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Relative Reactivities of Tethered Functional Groups in the Interior of a Zeolite

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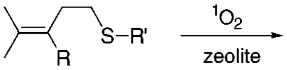
ABSTRACT

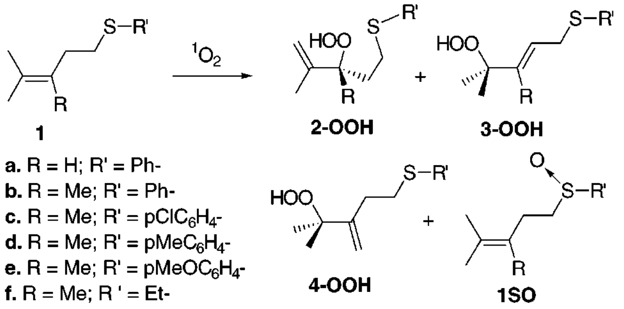


The reactions of singlet oxygen with substrates containing both sulfide and olefinic linkages have been examined. The dramatic increase in sulfoxide formation in the interior of the zeolite in comparison to solution is attributed to zeolite stabilization of the persulfoxide intermediate and concomitant inhibition of physical quenching of singlet oxygen.

Supramolecular control of organic reactions provides a powerful tool to control and alter well-documented homogeneous behavior.[1] Zeolites are attractive supramolecular hosts because of their well-characterized structures and properties.[2] Faujasite NaY, in particular, has attracted considerable attention because of its availability and pore structure, which can easily accommodate organic molecules of interest to the organic chemist. However, mechanistic work to understand the altered behavior of organic reactions in NaY is complicated by the fact that, despite its well-characterized structure, it offers to an organic molecule a heterogeneous environment with a variety of distinctly different absorption sites. In addition, reactions can occur between two molecules both absorbed on the interior surface of a supercage or between an absorbed substrate and a reaction partner which is free to diffuse in the solvent found in the zeolite pore structure.[3] Consequently, despite the widespread interest in molecular dynamics in restricted environments and on surfaces, extraction of kinetic data can be very complex and subject to the nuances of the mathematical model used to treat the data.[4]

To partially circumvent these problems inherent in obtaining precise kinetic information, we report here a competitive, rather than absolute, kinetic study of the reactions of singlet oxygen with two functional groups that are tethered together to ensure their proximity. The substrates chosen for this study **1** (Scheme 1) provide the first experimental evidence that physical quenching of singlet oxygen by sulfides is suppressed in the zeolite supercage.[5]

Scheme 1



Irradiation of oxygen-saturated 0.1 M CDCl$_3$ solutions of **1a−f** containing 3 × 10^{-4} M tetraphenyl porphyrin (TPP) were conducted at room temperature through 1 cm of a

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[1] (a) Ramamurthy, V.; Eaton, D. F.; Caspar, J. V. *Acc. Chem. Res.* **1992**, *25*, 299−307. (b) Scaiano, J. C.; García, H. *Acc. Chem. Res.* **1999**, *32*, 783−793.

[2] Dyer, A. *An Introduction to Zeolite Molecular Sieves*; John Wiley & Sons: New York, 1988; p 149.

[3] Drake, J. M.; Levitz, P.; Turro, N. J.; Nitsche, K. S.; Cassidy, K. F. *J. Phys. Chem.* **1988**, *92*, 4680−4684.

[4] (a) Thomas, J. K. *Chem. Rev.* **1993**, *93*, 301−380. (b) For an elegant kinetic study, see: Cozens, F. L.; O'Neill, M.; Schepp, N. P. *J. Am. Chem. Soc.* **1997**, *119*, 7583−7584.

[5] Zhou, W.; Clennan, E. L. *J. Am. Chem. Soc.* **1999**, *121*, 2915−2916.

