Proton-Transfer Reactions of Alkylaromatic Cation Radicals. The Effect of α-Substituents on the Kinetic Acidity of *p*-Methoxytoluene Cation Radicals

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Abstract: The rates of deprotonation for a number of α-substituted *p*-methoxytoluene cation radicals (4-$MeOPhCH_2X^{\bullet+}$ with X = H, Me, OAc, OH, OMe, Cl, CN, Ph, 4-MeOPh, and 4-$MeOPhCD_3^{\bullet+}$) have been determined by a laser photolysis technique in MeCN. The cation radicals have been generated from the corresponding neutral substrates either by biphenyl/9,10-dicyanoanthracene photosensitized oxidation or by reaction with $NO_3^{\bullet}$ generated by photolysis of cerium(IV) ammonium nitrate. The deprotonations have been induced by 2,6-lutidine in the former case and by NO_3^- in the latter. It has been found that all α-substituents increase the deprotonation rate, with the rate constant (k_{2obs}) almost reaching the diffusion-controlled limit when X = CN and the base is NO_3^-. The k_{2obs} values appear to parallel the thermodynamic acidity of the cation radicals, and good Brönsted correlations have been obtained with α values of 0.24 for both the bases, which indicates a reactant-like transition state, with very little buildup of positive charge at the α-carbon, a conclusion also supported by the small (2.1 with 2,6-lutidine and 2.0 with NO_3^-) deuterium kinetic isotope effects. The data have also been treated in terms of the Marcus equation, and intrinsic barriers of 12.2 and 15.2 kcal mol^{-1} for the proton-transfer reactions induced by NO_3^- and 2,6-lutidine, respectively, have been calculated. These values are very close to those generally found in acid–base reactions of carbon acids. Comparison of these deprotonation rates with those of α-substituted *p*-xylene cation radicals, has, however, revealed that α-substituents of +R type (OH, OMe, and, to a less extent, Me) have a much larger rate-enhancing effect in the deprotonation of 4-$MePhCH_2X^{\bullet+}$ than in that of 4-$MeOPhCH_2X^{\bullet+}$; the contrary is instead observed with the α-CN substituent (–I or –R). It is suggested that the kinetic effect of an α-substituent on the deprotonation rate of an alkylaromatic cation radical is controlled by its capacity to change the homolytic C–H bond dissociation energy as well as by the extent of positive charge which develops at the α-carbon in the transition state. The latter in turn may be influenced by the nature of ring substituents, depending on their relative ability to delocalize a positive charge.

One of the most important reactions of alkylaromatic cation radicals is the deprotonation by a base B to give a benzyl radical, as shown in eq 1. This reaction is attracting continuous attention

$$ArCH_3^{\bullet+} + B \rightarrow ArCH_2^{\bullet} + BH^+ \qquad (1)$$

from both the practical and the theoretical points of view. Accordingly, reaction 1 is the key step in the one-electron side chain functionalization of alkylaromatic compounds,[1] a very important synthetic process with industrial applications. Moreover, the deprotonation of alkylaromatic cation radicals exhibits features of great theoretical interest, being a very peculiar acid–base reaction: a benzyl radical is the conjugate base, and the cleavage of the C–H bond must be accompanied by extensive electronic reorganization, thereby one of the electrons of the σ C–H bond has to be completely transferred to the aromatic π system.

Indeed, recent work has indicated that such an intramolecular electron transfer can significantly influence the kinetic acidity of alkylaromatic cation radicals. Thus, the observation that the rate of reaction 1 is subject to stringent stereoelectronic control has been rationalized on this basis,[2] and in studies on the deprotonation of α-substituted *p*-xylene cation radicals,[2a] differences in the degree of intramolecular electron transfer in the transition state have been suggested by one of us to explain the finding that both electron-releasing and electron-withdrawing α-substituents enhance the deprotonation rate, the effect, however, being much larger with +R groups (alkoxy or methyl) than with –I and –R groups (CN). It is also important to mention that Saveant and his associates have presented results concerning the kinetic acidity of cation radicals of NADH analogues and found that the intrinsic barriers of the deprotonation process correlate with the homolytic C–H bond dissociation energies, but not with the thermodynamic acidities.[3] Their conclusion is that proton transfer from cation radicals should be viewed as a concerted electron–hydrogen atom transfer.

