecular reaction increases as the reaction proceeds (trapping by initially formed sulfoxide), the isotope analysis of the sulfone should preferably be done at low conversion or extrapolated back to zero conversion. Three labeling experiments have been reported, with varying conclusions. Watanabe et al. found that essentially all the sulfone was formed by an intramolecular pathway when phenyl methyl sulfide or octyl methyl sulfide was reacted in benzene, even at high conversions (65%).[24] Clennan and Zhang, in contrast, found that for diethyl sulfide at 5−10% conversion in benzene, all (within experimental uncertainty) of the sulfone product is formed intermolecularly.[41] Clennan and Yang also found only isotopic scrambling, i.e., intermolecular oxidation, for phenyl butyl sulfide in aprotic solvents containing $\sim$10% MeOH, although this was for complete conversion.[36a] The study by Clennan and Zhang showed that the same was true for sulfenamides and sulfenate esters, but that essentially all the thiosulfonate (sulfone) product from disulfides is formed intramolecularly.[41]

A further clue bearing on the origin of the sulfone is provided by the observation that photooxidation of perdeuteriodimethyl sulfide in the presence of H_2O gives sulfone products where a deuterium atom is lost (Scheme 6).[12] Since only hexadeuterio sulfoxide is produced, this clearly points toward a second

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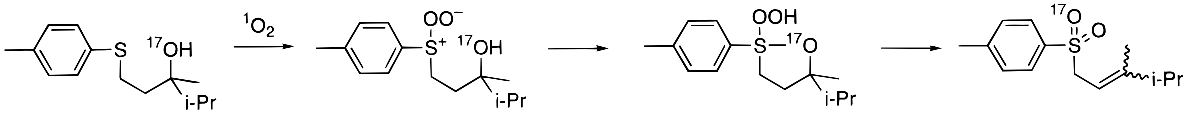
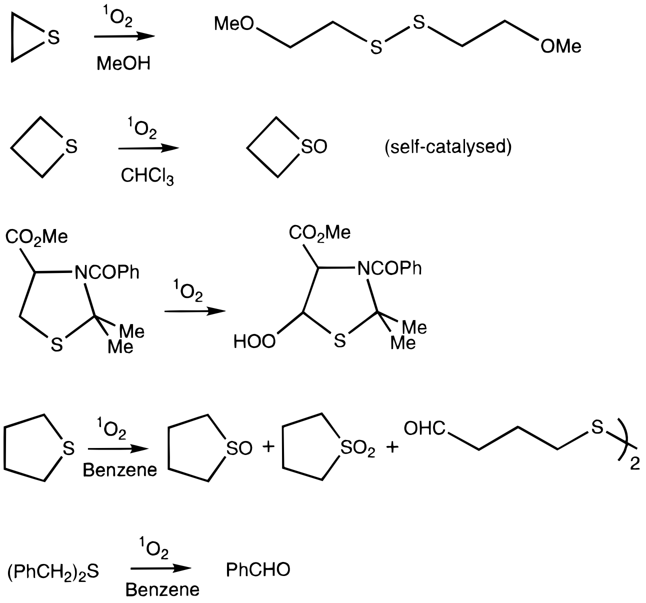
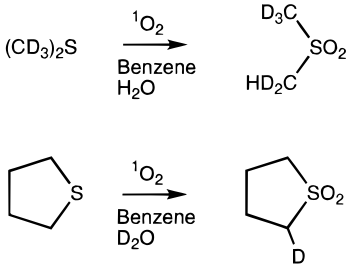
Scheme 4



Scheme 5



Scheme 6



pathway for sulfone formation, in addition to the trapping mechanism. Extrapolation to zero conversion suggests that only the sulfone product formed by an intramolecular path is susceptible to hydrogen/deuterium exchange. A similar observation has been made for thiolane when the reaction is carried out in the presence of D_2O, where deuterium incorporation is observed at the α-position in the sulfone product, but not in the sulfoxide (Scheme 6).[38]

Photooxidation of $(CH_3)_2S/(CD_3)_2S$ or $PhSCH_3/PhSCD_3$ mixtures gave an isotope effect of 2−4 for sulfone formation, but no (or possibly slight inverse) effect on the sulfoxide product.[12] A similar sized isotope effect was obtained for formation of benzaldehyde from photooxidation of PhSCHDPh, suggesting that the cleavage product obtained in benzylic sulfides may arrive via a similar pathway as the sulfone product in other systems.

Clennan et al. have reported an interesting effect on the sulfone/sulfoxide ratio upon addition of MeOH to the photooxidation of sulfides in benzene.[36,42] Small amounts of MeOH increase the sulfone/sulfoxide ratio, but the ratio decreases again for large amounts of added MeOH. Watanabe et al. have reported that addition of polar solvents such as DMF or HMPA increases the yield of the sulfoxide, but has no effect on the amount of sulfone formed.[24]

Sulfides with groups other than carbon attached to sulfur have also been studied. Sulfenamides ($RSN(R')_2$) display less quenching than sulfides, but yield the expected sulfinamides product, analogous to sulfoxides.[42,43] Trapping experiments indicate that two intermediates are required to explain the observed kinetic behavior. Sulfenate esters (RSOR′) also reduce the physical quenching and give the expected oxidized products (sulfinate and sulfonate esters), but in this case only one intermediate is necessary.[44] The intermediate acts as a nucleophile in reactions with both diphenyl sulfides ($\rho = 0.3$) and sulfoxides ($\rho = 1.4$). Disulfides also give two oxidized products (thiosulfinates and thiosulfonates);[45] however, in this case the thiosulfonate is the major product.[46]

Since a direct observation of intermediates has not been possible, theoretical calculations have been employed for establishing geometries and energetics of proposed intermediates.[9,10] A structure corresponding to the peroxysulfoxide with the outer oxygen bisecting the two alkyl groups was found to be a weakly bound species, with a low barrier for dissociation back to the reactants. At the HF level of theory, a second intermediate corresponding to a rotational isomer (122° rotation around the S−O bond) of the peroxysulfoxide was also found. Upon reoptimization at the MP2 level, however, this collapses to a ring-closed thiadioxirane structure. The thiadioxirane is essentially isoenergetic with the peroxysulfoxide, but the transition state (TS) for interconversion between the two species is ~20 kcal/mol. Such a high barrier is clearly not consistent with the proposed mechanism involving rapid interconversion even at low temperature (−78 °C). Theoretical calculations thus confirm the presence of both proposed intermediates; however, the energetics are inconsistent with the thiadioxirane playing any important role in the reaction mechanism. Furthermore, it has not been possible to locate a reaction path for rearrangement of the thiadioxirane to the sulfone.

Results

The currently proposed reaction scheme with the employed notation is shown in Scheme 7. The calculated structures are shown in Figures 1 and 2. The structural and energetic features for the parent dimethyl sulfide will be discussed first, followed by results for cyclic and substituted sulfides.

