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Tetrahedron 62 (2006) 10716–10723
Tetrahedron

Reaction of singlet oxygen with some benzylic sulfides

Sergio M. Bonesi,[a,b] Maurizio Fagnoni,[b] Sandra Monti[c] and Angelo Albini[b,*]

[a]*CHIDECAR-CONICET, Dep. Quim. Org., Fac. Cien. Ex. Nat., Universidad de Buenos Aires, Ciudad Universidaria, 1428 Buenos Aires, Argentina*
[b]*Department of Organic Chemistry, University of Pavia, v. Taramelli 10, 27100 Pavia, Italy*
[c]*ISOF-CNR Institute, v. Gobetti 123, 40129 Bologna, Italy*

Received 8 June 2006; revised 25 July 2006; accepted 28 July 2006
Available online 27 September 2006

Abstract—Product distribution, total quenching rate (k_T), and rate of chemical reaction (k_r) with singlet oxygen have been determined for some alkyl, benzyl, α-methylbenzyl, and cumyl sulfides. Their contributions depend on the steric hindering around the sulfur atom. In protic solvents, the sulfoxide is the main product via a hydrogen-bonded persulfoxide. In apolar solvents, intramolecular α-H abstraction leads to oxidative C–S bond cleavage, with varying efficiency. The behavior of sulfides is compared to that of alkenes and amines.

1. Introduction

The fascinating chemistry of singlet oxygen remains an appealing field of research and continues to reveal new mechanistic facets and synthetic applications.[1,2] This strong electrophile attacks either a π nucleophile (alkenes, polyenes, electron-rich aromatics, and heterocycles) or a nucleophile (organic sulfur or phosphorous derivatives). The interaction with most nucleophiles (D:) leads to a weakly bonded complex that evolves either toward the formation of a stable product or toward the starting compound and triplet oxygen (Eqs. 1–3).[3]

$$\mathrm{D:} + {}^1\mathrm{O_2} \rightarrow [\mathrm{D:}\cdots\mathrm{O_2}] \quad (1)$$

$$[\mathrm{D:}\cdots\mathrm{O_2}] \rightarrow \mathrm{D:} + {}^3\mathrm{O_2} \quad (2)$$

$$[\mathrm{D:}\cdots\mathrm{O_2}] \rightarrow \text{products} \quad (3)$$

Thus, a single intermediate leads both to chemical reaction and to physical quenching. Both the extent to which the initial complex is formed (in competition with singlet oxygen decay) and the ratio between the ensuing processes vary greatly depend on the structure of the nucleophile as well as on the experimental conditions (solvent, temperature, pressure, catalysis by various additives). As an example, chemical reaction is all important with alkenes, while both aromatic and aliphatic amines mainly act as physical quenchers and sulfides lie in between, with the portion of chemical reaction varying from a few percent to almost quantitative. The important role that oxygen and its excited states have in chemical and biological reactions of sulfur-containing compounds has stimulated a host of experimental and computational studies aimed at the rationalization of the mechanism(s) involved.[4–10] Several years ago we initiated a program to study the photooxygenation of sulfides, in particular benzyl sulfides.[11–14] Presently, we report some new results on related substrates and attempt to frame the findings in the general picture of singlet oxygen reactions.

2. Results

The oxygenation of a series of benzyl sulfides was carried out by visible light irradiation of a sensitizer (Rose Bengal in alcohols and in acetonitrile, tetraphenylporphine in benzene) in an oxygen saturated solution. The conversion was limited to ca. 30%, in order to limit secondary photoreactions, and the mass balance was good, except when noted. The solvents used were apolar benzene, polar acetonitrile, and protic methanol. The results are reported in Table 1. It is well known that aliphatic sulfides yield the sulfoxides with a small amount of the sulfones. We examined phenethyl ethyl sulfide (**1**) and found that, while the sulfoxide is virtually the only product in methanol, in acetonitrile, and in benzene a significant amount of phenylacetaldehyde (43% in the last solvent) was formed (see Scheme 1, Table 1). Essentially the same pattern was followed when using phenethyl phenyl sulfide (**2**).

* Corresponding author. Tel.: +39 0382 987316; fax: +39 0382 987323; e-mail: angelo.albini@unipv.it

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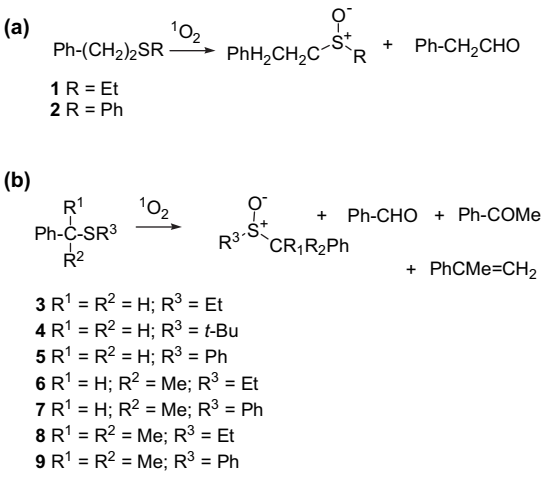
doi:10.1016/j.tet.2006.07.110

