

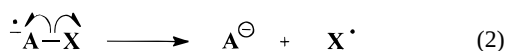
Intrinsic Barriers of the Alternative Modes of Mesolytic Fragmentations of C–S Bonds

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Received March 6, 1996

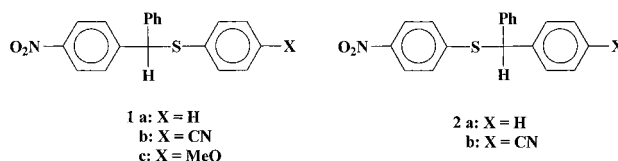
Unimolecular fragmentation reactions of radical ions to radicals and ions (mesolytic cleavages¹) have been used to experimentally probe the relationship between the kinetics and thermodynamics of elementary reactions.^{2,3} An important goal of such investigations is the quantitative evaluation of factors contributing to the intrinsic barriers.⁴ In the fragmentation of radical ions wherein the unpaired electron resides initially in a π orbital on one side of the scissile bond, two modes of electron apportionment are possible.⁵ For example, in radical anions the heterolytic mode of fragmentation results in the transfer of charge across the scissile bond (eq 1), while in the homolytic mode the charge remains localized on the same moiety (eq 2).



We present here the first quantitative comparison of the two cleavage modes in radical anions and show that for mesolysis of C–S bonds the intrinsic barriers of the homolytic mode are substantially higher (by ca. 3 kcal/mol) than those of the heterolytic mode.

The systems investigated included radical anions of **1** and **2**. In both systems the unpaired electron was initially highly localized on the nitrophenyl moiety, as indicated by ESR studies. The radical anions of **1a–c** underwent unimolecular fragmentation according to the heterolytic mode (eq 1), yielding the 4-nitrodiphenylmethyl radical (not directly observed) and the corresponding thiophenoxide. Similarly, as was shown before⁶ by Vianello *et al.*, and confirmed by us, **2a–b**^{•–} fragmented in a unimolecular reaction following the homolytic mode (eq 2), giving 4-nitrothiophenoxide and the corresponding diphenylmethyl radical (not directly observed). The rates and activation parameters for these reactions have been obtained in DMF by cyclic voltammetry (CV) and are collected in Table 1.

The thermodynamics of the cleavage reactions has been evaluated from a thermochemical cycle:^{3,7} $\Delta G_m = \Delta G_h - 23.06 - (E^{\text{ox}} - E^{\text{r}})$, where the free energy of mesolysis (ΔG_m , in kcal/



mol) is obtained by subtracting the difference in redox potentials between the radical anion precursor (E^{r}) and thiophenoxide (E^{ox}) from the homolytic free energy (ΔG_h) of the neutral precursor of the radical anion. The homolytic free energy of the unsubstituted analog ($\Delta G_h(\mathbf{3}) = 43$ kcal/mol, where **3** is diphenylmethyl phenyl sulfide) was estimated from the known heats of formation of the diphenylmethyl and thiophenyl radicals using the Benson group additivity approach.⁸ The effect of the substituents on ΔG_h values in **1** and **2** was evaluated with the help of competitive thermolysis reactions.⁹ All substituents showed bond-weakening effects smaller than 2 kcal/mol. The data obtained are presented in Table 1. The reversible reduction potentials for all the nitro compounds were measured by CV, and the reversible oxidation potentials for the thiophenoxides were available from the literature.¹⁰ These data are also gathered in Table 1.

The radical anions of **1a** and **2a** have very similar rates and activation energies of fragmentation. The cleavage of **2a**^{•–} is, however, less endergonic than that of **1a**^{•–} by nearly 8 kcal/mol. The fragmentation of **1b**^{•–}, which has ΔG_m similar to that of **2**^{•–}, has an activation energy that is lower than that of **2a**^{•–} by ca. 3 kcal/mol.

