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Solvation Control of Chemoselectivity in Reactions of Radical Cations[1]

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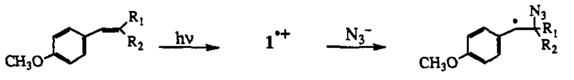
Synthetic and mechanistic aspects of reactions of radical cations have been an area of continuing interest.[2–5] As part of our investigations into the development of "clocks" for the reactions of radical cations, we have investigated the reactivity of azide (N_3^-) with a variety of radical cations. Azide is a powerful nucleophile that has been used as a "clock" for obtaining absolute rate constants for the reactions of nucleophiles with carbocations.[6,7] However, in principle the reaction between a nucleophile and a radical cation can proceed by either polar addition or electron transfer (ET). The extent to which these two processes are involved in the primary interaction in nucleophile–radical cation reactions is still a subject of controversy.[8] We now report an interesting solvent effect on the competition between ET and addition for reactions of olefinic and aromatic radical cations with azide. In particular, the radical cations of 4-methoxystyrenes **1a–c** and anthracenes **2a–c** are shown to react with azide by ET in acetonitrile (MeCN), but to react by nucleophilic addition in 2,2,2-trifluoroethanol (TFE). Interestingly, evidence for ET quenching of the radical cations in MeCN includes the observation of a transient we have assigned to the radical anion, N_6^{-}. The change in mechanism from ET to nucleophilic addition demonstrates the possibility of solvation control of chemoselectivity in reactions of radical cations.

Second-order rate constants for reactions (k_q) of the radical cations **1a–c** and **2a–c** with azide in MeCN and TFE were obtained from plots of the pseudo-first-order rate constants for decay of the radical cation (determined by nanosecond laser flash photolysis)[9] *versus* the concentration of added azide and are listed in Table 1. Rate constants in MeCN are all diffusion controlled (*ca.* 2–4 × 10^{10} M^{-1} s^{-1}) and exhibit essentially no selectivity. On the other hand, in TFE the rate constants are substrate dependent, with only the reaction of the radical cation of **1a** proceeding at the diffusion-controlled rate (*ca.* 7 × 10^9 M^{-1} s^{-1} for this solvent). Initially, we believed that the lack of selectivity in MeCN was an indication that nucleophilic addition of azide in this solvent is extremely rapid, similar to that observed for the reaction of azide with unstable carbocations.[7] However, transient absorption spectra measured on solutions of **1a–c** and **2a–c** in the presence of azide gave no indication of the radical intermediates that would be expected from addition of azide to the radical cation (see eqs 1 and 2). These radical intermediates are expected to have sharp absorptions with maxima in the region between 310 and 340 nm.[4,5,10]

Table 1. Second-Order Rate Constants for the Reaction of Azide with the Radical Cations in Acetonitrile (MeCN)[a] and 2,2,2-Trifluoroethanol (TFE) and the Oxidation Peak Potential of the Substrates[b]

	$k_q/10^9$ M^{-1} s^{-1} [c]		$E°$/V (*vs* ferrocene)[d]	
substrate	MeCN	TFE	MeCN	TFE
1a	42	7.0	1.015[e]	0.970[e]
1b	29	3.5	0.915[e]	0.900[e]
1c	30	1.0	0.865[e]	0.860[e]
2a	42	3.3	0.860	0.830
2b	28	0.45	0.832	0.807
2c	25	0.0043	0.812	0.787
N_3^-			0.275 (0.408)[e]	0.802 (0.927)[e]

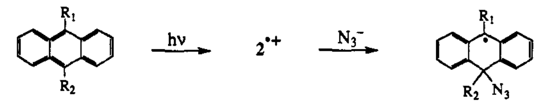
[a] Measured by nanosecond laser flash photolysis techniques at room temperature using air-saturated, 1 × 10^{-4} M solutions of substrate. Rate constants for reaction (k_q) were determined from the slopes of the plots of the pseudo-first-order rate constants for decay of the radical cation (k_{decay}) *versus* the concentration of added azide according to the expression $k_{decay} = k_0 + k_q[N_3^-]$. Tetrabutylammonium azide was used as the source of azide. [b] Measured using a standard three-electrode arrangement using a platinum working electrode. Solutions contained 1–2 mM of substrate in 0.1 M tetrabutylammonium perchlorate (TBAP) as the supporting electrolyte. [c] Errors are ±10–15%. [d] Oxidation potential measured at a sweep rate of 0.1 V/s reported relative to the ferrocene/ferrocenium couple. Errors are *ca.* ±5–10 mV. [e] Irreversible oxidation. Value reported is the oxidation peak potential. The values in parentheses for azide are the estimated $E°$ values assuming a diffusion-controlled EC dimerization mechanism (ref 20).