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saturated sodium nitrite filter solution with a 600 W tungsten–halogen lamp. Electron-rich tetrasubstituted olefins **1b**–**e** reacted exclusively at the olefinic linkage to give a mixture of ene products **2-OOH** and **4-OOH** (Table 1). The hydroperoxides were indefinitely stable in solution at room temperature. However, removal of the reaction solvent resulted in a small amount of alcohol formation, presumably by reduction with the sulfide linkages in the reaction mixture. Addition of PPh_3 to the photooxidation mixtures resulted in quantitative formation of $OPPh_3$ and reduction of the hydroperoxides to the corresponding alcohols. The alcohols and hydroperoxides could easily be distinguished by their distinctively different ^1H NMR spectra.[6]

Table 1. Photooxidations of **1** in Solution[a,b]

substrate	% convn	**1SO**	**2OOH**	**3OOH**	**4OOH**
1a	47	14	46	40	
	64	18	42	40	
1b	20		55		45
	62		55		45
	87		53		47
1c	48		53		47
1d	41		53		47
1e	27		54		46
1f	17	44	34		23
	29	39	36		24
	46	45	21		18

[a] In $CDCl_3$ at rt using 0.1 M **1** and 3×10^{-4}M TPP. [b] Product ratios were measured directly by ^1H NMR in the photooxidation mixtures and are reproducible to ±4%.

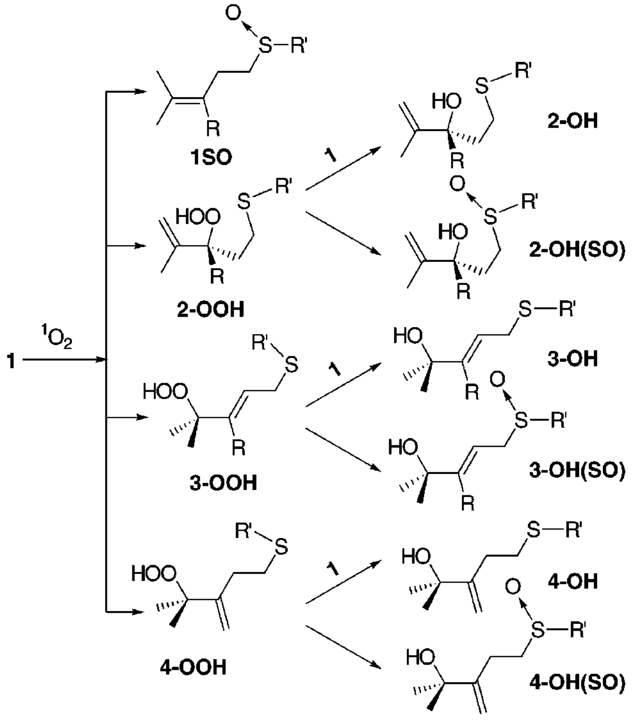
Decreasing the nucleophilicity of the double bond as in **1a** or decreasing the steric hindrance around sulfur as in **1f** allowed oxidation at sulfur to compete with the facile ene reaction.

The intrazeolite photooxidations used a sensitizer-doped faujasite, NaMBY, which was produced using a procedure similar to that reported by Ramamurthy and co-workers.[7] A weighed sample of NaY (Aldrich) was added to an aqueous solution of methylene blue, MB, and allowed to stir until the blue solution turned colorless. The methylene blue doped NaY (NaMBY) was filtered and air-dried and then placed on a vacuum line at 10^{-4} Torr and heated at 100 °C for 8–10 h. It was then removed from the vacuum line and stored in a desiccator prior to use. At the low doping levels used in this study, the diffuse reflectance spectra revealed that the methylene blue was monomeric in the zeolite supercages.

The zeolite reaction mixtures were prepared by taking 5 mL of a hexane solution, either 0.05 or 0.1 M in **1**, and adding 0.3 g of NaMBY (occupancy $\langle S \rangle = 0.01$; 1 molecule of MB per 100 supercages). This hexane slurry was saturated with oxygen and stirred for 15 min and then irradiated under continuous oxygen agitation with a 600 W tungsten lamp through 1 cm of a 12 M $NaNO_2$ filter solution. The zeolite powder was placed in a Soxhlett cup and continuously extracted overnight with chloroform. In a procedure similar to that of Tung and co-workers,[8] the zeolite was then destroyed by 5 mL of 10% HCl and the mixture extracted with four 10 mL portions of chloroform. The combined organic extracts were then washed with aqueous Na_2CO_3 and dried with $MgSO_4$, and the solvent was removed under reduced pressure. The mass balances in all of the reactions were shown to exceed 97% by NMR analysis using an internal standard. As a control, a reaction mixture from the solution photooxidation of **1a** was subjected to the same gentle acid wash and extraction procedure and was shown to survive unchanged.