It is instructive to divide the barriers for endergonic reactions, such as these presented here, into a thermodynamic component, due purely to the energy difference between the initial and the final states, and the kinetic component, termed the “overhead,” that represents the *extra* energy costs associated with the reorganization of the initial state necessary to reach the transition state and includes all electronic (preexponential) factors.⁴ In general, the overhead is the free-energy barrier to the exergonic reverse reaction, and it is a function of ΔG . If the free energy relationship for the reaction is known, the overhead can be explicitly replaced with the intrinsic barrier,⁴ i.e., one observed for $\Delta G = 0$. In the absence of a well-defined free-energy relationship, the overhead may serve as a quantitative substitute for the intrinsic barrier in comparisons of reactions with similar driving forces. In these terms, the homolytic fragmentation mode of **2**^{•–} has overheads that are significantly larger than those found for the heterolytic mode of scission in **1**^{•–} in general, and in **1b**^{•–} in particular.

The fragmentation reaction involves transfer of electron density from the π system with the unpaired electron to the space between the carbon and sulfur atoms of the scissile bond ($\sigma^*_{\text{C-S}}$). The good overlap between the orbitals involved is, therefore, crucial for a “smooth” transfer of electron density accompanying the cleavage.⁴ The importance of this stereo-

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(4) The “intrinsic barrier” denotes here the reaction barrier (overhead) at $\Delta G = 0$. Our procedure does not allow for distinction of the preexponential effects from the reorganization energy component; i.e., the same rate may be accounted for by a large preexponential factor and large $\Delta G^\ddagger$ or by a small preexponential factor and small $\Delta G^\ddagger$. We assume $\kappa = 1$ in the Eyring treatment. The distinction is possible only if the free-energy relationship ($k_m = f(\Delta G_m)$) is known. See, for example: Adcock, W.; Andrieux, C. P.; Clark, C. I.; Neudeck, A.; Savéant, J.-M.; Tardy, C. *J. Am. Chem. Soc.* **1995**, 117, 8285.

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(9) Competitive thermolysis of **1** or **2** vs **3** was carried out in the mixture of decalin, styrene, and 1,4-hexadiene. The initial rates of disappearance of sulfides (10–15% conversion) were used to obtain the relative activation energies for homolysis. The values of $\Delta\Delta G_h^\ddagger$ obtained at 140 and 180 °C were used to calculate the ΔG_h for the substituted compounds.

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Table 1. Thermodynamic and Kinetic Data for Fragmentation of $1^{\bullet-}$ and $2^{\bullet-}$

RI ^a	E^r ^b (V)	E^{ox} ^c (V)	ΔG_h^d (kcal/mol)	ΔG_m^e (kcal/mol)	k_m^f (T) [s ⁻¹ (K)]	ΔH_m^g (kcal/mol)	ΔS_m^h (eu)	ΔG_m^i (kcal/mol)	pK _a ^j
1a	-1.127	0.100	42.2	13.9	0.6 (276)	17.3	3	16.3	10.3
1b	-1.120	0.400	41.8	6.7	0.1 (217)	14.5	5	13.0	6.5 ^k
1c	-1.159	-0.035	41.9	16.0	0.09 (276)	16.7	-3	17.5	11.2
2a	-1.114	0.455	42.3	6.1	0.7 (276)	16.6	1	16.3	32.2
2b	-1.110	0.455	41.6	5.5	0.01 (217)	13.6	-4	14.7	25.3

^a Radical anion precursors. ^b Reversible reduction potential (vs SCE) of the radical anion precursors in CH₃CN/0.1 M tetrabutylammonium perchlorate (TBAP). ^c Reversible oxidation potential of the corresponding thiophenoxide (vs SCE) in CH₃CN/0.1 M Et₄NBF₄ (ref 10). ^d Free energy of homolysis of neutral **1** or **2** at 300 K, obtained by correcting $\Delta G_h(\mathbf{3})$ using the relative activation parameters obtained from competitive thermolysis (ref 9). ^e Free energy of mesolysis at 300 K, evaluated from the thermodynamic cycle (see text). ^f Rate constants for the unimolecular fragmentation of radical ions were measured by CV in DMF/0.1 M TBAP (**1a,c**, **2a**, from 34 to -24 °C) or in CH₃CH₂CN (20% v/v)/DMF/0.1 M TBAP (**1b**, **2b** from -46 to -74 °C). ^g Enthalpies of activation (± 1 kcal/mol). ^h Entropies of activation (± 4 eu). ⁱ Free energies of activation at 300 K. ^j pK_a values of the corresponding thiophenols (for **1**, ref 20) and diphenylmethanes (for **2**, ref 21) in Me₂SO. ^k Estimated (ref 20).