Dimethyl Sulfide: Structural Features. Previous studies have shown that both the peroxysulfoxide (**2**) and thiadioxirane (**3**) structures are minima on the MP2/6-31G(d) potential energy surface for dimethyl sulfide.[9] The peroxysulfoxide has C_s symmetry with the outer oxygen located above the two methyl groups, and MP2/6-311+G(2df) calculated S−O and O−O bond lengths of 1.59 and 1.44 Å (Figure 1). The thiadioxirane has

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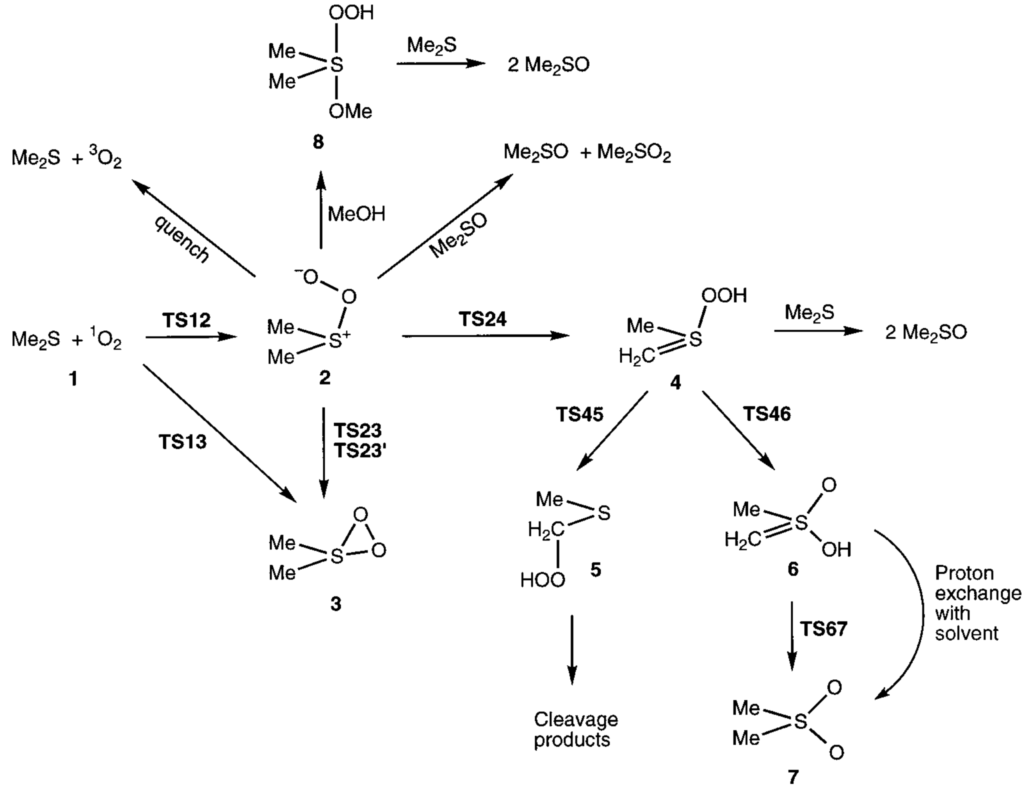
Scheme 7



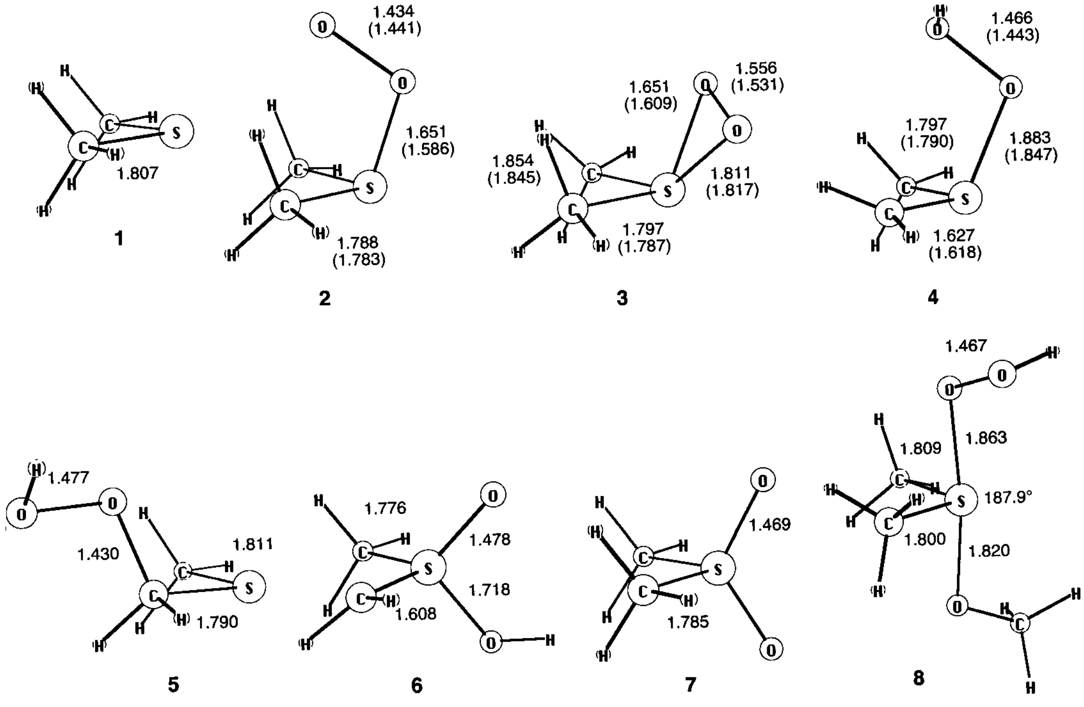


Figure 1. MP2/6-31G(d) optimized geometries (bond distances in Å) of minima. Values in parentheses are MP2/6-311+G(2df) results.

no symmetry, with S−O bond distances of 1.61 and 1.82 Å, and an O−O distance of 1.53 Å. In our previous work, a third intermediate (*S*-hydroperoxysulfonium ylide (**4**)) was established as a viable species.[11] The *S*-hydroperoxysulfonium ylide has previously been suggested as an intermediate by Ishiguro et al. (using PM3 calculations),[12] Corey and Quannes,[39] and Ando et al.[35,37] The *S*-hydroperoxysulfonium ylide is derived formally from an intramolecular hydrogen abstraction in the peroxysulfoxide **2**. The *S*-hydroperoxysulfonium ylide has a short CH_2−S bond with substantial double bond character (1.62 Å at MP2/6-311+G(2df)) and a long S−O bond length (1.85 Å), similar to that found in sulfuranes.[47] There are several conformations available for **4**, but the most stable (shown in Figure 1) has the peroxy hydrogen located above the CH_2 group.

The peroxysulfoxide **2** is formed from the reactants via **TS12** (Figure 2). The reaction can be envisioned as donation of the sulfur lone pair into the empty π_g orbital of $^1O_2$. The geometry of **TS12** is very similar to that of **2** itself, indicating a very

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(47) Lam, W. Y.; Duesler, E. N.; Martin, J. C. *J. Am. Chem. Soc.* **1981**, *103*, 127-135.

