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Rates of C–S Bond Cleavage in *tert*-Alkyl Phenyl Sulfide Radical Cations

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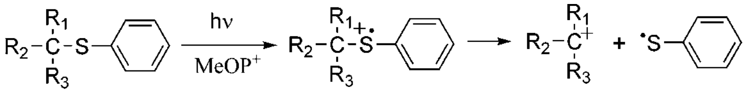
ABSTRACT

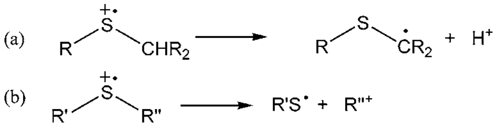


1 $R_1,R_2,R_3=C_6H_5$; **2** $R_1,R_2=C_6H_5,R_3=CH_3$; **3** $R_1=C_6H_5,R_2,R_3=CH_3$; **4** $R_1,R_2,R_3=CH_3$

Radical cations of *tert*-alkyl phenyl sulfides 1–4 have been generated photochemically in MeCN in the presence of the *N*-methoxyphenanthridinium cation (MeOP$^+$), and the rates of C–S bond cleavage have been determined by laser flash photolysis.

The fragmentation reactions of radical cations are attracting continuous interest both from the practical and theoretical points of view.[1] In this area, particular attention is devoted to sulfide radical cations for their role as intermediates in important chemical and biological processes as well as for the manifold aspects of their chemistry.[2] A case in point is that these species not only undergo the most common reaction of radical cations that is the cleavage of a bond β to the center of positive charge (β-cleavage) (an important example is the C−H deprotonations of alkyl sulfide radical cations shown in Scheme 1a), but they can also follow another fragmentation pathway, that is the breaking of the C−S bond with formation of a sulfanyl radical and a carbocation (Scheme 1b).[3]

Scheme 1



This process represents a peculiar type of S_N1 reaction where the leaving group is a radical. Moreover, the scissile bond is directly connected with the atom bearing most of the positive charge,[4] and therefore, the intramolecular electron-transfer accompanying the cleavage process may present behaviors different with respect to that of the more investigated β cleavage.

While the stereochemistry of the C−S bond fragmentation in sulfide radical cations has been investigated, supporting

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(1) (a) E. Baciocchi, M. Bietti, O. Lanzalunga *Acc. Chem. Res.* **2000**, *33*, 243. (b) Gaillard, E. R.; Whitten, D. G. *Acc. Chem. Res.* **1996**, *29*, 292. (c) Maslak, P. *Top. Curr. Chem.* **1993**, *168*, 1. (d) Albini, A.; Fasani, E.; d'Alessandro, N. *Coord. Chem. Rev.* **1993**, *125*, 269.

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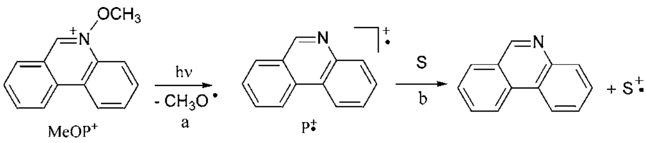
the unimolecular character of the cleavage,[5] very little is known about the kinetic aspects and the structural effects on reactivity. As far as we know, the only study that has addressed this problem concerns the C−S bond cleavage in benzyl aryl sulfide radical cations that was investigated in H_2O, by pulse radiolysis.[3c] It was found that C−S bond cleavage is a relatively slow process occurring in competition with β-C−H deprotonation. An extension of this study, however, was considered impractical in view of the generally low solubility of sulfides in H_2O.[6]

Given also the importance that the knowledge of the fragmentation rates of sulfide radical cations may have with respect to mechanistic studies of enzymatic oxidations of sulfides,[3a,d,7] we have then considered the possibility of generating the sulfide radical cations using the flash photolysis technique, which permits the use of a large variety of organic solvents. An attempt in this direction using the very powerful electron-transfer sensitizer *N*-methylquinolinium tetrafluoroborate was successful with respect to the formation of the radical cations, but failed with respect to the possibility of measuring their C−S bond cleavage rates as these turned out to be much slower than the back-electron transfer from the reduced sensitizer.[8] Accordingly, the radical cations decayed by second-order kinetics with rates almost insensitive to the sulfide structure.