Table 1. Products from the photosensitized oxidation of some sulfides[a]

Sulfide	Solvent	Products, %	
		S-Oxidation	Cleavage
1, $PhCH_2CH_2SEt$	MeOH	$PhCH_2CH_2SOEt$, 74	—
	MeCN	$PhCH_2CH_2SOEt$, 61	$PhCH_2CHO$, 15
	C_6H_6	$PhCH_2CH_2SOEt$, 57	$PhCH_2CHO$, 43
2, $PhCH_2CH_2SPh$	MeOH	$PhCH_2CH_2SOPh$, 100	—
	MeCN	$PhCH_2CH_2SOPh$, 80	$PhCH_2CHO$, 20
	C_6H_6	$PhCH_2CH_2SOPh$, 58	$PhCH_2CHO$, 42
3, $PhCH_2SEt$	MeOH	$PhCH_2SOEt$, 63	PhCHO, 25
	MeCN	$PhCH_2SOEt$, 6	PhCHO, 90
	C_6H_6	$PhCH_2SOEt$, 2	PhCHO, 89
4, $PhCH_2S$-*t*-Bu	MeOH	$PhCH_2SO$-*t*-Bu, 95	PhCHO, 5
	MeCN	$PhCH_2SO$-*t*-Bu, 18	PhCHO, 45
	C_6H_6	$PhCH_2SO$-*t*-Bu, 27	PhCHO, 43
5, $PhCH_2SPh$	MeOH	$PhCH_2SOPh$, 65; $PhCH_2SO_2Ph$, 4	PhCHO, 27; $(PhS)_2$, 4
	MeCN	$PhCH_2SOPh$, 11	PhCHO, 77; $(PhS)_2$, 17
	C_6H_6	$PhCH_2SOPh$, 13	PhCHO, 51; $(PhS)_2$, 11
6, PhCHMeSEt	MeOH	PhCHMeSOEt, 51; $PhCHMeSO_2Et$, 2	PhCOMe, 2
	MeCN	PhCHMeSOEt, 66; $PhCHMeSO_2Et$, 1	PhCOMe, 6
	C_6H_6	PhCHMeSOEt, 37; $PhCHMeSO_2Et$, 15	PhCOMe, 7
7, PhCHMeSPh	MeOH	PhCHMeSOPh, 53; $PhCHMeSO_2Ph$, 5	PhCOMe, 1
	MeCN	PhCHMeSOPh, 21	PhCOMe, 73; $(PhS)_2$, 11
	C_6H_6	PhCHMeSOPh, 36	PhCOMe, 37; $(PhS)_2$, 13
8, $PhCMe_2SEt$	MeOH	—	PhCOMe, 16; $(PhCMe_2S)_2$, 1
	MeCN	—	PhCOMe, 5; $PhCMe{=}CH_2$, 1; $(PhCMe_2S)_2$, 8
	C_6H_6	—	PhCOMe, 15; $PhCMe{=}CH_2$, 3; $(PhCMe_2S)_2$, 23
9, $PhCMe_2SPh$	All	—	—

[a] The dye-sensitized photooxidation of sulfides **3** and **6** has been previously reported (Ref. 14). The small differences in the product distribution depend on the different irradiation time.



Scheme 1.

With benzyl ethyl sulfide (**3**), as already known,[13–15] cleavage to benzaldehyde is an important path, which predominates in nonprotic solvents. Similar results were obtained with other benzyl derivatives, viz. the *tert*-butyl (**4**) and the phenyl sulfides (**5**, see Scheme 1 and Table 1); some phenyl disulfide was also obtained in the last case.

α-Methylbenzyl sulfides were next examined. With the ethyl derivative (**6**) the sulfoxide was the main product in all of the solvents tested, with acetophenone remaining below 7%. On the other hand, the corresponding phenyl derivative (**7**) exhibited again a medium-depending oxygenation, with a large predominance of the sulfoxide in methanol, but acetophenone (accompanied by some phenyl disulfide) was the main product in the other cases.

Finally, cumyl ethyl sulfide (**8**) was consumed under photooxygenation conditions, but gave no sulfoxide. The products formed were acetophenone and α-methylstyrene along with some cumyl disulfide. The yields were low in this case, possibly because the oxygenation was quite sluggish and secondary photodecomposition was important. The corresponding phenyl derivative (**9**) was virtually stable under photooxygenation conditions.

The kinetics of these photooxygenations was then studied by measuring the total rate constant for the quenching of singlet oxygen (k_T) through the change in the luminescence lifetime. As it appears in Table 2, the values varied considerably, dropping by 3 orders of magnitude from ethyl sulfide to cumyl phenyl sulfide. These values were measured in deuterochloroform in order to obtain meaningful data also for the entire range of sulfides including the least reactive derivatives, which would not be possible in solvents where the singlet oxygen lifetime is shorter. On the other hand, previous studies showed that k_T changes very little with the solvent characteristics, including polarity, for example, by $<10\%$ with benzyl ethyl sulfide[13] and by $<20\%$ for diethyl sulfide[16] in solvents of different polarity, for example, when passing from benzene to acetonitrile. Therefore, the reported values should be reasonably valid also for the other solvents.

