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Laser Flash Photolysis Studies of Alkoxyl Radical Kinetics Using 4-Nitrobenzenesulfenate Esters as Radical Precursors

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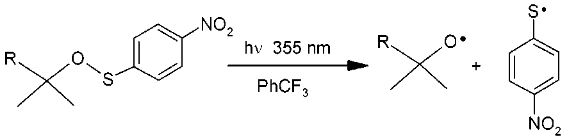
ABSTRACT



4-Nitrobenzenesulfenate esters were used as precursors for the generation of alkoxyl radicals under laser flash photolysis conditions. The esters were efficiently cleaved using the Nd:YAG third harmonic (355 nm) to produce alkoxyl radicals and the 4-nitrobenzenethiyl radical. Rate constants for β-scission and 1,5-hydrogen abstraction reactions of alkoxyl radicals were measured.

Alkoxyl radicals are important, highly reactive intermediates. Under conditions where intermolecular hydrogen abstraction can be minimized (in the gas phase or in an inert solvent), alkoxyl radicals are well-known to undergo intramolecular reaction either by β-scission or by 1,5-hydrogen abstraction.[1] Although both of these reactions are used synthetically,[2] there have been relatively few solution phase studies of the absolute kinetics of either reaction. Rates of β-scission of *tert*-butoxyl radical and cumyloxyl radicals were measured by laser flash photolysis and kinetic ESR methods.[3] Competition kinetics also have been used to study β-scissions and 1,5-hydrogen abstractions of alkoxyl radicals.[4]

We report here the generation of alkoxyl radicals from 4-nitrobenzenesulfenate esters using the Nd:YAG third harmonic (355 nm) and the subsequent direct observation of β-scission and 1,5-abstraction reactions of the initially generated alkoxyl radicals. 4-Nitrobenzenesulfenate esters have an intense long wavelength chromophore suitable for irradiation at 355 nm and have been used previously in steady state photolyses to generate alkoxyl radicals.[5] The required esters were easily prepared by the reaction of the appropriate alcohols with 4-nitrobenzenesulfenyl chloride. The alcohols used were characterized by ^{1}H NMR and ^{13}C NMR spectroscopy and high-resolution mass spectrometry. The 4-ni-

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(4) (a) Beckwith, A. L. J.; Hay, B. P. *J. Am. Chem. Soc.* **1989**, *111*, 1, 230−234. (b) Nakamura, T.; Busfield, W. K.; Jenkins, I. D. Rizzardo, E.; Thang, S. H.; Suyama, S. *J. Org. Chem.* **2000**, *65*, 16−23. (c) Platz, J.; Sehested, J.; Nielsen, O. J.; Wallington, T. J. *J. Phys. Chem. A* **1999**, *103*, 2688−2695. (d) Heiss, A.; Sahetchian, K. *Int. J. Chem. Kinet.* **1996**, *28*, 531−534.

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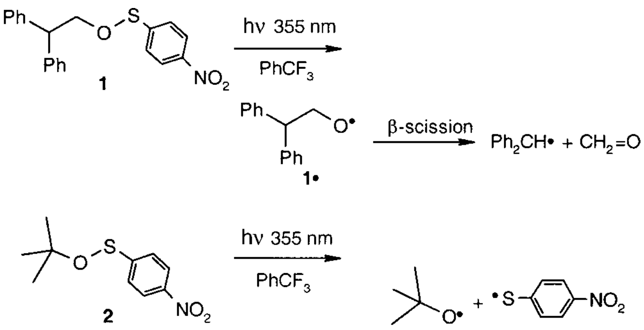
trobenzenesulfenates, purified by chromatography, were greater than 95% pure by ^{1}H NMR and ^{13}C NMR.

Preliminary experiments were carried out with precursors **1** and **2** to generate the 2,2-diphenylethoxyl (**1**•) and *tert*-butoxyl radicals (**2**•), respectively. When subjected to LFP in (trifluoromethyl)benzene using the Nd:YAG third harmonic (355 nm), precursor **1** gave an intense signal (λ_{max} 330 nm) consistent with formation of the diphenylmethyl radical within the 7 ns duration of the laser pulse (Scheme 1). The estimated yield of radicals in the laser path is 50%; it is likely that 100% cleavage occurred with 50% cage recombination. Cooling to −20 °C led to no noticeable change in the observed kinetic traces. On the basis of these observations, it can be concluded that **1**• fragments at $>2 \times 10^{8}$ s^{-1} at −20 °C. The UV−vis spectrum generated 41 ns after the laser pulse is given in Figure 1a. In addition to the diphenylmethyl radical signal at 330 nm, bleaching of the precursor is readily apparent in the range 340−380 nm. A weak broad signal was also observed between 390 and 500 nm, consistent with formation of the 4-nitrobenzenethiyl radical, for which a visible spectrum (>400 nm) has been reported.[6]