Recently, Dinnocenzo and Farid have proposed a new method for the photochemical generation of radical cations based on the very fast light-induced (370 ± 15 nm) breaking of the N−O bond in *N*-methoxyphenanthridinium cation ($MeOP^+$).[9] From this breaking, the phenanthridinium radical cation ($P^{\bullet+}$) is formed[10] that is a quite powerful oxidant and can be used in subsequent bimolecular reactions to generate the radical cations of added donors with $E° < 1.9$ V (vs SCE) (Scheme 2).

Scheme 2



Since sulfides have oxidation potentials around or lower than 1.6 V vs SCE[3e,11] this new approach appears well suited for the generation of sulfide radical cations and for the study of the C−S bond cleavage reactions that no longer have to compete with the back electron-transfer process (an endergonic reaction). Thus, a steady state and laser flash photolysis investigation of *tert*-alkyl phenyl sulfides **1**−**4** (where no competition with β-C−H bond cleavage reactions is possible) in the presence of $MeOP^+$, in MeCN was carried out and the results are reported herewith. This is the first study that quantitatively addresses kinetics and structural effects of C−S bond cleavage reactions of sulfide radical cations.

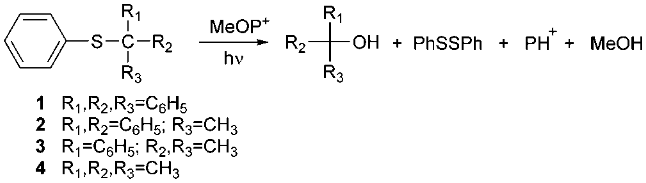
Steady-State Photolysis. The steady-state photolysis of *tert*-alkyl phenyl sulfides **1**−**4** (1×10^{-2} M) sensitized by $MeOP^+$ (5×10^{-3} M) was carried out in N_2-saturated CD_3CN. No reaction was observed in the absence of the sensitizer. The reaction products were identified by ^1H NMR, GC, and HPLC (for comparison with authentic specimens, see the Supporting Information). The sulfide fragmentation products, namely diphenyl disulfide from the sulfide moiety and tertiary alcohols from the *tert*-alkyl carbocations,[11] were obtained in substantial amounts, with the exception of **4** that was almost unreactive (Table 1). The material balance was always excellent (>90%). Other products observed were those deriving from the N−O fragmentation of $MeOP^+$ (protonated phenanthridine, PH^+ and methanol) (Scheme 3).

Table 1. Products and Yields (%) Formed in the Photooxidation of *tert*-Alkyl Phenyl Sulfides (**1-4**) Sensitized by $MeOP^+$ in CD_3CN[a]

	products (yield, %)[b]	
sulfide	$R_1R_2R_3COH$	PhSSPh
1	27	13
2	38	18
3	28	14
4	3	1

[a] [Sulfide] = 1.0×10^{-2} M [$MeOP^+$] = 5×10^{-3} M under nitrogen. [b] Yields are referred to the initial amounts of substrate. The error is ±10%.

Scheme 3



The structure of photoproducts formed can reasonably be rationalized on the basis of the formation of the sulfide radical cations followed by the cleavage of the C−S bond. This process leads to the tertiary cation and the phenylthiyl radical (Scheme 1b, $R' = C_6H_5$, $R'' =$ *tert*-alkyl). The cations

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(5) Baciocchi, E.; Fasella, E.; Lanzalunga, O.; Mattioli, M. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 1071.

(6) In this study, the problem was overcome by synthesizing benzyl aryl sulfides containing the $CH_2SO_3^-$ group in the aryl ring.

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(10) Mee, J. D.; Heseltine, D. W.; Taylor, E. C. *J. Am. Chem. Soc.* **1970**, *92*, 5814.

(11) Baciocchi, E.; Crescenzi, C.; Lanzalunga, O. *Tetrahedron* **1997**, *53*, 4469.

can then react with adventitious water to form the alcohols. Dimerization of phenylthiyl radical leads to diphenyl disulfide. As expected, the amount of diphenyl disulfide is about half of that of tertiary alcohol.