The rate for chemical reaction (k_r), as opposed to physical quenching, was then measured in competition experiments, as previously done in the literature, by using the oxidation of

Table 2. Rate of total quenching (k_T) and rate of chemical reaction (k_r) for the singlet oxygen reaction with some sulfides

Sulfide	Solvent	$k_r\times10^7$, $M^{-1}\,s^{-1}$	*S*-Oxidation versus cleavage	k_r/k_T	$k_T\times10^7$, $M^{-1}\,s^{-1}$ in $CDCl_3$
Et_2S	MeOH	6.6×10^7[a]		1.8	3.0[b]
	C_6H_6	0.39[a]		0.11	
1, $PhCH_2CH_2SEt$	MeOH	0.9	95:5	0.6	1.5
	MeCN	0.24	80:20	0.16	
	C_6H_6	0.2	57:43	0.13	
2, $PhCH_2CH_2SPh$	MeOH	0.027	100:0	0.51	0.53
	MeCN	0.004	80:20	0.08	
	C_6H_6	0.008	58:42	0.15	
3, $PhCH_2SEt$	MeOH	1.2	72:28	1	1.2
	MeCN	0.61	4:96	0.51	
	C_6H_6	0.55	2:98	0.46	
4, $PhCH_2S$-*t*-Bu	MeOH	0.027	72:28	0.08	0.35
	MeCN	0.085	29:71	0.24	
	C_6H_6	0.062	39:61	0.18	
5, $PhCH_2SPh$	MeOH	0.026	72:28	0.45	0.058
	MeCN	0.017	13:87	0.29	
	C_6H_6	0.016	20:80	0.28	
6, PhCHMeSEt	MeOH	0.11	96:4		
	MeCN	0.07	92:8		
	C_6H_6	0.03	84:16		
7, PhCHMeSPh	MeOH	0.018	98:2		
	MeCN	0.009	22:78		
	C_6H_6	0.001	50:50		
8, $PhCMe_2SEt$	MeOH	0.026	≈0:100	0.16	0.165
	MeCN	0.12	≈0:100	0.73	
	C_6H_6	0.17	≈0.100	1.03	
9, $PhCMe_2SPh$	All	<0.001		<0.3	0.0034

[a] From Ref. 16.
[b] In benzene, from Ref. 16.

an alkene (octaline) under the same conditions as the standard.[16,17] The values obtained are reported in Table 2.

3. Discussion

3.1. Physical and chemical quenching by sulfides: dependence on the structure

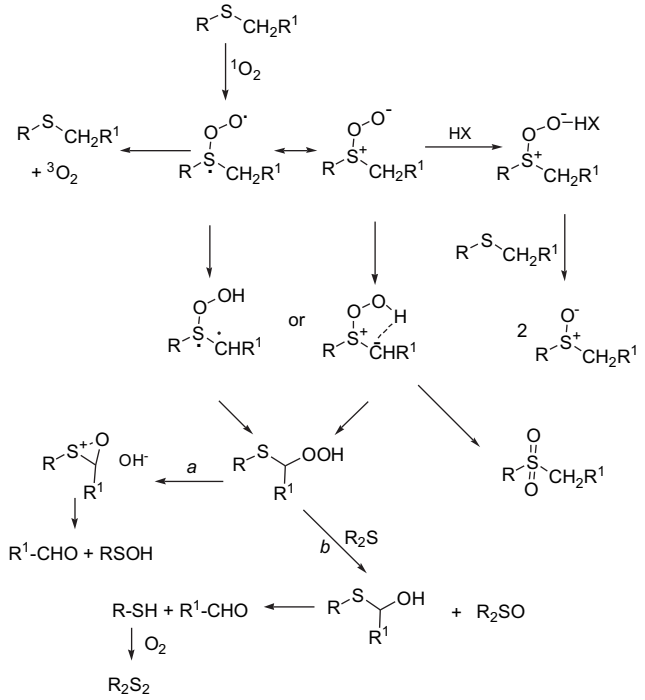
All of the present reactions likely occur via a persulfoxide,[18] generally accepted as the first intermediate in the reaction of singlet oxygen with sulfides, and the extent of chemical versus physical quenching is determined by the relative importance of the different paths from this species. As for the formation of this intermediate, the k_T data in Table 2 support earlier observations[19] and show that the total quenching rate is decreased when the sulfur atom is bonded to a phenyl group (by a factor 20–50, see the pairs **1/2**, **3/5**, **8/9**) or to a tertiary carbon (by a factor 4–15, see the pairs **3/4**, **3/8**, **5/9**). This correlates with steric hindrance, and thus with nucleophilicity, rather than with oxidizability (see below).