electronic factor has been demonstrated experimentally in fragmentation reactions of radical anions and cations.^{4,11} That factor is, however, not important in the present case.

As shown by ESR studies carried out on radical anions of methyl and tert-butyl nitrophenyl sulfides,¹² the preferred conformation maximizes the overlap between the π system and the σ^*_{C-S} bond. In other words, S-R substituents behave as electron acceptors. This trend is also followed by R = CHPh₂ in **2** which has a slightly lower reduction potential than that of **1**. Calculations by semiempirical methods (PM3)¹³ for $2^{\bullet-}$ and *ab initio* methods for small model compounds¹⁴ indicate that the lowest energy conformations in radical anions have a near perfect dihedral angle (close to 90°) between the plane of the π system and the scissile bond. Additionally, as shown by semiempirical calculations, in $2^{\bullet-}$ the rotation around the C_{Ph}-S bond has only a small barrier (ca. 2 kcal/mol). All these considerations exclude the interference of a nonreactive conformation as a reason for the increased overhead in $2^{\bullet-}$ as compared to $1^{\bullet-}$.

The difference in reactivity between the two modes of fragmentation may be traced to the delocalization of charge in the transition state. The shift of the electron density into the σ^*_{C-S} bond is easily accommodated in $1^{\bullet-}$, with the thiophenyl moiety being able to stabilize the charge quite well. In $2^{\bullet-}$, the diphenylmethyl moiety is a much poorer electron-density acceptor. As the result, the transition state for cleavage of $1^{\bullet-}$ has the "excess" negative charge delocalized over the entire molecule, while the delocalization of charge in $2^{\bullet-}$ is largely limited to the nitrophenylthio moiety.

These delocalization effects are clearly visible in the way the substituents affect the activation energy of fragmentation. In $1^{\bullet-}$ the change in the activation energy upon substitution follows the same trend as one observed for the pK_a values of the corresponding thiophenols. Indeed, ca. 70% of the relative thiophenoxide stabilization energy due to the substitution (2.3RTΔpK_a) is reflected in the transition state. In $2^{\bullet-}$ the

substituent effect is much smaller; only ca. 20% of the relative diphenylmethyl anion stabilization energy (based on pK_a values) contributes to the lowering of the activation energy of the fragmentation process.

This effect of the extent of charge delocalization in the transition state is a general property of the fragmentation reaction; i.e., the heterolytic mode of mesolysis is expected to have a smaller overhead than the homolytic mode. The difference in overheads should depend on the difference in the electronegativity of the atoms of the scissile bond, i.e., the relative ability of the fragments to accommodate the charge. As have been qualitatively demonstrated previously,^{5,15,16} such differences are large for C-O or C-N and small for C-C bond fragmentations in radical anions. In the fragmentation of C-S bonds presented here, both modes of cleavage are directly observable, and the intrinsic barrier differences (ca. 3 kcal/mol) are sufficiently large to be outside of the experimental error.¹⁷

In light of these experiments, it is perhaps not surprising that the large majority of radical ion fragmentations reported in the literature^{2a,b,18} are examples of the heterolytic mode of cleavage and that the radical-anion coupling reactions (that are a component of many S_{RN}1 reactions^{2a,b,19}) are formally heterogenic processes (reverse of eq 1). These intrinsic barrier differences should be explicitly included in any free-energy relationship for mesolytic fragmentation.

Acknowledgment. This research has been sponsored by a grant from the NSF.

JA960735X

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