Laser Flash Photolysis Studies. By laser photolysis (λ_{exc} = 355 nm) of MeOP$^+$ in CH_3CN solution, a broad absorption with maximum around 670 nm was detected just after the laser pulse. This band was assigned to the phenanthridine radical cation ($P^{\bullet+}$) formed by N−O bond fragmentation in the MeOP$^+$ excited state (Scheme 2) as reported by Dinnocenzo et al.[9]

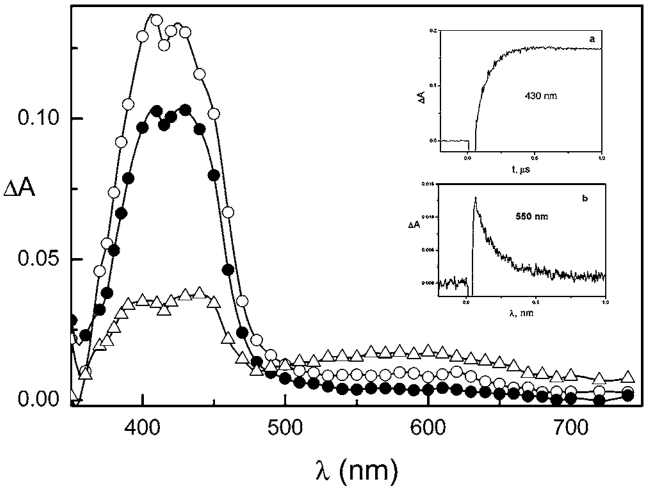

Figure 1. Time-resolved absorption spectra of the MeOP$^+$ (2.4 × 10^{-4} M)/Ph_3CSPh (1.13 × 10^{-2} M) system in N_2-equilibrated CH_3CN recorded 0.088 (△), 0.42 (○) and 3.1 (●) μs after the laser pulse. λ_{ecc} = 355 nm. Inset: (a) buildup kinetic recorded at 430 nm; (b) decay kinetic recorded at 550 nm.

Upon laser excitation of MeOP$^+$ and sulfide **1** in N_2-saturated CH_3CN, the maximum at 670 nm is replaced, 88 ns after the laser pulse, by three absorption bands centered at 400, 430, and 550 nm (Figure 1, empty triangles). The broad absorption band centered at 550 nm can be assigned to $\mathbf{1}^{\bullet+}$ in the monomeric form,[8] while the two absorption bands at 400 and 430 nm can be assigned to the trityl cation Ph_3C^+ (λ_{max} = 404 nm, 430 nm).[12] Analysis of the time-evolution of the absorption spectra shows that the signal at 550 nm decays by a clean first-order kinetic and is coupled with the growth of the very intense absorption at 400−430 nm.[13] The absorption of the trityl cation is much more intense than that of the radical cation as expected on the basis of the much higher extinction coefficient of the former species [ϵ (428 nm) = 3.9 × 10^4 M^{-1} cm^{-1} for Ph_3C^+;[14] the extinction coefficient of $\mathbf{1}^{\bullet+}$ is not available, but it should not be too different from that of $PhCH_2S^{\bullet+}PhCH_2SO_3^-$ ϵ(550 nm) = 4.0 × 10^3 M^{-1} s^{-1} [3c]]. Time-resolved absorption spectra are not modified by the presence of oxygen, thus confirming the cationic nature of the transients. Clearly, the observation of Ph_3C^+ indicates that, in accordance with the results of steady-state photolysis, the decay of $\mathbf{1}^{\bullet+}$ is due to the fast fragmentation reaction involving the heterolytic C−S bond cleavage (Scheme 1b).[15] Accordingly, the decay rate of $\mathbf{1}^{\bullet+}$, determined by following the absorption decay at 550 nm (k_1 = 9.5 × 10^6 s^{-1}, see Figure 1, inset b) is almost equal to the rate of the buildup of the absorption at 430 nm (k_1 = 1.0 × 10^7 s^{-1}, see Figure 1, inset a).

Laser excitation of MeOP$^+$/**2** and MeOP$^+$/**3** in N_2-saturated CH_3CN also produced absorption bands centered at 530 nm just after the laser pulse, which can be assigned to the radical cations $\mathbf{2}^{\bullet+}$ and $\mathbf{3}^{\bullet+}$, respectively (Figures S1 and S2 in the Supporting Information). The time-evolution of the absorption spectra shows that the signal decay recorded at 530 nm is coupled with the growth of the absorption around 400 nm that can be reasonably attributed to the formation of the 1,1-diphenylethyl cation $Ph_2CCH_3^+$ (λ_{max} = 425 nm)[16] from $\mathbf{2}^{\bullet+}$, and the cumyl cation $PhC(CH_3)_2^+$ (λ_{max} = 410 nm)[17] from $\mathbf{3}^{\bullet+}$. However, in both cases, the rise of the absorption bands due to the carbocations is much less evident than with $\mathbf{1}^{\bullet+}$, probably due to the fact that the rates of formation of $Ph_2CCH_3^+$ and $PhC(CH_3)_2^+$ are much lower than that of Ph_3C^+ (vide infra), and are comparable with their decay rates.