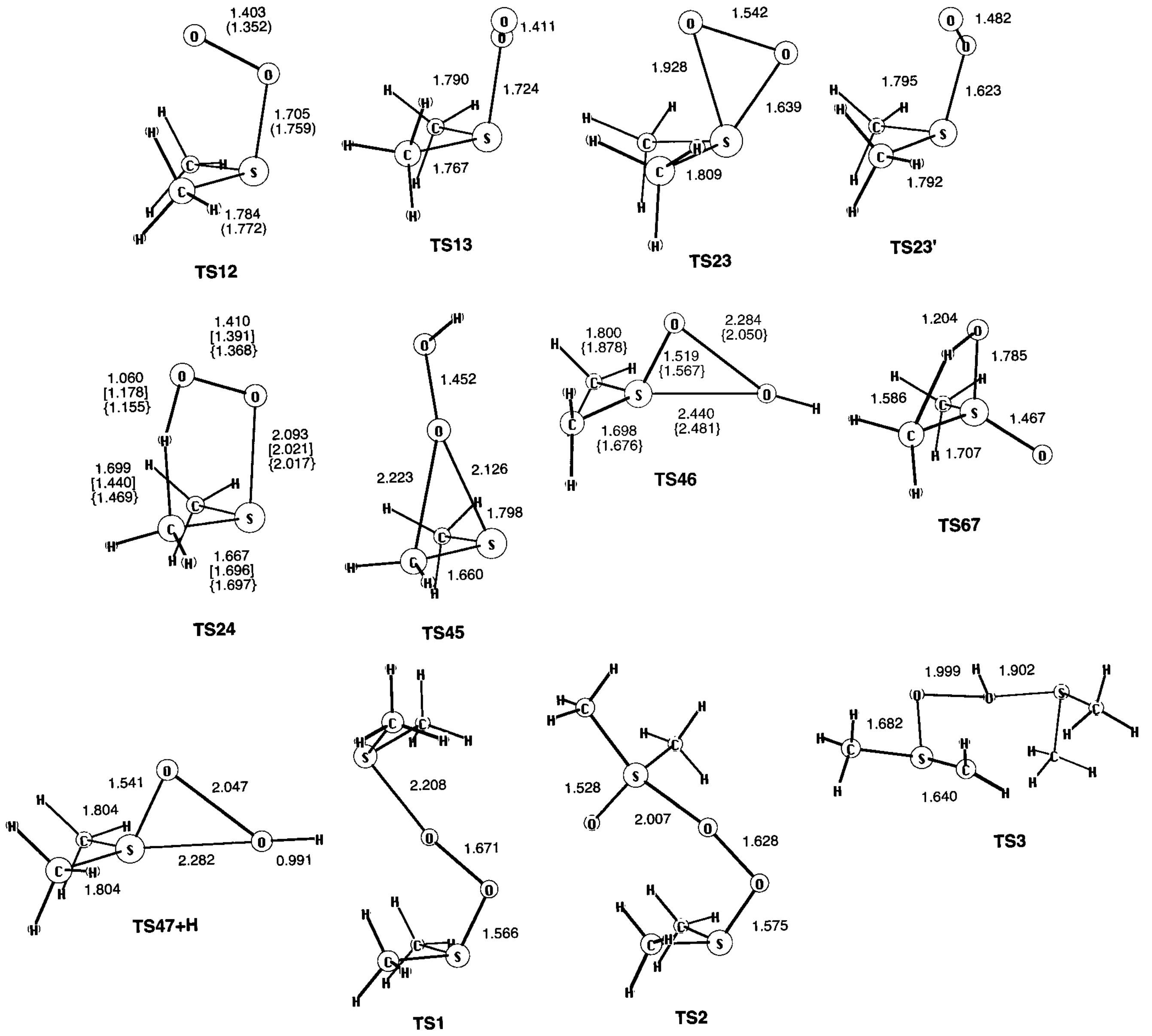

Figure 2. MP2/6-31G(d) optimized geometries (bond distances in Å) of transition structures. Values in parentheses are MP2/6-311+G(2df) results; brackets indicate CCSD(T)/6-31G(d) and curly brackets B3LYP/6-31G(d) optimized structures.

small barrier for back dissociation. Thiadioxirane **3** can be formed directly from the reactants via **TS13**, which resembles **TS12** with the outer oxygen rotated 99° around the S−O bond. We have previously reported a rearrangement path from **2** to **3** corresponding to a ring closure followed by rotation of the O−O moiety.[9] This transition structure, labeled **TS23**, has C_s symmetry and therefore involves a reaction path bifurcation occurring after the TS. During this work a second transition structure for interconversion of **2** and **3** was located, denoted **TS23′**. The structure of this may be considered as a rotation around the S−O bond, followed by ring closure. **TS23′** is structurally very close to **TS13** (Figure 2), which may explain why it had been missed previously. **TS23′** has a slightly shorter S−O (0.10 Å) and a slightly longer O−O bond (0.07 Å) compared to **TS13**, and the CSOO torsional angle is 26° smaller (44° vs 18°). The authenticity of these TSs have been established by IRC tracing. There are a number of transition structures for interconvertions of equivalent thiadioxiranes which have been discussed previously.[9]

At the HF/6-31G(d) level **4** is formed by an intramolecular hydrogen abstraction in **2**, similar to the ene reaction displayed by singlet oxygen with allylic hydrogens. At the MP2/6-31G(d) level, however, the energy of this TS drops below that of **2** by 6 kcal/mol, and the reaction therefore occurs in a single step directly from the reactants (as has been confirmed by tracing the IRC). The geometries at these two levels are substantially different; for example, the S−O bond changes from 1.63 Å at HF to 2.09 Å at MP2, and the breaking C−H bond changes from 1.41 to 1.70 Å. Single point energies at either the HF or MP2 geometries indicate little change in the energetics upon improving the basis set to 6-311+G(2df); however, inclusion of additional electron correlation with the CCSD(T)/6-31G(d) method increases the energy by 10 kcal/mol, i.e., the TS here is 4 kcal/mol above that of **2**. Consequently, we reoptimized the TS at the CCSD(T)/6-31G(d) level (Figure 2), which yielded a structure somewhat intermediate with the HF and MP2 results (e.g., S−O and C−H distances of 2.02 and 1.44 Å), and which is consistent with an intramolecular H-transfer from **2** to **4**. A frequency calculation and IRC tracing at the CCSD(T)/6-31G(d) level is currently impractical, but the geometry and energetics are consistent with the TS connecting **2** and **4** (not **1** and **4**), and we have assigned it as **TS24**. We note that the CCSD(T)

Table 1. Energies Relative to Dimethyl Peroxysulfoxide (**2**) (kcal/mol) as a Function of Level of Theory[a]