1a: $R_1 = R_2 = H$
1b: $R_1 = CH_3$, $R_2 = H$
1c: $R_1 = R_2 = CH_3$

3a-c

[1]



2a: $R_1 = R_2 = H$
2b: $R_1 = C_6H_5$, $R_2 = H$
2c: $R_1 = R_2 = C_6H_5$

4a-c

[2]

Transient absorption spectra measured on MeCN solutions of **1** and **2** in the presence of sufficient azide to completely quench the radical cations exhibit a broad, featureless absorption with a maximum at 700 nm and exhibit no features characteristic of species **3** or **4**. Figure 1 illustrates the spectrum obtained for a solution of **2b** in the presence of 6 mM azide. The 700-nm transient is long-lived (half-life of *ca.* 12 μs)[11] and unreactive toward oxygen (*i.e.*, it is not the radical anion of the aromatic precursor). Furthermore, its optical density increases as the azide concentration increases. We assign this transient to the radical

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[1] Issued at NRCC as No. 37223.

[2] (a) Fox, M. A., Chanon, M., Eds. *Photoinduced Electron Transfer*; Elsevier: Amsterdam, 1988. (b) Yoon, U. C.; Mariano, P. S. *Acc. Chem. Res.* **1992**, *25*, 233–240. (c) Parker, V. D. *Acc. Chem. Res.* **1984**, *17*, 243–250. (d) Eberson, L. *Adv. Phys. Org. Chem.* **1982**, *18*, 79–185.

[3] (a) Lewis, F. D. In *Photoinduced Electron Transfer*; Fox, M. A., Chanon, M., Eds.; Elsevier: Amsterdam, 1988; Part C, Chapter 4. (b) Popielarz, R.; Arnold, D. R. *J. Am. Chem. Soc.* **1990**, *112*, 3068–3082 and references cited therein. (c) Trampe, G.; Mattay, J.; Steenken, S. *J. Phys. Chem.* **1989**, *93*, 7157–7160. (d) Yasuda, M.; Shiomori, K.; Hamasuna, S.; Shima, K.; Yamashita, T. *J. Chem. Soc., Perkin Trans. 2* **1992**, 305–310 and references cited therein. (e) Sankararaman, S.; Perrier, S.; Kochi, J. K. *J. Am. Chem. Soc.* **1989**, *111*, 6448–6449.

[4] Schepp, N. P.; Johnston, L. J. *J. Am. Chem. Soc.* **1993**, *115*, 6564–6571.

[5] Workentin, M. S.; Johnston, L. J.; Wayner, D. D. M.; Parker, V. D. Unpublished results.

[6] For example, see: (a) Richard, J. P. *J. Am. Chem. Soc.* **1989**, *111*, 1455–1465. (b) Amyes, T. L.; Jencks, W. P. *J. Am. Chem. Soc.* **1989**, *111*, 7888–7900.

[7] McClelland, R. A.; Kanagasabapathy, V. M.; Banait, N. S.; Steenken, S. *J. Am. Chem. Soc.* **1991**, *113*, 1009–1014.

[8] (a) Pross, A.; Shaik, S. *Prog. Phys. Org. Chem.* **1985**, *15*, 197–337. (b) Eberson, L. In *Electron Transfer Reactions in Organic Chemistry*; Springer-Verlag: Heidelberg, 1987. (c) Kochi, J. K. *Angew. Chem., Int. Ed. Eng.* **1988**, *27*, 1227–1266. (d) Ki Cho, J.; Shaik, S. *J. Am. Chem. Soc.* **1991**, *113*, 9890–9891. (e) Shaik, S.; Pross, A. *J. Am. Chem. Soc.* **1989**, *111*, 4306–4312.

[9] The radical cations of **1a–c** and **2a–c** were readily generated by photoionization using 308- or 355-nm nanosecond laser flash photolysis techniques. The assignments of the resulting transients to the corresponding radical cations have been previously established. References 3 and 4 and the following: (a) Shida, T. *Electronic Absorption Spectra of Radical Ions*; Elsevier: Amsterdam, 1988. (b) Masnovi, J. M.; Kochi, J. K. *J. Am. Chem. Soc.* **1985**, *107*, 7880–7893.

[10] By analogy with the more well-known benzyl and phenethyl radicals as well as diphenyl- and triphenylmethyl radicals: Chatgilialoglu, C. In *Handbook of Photochemistry*; Scaiano, J. C., Ed.; CRC Press: Boca Raton, FL, 1989; Vol. II, Chapter 1.