As for the ensuing chemistry, two different reactions occur, viz. sulfoxidation and C–S bond cleavage to yield carbonyl derivatives. Table 2 shows that chemical reaction is the main path ($k_r>0.5k_T$) for nonhindered sulfides (Et_2S, **1**–**3**, **5**) in methanol and in this case the product is the sulfoxide. This is attributed to hydrogen bonding of the persulfoxide that makes it a stronger electrophile and thus facilitates oxygen transfer to a second sulfide molecule (the 'single intermediate' mechanism initially proposed by Foote,[5] and known to be promoted by acids).[13,16] Accordingly, the limiting value of k_r is $2k_T$, as indeed observed with dialkyl sulfides (see diethyl sulfide in Table 2). The presence of substituents in α-position in the chain makes the reaction less effective, reasonably because of the steric hindrance encountered by the approaching sulfides makes oxygen transfer less competitive with decay of the persulfoxide. The effect of inserting two methyl groups in α is apparent: with both **4** and **8** k_r is $<0.15k_T$ and the reaction in methanol becomes slower than that in aprotic solvents. A phenyl group likewise limits k_r, but in this case some effect is exerted also when the substituent is in the β-position.

In aprotic solvent, however, chemical reaction is generally less competitive with physical decay and may be dominated by C–S bond cleavage. This process involves hydrogen transfer to form an intermediate ylide (see below).[20–23] Contrary to sulfoxide formation, this is scarcely affected by bulky groups around the sulfur atoms (the efficiency moderately changes in *S*-ethyl, phenyl, and *tert*-butyl derivatives, see the series **3**–**5**), while its role depends on the presence of a weak α C–H bond. Thus, with diethyl and dibutyl sulfide C–S cleavage has been detected as an inefficient process ($k_r/k_T\leq0.05$), though this is more important for phenethyl sulfides ($k_r/k_T\approx0.1$). With benzyl sulfides, however, the value of k_r increases up to $0.5k_T$. Furthermore, with the first two sulfides cleavage is always accompanied by an equally efficient sulfoxidation, while with benzyl derivatives sulfoxidation is all but negligible in aprotic solvents (the sluggish C–S cleavage in sulfide **8**, lacking a α-H apparently involves a different path).

The dependence on the C–H bond strength suggests that, as proposed earlier,[13,24] this is a radical process and the ylide is to be regarded as a diradical rather than as a zwitterion (with anion stabilizing substituent the situation is different).[24,25] However, stereoelectronic factors also operate. In low-energy conformations the S^+–O–O^- moiety bisects the angle between the S-bonded groups R–S–R′ and the outer oxygen may be close to an α-CH.[20,21] This determining factor depends on the nature of both R and R′. Thus, the inefficient C–S bond cleavage from the α-methylbenzyl ethyl sulfide **5**, as opposed to the high reactivity of the non-methylated analogue **5** has been rationalized through PM3 calculations as due to a long $O^-\cdots H$ distance in two out of four of the low-energy conformations of the corresponding persulfoxide.[26] However, Table 1 shows that with the *S*-phenyl analogue **7** C–S bond cleavage is restored as the main process in aprotic solvents, reasonably because the bulky phenyl group pushes the oxygen toward the benzylic hydrogen.

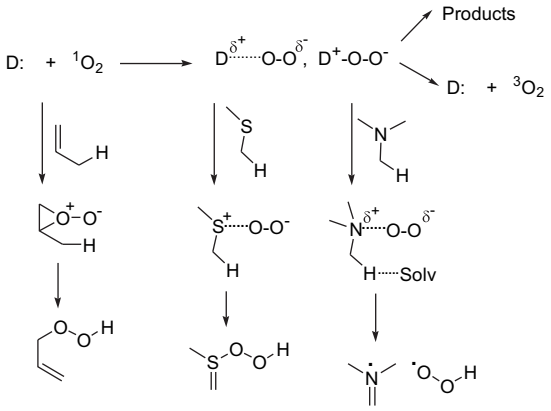
In turn, the ylide rearranges to a α-hydroperoxy sulfide and this intermediate gives the end product via either intramolecular or intermolecular oxygen transfer, as suggested by Clennan (Scheme 2).[24] The first path (a in Scheme 2) gives the carbonyl derivatives along with sulfinates or other oxidized sulfurated products, the latter one (path b) equimolecular amounts of sulfoxide, carbonyl, and mercaptan (the latter oxidized under these conditions to the disulfide). Table 1 shows that path b is followed by the alkyl sulfides **1** and **2** in benzene. As for the benzyl sulfides, the reaction in the same solvent shifts from path a exclusively for **3** to increasing component of path b in **4** and **5** and path b exclusively with **7**. Apparently, sterical hindering at the sulfur atom discourages formation of the thiaoxiranium ring more than accepting an oxygen from a hydroperoxide.



Scheme 2.