Scheme 1



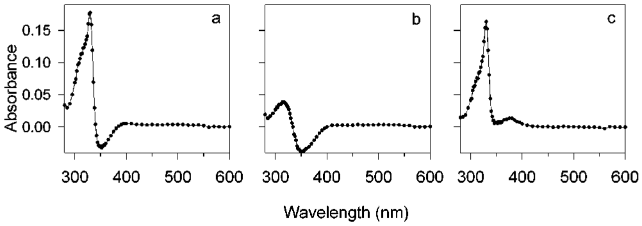
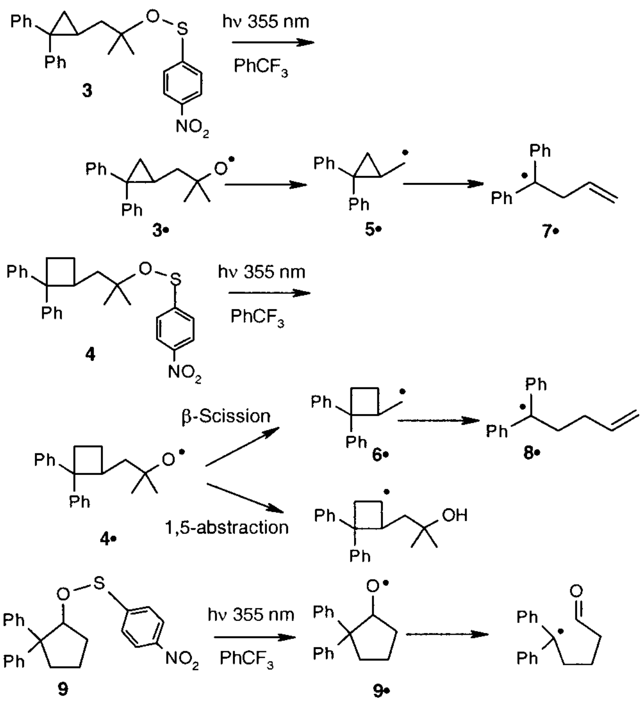


Figure 1. Uv−vis spectra (41 ns) generated by LFP (355 nm) of 4-nitrobenzenesulfenate esters **1** and **2**: (a) compound **1**, (b) compound **2**, (c) spectrum b subtracted from spectrum a.

To correct for bleaching and the presence of the 4-nitrobenzenethiyl radical, precursor **2** was cleaved under conditions matched for sample absorbance with precursor **1**. The resulting spectrum (Figure 1b) exhibits bleaching (340−370 nm) due to destruction of the precursor in addition to a weak absorbance centered at 320 nm apparently due to a previously unobserved absorbance of the 4-nitrobenzenethiyl radical. The *tert*-butoxyl radical is known to exhibit only weak absorbances at $\lambda > 300$ nm.[3a] The spectrum generated by cleavage of **2** was subtracted from the spectrum generated from **1** to give the corrected spectrum in Figure 1c, which clearly shows only the intense absorbance due to the diphenylmethyl radical centered at 330 nm.

The rapid β-scission of **1**• to give the highly stabilized diphenylmethyl radical is consistent with the known tendency for the rate of β-scission to increase with increasing stability of the radical being eliminated. Recent calculations for cleavage of simple alkoxyl radicals show a linear relationship between calculated reaction enthalpy and calculated transition state energies.[7] This relationship prompted us to investigate the kinetics of reactions of radicals **3**• and **4**• (Scheme 2).

Scheme 2



Because of the stabilization imparted by a cyclopropyl ring to an adjacent radical center, **3**• was expected to undergo β-scission faster than the cyclobutyl analogue **4**•.[8,9] Upon photolysis, **3** and **4** should yield the alkoxyl radicals (**3**• and **4**•), which were expected to cleave to the 2,2-diphenylcyclopropylcarbinyl radical (**5**•) and the 2,2-diphenylcyclobutylcarbinyl radical (**6**•), respectively. Radicals **5**• and **6**• have been shown to open to **7**• and **8**• with rate constants of 4×10^{11} s^{-1} and 2.5×10^{8} s^{-1}, respectively, at 20 °C.[10] Thus, the kinetic slow steps in these sequences were expected to be the β-scission processes. Previous experiments showed

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(5) (a) Pasto D. J.; Cottard, F. *J. Am. Chem. Soc.* **1994**, *116*, 8973−8977. (b) Pasto, D. J.; Cottard, F.; Picconatto, C. *J. Org. Chem.* **1994**, *59*, 7172−7177.