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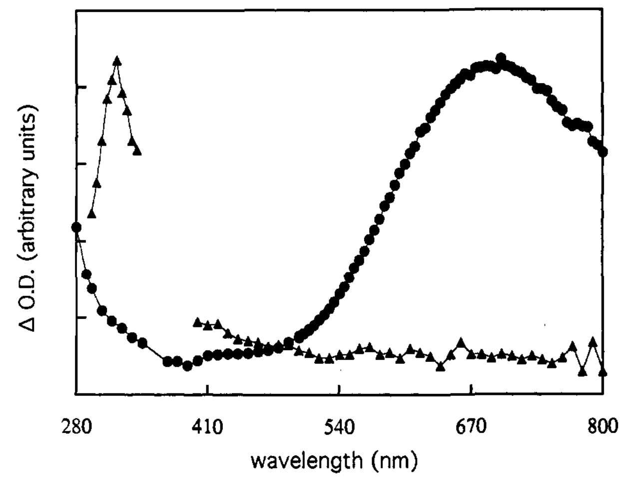

Figure 1. Transient absorption spectra from air-saturated, 1 × 10^{-4} M solutions of **2b** at ambient temperature: (i) (●) spectrum in acetonitrile in the presence of 6 mM azide, recorded 1 μs after the laser pulse; (ii) (▲) spectrum in TFE in the presence of 0.25 M azide, recorded 0.8–0.9 μs after the laser pulse. The spectra are normalized with respect to the absorption maxima.

anion, N_6^-, generated from the reaction of the azidyl radical with excess azide according to eqs 3 and 4. This suggests that the azidyl radical is formed by electron transfer from azide to the radical cation of $1^{\bullet+}$ or $2^{\bullet+}$. Additional support for this mechanism is obtained from the observation that all of the originally bleached (*i.e.*, photoionized) **1** or **2** recovers at a rate which is the same as the rate of decay of the corresponding radical cations (which means that the product of reaction of the radical cation with azide is the neutral aromatic). Thus, observation of N_6^- provides a useful method to probe for the involvement of an electron-transfer process in these systems.[12]

$$\mathbf{1}^{\bullet+} \text{ (or } \mathbf{2}^{\bullet+}) + N_3^- \rightleftharpoons \mathbf{1} \text{ (or } \mathbf{2}) + N_3^{\bullet} \tag{3}$$

$$N_3^{\bullet} + N_3^- \rightleftharpoons N_6^{\bullet-} \tag{4}$$

This radical anion, which is analogous to other more well documented dihalide or pseudohalogen radical anions such as Br_2^- and $(SCN)_2^-$,[13] to the best of our knowledge has not been observed previously in nonaqueous media. Studies involving the azidyl radical in water[14] have shown that N_6^- (λ_{max} = 645 nm) is formed in observable quantities only in the presence of molar concentrations of azide.[15] We have found the equilibrium to be solvent dependent, and in MeCN we estimate K_4 to be *ca.* 200 M^{-1}, making N_6^- a relatively stable species observable at only millimolar concentrations of azide.[16]

Transient absorption spectra of **1** and **2** measured in TFE in the presence of azide exhibit in all cases absorptions which can be assigned to the adduct radicals **3** or **4** (eqs 1 and 2). The spectrum obtained for a solution of **2b** in TFE is illustrated in Figure 1. No absorption of N_6^- was observable in any case even at molar concentrations of azide.[17] The selectivities exhibited in TFE for reactions of azide are indicative of a nucleophilic reaction. The rate differences between **1a–c** and **2a–c** are consistent with the higher reactivity of olefinic radical cations compared to aromatic radical cations. The change in kinetics as one proceeds from **a** to **c** in either series will be determined by simple steric factors (which impede reaction either at the β-carbon in **1a–c** or at the 9-and 10-positions in **2a–c**[18]) as well as the overall thermodynamics of the addition (*i.e.*, the relative stability of the radical cation *versus* the adduct radical).