	MP2 6-31G(d)	MP2 6-311+G(2df)	CCSD(T) 6-31G(d)	CCSD(T)[b] 6-311+G(2df)	ΔZPE[c]
1	−22.4	−7.1	−17.2	−1.8	−2.0
2	0.0	0.0	0.0	0.0	0.0
3	−3.0	−4.2	2.6	1.4	0.4
4	−9.7	−10.8	−4.7	−5.8	−0.6
5	−55.6				
6	−46.6	−61.3	−35.7	−50.4	0.0
7	−97.5				
8[f]	(−28.7)	(−28.4)	(−22.8)	(−22.5)	
TS12	0.1	0.8	−0.4	0.4	−0.5
TS13	10.4	10.0	9.9	9.4	−1.0
TS24	−5.6	−4.5	4.1	5.1	−1.7
TS24[d]	−4.2	−2.1	5.8	7.8	
TS24[e]	−3.8	−2.4	6.2	7.6	
TS23	19.0	17.2	22.4	20.6	−0.2
TS23′	13.2	11.1	13.2	11.1	−0.3
TS45	8.9 (18.5)	8.3 (19.1)	11.0 (15.7)	10.5 (16.3)	−1.2 (−0.6)
TS46	25.3 (34.9)	15.7 (26.5)	27.1 (31.8)	17.6 (23.4)	−2.9 (−2.3)
TS46[e]	25.6 (35.2)	15.1 (25.8)	24.2 (28.9)	13.7 (19.5)	
TS67	−29.3 (17.3)	−45.6 (15.7)	−17.4 (18.3)	−33.7 (16.7)	−1.7 (−1.7)
TS47+H[g]	(47.1)	(45.2)	(40.2)	(38.3)	

[a] Geometries are optimized at the MP2/6-31G(d) level unless noted otherwise. Values in parentheses for transition structures are relative to the highest energy minimum they connect. [b] Estimated as CCSD(T)/6-31G(d) − MP2/6-31G(d) + MP2/6-311+G(2df).[19] [c] Based on MP2/6-31G(d) harmonic frequencies scaled by 0.967.[20] [d] CCSD(T)/6-31G(d) optimized geometry. [e] B3LYP/6-31G(d) optimized geometry. [f] Relative to **2** + MeOH. [g] Relative to protonated **4**.

Table 2. Energy of the Reactants (**1**, $(CH_3)_2S + {}^1O_2$) Relative to Dimethyl Peroxysulfoxide (**2**) (kcal/mol) as a Function of Level of Theory[a]

basis set	MP2	CCSD(T)
cc-pVDZ	−26.8 (−53.6)	−20.4 (−47.3)
cc-pVTZ	−8.6 (−33.3)	(−30.9)
cc-pVQZ	−3.5 (−27.3)	
cc-pV5Z	(−24.6)	
extrapolated[b]	2.8 (−21.0)	

[a] Corresponding values for H_2S are given in parentheses. Geometries are optimized at the MP2/6-31G(d) level. [b] Reference 49.

geometry is remarkably similar to that obtained with the B3LYP/6-31G(d) method (Figure 2).[13] For **TS24** we have therefore also employed B3LYP/6-31G(d) geometries for the cyclic and substituted sulfides discussed below. The MP2/6-31G(d) kinetic isotope effect ($(CH_3)_2S$ vs $(CD_3)_2S$) is 2.1, while a significantly larger value of 4.5 is obtained at the B3LYP/6-31G(d) level. On the basis of the similarity of the geometries, the latter value is presumably closer to the expected CCSD(T) value.

The *S*-hydroperoxysulfonium ylide **4** is an attractive candidate for formation of α-hydroperoxysulfide (**5**), which has been isolated in the case of thiazolidine reaction with $^1O_2$, and assumed to be the precursor for aldehyde cleavage products in thiolane and dibenzyl sulfide (Scheme 5).[35b,38,39] The TS (**TS45**) for a 1,2-OOH shift from **4** to **5** is shown in Figure 2. Cleavage of the peroxy bond in **5** followed by C−S bond fission would appear as a reasonable pathway for formation of aldehyde disulfides (Scheme 5).

An intramolecular pathway for sulfone formation has so far not been established. Experimental data suggest that the second intermediate (**B** in Scheme 1) can rearrange to a sulfone intramolecularly. With the original assignment of **B** as a thiadioxirane **3**, the rearrangement to the sulfone corresponds to breaking of the O−O bond followed by migration of one of the oxygen atoms to the opposite side of the CSC plane. Despite this seemingly "easy" pathway, we were unable to find such a TS, despite an extensive search.[9] With the present assignment of **B** as a *S*-hydroperoxysulfonium ylide **4**, however, a viable pathway to the sulfone has been found. The transition structure **TS46** (Figure 2) corresponds to a 1,2-migration of the OH group from O to S. Tracing of the IRC at the HF/6-31G(d) level established that it indeed connects **4** with the protonated sulfone ylide **6**. At the MP2 level, however, the energy of the TS is above the dissociation limit for breaking the O−O bond in **4**, and the IRC therefore connects **6** with a complex between a sulfoxide ylide ($CH_2{=}S(O){-}CH_3$) and OH radical. The wave function for **TS46** consequently has a large biradical character and is difficult to describe with single determinant based methods.[48] The MP2 optimized geometry of **TS46** is therefore expected to be less reliable than that for other stationary points. Single point calculations with the three standard levels of theory (MP2 with either the 6-31G(d) or 6-311+G(2df) basis sets, or CCSD(T)/6-31G(d)) at the MP2/6-31G(d) geometry are all above the O−O dissociation limit (by 9, 3, and 11 kcal/mol, respectively). Although a substantially larger basis set than 6-311+G(2df) may eventually bring the TS energy below the dissociation limit, this is currently not feasible. We attempted reoptimizations at the [10,10]-CASSCF/6-31G(d) and CCSD(T)/6-31G(d) levels, but these failed to converge, most likely due to the energy being above the O−O dissociation limit. It is possible that a TS for a concerted 1,2-OH migration does not exist in the gas phase; however, solvent effects are estimated to preferentially stabilize the TS (vide infra), which brings the barrier below the O−O dissociation limit.

The TS corresponding to 1,2-OH migration obtained with the B3LYP method is somewhat different.[13] The MP2 geometry has the OH migration taking place essentially in the plane bisecting the two carbon atoms through the sulfur atom. The B3LYP geometry, however, has the OH group substantially out of this plane toward the CH_2 group (the C−O distance is 3.90 Å at MP2 but only 2.83 Å at B3LYP). An IRC tracing from this TS at the B3LYP level actually leads to an α-hydroxysulfoxide structure ($HOCH_2S(O)CH_3$) instead of **6**. Due to the problem of being close to the O−O dissociation limit in **4**, this may be an artifact. Nevertheless, we have included it in Tables 1 and 3 as **TS46**. Indeed the corresponding TS for thiethane has IRCs which connect structures **4** and **6**.