3.2. The oxidation of sulfides versus that of alkenes and amines: the first intermediate

It may be useful to consider the mechanism in Scheme 2 in the general frame of singlet oxygen reactions. A first-sight comparison of the oxidation of sulfides via persulfoxide and the ylide with the ene reaction of alkenes via a perepoxide as well as with the oxidation of amines via a complex and α-deprotonation (Scheme 3) seems to imply an analogous reaction course, involving transfer of an α-hydrogen after electrophilic attack. One may wonder, how far can the analogy be carried; as an example, is there a similar structure dependence? This is not the case: introducing a phenyl ring onto the reacting moiety increases k_T with amines ($PhNR_2 > R_3N$), but decreases it with sulfides and moderately affects the k_r/k_T ratio in both cases; with alkenes, phenyl substitution induces only a partial regioselectivity.[27a] A phenyl group in α greatly increases k_r/k_T in sulfides by making intramolecular hydrogen abstraction possible, but has little effect with alkenes (attack at the benzylic hydrogen is not or moderately preferred in benzyltrimethylethylene);[27b,c] k_T does not change in both cases. Below we consider in some detail the three photooxygenations.



Scheme 3.

Both with π (alkenes) and with n (sulfides or amines) donors, the first intermediate is a more or less labile adduct where *one of* the oxygen atom is engaged. Clearly the CT character of such complexes is much stronger with good donors such as amines with respect to the other cases, as evidenced, for example, by the dramatic dependence of k_T on the solvent polarity with these donors[3,28–30] in contrast to the near independence with alkenes and sulfides. However, singlet oxygen is a relatively poor oxidant [$E^0(O_2^{-\bullet}/{}^1O_2)$=0.11 V vs SCE][31] and even with amines [e.g. E^0 (DABCO) 1.02 V, $PhNMe_2$ 0.71 V] 'full' electron transfer remains endothermic (Table 3). There is a dependence of k_T on ΔG_{ET} and for various families of donors the total quenching rate constants roughly follow such dependence (notice however that with amines k_T changes over 2–4 orders of magnitude with solvent polarity; therefore care is required in the evaluation of the results with these substrates).[3,32,33] This is illustrated in Figure 1, where a plot of log (k_T) versus E^0 for sulfides, amines, alkenes, and aromatics is presented (see Table 3 for details on the data used). It is apparent that aromatic sulfides (like alkenes and amines) show some dependence, while aliphatic sulfides do not (points lie on an almost vertical line).

Table 3. Total quenching rate of singlet oxygen and oxidation potential for various donors used in Figure 1

	k, $M^{-1}\,s^{-1}$	$\log k$	E^0, V versus SCE
Aliphatic amines[a]			
Et_3N	6.5×10^7	7.80	1.53
n-Bu_3N	5.8×10^7	7.76	1.34
N-Methylpiperidine	5.3×10^7	7.72	1.73
DABCO	5.2×10^7	7.71	1.02
$(n\text{-Pr})_2NH$	1.8×10^7	7.25	1.96
Et_2NH	1.5×10^7	7.18	2.04
Piperidine	5.8×10^6	6.76	2.07
$(i\text{-Pr})_2NH$	1.8×10^6	6.25	1.83
i-$BuNH_2$	4.1×10^5	5.61	2.66
n-$PrNH_2$	2.3×10^5	5.36	2.75
Aromatic amines (in MeCN)[b]			
TMPD	5.2×10^9	9.71	0.16
p-Phenylenediamine	2.8×10^{10}	10.45	0.18
p-Aminodiphenylamine	1.1×10^9	9.04	0.27
N,*N*-Diphenyl-*p*-phenylenediamine	4.5×10^8	8.65	0.34
N,*N*,*N*′*N*′-Tetramethylbenzidine	1.8×10^9	9.25	0.43
o-Phenylenediamine	8.0×10^8	8.90	0.40
2-Aminoanthracene	2.3×10^8	8.36	0.44
1-Naphthylamine	2.7×10^8	8.43	0.54
N,*N*-Dimethyl-*p*-toluidine	1.0×10^9	9.00	0.65
N,*N*-Dimethylaniline	2.85×10^8	8.45	0.71
Diphenylamine	1.8×10^7	7.25	0.83
N-Methyl-*N*,*N*-diphenylamine	4.1×10^6	6.61	0.84
Aniline	1.06×10^7	7.02	0.87
p-Iodoaniline	5.1×10^6	6.70	0.88
p-Bromoaniline	7.1×10^6	6.85	0.89
p-Chloroaniline	7.6×10^6	6.88	0.90
Triphenylamine	4.1×10^7	7.61	0.92
N,*N*-Dimethyl-*p*-nitroaniline	1.1×10^6	6.04	1.19
Alkenes (in MeOH)[c]			
Tetramethylethylene	4.35×10^7	7.64	1.78
1,2-Dimethylcyclohexene	7.35×10^6	6.87	1.64
2-Methyl-2-butene	2.45×10^6	6.39	2.21
1-Butene	1.2×10^4	4.08	2.50
1-Methylcyclopentene	7.3×10^5	5.86	2.06
1-Methylcyclohexene	1.2×10^5	5.08	2.00
Cyclopentene	8.7×10^4	4.94	2.49
Cyclohexene	5.4×10^3	3.73	2.33
Aromatics (in MeCN)[b]			
1,2,4-Trimethoxybenzene	4.4×10^7	7.64	1.12
1,4-Dimethoxybenzene	6.4×10^6	6.81	1.34
1,2,3-Trimethoxybenzene	1.7×10^5	5.23	1.42
1,2-Dimethoxybenzene	7.4×10^5	5.87	1.45
Hexamethylbenzene	6.4×10^6	6.81	1.46
1,3-Dimethoxybenzene	2.2×10^5	5.34	1.49
1,3,5-Trimethoxybenzene	2.6×10^5	5.41	1.49
Pentamethylbenzene	1.2×10^6	6.08	1.58
1,2,4,5-Tetramethylbenzene	3.2×10^5	5.50	1.59
1,2,4-Trimethylbenzene	4.1×10^4	4.61	1.71
Aliphatic sulfides			
EtSEt[d]	3.0×10^7	7.50	1.57[i]
t-BuS-*t*-Bu[e]	4.7×10^4	4.67	1.59[i]
$PhCH_2CH_2SEt$[f]	1.5×10^7	7.18	1.65[j]
$PhC(CH_3)_2SEt$[f]	1.6×10^6	6.20	1.60[k]
$PhCH_2SEt$[g]	1.0×10^7	7.00	1.60[k]
Aromatic sulfides			
PhS-*t*-Bu[e]	1.2×10^4	4.08	1.70[l]
PhSPh[e]	3.9×10^4	4.59	1.43[i]
PhSMe[h]	2.3×10^6	6.36	1.34[h]
p-MePhSMe[h]	4.6×10^6	6.66	1.24[h]
p-MeOPhSMe[h]	7.6×10^6	6.88	1.13[h]
p-BrPhSMe[h]	1.1×10^6	6.04	1.41[h]
p-CNPhSMe[h]	7.3×10^4	4.86	1.61[h]
p-NO_2PhSMe[h]	8.7×10^4	4.94	1.70[h]
$PhCH_2CH_2SPh$[f]	5.3×10^5	5.72	1.21[m]
$PhCH_2SPh$[f]	5.8×10^5	5.76	1.43[n]
$PhC(CH_3)_2SPh$[f]	3.4×10^4	4.53	1.64[k]