The NMR spectra of the reaction mixtures clearly demonstrated the absence of ketones or aldehydes from acid-catalyzed[9] or intrazeolite[10] cleavages of the hydroperoxides. Nevertheless, the reaction mixtures from the intrazeolite photooxidations of **1** were more complex than their solution counterpart. Allylic alcohols, **2-OH**, **3-OH**, and **4-OH**, their sulfoxide analogues, **2-OH(SO)**, **3-OH(SO)**, and **4-OH(SO)**, and **1SO** were all isolated (Scheme 2). However, in stark contrast to the intrazeolite photooxidations of simple olefins, hydroperoxides were not isolated or detected in the reaction mixtures.

Scheme 2



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(6) ^1H NMR ($CDCl_3$): **2a-OOH** δ 5.03 (bs, 2H), 4.49 (dd, *J* = 7.9, 7.8 Hz 1H), 3.0 (m, 2H), 1.7–2.0 (m, 2H), 1.68 (s, 3H); **3a-OOH** δ 5.70 (dt, *J* = 15.7, 7.1 Hz, 1H), 5.50 (bd, *J* = 15.7 Hz, 1H), 3.53 (dd, *J* = 7.1, 1.2 Hz, 2H), 1.21 (2, 6H); **2a-OH** δ 4.97 (s, 1H), 4.88 (s, 1H), 4.22 (t, *J* = 6.1 Hz, 1H), 3.01 (m, 2H), 1.86 (q, *J* = 7.0 Hz, 2H), 1.65 (s, 3H); **3a-OH** δ 5.62 (d, *J* = 15.4 Hz, 1H), 5.69 (dt, *J* = 15.4, 6.5 Hz, 1H), 3.51 (d, *J* = 6.5 Hz, 2H), 1.20 (s, 6H); **2b-OOH** δ 5.02 (bs, 1H), 4.98 (bs, 1H), 2.95 (m, 2H), 2.01 (m, 2H), 1.38 (s, 3H); **4b-OOH** δ 5.26 (s, 1H), 5.08 (bs, 1H), 3.18 (t, *J* = 7.3 Hz, 2H), 2.52 (t, *J* = 7.1 Hz, 2H), 1.38 (s, 6H); **2b-OH** δ 5.04 (bs, 1H), 4.90 (bs, 1H), 2.8–3.0 (m, 2H), 1.96 (m, 2H), 1.72 (bs, 3H), 1.32 (s, 3H); **4b-OH** δ 5.18 (s, 1H), 4.87 (bs, 1H), 3.10 (t, *J* = 8.0 Hz, 2H), 2.45 (t, *J* = 8.0 Hz, 2H), 1.34 (s, 3H).

(7) Ramamurthy, V.; Sanderson, D. R.; Eaton, D. F. *J. Am. Chem. Soc.* **1993**, *115*, 10438–10439.

We suggest that the sulfide moiety, by an intermolecular process with perhaps a small contribution from an intramolecular process, spontaneously reduced the allylic hydroperoxides. To provide support for this suggestion, a preformed mixture consisting of **1a** (58%), **1a(SO)** (9%), **2a-OOH** (14%), **3a-OOH** (13%), **2a-OH** (2.1%), **3a-OH** (1.7%), and 2.9% of several ene sulfoxides (e.g., **2a-OH-(SO)**, **3a-OH(SO)**, etc.) was added to a hexane slurry of NaY. This reaction mixture was then subjected to the same isolation procedure described previously, and the products were identified and quantitated by NMR. Analysis of the result led to the following conclusions: (1) The hydroperoxy groups are completely reduced to the alcohols in NaY in the absence of methylene blue. (2) The concentration of **1a** decreased by 9.7% and the concentration of **1a(SO)** increased by 9.4%, providing direct evidence of intermolecular reductions of the hydroperoxides by **1a**. (3) The absence of any spectral evidence for two diastereomers of **2a-OH(SO)** suggests the possibility that a six-membered ring intramolecular process may be involved in its formation.

The product distributions for the intrazeolite photooxidations of **1a**−**c** and **1f** are given in Table 2 at the lowest percent conversions convenient for analytical analysis. Sulfides **2-OH**, **3-OH**, and **4-OH** are all sensitive to overoxidation at high conversions. This susceptibility is especially evident for sulfoxide **1SO**, which is formed in large amounts early in the reaction. Consequently, the contribution of **1SO** to the reaction mixtures may be slightly underestimated for all the substrates even at the moderate percent conversions reported in Table 2.