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(48) The [10,10]-CASSCF/6-31G(d) natural occupation numbers for the HOMO-LUMO orbitals are 1.22 and 0.78, respectively, at the MP2/6-31G(d) geometry. The corresponding CCSD(T) values are 1.25 and 0.69.

Table 3. MP2/6-31G(d) Energies (kcal/mol) Relative to **2** for Cyclic Sulfides[a]

sulfide	dimethyl	thiirane	thietane	thiolane
1	−22.4	−28.5	−19.9	−21.1
3	−3.0	−4.4	−8.0[b]	−2.3
4	−9.7	7.1	−6.3	−10.1
5	−55.6	−65.2	−58.1	
6	−46.6	−24.0	−45.4	−43.7
TS12	0.1		0.7	1.6
TS13	10.4			8.1
TS23	19.0	16.4	21.4	
TS23′	13.2		13.2	
TS24	−5.6	0.4	−3.2	−6.8
TS24[c]	−3.8		0.4	−6.2
TS45	8.9 (18.5)	12.4 (5.3)	9.3 (15.6)	5.9 (16.0)
TS46[c]	25.6 (35.2)		47.7 (54.0)	21.7 (31.7)

[a] Geometries are optimized at the MP2/6-31G(d) level unless noted otherwise. Values in parentheses for **TS45** and **TS46** are relative to **4**. [b] This value differ from the previously reported,[51] and is due to the location of a slightly lower energy conformation. [c] B3LYP/6-31G(d) optimized geometry.

A comparison of the geometries of **4**, **6**, and the connecting **TS46** shows that the p-orbital on the ylide carbon is directed toward the migrating OH group during the reaction. The MP2/6-31G(d) calculated rotational profile for the CH_2 group at the **TS46** geometry indicates that the conjugation stabilizes the TS by ∼10 kcal/mol. This may indicate that factors such as confining the sulfur in a ring system or introduction of substitutients can significantly affect the yield of intramolecularly formed sulfone product.

The calculated kinetic isotope effect ($(CH_3)_2S$ vs $(CD_3)_2S$) using MP2/6-31G(d) frequencies is 2.6, which is surprisingly high for an OH migration. It is presumably due to the reaction coordinate containing strong components corresponding to OOH bending and rotation of the CH_2 group. Although it could be an artifact of the MP2 method, as **TS46** most likely is rather poorly described at this level of theory, it shows that there may be a significant isotope effect for this step in intramolecular sulfone formation.

The protonated sulfone ylide **6** can undergo an intramolecular proton transfer (a keto−enol type reaction) to give sulfone **7**; the corresponding transition structure is shown in Figure 2 as **TS67**. Alternatively, the dipolar ylide **6** may be converted to **7** by a protonation/deprotonation sequence involving an external proton donor. This would readily explain how solvent proton or deuterium can be incorporated in the sulfone product (Scheme 6). An alternative mechanism for transforming **4** to **7** would be protonation of **4** followed by 1,2-OH migration analogous to **TS46** to form a protonated sulfone. Such a TS was also found, denoted **TS47+H** in Figure 2; however, it is significantly higher in energy, as discussed in the next section. In contrast to **TS46**, **TS47+H** is readily described by a single determinant wave function.

In MeOH as a solvent, a sulfurane structure corresponding to **8** has been suggested, the associated optimized geometry is shown in Figure 1. We note that the structural features of the SOOH moiety are similar to those of **4**. It is possible that **8** may also be able to rearrange to a sulfone with extrusion of MeOH, but due to the size of the system and the difficulties describing the wave function for **TS46**, we have not investigated such reactions. Furthermore, the reduced yield of sulfone in MeOH as a solvent suggests that formation of sulfone directly from the sulfurane is not a major pathway. We also attempted calculation of stabilizations due to coordination by solvent or substrate to either **2** or **3** (i.e. coordination by either MeOH, H_2S, or Me_2S, Scheme 3); however, the energetics proved very susceptible to basis set superposition errors and are therefore not of sufficient quality to warrant discussion.

Recognizing that transformation of peroxysulfoxide **2** to *S*-hydroperoxysulfonium ylide **4** only involves a proton transfer, it is possible that this reaction may be catalyzed by protic solvents, such as MeOH. The curious effect of added MeOH on the sulfone/sulfoxide ratio may possibly be due to MeOH primarily acting as a proton source at low concentrations, facilitating the conversion of **2** to **4** and further on to sulfone, while at higher concentrations MeOH actually adds to **2** to form the sulfurane **8**, which inhibits sulfone formation. Although this clearly is highly speculative, it does provide a rationale for the observation that the sulfone/sulfoxide ratio passes through a maximum as a function of MeOH concentration.[36,42]

The peroxysulfoxide **2** is proposed to be responsible for oxidizing sulfoxides. We have located transition structures corresponding to transfer of the outer oxygen to either dimethyl sulfide or dimethyl sulfoxide (**TS1** and **TS2**, Figure 2). At the MP2/6-31G(d) level **TS1** for transferring an oxygen to dimethyl sulfide is 5 kcal/mol above the separated species (i.e. **2** and $(CH_3)_2S$), while **TS2** for transferring an oxygen to dimethyl sulfoxide is 6 kcal/mol *below* the separation limit (**2** and $(CH_3)_2SO$). This result is most likely due to basis set superposition errors, and higher level calculations are expected to change these values. Nevertheless, the MP2/6-31G(d) values indicate that oxygen transfer to a sulfoxide should be substantially favored relative to oxidation of a sulfide, in agreement with experimental data. We have also searched for a TS for oxidation of dimethyl sulfide by *S*-hydroperoxysulfonium ylide **4**. The **TS3** structure shown in Figure 2 corresponds to transfer of the OH group, which upon backtransfer of the hydrogen would give 2 mol of dimethyl sulfoxide. **TS3** is above the dissociation limit for the O−O bond in **4**, and it is therefore likely that higher level calculations will yield a different structure. Attempts at optimizing a TS where the hydroxyl hydrogen is transferrred to the CH_2 group simultaneously with transfer of oxygen to dimethyl sulfide gave instead **TS1**.

Dimethyl Sulfide: Energetic Features. Relative energies at the MP2/6-31G(d), MP2/6-311+G(2df), and CCSD(T)/6-31G(d) levels, as well as zero point vibrational energies obtained at the MP2/6-31G(d) level, for the dimethyl sulfide system are shown in Table 1. In the spirit of the G2 method[19] we have estimated CCSD(T)/6-311+G(2df) values as CCSD(T)/6-31G(d) − MP2/6-31G(d) + MP2/6-311+G(2df). Only these extrapolated values are discussed in the text; Table 1 may be consulted for more details. In the absence of large discrepancies between the three standard levels of theory, we assign error limits of ±2−3 kcal/mol for the extrapolated values, based on experience with similar procedures.[19]

The energy of the reactants **1** relative to the peroxysulfoxide **2** is very sensitive to the basis set, and it is not clear that the 6-311+G(2df) basis set is sufficiently large for estimating a "converged" value. Table 2 shows how the value converges as the basis set is systematically increased with the correlation consistent basis sets.[17] The basis set limiting value at the MP2 level is ∼3 kcal/mol,[49] i.e., a 10 kcal/mol change relative to the 6-311+G(2df) value. Addition of more correlation with the CCSD(T) method increases the value by ∼2 kcal/mol, while inclusion of zero point energies decreases it by a similar amount

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(49) The extrapolation to the complete basis set limit has been done by fitting the total energies at the HF level with an exponential function of the type $A + B\exp(-CX)$ and a function of the type $A + B/(X + 1)^C$ for the MP2 correlation contribution, Wilson, A. K.; Dunning, T. H., Jr. *J. Chem. Phys.* **1997**, *106*, 8718−8726.