(6) Alam, M. M.; Ito, O. *J. Org. Chem.* **1999**, *64*, 1285−1290.

(7) Wilsey, S.; Dowd, P.; Houk, K. N. *J. Org. Chem.* **1999**, *64*, 8801−8811.

(8) Walton, J. C. *Magn. Reson. Chem.* **1987**, *25*, 998−1000.

that **7·** and **8·** absorb strongly near 330 nm; therefore LFP of **3** and **4** were expected to produce changes in absorbance at 330 nm proportional to the rate of β-scission.

LFP of compound **3** in (trifluoromethyl)benzene led to the formation of an intense signal ($\lambda_{max} = 334$ nm) that was observed to grow in with a rate constant of 2.2×10^7 s^{-1} at 20 °C. The time-resolved spectrum is shown in Figure 2a. Variable temperature data (52.5 to −30.6 °C) gave the Arrhenius function in eq 1 where $\theta = 2.303/RT$ kcal/mol. The observed log A value is typical of that expected for a fragmentation in solution and is similar to results for the β-scission of the *tert*-butoxyl radical in aromatic solvents of Fischer and Tsentalovitch who found values ranging from 12.8 to 13.4.[1e,3a]

$$\log (k/\mathrm{s}^{-1}) = (12.43 \pm 0.09) - (6.78 \pm 0.11)/\theta \qquad (1)$$

LFP of compound **4** in (trifluoromethyl)benzene led to the formation of a signal ($\lambda_{max} = 334$ nm) that was observed to grow in at 1.5×10^7 s^{-1} at 20.1 °C. The time-resolved spectrum is given in Figure 2b. When a comparison is made between the signal intensities resulting from the photolysis of solutions of **3** and **4** matched for absorbance at 355 nm, it is clear that the signal resulting from the cleavage of **4·** is less than one-half the intensity of that from **3·** (note absorbance scales in Figure 2).

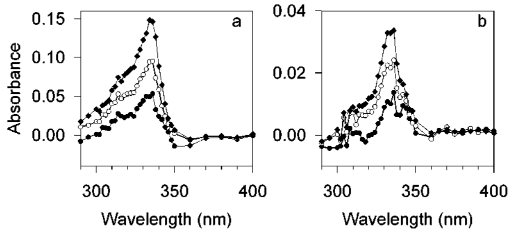

Figure 2. (a) Time-resolved spectra from LFP of **3** at 25 (●), 45 (○), and 105 ns (◆) . (b) Time-resolved spectra from LFP of **4** at 31 (●), 71 (○), and 200 ns (◆). In both cases a reference spectrum produced by the photolysis of **2** was subtracted.

Variable temperature data (51 to −22.7 °C) were collected for **4·**. The resulting Arrhenius plot is shown in Figure 3a along with the Arrhenius plot resulting from the cleavage of **3·**. The Arrhenius plot for **4·** is clearly nonlinear. In addition, the signal intensity of the 330 nm absorbance was found to decrease as the sample temperature was reduced. These observations are consistent with the presence of two competing pathways (β-scission and 1,5 hydrogen abstraction) for the disappearance of **4·**. At higher temperatures, β-scission dominates due to its higher E_a and log A. As the temperature is reduced, the rate of β-scission decreases more rapidly than the rate of 1,5-abstraction. At any given temperature, the observed rate constant will be the sum of the two processes, but since only β-scission gives rise to an observable signal, at lower temperature the signal intensity for the formation of **8·** diminishes.

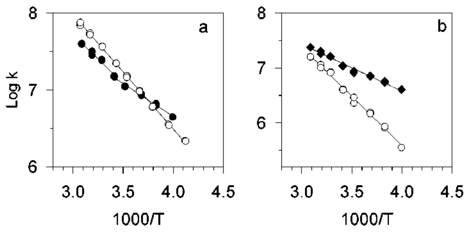

Figure 3. (a) Arrhenius plot for the disappearance of **3·** (○) and **4·** (●). (b) Arrhenius plot for the disappearance of **4·** separated into components for β-scission (○) and 1,5-abstraction (◆).