[a] Ref. 36.
[b] Ref. 33.
[c] Ref. 57.
[d] Ref. 16.
[e] Ref. 12.
[f] This work.
[g] Ref. 13.
[h] Ref. 11.
[i] Ref. 58.
[j] Assumed equal to that of diethyl sulfide.
[k] Ref. 59.
[l] Ref. 60.
[m] Ref. 61.
[n] Ref. 62.

When donors of the same family and similar bulk at the reacting site are compared, a good correlation with calculated ΔG_{ET} is observed as is the case for 4-substituted thioanisoles. As shown in Figure 1, a good correlation of k_T with E^0 of the donor has been found (or with the substituent σ values, themselves proportional to E^0).[11] The correlation with σ is consistent with the strong electrophilic character of singlet oxygen (when compared with the ρ value obtained with other oxygen transfer reagents, ρ ($^1O_2$) is larger than with negatively charged species, though smaller than with the positive ones (see Table 4).

However, when donors with different steric hindrance are considered the correlation with calculated ΔG_{ET} breaks

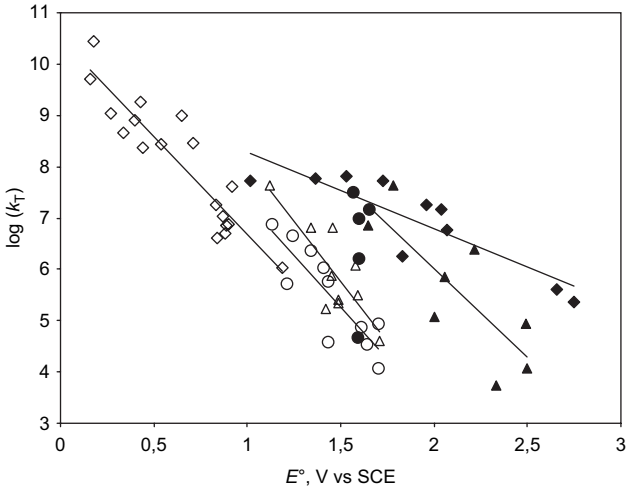


Figure 1. Rate constants for total quenching of singlet oxygen by sulfides (circles) and amines (diamonds) (filled symbols, aliphatic; empty symbols, aromatic derivatives) as well as alkenes (▲) and electron-rich aromatics (△) versus the nucleophile E^0. See Table 3 for details.