Table 2. Product Distributions in Intrazeolite Photolysis

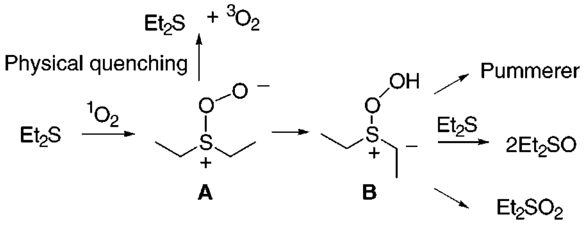
substrate	**1a**	**1b**	**1c**	**1f**
% conversion	26	30	26	40
1SO	73	57	53	68
2-OH	13	19	10	14
2-OH(SO)	14	10	18	9
3-OH	*a*			
3-OH(SO)	*a*			
4-OH		6	7	3
4-OH(SO)		8	12	6

[a] Formed at higher conversions.

The involvement of singlet oxygen in the oxidation of the sulfur in **1** is convincingly demonstrated using diphenyl sulfide, Ph_2S, as a model substrate.[5] Irradiation of a hexane slurry of Ph_2S encapsulated in NaMBY ($\langle S \rangle = 0.01$) resulted in formation of Ph_2SO as the major product and a small amount of sulfone, Ph_2SO_2. The reaction did not occur in the absence of MB or oxygen, and NaMBY did not bleach during the oxidation. In addition, the intrazeolite photooxidation of Ph_2S was quenched in the presence of 2,3-dimethyl-2-butene, a specific singlet oxygen chemical quencher.

A comparison of the data in Tables 1 and 2 reveals that a change in reaction medium from $CDCl_3$ to the interior of the zeolite for the photooxidations of **1a**−**c** and **1f** is accompanied by a dramatic increase in sulfoxide **1SO** formation. For example, the sulfoxide yield from photooxidation of **1a** increases from 14 to 18% of the product mixture in solution to 73% in the zeolite. This surprising result can be understood by consideration of the accepted mechanism for homogeneous sulfide photooxidations as illustrated for Et_2S in Scheme 3.[11]

Scheme 3



The solution photooxidation occurs via two intermediates, the persulfoxide, **A**, and the hydroperoxy sulfonium ylide, **B**. The hydroperoxy sulfonium ylide has a variety of options available to it depending upon its precise structure and on the reaction conditions. These include the Pummerer rearrangement, which ultimately leads to C−S cleavage, reduction with starting material, and conversion to sulfone. The persulfoxide, **A**, also has a variety of options available to it including its decomposition to starting material and triplet oxygen. This decomposition is responsible for the inefficiency observed for many homogeneous sulfide photooxidations. For example, >95% of the singlet oxygen produced during its reaction with Et_2S does not end up in the oxidation products. The overall process, $Et_2S + {}^1O_2 \rightarrow Et_2S + {}^3O_2$, via intermediate **A**, represents the deactivation (physical quenching) of singlet oxygen and does not involve product formation.

We suggest that the increase in efficiency of sulfoxide formation, relative to olefin oxidation, in **1** is a result of the suppression of the physical quenching of singlet oxygen by stabilization of the persulfoxide, **A**, in the interior of the zeolite. The inefficiency (physical quenching) in the reaction of sulfides with ${}^1O_2$ in homogeneous medium has been detected by comparing the rate constant for substrate-induced removal of singlet oxygen, k_T, to the rate constant for product formation, k_r[12] (i.e., $k_r \ll k_T$). If physical quenching is completely suppressed by using homogeneous conditions or in the zeolite, then $2k_T = k_r$ for the sulfide since for every singlet oxygen that disappears two molecules of sulfoxide are produced. In contrast, simple isolated olefins do not physically quench ${}^1O_2$ and $k_T = k_r$, and as a consequence $2[k_T(\text{sulfide})/k_T(\text{olefin})] = [k_r(\text{sulfide})/k_r(\text{olefin})]$.

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(8) Tung, C.-H.; Wu, L.-Z.; Yuan, Z.-Y.; Su, N. *J. Am. Chem. Soc.* **1998**, *120*, 11594−11602.

(9) Porter, N. A. In *Organic Peroxide*; Ando, W., Ed.; John Wiley & Sons: New York, 1992; pp 101−156.