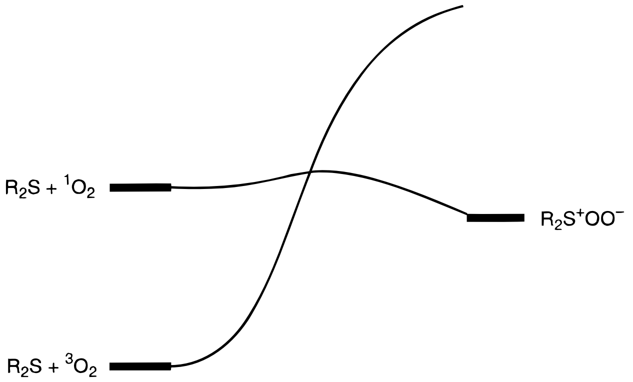

Figure 3. Illustration of the singlet−triplet energy surface crossing occurring in the initial phase of the reaction.

(Table 1). These results indicate that **2** is ∼3 kcal/mol below the reactants in the gas phase, and solvent effects will preferentially stabilize the more polar peroxysulfoxide. Calculations at the B3LYP/6-31G(d) level with the PCM model[50] suggest that the effect is 7 kcal/mol for benzene and 13 kcal/mol for acetone. On the *enthalpic* energy surface the reaction from sulfide and singlet oxygen to form a peroxysulfoxide **2** is probably without a barrier; however, formation of a single molecule from two isolated reactants has a substantial negative entropy change (the calculated value is $\Delta S = -36$ eu). On the *free energy* surface it is therefore likely that there is a small barrier due to entropy. The experimental values of $\Delta H^{\ddagger} = -4$ kcal/mol and $\Delta S^{\ddagger} = -46$ eu in acetone[26] suggest a barrier of 10 kcal/mol on the free energy surface at $T = 300$ K, being lowered to 5 kcal/mol at 200 K. The calculated enthalpy difference between reactants and peroxysulfoxide of 16 kcal/mol (including a solvent stabilization of 13 kcal/mol) is fully in line with the experimental results. Including the calculated entropy difference ($-T\Delta S = 11$ kcal/mol at $T = 300$ K), this suggests that **2** is bound by ∼5 kcal/mol on the free energy surface relative to the reactants. The calculated energy difference between **2** and **TS12** is only a few tenths of a kilocalorie per mole; however, due to the strong basis set dependency of the energy difference between **1** and **2** and the large entropy component, this is not a realistic structure of the transition state for formation of **2**. Nevertheless, the existence of **TS12** shows that **2** is a bound species on the MP2/6-31G(d) surface, in contrast to DFT methods.[13]

These results indicate that the initial reaction occurs on a very flat part of the energy surface, which provides a rationale for the mechanism of physical quenching. In the reactants the triplet state is lower in energy (${}^3O_2$); however, the energy will rise rapidly as the S−O distance decreases. In the early part of the reaction the singlet and triplet PESs will therefore be close in energy or possibly cross, as illustrated in Figure 3. A scan of the PES (MP2/6-31G(d)) as a function of the S−O distance with fixed geometries for O_2 and $(CH_3)_2S$ suggests that the triplet is raised by 23 kcal/mol when the S−O distance is ∼2.6 Å, i.e., this is presumably the region where the intersystem crossing takes place (the singlet−triplet energy gap in O_2 is 22.5 kcal/mol[18]). Since there is a very small energy penalty associated with movement along the reaction coordinate on the singlet surface, physical quenching will compete with other reaction pathways (such as trapping) from the peroxysulfoxide **2**. It also indicates that factors which stabilize the peroxysulfoxide relative to the reactants will reduce quenching. Lowering the temperature will stabilize the peroxysulfoxide, since the entropy contribution is reduced, as will an increase in solvent polarity, with both factors leading to less quenching. When MeOH is used as a solvent, the peroxysulfoxide is rapidly transformed into sulfurane **8** with an exothermicity of 23 kcal/mol, essentially eliminating the quenching pathway.

The energy of **TS13** for a direct formation of the thiadioxirane **3** is ∼9 kcal/mol higher than **2**, and is therefore not an important reaction pathway. It can also be noted that a parallel formation of two intermediates from the reactants is inconsistent with the trapping experiments leading to the mechanism shown in Scheme 1. Combined with the above estimate for the reactant−peroxysulfoxide energy difference, **TS13** is probably above the dissociation limit of the S−O bond in **2**, at least in the gas phase. The rearrangement paths via **TS23** or **TS23′** are even higher and therefore not important either. These results confirm previous conclusions that ruled out the thiadioxirane **3** as a viable intermediate based on energetics.[9]

At the MP2 level the TS for formation of *S*-hydroperoxysulfonium ylide **4** is lower in energy than that of peroxysulfoxide **2**, and must therefore occur in a single step directly from the reagents. As discussed above, it is likely that **4** is formed by an intramolecular hydrogen abstraction from **2** at the CCSD(T) level. Our best estimate for the activation energy is 6 kcal/mol, including the zero point energy correction (the calculated barrier at the PM3 level is 19 kcal/mol,[12] placing it well above the dissociation limit). PCM calculations indicate that solvation may increase this value by a few kilocalories per mole. This is fully consistent with experimental results which require a rapid interconversion even at low temperatures. The barrier for rearrangement of **2** to **4** is comparable with the back dissociation to reactants (including the entropic part of the barrier), which can lead to quenching as discussed above. Once the *S*-hydroperoxysulfonium ylide **4** is formed, however, there is a reverse barrier of ∼12 kcal/mol, and it will therefore eventually lead to products by reaction with a second sulfide molecule or rearrangement to a sulfone.

The barrier for further rearrangement of **4** to the α-hydroperoxysulfide **5** is calculated to be 16 kcal/mol. Compared to the barrier for reversion to **2** (**TS24**, 12 kcal/mol), this suggests that it is not an important pathway for the parent dimethyl sulfide. It is, however, so close in energy that it may become a compatible pathway in some substrates, such as five-membered rings and benzylic systems.