Table 4. ρ Values from the oxidation of some thioanisoles

Reagent	ρ	Ref.
$Me_2B(OH)_2(OOH)^{2-}$	−0.65	53
$Me_2B(OH)_3(OOH)^-$	−1.5	53
$^1O_2$	−1.97	11
tert-Butylperoxyiodanes	−3.32	54

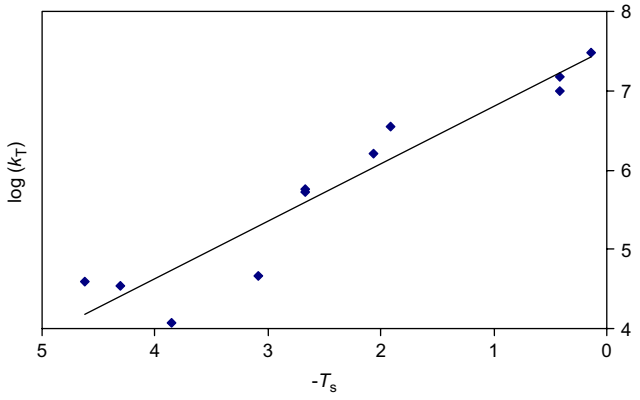


Figure 2. Rate constants for total quenching of singlet oxygen by aliphatic and aromatic sulfides versus the Taft steric parameters T_s.[55,56] See Table 5 for details.

down.[34] The order of reactivity of aliphatic sulfides depends here on nucleophilicity, and thus on bulky substituents ($R_2S \approx PhCH_2SR > PhSR > Ph_2S$, the same order observed in sulfoxidation by metal oxo complexes).[35] The slowing effect of substituents close to the moiety involved in the interaction with singlet oxygen has been observed with amines[36,37] and sulfides.[38] Indeed, Clennan showed that $\log(k_T)$ linearly correlated with the Taft steric parameter T_s with hydrazines (slope 0.9)[39] and sulfenamides (1.47),[40] although this was not the case for disulfides.[40]

In the present case, we observed that the various families of sulfides we considered (RSEt, RS-*tert*-Bu, RSPh) all had a similar dependence on the T_s value of substituent R. Indeed, when a single correlation with the parameters of both substituents for sulfides RSR^1 according to Eq. 2 was attempted, a trend, if not a linear dependence was observed, with a slope somewhat lower than those quoted above (slope −0.72, r^2 0.91, see Fig. 2, both the presently studied substrates and other bulky aliphatic and aromatic sulfides are included, see Table 5).

$$\log(k_T) = \text{constant} + K\left[T_s(R) + T_s(R^1)\right] \quad (4)$$

Table 5. Total quenching rate of singlet oxygen and Taft parameters for various sulfides used in Figure 2

Sulfide RSR^1	$\log(k_T)$[a]	T_s[b]	Summed up T_s for the two substituents
EtSEt	7.48	Et, 0.07	0.14
t-BuSt-Bu	4.67	*t*-Bu, 1.54	3.08
PhSt-Bu	4.08	Ph, 2.31	3.85
PhSPh	4.59		4.62
$PhCH_2CH_2SEt$	7.18	$PhCH_2CH_2$, 0.38	0.42
$PhCH_2St$-Bu	6.54	$PhCH_2$, 0.38	1.92
$PhC(CH_3)_2SEt$	6.2	$PhC(CH_3)_2$, 2	2.07
$PhCH_2CH_2SPh$	5.72		2.67
$PhCH_2SPh$	5.76		2.67
$PhC(CH_3)_2SPh$	4.53		4.31
$PhCH_2SEt$	7.0		0.42

[a] For the k_T values see previous[12] and present work.
[b] The T_s parameters are taken from the compilations by Taft[55] and Dubois.[56] The value for the $PhCMe_2$ group is not available in these references. It has been taken as 2.0 by correcting the value for the benzyl group proportionally to the change observed in passing from Et to *iso*-Pr and *tert*-Bu.

We feel that this result is informative. Recent calculations show that singlet oxygen, besides being a strong electrophile, has also some nucleophilic character due to the presence of a high energy HOMO geometrically orthogonal to the LUMO.[41,42] This has been recognized as the source of the asynchronicity of the ene reaction, due to the tendency for both the HOMO and the LUMO of the alkene to be involved in an interaction with a single oxygen atom. Thus, tendency toward 1,1 bond formation distinguishes the ene reaction, 'as opposed to the simultaneous 1,2-bond formation distinctive of synchronous, concerted transition states of the Diels–Alder reaction'.[42]

On the other hand, with n donors such as sulfides and amines the nucleophilic contribution scarcely operates (and if it does, more with the former donors). The initial adduct appears to be slightly less stable than the reagents (by 6.6 kcal/mol, or at most isoenergetic depending on the method used) with the sulfides[20,21,43,44] and markedly less stable with amines (8 to >20 kcal/mol).[45] Notice that also in the latter case a close proximity between nitrogen and one of the oxygen atoms is required in the complex. Summing up, steric factors are important and k_T depends on the nucleophilicity of the quencher.