In the LFP experiment with the MeOP$^+$/**4** system again the absorption band of the radical cation $\mathbf{4}^{\bullet+}$ centered at 530 nm appeared just after the laser pulse. (Figure S3 in the Supporting Information). The time-evolution of the absorption spectra showed a slow decay of the radical cation (∼10^4 s^{-1}). However, considering the very small amounts of photoproducts formed in the steady-state photolysis, it is unlikely that this decay is due to C−S bond cleavage in $\mathbf{4}^{\bullet+}$. Other deactivation processes such as reaction of $\mathbf{4}^{\bullet+}$ with reducing impurities of the solvents is a more probable possibility.[9]

Rates of C−S Bond Cleavage. The decay of the radical cations at 530 nm (insets of Figures 1 and S1−S3 (Supporting Information)) followed clean first-order kinetics, in accordance with the unimolecular fragmentation process. The rate constants, k_1, measured at 25 °C are reported in Table 2. For $\mathbf{4}^{\bullet+}$, only a higher limit is given for the reasons discussed above.

In Table 2 are also listed the activation parameters ($\Delta H^{\ddagger}$, $\Delta S^{\ddagger}$, and $\Delta G^{\ddagger}$) for the C−S bond fragmentations of $\mathbf{1}^{\bullet+}$−$\mathbf{3}^{\bullet+}$, determined from Eyring analysis of k_1 over the temperature range −25 to 75 °C (Figure S4, Supporting Information) and the C−S bond dissociation free energies (BDFEs) for the radical cations. These latter values were obtained by the classical thermochemical cycle from the C−S BDFEs

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[12] Faria, J. L.; Steenken, S. *J. Am. Chem. Soc.* **1990**, *112*, 1277.

[13] A significant amount of the trityl cation is already formed after 88 ns.

[14] McClelland, R. A.; Banait, N.; Steenken, S. *J. Am. Chem. Soc.* **1986**, *108*, 7023.

[15] The other transient that should form from the radical cation ($PhS^{\bullet}$, λ_{max} = 460 nm, ϵ = 2.6 × 10^3 M^{-1} s^{-1}; Tripathi, G. N. R.; Sun, Q.; Armstrong, D. A.; Chipman, D. M.; Schuler, R. H. *J. Phys. Chem.* **1992**, *96*, 5344) does not emerge on the spectra, likely because its low extinction coefficient.

[16] McClelland, R. A.; Kanagasabapathy, V. M.; Steenken, S. *J. Am. Chem.* Soc. **1988**, *110*, 6913.

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Table 2. C−S Bond Dissociation Free Energies, Decay Rate Constants at 25 °C, and Activation Parameters for the C−S Bond Cleavage Reactions of $\mathbf{1}^{\bullet+}$−$\mathbf{4}^{\bullet+}$ in MeCN

radical cations	BDFE^{a-c}	k_1 (10^5 s^{-1})^{c,d}	$\Delta H^{\ddagger\ b}$	$\Delta S^{\ddagger\ e}$	$\Delta G^{\ddagger\ b,c,f}$
$\mathbf{1}^{\bullet+}$	−12.3	95	2.0 ± 0.3	−21 ± 1	8.2
$\mathbf{2}^{\bullet+}$	−2.2	2.0	5.0 ± 0.3	−17 ± 1	10.1
$\mathbf{3}^{\bullet+}$	1.1	0.66	4.8 ± 0.7	−20 ± 2	10.8
$\mathbf{4}^{\bullet+}$	10.7	<0.1			

[a] Free energy for the cleavage of the C−S bond in the cation radical. [b] kcal mol^{-1}. [c] At 298 K. [d] The error is ± 10%. [e] cal mol^{-1} K^{-1}. [f] From $\Delta G^\ddagger = \Delta H^\ddagger - T\Delta S^\ddagger$.

of the neutral sulfides obtained by the bond dissociation energies (DFT calculations) corrected for the entropic factor, the peak oxidation potentials of the sulfides, experimentally determined, and the reduction potentials of the leaving carbocations available from the literature.[18] All details are in the Supporting Information.