As discussed in the previous section, the wave function for **TS46** (rearrangement of *S*-hydroperoxysulfonium ylide **4** to protonated sulfone ylide **6**) is difficult to describe. Our extrapolated CCSD(T)/6-311+G(2df) barrier is 23 kcal/mol at the MP2/6-31G(d) optimized geometry, and 20 kcal/mol at the B3LYP/6-31G(d) geometry. The estimated QCISD(T)/6-311+G-(3df,2p) value at the B3LYP/6-31+G(d) optimized geometry is 8 kcal/mol[13] (we note that this TS may not be for the **4** to **6** rearrangement, as discussed above). Due to the large multireference character of the wave function, these values are less reliable than the other energy differences. An upper limit for **TS46** may be derived from the O−O bond dissociation energy in **4**, which is calculated to be 19 kcal/mol at the CCSD(T)/6-311+G(2df) level. Since 1,2-OOH migration to form α-hydroperoxysulfide **5** is not observed experimentally, it follows that **TS46** must have a barrier lower than 16 kcal/mol (calculated value for **TS45**). PCM calculations suggest that solvent (acetone) effects will lower the activation energy by ∼3 kcal/mol for **TS45** and ∼6 kcal/mol for **TS46**. Sulfoxide formation by trapping of **4** thus competes with a unimolecular rearrange-

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[50] Cossi, M.; Barone, V.; Cammi, R.; Tomasi, J. *Chem. Phys. Lett.* **1996**, *255*, 327−335.

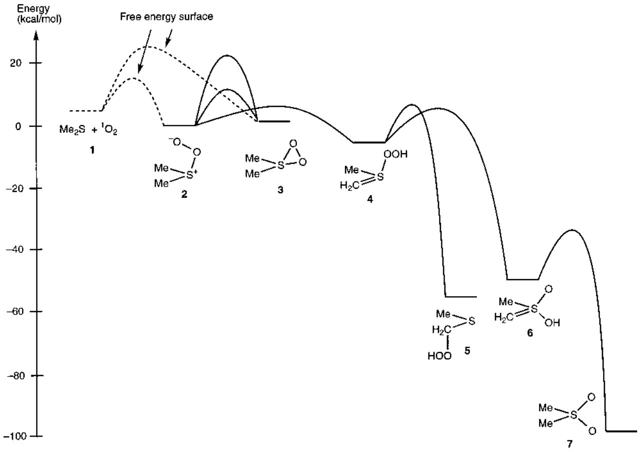

Figure 4. Energy profile in solution for the reaction of dimethyl sulfide with singlet oxygen based on computational and experimental data.

ment path leading to the sulfone ylide **6** (and from there to the sulfone **7**), and therefore depends on the sulfide concentration. The fact that the sulfone product only is a minor component indicates that the oxygen transfer from **4** to a second sulfide molecule is a facile process (the exothermicity is calculated to be 68 kcal/mol). The reaction from **4** to **6** is highly exothermic by 44 kcal/mol, and once **6** is formed there is a barrier of 15 kcal/mol for the keto−enol type proton transfer to yield the final sulfone product **7**. This means that **6** is sufficiently long-lived to allow a solvent catalyzed pathway with incorporation of solvent hydrogen/deuterium, which is likely to be the favored path if a proton donor is available. Protonation of the α-carbon in **4** followed by a 1,2-OH shift to form a protonated sulfone **7+H** (**TS47+H**) is calculated to have a barrier of 38 kcal/mol, i.e., this is not a viable pathway.

Our final estimate of the reaction profile in solution for unimolecular rearrangements based on computational and experimental results is shown in Figure 4. One of the remarkable features is the presence of three transition states (**TS24**, **TS45**, and **TS46**) with almost equal energy. This means that even small changes in sulfide structure or solvent may shift the preferred reaction mode and the observed kinetics.

Cyclic Sulfides. We have previously reported computational results for **2**, **3**, and **TS23** for the three-, four-, and five-membered cyclic sulfides.[51] These results, together with additional data at the MP2/6-31G(d) level, are given in Table 3. The energy difference between **1** and **2** is much too high at this level of theory as shown in Tables 1 and 2; however, it is likely that the error to a large extent is constant. From Table 3 it is clear that thiadioxiirane **3** does not play a role for cyclic sulfides either. The S−C double bond character significantly destabilizes the *S*-hydroperoxysulfonium ylide **4** in the thiirane system (by 17 kcal/mol), and also raises the energy of this intermediate by 3 kcal/mol (relative to **2**) for thietane. For thiirane this means that only the peroxysulfoxide **2** is expected to play a role. The barrier for rearrangement of **2** to **4** is slightly higher (∼4 kcal/mol) for thietane than for the dimethyl system, while thiolane has a slightly lower barrier (∼2 kcal/mol).

The unimolecular reaction pathways for *S*-hydroperoxysulfonium ylide **4** are a 1,2-OOH shift to the α-hydroperoxide **5** and a 1,2-OH shift to the sulfone yilde **6**, both of which compete with intermolecular trapping by sulfides. In the parent dimethyl system, experimental evidence indicates that **TS46** is lower in energy than **TS45**, i.e., sulfone formation is favored over α-hydroperoxide formation. Intermolecular trapping, however, is nearly always the favored reaction mode. The reaction barrier for α-hydroperoxide formation (**TS45**) is essentially the same for thietane and thiolane, and slightly lower than that for dimethyl sulfide. At the MP2 level we have been unable to find a transition structure for the conversion of **4** to **6**; however, at the B3LYP level structures analogous to **TS46** for dimethyl sulfide have been obtained for thietane and thiolane. Tracing of the IRC for thietane establishes that this indeed connects **4** and **6**, in contrast to the dimethyl system. MP2/6-31G(d) calculations at the B3LYP geometries indicate that the 1,2-OH migration is substantially disfavored (by 19 kcal/mol) in thietane relative to dimethyl sulfide, but is favored by 4 kcal/mol in thiolane. The latter is consistent with the observation that deuterium is incorporated in the α-position for the thiolane sulfone,[38] and our computational results predict that this should not be the case for thietane sulfone.

Substituted Sulfides. Structural and energetic features of **2**, **3**, and **TS23** for CH_3SX (X = NH_2, OH, F, $N(CH_3)_2$, OCH_3, SH, and Cl) have been reported recently.[11] In the case of X = NH_2, OH, and SH, peroxysulfoxide structures **2** do not exist, they collapse spontaneously to a structure corresponding to ylide **4**. As shown in Table 4, both amino and alkoxy substituents stabilize **2** relative to the reactants, in comparison with dimethyl sulfide. According to the quenching mechanism discussed above, this should lead to reduced physical quenching, in agreement with experimental data.[40−42] Dimethyl disulfide should show similar quenching characteristics to dimethyl sulfide, consistent with recent experimental findings.[52] There is also a clear tendency that thiadioxirane **3** is stabilized relative to peroxysulfoxide **2** as X becomes more electronegative. The barrier for interconversion (**TS23** or **TS23′**) is slightly lower than that for dimethyl sulfide, i.e., 9−11 kcal/mol depending on the substituent. Given that the MP2/6-31G(d) calculations predict that the peroxysulfoxides corresponding to **2** are stabilized by 12−15 kcal/mol relative to the dimethyl systems for X = $N(CH_3)_2$, OCH_3, and F, this places **TS23**/**TS23′** below the dissociation limit for the S−O bond in **2** for these systems. In all cases, however, **TS24** for formation of *S*-hydroperoxysulfonium ylide **4** is lower in energy, i.e., a thiadioxirane structure is not expected to play any role for these substituted sulfides either.