Thus, the matter appears very complex and much more information than that presently available is certainly required to reach a satisfactory rationalization of the influence of structural changes upon the deprotonation rate of alkylaromatic cation radicals. In this respect, we feel that valuable information can be acquired from the knowledge of the effect of α-substituents on the kinetic acidity of alkylaromatic cation radicals. Accordingly, these effects should be very sensitive to the electronic situation at the C_α–H bond undergoing cleavage and should therefore give important indications on the structure of the transition state of the deprotonation process. On this basis, we have considered it worthwhile to complement our previous study of the effect of α-substituents on the deprotonation of *p*-xylene cation radicals, where we could only determine relative rate data, with a laser photolysis investigation of the deprotonation reactions of a series of α-substituted *p*-methoxytoluene cation radicals (4-$MeOPhCH_2X^{\bullet+}$, with X = H, Me, OH, OMe, OAc, Ph,

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[1] Sheldon, R. A.; Kochi, J. K. *Metal Catalyzed Oxidation of Organic Compounds*; Academic Press: New York, 1981.

[2] (a) Baciocchi, E.; Mattioli, M.; Romano, R.; Ruzziconi, R. *J. Org. Chem.* **1991**, *56*, 7154. (b) Tolbert, L. M.; Khanna, R. K.; Popp, A. E.; Gelbaum, L.; Bettomley, L. A. *J. Am. Chem. Soc.* **1990**, *112*, 2373.

[3] Anne, A.; Hapiot, P.; Moiroux, J.; Neta, P.; Saveant, J.-M. *J. Am. Chem. Soc.* **1992**, *114*, 4694.

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4-MeOPh, Cl, and CN) and 4-MeOPhCD$_3^{\bullet+}$. The ring methoxy group was necessary in order to get radical cations sufficiently stable to be detected and studied on the time scale (ns) of our laser apparatus. The cation radicals were generated in MeCN from the corresponding *p*-methoxytoluenes either by 9,10-dicyanoanthracene (DCA) in the presence of biphenyl (BP) as secondary electron-transfer cosensitizer or by reaction with NO$_3^\bullet$ radicals formed in the photolysis of ceric ammonium nitrate (CAN). The deprotonations of 4-MeOPhCH$_2$X$^{\bullet+}$ and 4-MeOPhCD$_3^{\bullet+}$ were induced by 2,6-lutidine in the former case and by NO$_3^-$ in the latter. The results of this study are reported and discussed in the present paper.

Results

Steady-State Photochemical Oxidations. First, we have determined the reaction products formed in preparative photochemical experiments carried out under conditions as close as possible to those used in the laser photolysis experiments. For the reactions sensitized by DCA, O$_2$-saturated MeCN solutions containing DCA and 4-MeOPhCH$_2$X were irradiated by a pyrex-filtered high-pressure mercury lamp (500 W) to ensure the excitation of only the sensitizer ($\lambda > 280$ nm). The oxidations induced by CAN were carried out in MeCN (pyrex filter), again by using the 500-W high-pressure mercury lamp. In both cases, after a standard workup, the products were analyzed by NMR, GC, and GC-MS (comparison with authentic specimens).

Under both the photochemical conditions, 4-MeOPhCH$_2$X was converted into the side chain oxidation product(s) 4-MeOPhCHO and/or 4-MeOPhCOX, depending upon the nature of the α-substituent X. The only exception was the photochemical reaction of *p*-methoxytoluene in the presence of CAN which, in addition to 4-MeOPhCHO, led to benzylic derivatives (nitrate and alcohol). Clearly, the products obtained in the reactions of 4-MeOPhCH$_2$X (X $\neq$ H) derive from first-formed α-substitution products which are hydrolyzed (during workup) to 4-MeOPhCHO or can undergo further oxidation followed by hydrolysis to 4-MeOPhCOX. The product yields did not change significantly when 2,6-lutidine or NO$_3^-$ was added (see infra).

Laser Photolysis Experiments. α-Substituted *p*-methoxytoluenes and 4-MeOPhCD$_3$ were subjected to laser photolysis in MeCN and in the presence of either CAN or DCA/BP. It is well-known that under these conditions the strong electron acceptors, NO$_3^\bullet$ and BP$^{\bullet+}$, respectively, are formed, as shown in eqs 2–4.[4] For the DCA/BP system, the photolysis was carried

$$\mathrm{DCA} \xrightarrow{h\nu} {}^1\mathrm{DCA}^* \tag{2}$$

$${}^1\mathrm{DCA}^* + \mathrm{BP} \rightarrow \mathrm{DCA}^{\bullet-} + \mathrm{BP}^{\bullet+} \tag{3}$$

$$\mathrm{Ce(NO_3)_6}^{-2} \xrightarrow{h\nu} \mathrm{NO_3}^{\bullet} + \mathrm{Ce(NO_3)_5}^{-2} \tag{4}$$

out under O$_2$-saturated conditions to avoid spectral interference from DCA$^{\bullet-}$. Indeed, in the presence of O$_2$, DCA$^{\bullet-}$ is converted into DCA; O$_2^{\bullet-}$ is formed, which is transparent in the region of interest.