3.3. The chemical reaction

The comparison can be extended to the ensuing evolution of the first intermediate, which determines the chemical or physical nature of the quenching. The ene reaction with alkenes is concerted and bonding of the *second* oxygen atom occurs as the first intermediate evolves to the products via a valley ridge with no barrier. As for sulfides, a path involving bonding of the second oxygen atom would be the formation of a thiadioxirane, which has been located as a reasonably stable intermediate, but is separated from the initial persulfoxide by an insurmountable barrier of 10–20 kcal/mol.[20]

The other intramolecular possibility is the above discussed hydrogen (or proton) transfer from the position α to the heteroatom, a path that is indeed analogous to the perepoxide–alkylhydroperoxide conversion with alkenes, but differs from that case in that it is not barrierless. In the case of dimethylpersulfoxide, a 6–7 kcal/mol activation energy has been calculated for this path, which is only 1/20th of physical quenching in apolar, nonhydrogen bonding solvents, but is made more effective by α-phenyl substitution (k_r can be as large as 50% of k_T for some benzyl sulfides, provided that conformational factors do not prevent it).

This path is even less efficient with amines ($k_r < 0.1k_T$ with tertiary aliphatic amines, negligible with aromatic tertiary amines).[46] The role of this path increases both in a nucleophilic solvent, which is able to accept the α-proton, and when a better electrofugal group is present, as with α-trimethylsilyl derivatives.[46]

Finally, intermolecular activation of the first intermediate is possible, provided that this is sufficiently long-lived. With sulfides indeed activation by acids (or by nucleophiles) is effective, so that a more active species is formed and transfers oxygen to a second molecule of sulfide (see Scheme 1;

this step, as mentioned above, is again subjected to steric hindrance). This mechanism is followed in methanol and, when intramolecular activation is slow, also in a polar aprotic solvent such as MeCN. However, this path is less important with amines (the barely bonded CT complex is too short-lived for activation) as well as, for the opposite reason, with alkenes (the strength of the bonds formed leaves little room for improvement).

In conclusion, the reaction of singlet oxygen with a series of benzyl sulfides was examined. The total quenching rate (k_T) depends on the nucleophilicity of the sulfide, since the persulfoxide is formed over an essentially flat surface and bulky substituents tilt the balance against bonding with singlet oxygen, drastically lowering k_T. The strength of the S–O bond formed with sulfides is intermediate between the strong C–O bond formed with alkenes and the weak N–O bond with amines, resulting in largely variable proportion of chemical quenching (k_r/k_T). Two types of chemical reactions contribute. The path leading to sulfoxide via the protonated persulfoxide observed in a protic medium depends again on the sulfide nucleophilicity (making the overall dependence quadratic). The photocleavage reaction observed in aprotic solvent depends on the strength of the α-CH bond.

4. Experimental

4.1. Materials

Sulfides **1**, **2**,[47] **3–5**,[48] **6**, **7**,[49] **8**, and **9**[50] were prepared according to the published procedures. 5,10,15,20-Tetraphenyl-21*H*-porphine (Aldrich) and $CDCl_3$ (Carlo Erba) were used without further purification. Samples of sulfoxides and sulfones[51] as well as of diphenyl disulfide[52] for the quantitative analysis of the photoproducts were prepared according to the published procedures. The other photooxidation products were commercially available.

4.2. Photoreactions

The photooxidations were carried out by using 0.01–0.1 M solutions of the sulfides in the presence of Rose Bengal (in methanol or acetonitrile) or of tetraphenylporphine in benzene. The solutions were contained in rubber-stoppered Pyrex tubes. These were exposed to four phosphor-coated 15 W lamps (Applied Photophysics) emitting from 350 to 700 nm while a steam of dry oxygen saturated with the appropriate solvent was passed in the solution through a needle.

The products formed were determined by capillary GC (HP1) on the basis of calibration curves in the presence of cyclododecene as the internal standard or by reverse phase HPLC with MeCN–H_2O mixture as the eluant, λ 230 and 260 nm, respectively, with biphenyl as the internal standard.

4.3. Rate of photoreactions

Rate constants for the quenching of singlet oxygen were obtained from the shortening of the $(O_2)^1\Delta_g$ emission lifetime at 1.27 μm in the presence of known amounts of sulfides in aerated $CDCl_3$. Singlet oxygen was generated by energy transfer to O_2 from the triplet state of TPP, populated by laser excitation (Nd:YAG laser, 532 nm). The near-IR luminescence of molecular oxygen was observed at 90° geometry through a 5 mm thick AR coated silicon metal filter with wavelength pass >1.1 μm and an interference filter at 1.27 μm by means of a preamplified (low-impedance) Ge-photodiode cooled at 77 K (Applied Detector Corporation, Model 403 HS, time resolution 300 ns). Single exponential analysis of the emission decay was performed with the exclusion of the initial part of the signal, affected by scattered light, sensitizer fluorescence, and formation profile of the emission signal itself. The rate of chemical reaction was determined by comparing the oxidation of octaline ($k_r=1.83\times10^6\ M^{-1}\ s^{-1}$) under the same conditions.

Acknowledgements

Partial support of this work by MURST, Rome, is gratefully acknowledged.

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