The change in mechanism from ET in MeCN to nucleophilic addition in TFE is supported by measurements of the oxidation potentials of the substrates. This data is included in Table 1 and suggests that in MeCN eq 3 is exergonic by at least 9 kcal/mol and thus should proceed at diffusion-controlled rates, as is observed.[19] In TFE the oxidation potentials of **1a–c** and **2a–c** do not change appreciably (<30 mV) from those measured in MeCN, suggesting little change in the solvation of the radical cations in these two solvents. On the other hand, the peak potential for N_3^- shifts ca. 0.5 V to more positive potentials in TFE.[20] This dramatic shift is presumably due to stabilizing hydrogen-bonding interactions of the solvent with the anion thus making oxidation more difficult. The shift in the potential of N_3^- is of sufficient magnitude to make ET endergonic for all but one radical cation in TFE and thus allows addition to compete effectively. In fact, our observations suggest that nucleophilic addition dominates the reactivity in TFE. The results demonstrate the importance of understanding the redox properties (which reflect relative solvation energies) of the reactive partners in the reactions of radical cations with nucleophiles. Further work aimed at examining the use of solvation properties as a method to manipulate chemoselectivity of reactions of radical cations with azide and other nucleophiles, as well as studies of the reactivity of N_6^-, is currently in progress.

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(11) The kinetics of decay of the 700-nm transient are dependent on the substrate involved. In the case of **1a–c** the decay is first order and the transient is shorter lived while for **2a–c** the decays follow mixed-order kinetics and the half-life is as described in the text. The decay of this transient is also a function of the concentration of added **1** or **2**, suggesting that a decay process involving the reaction of either the azidyl radical or N_6^- is involved. This will be discussed in the full account of this work.

(12) The N_6^- absorption may also be used to probe the reactions of the azidyl radical with other substrates. Similar methodology has been used with Br_2^- to probe the reactivity of bromine atoms: Scaiano, J. C.; Barra, M.; Krzywinski, M.; Sinta, R.; Calabrese, G. *J. Am. Chem. Soc.* **1993**, *115*, 8340–8344.

(13) (a) Fornier de Violet, Ph. *Rev. Chem. Intermed.* **1981**, *4*, 121–169. (b) Schuler, R. H.; Patterson, L. K.; Janata, E. *J. Phys. Chem.* **1980**, *84*, 2088–2089 and references cited therein. (c) Behar, D.; Bevan, P. L. T.; Scholes, G. *J. Phys. Chem.* **1972**, *76*, 1537–1542.

(14) (a) Butler, J.; Land, E. J.; Swallow, A. J.; Prutz, W. *Radiat. Phys. Chem.* **1984**, *23*, 265–270. (b) Ram, M. S.; Stanbury, D. M. *J. Phys. Chem.* **1986**, *90*, 3691–3696. (c) Alfassi, Z. B.; Prutz, W. A.; Schuler, R. H. *J. Phys. Chem.* **1986**, *90*, 1198–1203. (d) Alfassi, Z. B.; Schuler, R. H. *J. Phys. Chem.* **1985**, *89*, 3359–3363. (e) Hurley, J. K.; Linschitz, H.; Treinin, A. *J. Phys. Chem.* **1988**, *92*, 5151–5159.

(15) An equilibrium constant (K_4) of 0.33 M^{-1} has been estimated for reaction 4 in water by a number of techniques.[14] In DMF the equilibrium constant has been estimated as 250 M^{-1}. Further details of the solvent effects on this equilibrium are to be reported in the full account of this work.

(16) The ΔOD of the 700-nm transient depends on the concentration of azide, and thus the equilibrium constant (K_4) was estimated by plotting 1/ΔOD *vs* $1/[N_3^-]$ according to the expression $1/\Delta OD = \alpha + (\alpha/K_{eq}[N_3^-])$.

(17) The K_4 in TFE might be expected to be similar to that observed in water, and thus N_6^- would only be observable at high azide concentrations.

(18) Nucleophiles are known to add preferentially to the β-position in the radical cations of styrenes (ref 3) and to the 9- or 10-positions of anthracenes; see, for example: (a) Yashuda, M.; Matsuzaki, Y.; Shima, K. *J. Chem. Soc., Perkin Trans. 2* **1988**, 745–751 and references cited therein. (b) Reitstöen B.; Parker, V. D. *Acta Chem. Scand.* **1992**, *46*, 464–468 and references cited therein.

(19) The upper limit of driving force (*i.e.*, most positive number) for electron transfer was calculated using the electrode potentials for the reduction of the radical cations and the estimated standard potential of azide (Table 1) using the Rehm–Weller expression.

(20) The E_p of the azide oxidation is shifted to less positive potentials than the actual $E°$ as a result of the fast chemical reactions of the azidyl radical. The magnitude of the shift is estimated to be 150 mV based on a radical coupling process (EC dimerization) being the major reaction of the azidyl radical. (a) Wayner, D. D. M.; Parker, V. D. *Acc. Chem. Res.* **1993**, *26*, 287–294. (b) Parker, V. D. *Adv. Phys. Org. Chem.* **1983**, *19*, 131–222.