To estimate the fraction of reaction occurring by β-scission at each temperature, the β-scission of the 2,2-diphenylcyclopentoxyl radical (**9·**) was used as an external standard. Solutions of precursors **4** and **9** were matched for absorbance at 355 nm and subjected to LFP at temperatures ranging from 50 to 10 °C. Kinetic traces were collected at 334 nm, and after subtracting a small contribution for the 4-nitrobenzenethiyl radical at this wavelength, the intensities were compared to estimate the percent reaction occurring by β-scission. The remainder of reaction of **4·** was assumed to be 1,5-abstraction from the cyclobutyl ring. The amount of fragmentation was found to vary from 40% at 50 °C to 21% at 10 °C. These data were extrapolated to lower temperatures to obtain estimates of the percent of β-scission down to −20 °C. Multiplying the observed rate constant by the fraction of reaction occurring by each pathway yielded rate constants for β-scission and 1,5-abstraction over the temperature range 51 to −22 °C. Arrhenius plots (Figure 3b) of the two sets of data gave the Arrhenius functions in eqs 2 and 3 for β-scission and 1,5-hydrogen abstraction, respectively. As with **3·**, the log A value for β-scission is within the range expected. The log A value for 1,5-hydrogen abstraction is consistent with the much higher entropic penalty incurred in organizing the six-membered transition state required for abstraction.

$$\log (k/\mathrm{s}^{-1}) = (12.73 \pm 0.36) - (8.17 \pm 0.28)/\theta \qquad (2)$$

$$\log (k/\mathrm{s}^{-1}) = (10.0 \pm 0.23) - (3.91 \pm 0.30)/\theta \qquad (3)$$

The 1,5-hydrogen abstraction process was further investigated using precursor **10** (Scheme 3), which cleaved to form **10·** when photolyzed under LFP conditions. Subsequent 1,5-abstraction gave **11·** which rapidly ring opened to **12·**. At

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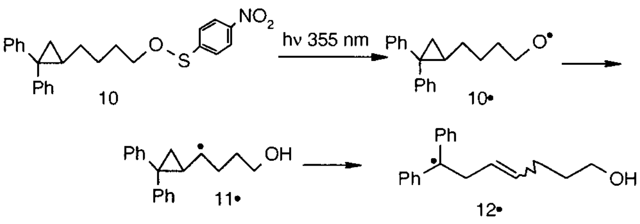
(9) B3LYP/6-31G** calculations on non-phenylated analogues of **3·** and **4·** predict that cleavage of the 3-cyclopropyl-2-methyl-2-propoxyl radical to give cyclopropyl-carbinyl radical and acetone should be more exothermic by 1.8 kcal/mol than cleavage of the 3-cyclobutyl-2-methyl-2-propoxyl radical to give the cyclobutylcarbinyl radical and acetone. Recent theoretical work (ref 3e) has shown that B3LYP/6-31G** accurately calculates activation barriers (typically within 2 kcal/mol) for alkoxy radical β-scission.

(10) (a) Newcomb, M.; Johnson, C. C.; Manek, M. B.; Varick, T. R. *J. Am. Chem. Soc.* **1992**, *114*, 10915−10921. (b) Newcomb, M.; Choi, S. Y.; Horner, J. H. *J. Org. Chem.* **1999**, *64*, 1225−1231. (c) Choi, S. Y.; Horner, J. H.; Newcomb, M. *J. Org. Chem.* **2000**, *2*, 4447−4449.

Scheme 3

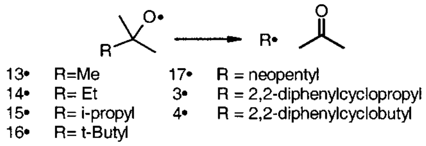


20 °C, 1,5-abstraction occurred at 2.7×10^7 s^{-1}. A variable temperature study gave the Arrhenius function in eq 4.

$$\log (k/\mathrm{s}^{-1}) = (10.36 \pm 0.13) - (4.93 \pm 0.17)/\theta \qquad (4)$$

Activation parameters for *tert*-butoxyl radical cleavage have been reported by Fischer and Tsentalovitch.[1e,3a] Their data can be combined with the recent kinetic data reported by Nakamura to evaluate the relationship of rate and reaction enthalpy.[4b] The enthalpies of formation for the radicals in Scheme 4 are either available experimentally or can be estimated reliably from group additivity methods.[11−13] Activation energies can be estimated for the Nakamura data by assuming a log *A* of 13 for the cleavage process. In a similar manner, enthalpies of reaction for the *β*-scission of radicals **3·** and **4·** can be calculated by group additivity. The results are summarized in Table 1 and shown in Figure 4.[14]