Compared to dimethyl sulfide, the rearrangement of **2** to **4** has higher barriers for X = $N(CH_3)_2$, OCH_3, and F (and **4** is somewhat less stable for X = $N(CH_3)_2$ and OCH_3). This would indicate that the peroxysulfoxide intermediate corresponding to **2** is longer-lived, and may therefore become the only chemically important species that can be trapped. This would agree with the experimental observation that only one intermediate is required in the case of sulfenate esters (RSOR′), and that it shows nucleophilic character.[44] The dimethyl disulfide (X = SCH_3) rearrangement barriers are very similar to those for the reference dimethyl sulfide system, i.e., kinetic and trapping experiments are predicted to indicate two intermediates.

Rearrangement of *S*-hydroperoxysulfonium ylide **4** to α-hydroperoxide **5** is increasingly disfavored by electronegative substituents, while dimethyl disulfide has a slightly lower barrier than dimethyl sulfide. Formation of α-hydroperoxides and subsequent cleavage products are therefore not expected, nor are they observed experimentally. As for the cyclic sulfides, we have been unable to locate MP2 transition structures for rearrangement from **4** to protonated sulfone ylide **6**. The

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[51] Greer, A.; Jensen, F.; Clennan, E. L. *J. Org. Chem.* **1996**, *61*, 4107−4110.

[52] Clennan, E. L.; Wang, D.; Clifton, C.; Chen, M.-F. *J. Am. Chem. Soc.* **1997**, *119*, 9081−9082.

Table 4. MP2/6-31G(d) Energies (kcal/mol) Relative to **2** for Substituted Sulfides, CH_3SX^a

X	CH_3	$N(CH_3)_2$	OCH_3	F	SCH_3
1	−22.4	−13.7	−12.1	−14.6	−26.8
3	−3.0	−9.3	-19.0^b	−31.1	-13.2^b
4	−9.7	−2.8	−5.7	−12.8	−9.4
5	−55.6			−45.2	
TS12	0.1	3.8	4.7	1.8	0.8
TS13	10.4				4.6
TS24	−5.6	1.8	2.2	2.7	−5.9
TS24[c]	−3.8	6.3	7.2	5.5	−3.1
TS23	19.0	12.6	10.8^b	10.2	11.9^b
TS23′	13.2	11.3	11.0	9.4	9.9
TS45	8.9 (18.5)	16.2 (18.9)	15.7 (21.4)	16.4 (29.2)	7.1 (16.5)

[a] Geometries are optimized at the MP2/6-31G(d) level unless noted otherwise. Values in parentheses for **TS45** are relative to 4. [b] These values differ from those previously reported,[11] due to the location of slightly lower energy conformations. [c] B3LYP/6-31G(d) optimized geometry.

B3LYP method in these cases leads to transition structures analogous to those in dimethyl sulfide which connect **4** with an α-hydroxy-sulfoxide structure ($HOCH_2S(O)X$). For X = F, the TS is qualitatively similar to **TS46** in dimethyl sulfide, but for X = OMe, NMe_2, and SMe the geometries are substantially different, with the OH group being transferred across the $H_2C{=}S$ bond to the lobe of the carbon p-orbital that is pointing toward the X group. Such geometries are clearly unrelated to a sulfone rearrangement path. We note that experimental observations indicate that a rearrangement leading to the sulfone product should be especially facile for disulfides.[41]

Conclusion

On the basis of high-level ab initio calculations we have established that an *S*-hydroperoxysulfonium ylide **4** is an energetically viable intermediate, and that it can be formed from a peroxysulfoxide **2** in a low-barrier reaction (∼6 kcal/mol). Furthermore, the *S*-hydroperoxysulfonium ylide intermediate can rearrange via reasonably low energy barriers (∼12 kcal/mol) to either an α-hydroperoxide **5** or to a protonated sulfone ylide structure **6**, which leads via a keto−enol rearrangement to the sulfone product **7**. Which of these intramolecular pathways is the lowest in energy will depend on the structure of the sulfide, which will also determine the degree of competition from intermolecular trapping. As a consequence, intramolecular sulfone formation should not be observed (or should at least be reduced) when products corresponding to oxidation of the α-carbon are observed.

The pathway leading to the sulfone readily explains how solvent hydrogen/deuterium can be incorporated in the sulfone, but not the sulfoxide, with keto−enol equilibration. The unimolecular pathway for sulfone formation would thus appear to go through the *S*-hydroperoxysulfonium ylide intermediate.

Given that the *S*-hydroperoxysulfonium ylide is expected to react as an electrophile, and that it is formed sequentially from the peroxysulfoxide, it is an alternative candidate for the second intermediate in aprotic solvents, rather than a thiadioxirane. At present there appears to be only one piece of experimental evidence that argues against this assignment. Ishiguro et al. have reported a kinetic isotope effect of 2−4 for the formation of the sulfone product, but not for the sulfoxide,[12] which appears inconsistent with a *S*-hydroperoxysulfonium ylide as a common precursor.[53] If the *S*-hydroperoxysulfonium ylide is not the intermediate responsible for sulfide oxidation, a third intermediate is required. Since sulfone is only a minor reaction product, this means that the barrier for formation of such a third intermediate must be substantially smaller than the ∼6 kcal/mol calculated for rearrangement to the *S*-hydroperoxysulfonium ylide. Although a solvent-coordinated peroxysulfoxide is likely to be formed with a very small barrier, the similar reaction kinetics and product distributions in different (aprotic) solvents speak against such a possibility. Coordination of the peroxysulfoxide by the reagent sulfide is evidently possible for thietane and 1,5-dithiacyclooctane, but this is not a general phenomenon. A final possibility would be coordination of either the sulfoxide or sulfone product to the peroxysulfoxide. An actual addition of a sulfoxide to the peroxysulfoxide to form a 1,3,4-trioxo-2,5-dithiacyclopentane does not appear to be a viable alternative, as optimizations of such a structure at either the MP2/6-31G(d) or B3LYP/6-31G(d) levels simply revert back to the components.

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(53) A kinetic isotope effect for sulfone, but not sulfoxide, formation may still be possible with a *S*-hydroperoxysulfonium ylide as a common precursor if the sulfone formation step has a substantially larger isotope effect than the intermolecular trapping step for formation of the sulfoxide. The calculated value for the sulfone step of 2.6 would mean that the intermolecular trapping should occur essentially without an isotope effect.