(10) Blatter, F.; Frei, H. *J. Am. Chem. Soc.* **1993**, *115*, 7501−7502.

(11) Jensen, F.; Greer, A.; Clennan, E. L. *J. Am. Chem. Soc.* **1998**, *120*, 4439−4449.

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The value of [k_r(sulfide)/k_r(olefin)] both in solution and in the interior of the zeolite can be calculate by a competitive kinetic method using eq 1[13−17] along with the product data given in Tables 1 and 2. In eq 1 C_0(sulfide) = C_0(olefin) = [**1**]$_0$ as a result of the tether which guarantees close proximity

$$\frac{k_r(\text{sulfide})}{k_r(\text{olefin})} = \frac{\ln[C_0(\text{sulfide})/C_t(\text{sulfide})]}{\ln[C_0(\text{olefin})/C_t(\text{olefin})]} \qquad (1)$$

of the sulfide and olefinic linkages. The concentration of sulfide at time t, C_t(sulfide), is given simply as [**1**]$_0$ − [**1SO**] in solution; however, it must be corrected for the amount of **1SO** formed by reduction of the hydroperoxides in the zeolite and is therefore set equal to [**1**]$_0$ − [**1SO**] + ([**2-OH**] + [**3-OH**] + [**4-OH**]) for the intrazeolitic oxidations. Finally, the concentration of olefin at time t, C_t(olefin), is given by [**1**]$_0$ − (Σ[ene products]). The resultant calculated values of [k_r(sulfide)/k_r(olefin)] are given in Table 3.

Table 3. Kinetic Data

substrate	medium	k_r(sulfide)/k_r(olefin)	$2k_t$(sulfide)/k_t(olefin)
1a	solution	0.14 ± 0.02	3.84
	zeolite	2.31 ± 0.22	
1b	solution		0.66[b]
	zeolite	0.87 ± 0.10	
1c	solution		0.28[c]
	zeolite	0.70 ± 0.07	
1f	solution	0.70 ± 0.07	6.0[d]
	zeolite	2.26 ± 0.41	

[a] Model system: $PhSCH_3$,[14] $k = 2.3 \times 10^6$ M^{-1} s^{-1}, and 2-methyl-2-pentene,[15] 1.2×10^6 M^{-1} s^{-1}. [b] Model system: $PhSCH_3$ and 2,3-dimethyl-2−butene,[16] $k = 7.0 \times 10^6$ M^{-1} s^{-1}. [c] Model system: $pClC_6H_4SCH_3$,[8] $k = 1.0 \times 10^6$ M^{-1} s^{-1}, and 2,3-dimethyl-2−butene. [d] Model system: Diethyl sulfide,[17] 2×10^7 M^{-1} s^{-1}, and 2,3-dimethyl-2-butene.

The value of 2[k_T(sulfide)/k_T(olefin)] can be estimated by using k_T values from suitable model compounds for both the sulfide and olefinic linkages. These [k_T(sulfide)/k_T(olefin)] values estimated from crude model systems do a reasonable job of reproducing the trend in [k_r(sulfide)/k_r(olefin)] values measured for the reactions of **1a−c** and **1f** in Na(MB)Y (Table 3). This congruence of values provides compelling evidence for the suppression of physical quenching via electronic stabilization of the persulfoxide in the interior of the zeolite.

Acknowledgment. We thank the National Science Foundation and the donors of the Petroleum Research Fund, administered by the American Chemical Society, for their generous support of this research.

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(13) This equation was first derived by Higgins et al. (Higgins, R.; Foote, C. S.; Cheng, H. In *Advances in Chemistry Series. Vol 77*; American Chemical Society: Washington, DC, 1968; pp 102−117) assuming a reaction first order in singlet oxygen and substrate.

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(16) Gollnick, K.; Hartmann, H.; Paur, H. In *Oxygen and Oxy-Radicals in Chemistry and Biology*; Rodgers, M. A. J., Powers, E. L., Eds.; Academic Press: New York, 1981; pp 379−395.

(17) This equation was derived for a reaction first order in singlet oxygen and first order in substrate. The same molecularity is most likely also observed in the zeolite and as a consequence eq 1 is adopted directly for these intrazeolite photooxidations. Nahm, K.; Foote, C. S. *J. Am. Chem. Soc.* **1989**, *111*, 1909−1910.