Scheme 4



A strong correlation is seen between reaction enthalpy and activation energy. The slopes in Figure 4 (1.0 including *tert*-butoxyl data and 0.8 excluding the *tert*-butoxyl points) are indicative of reactions controlled almost solely by enthalpy. The reaction enthalpy is influenced primarily by two factors: stability of the radical leaving group and destabilization of the alkoxyl radical by steric interactions. A comparison of the cleavages of **14·**, **17·**, and **4·**, where the product radical is in each case an unstabilized primary radical, reveals that the reaction enthalpy is affected strongly by steric interactions. Both **4·** and **17·** are destabilized by gauche-butane type interactions which serve to reduce the reaction enthalpy relative to **14·**. An examination of Figure 4 reveals that cleavage of *tert*-butoxyl (**13·**) is distinctly slower than predicted by the other data points. In passing we note that this trend was reproduced well by DFT calculations (B3LYP/6-31G**), which show product-like transition states with C−C bond lengths of greater than 2.0 Å for the bond undergoing *β*-scission.

Table 1. Comparison of Enthalpy of Reaction (ΔH_{rxn}) with Activation Energy for *β*-Scission of Alkoxyl Radicals **3·**, **4·**, **13·**, **14·**, **15·**, **16·**, and **17·**[14]

radical	ΔH_{rxn}	E_a	ref
13•	4.8	11.6	1e
13•	4.8	11.3	1e
13•	4.8	12.4	3a
13•	4.8	12.1	4b
14•	3.2	9.2	4b
15•	1.6	7.5	4b
16•	−1.2	5.3	4b
17•	1.9	7.6	4b
3•	0.54	6.8	this work
4•	2.7	8.2	this work

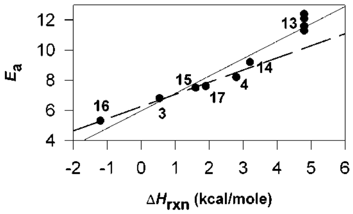


Figure 4. (a) Plot of reaction enthalpy against activation energy for alkoxyl radical *β*-scission. (—): correlation including *tert*-butoxyl data. (- - -): correlation excluding *tert*-butoxyl data. The numbers refer to specific alkoxyl radicals (Scheme 4 and Table 1).

This work has demonstrated that 4-nitrobenzenesulfenate esters are excellent precursors for the LFP (355 nm) generation of alkoxyl radicals. This has allowed us to study the *β*-scission and 1,5-abstraction processes of several alkoxyl radicals. The rates of *β*-scission of radicals **3·** and **4·** and other alkoxyl radicals correlate well with reaction enthalpies.

Acknowledgment. This work was supported by a grant from the National Science Foundation (CHE-9981746).

Supporting Information Available: Synthetic procedures and spectral data for compounds **1**, **2**, **3**, **4**, **9**, and **10**. Rate constants from variable temperature LFP studies of **3**, **4**, and **10**. This material is available free of charge via the Internet at http://pubs.acs.org.

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(11) Heats of formation for the alkoxy radicals were estimated using a bond dissociation energy of 105 kcal/mol for the corresponding alcohol. The heats of formation of the alcohols were estimated by group additivity. In three cases, **12· 13·**, and **14·**, experimental heats of formation were available for the alcohols (ref 12) and found to match group additivity within 0.2 kcal.

(12) Wiberg K. B.; Hao, S. *J. Org. Chem.* **1991**, *56*, 5108−5110.

(13) (a) Berkowitz, J.; Ellison, G. B.; Gutman, D. *J. Phys. Chem.* **1994**, *98*, 2744−2765 (b) Marsi, I.; Viskolcz, B. Seres, L. *J. Phys. Chem. A* **2000**, *104*, 4497−4504. (c) Seetula, J. A.; Slagle, I. R. *J. Chem. Soc., Faraday Trans.* **1997**, *93*, 1709−1719.

(14) The data summarized here were obtained in aromatic hydrocarbon solvents (benzene, fluorobenzene, cumene, and (trifluoromethy)lbenzene). The relatively small differences in solvent polarity should have a minimal effect on rates of *β*-scission.