A first observation is that, as generally observed for fragmentations of radical cations,[19] the C−S bond cleavage reaction of sulfide radical cations is characterized by a negative activation entropy and a relatively low activation enthalpy. The structural effects on the rates seem controlled by $\Delta H^\ddagger$, $\Delta S^\ddagger$ being approximately constant.

A clear dependence of the fragmentation rate on the BDFE of the C−S bond in the radical cation is also noted. Accordingly, k_1 increases in the order $\mathbf{4}^{\bullet+} < \mathbf{3}^{\bullet+} < \mathbf{2}^{\bullet+} < \mathbf{1}^{\bullet+}$, which is also the order of increasing stability of the carbocation leaving group $Me_3C^+ < PhMe_2C^+ < Ph_2MeC^+ < Ph_3C^+$.[20] However, the influence of the BDFEs on the rate of fragmentation is rather low: for about 13 kcal/mol difference in BDFE the difference in $\Delta G^\ddagger$ is of only 2−3 kcal/mol. Thus, a plot between $\Delta G^\ddagger$ and BDFE showed a very poor fit to the Marcus equation. The probable reason is that the intrinsic barrier, $\Delta G^\ddagger(0)$, for the C−S bond cleavage reaction is not constant but changes along the series. This was verified by calculating $\Delta G^\ddagger(0)$ for each radical cation by the Marcus equation. It was found that $\Delta G^\ddagger(0)$ is 10.2 kcal/mol for $\mathbf{3}^{\bullet+}$, 11 kcal/mol for $\mathbf{2}^{\bullet+}$, and 13 kcal/mol for $\mathbf{1}^{\bullet+}$. Probably, as recently suggested,[9] the intrinsic barrier that depends on the energy required for the electron reorganization associated to the fragmentation process, increases as the charge, in the formed carbocation, has more possibility of delocalization, that is it increases as the phenyl groups progressively replace the methyl groups (cumyl < diphenylmethyl < triphenylmethyl). Since the intrinsic barriers appear to increase in an order opposite to that of the C−S BDFEs, the thermodynamic contribution to the activation energy is in part compensated by the kinetic factor, which might explain the already noticed relatively small effect of changes in C−S BDFEs upon the C−S bond cleavage rates.

A final observation is that the introduction of the second phenyl group in the alkyl moiety has an effect on the cleavage rate (compare $\mathbf{2}^{\bullet+}$ with $\mathbf{3}^{\bullet+}$) significantly lower than that due to the introduction of the third phenyl group (compare $\mathbf{2}^{\bullet+}$ with $\mathbf{1}^{\bullet+}$). A similar situation holds with respect to the BDFE values, the difference between $\mathbf{2}^{\bullet+}$ and $\mathbf{1}^{\bullet+}$ being significantly larger than that between $\mathbf{2}^{\bullet+}$ and $\mathbf{3}^{\bullet+}$. Probably, in $\mathbf{1}^{\bullet+}$ the presence of three phenyl groups determines a considerable steric crowding [E_s for $CMePh_2$ (−3.55) is less negative than E_s for CPh_3 (−4.68)[21]] so that C−S bond cleavage is favored by steric relief.

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Supporting Information Available: Starting materials, steady-state and laser flash photolysis of the $MeOP^+$/**2**−**4** systems, C−S BDFEs for the sulfide radical cations, cyclic voltammetry and DFT calculations of sulfide C−S BDEs. This material is available free of charge via the Internet at http://pubs.acs.org.

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(20) Abboud, J.-L. M.; Alkorta, I.; Davalos, J. Z.; Müller, P.; Quintanilla, E.; Rossier, J.-C. *J. Org. Chem.* **2003**, *68*, 3786. This order holds in the gas phase. In solution, inversion between $PhMe_2C^+$ and Ph_2MeC^+ has been reported (Arnett, E. M.; Hofelich, T. C. *J. Am. Chem. Soc.* **1983**, *105*, 2889). However, these data were obtained in superacid media and the situation may be different in MeCN.

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