NO$_3^\bullet$ and BP$^{\bullet+}$ have already been successfully used to produce cation radicals of aromatics,[4a,5,6] and accordingly, we observed that a pulsed laser excitation (347 nm) of an oxygen-saturated MeCN solution of DCA (4 × 10^{-4} M), in the presence of BP (0.2 M) and 4-MeOPhCH$_2$X (1 × 10^{-3} M), resulted in rapid decay of the BP$^{\bullet+}$ absorbance (λ_{max} = 670 nm) with concomitant formation of a transient species with a λ_{max} in the 400–500-nm region (depending on X). Likewise, after laser excitation (308 or 347 nm) of an argon-saturated MeCN solution of CAN (2 × 10^{-4} M) in the presence of 4-MeOPhCH$_2$X (1 × 10^{-3} M), a rapid decay of the NO$_3^\bullet$ absorbance (λ_{max} = 630 nm) took place with the concomitant formation of a transient *identical* to that formed in the corresponding experiments with the DCA/BP system. These results are illustrated in Figure 1 for the case of the laser photolysis experiments with 4-MeOPhCH$_3$ as the substrate (the negative absorption in the 300–400-nm region is due to the ground-state depletion of CAN). The absorption spectrum of Figure 1a was obtained after subtraction of a long-lived transient recorded in the 450–550-nm region.[7]

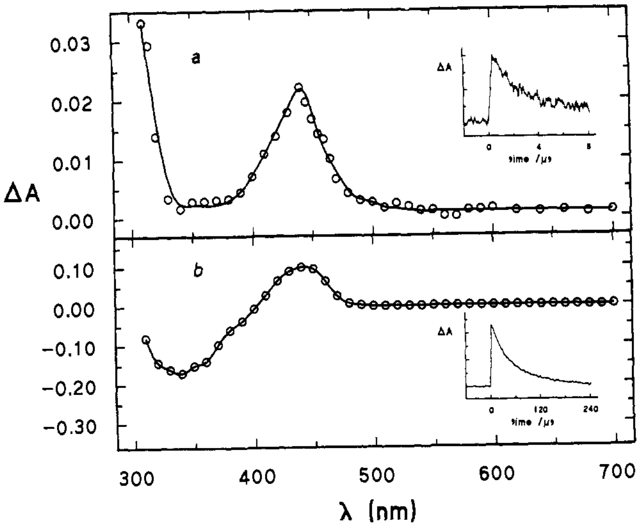

Figure 1. Absorption spectrum (a) produced by 347-nm photolysis of 1 × 10^{-3} M 4-MeOPhCH$_3$ in the presence of 4 × 10^{-4} M DCA and 0.2 M BP in O$_2$-saturated MeCN, recorded 0.6 μs after the laser pulse and obtained by subtracting the contribution of the long-lived transient (see text), and (b) produced by 308-nm photolysis of 1 × 10^{-3} M 4-MeOPhCH$_3$ in the presence of 2 × 10^{-4} M CAN in Ar-saturated MeCN and recorded 1 μs after the laser pulse. The negative absorption is due to the depletion of the ground state of CAN. Insets: decay kinetics of the cation radical recorded at 440 nm.

It seems, therefore, very reasonable to assign the above transients to the 4-MeOPhCH$_2$X cation radicals (eqs 5 and 6),

$$\mathrm{BP}^{\bullet+} + \text{4-MeOPhCH}_2\mathrm{X} \rightarrow \mathrm{BP} + \text{4-MeOPhCH}_2\mathrm{X}^{\bullet+} \tag{5}$$

$$\mathrm{NO_3}^{\bullet} + \text{4-MeOPhCH}_2\mathrm{X} \rightarrow \mathrm{NO_3}^{-} + \text{4-MeOPhCH}_2\mathrm{X}^{\bullet+} \tag{6}$$

a conclusion in line with the results of previous studies and also supported by the fact that the observed absorptions are in the spectral region typical of aromatic cation radicals.[5] It should be noted that, judging from the absorbance values obtained after the pulse, the efficiency in the formation of the cation radical is much higher with CAN than with the DCA/BP system, probably due to differences in the back-electron-transfer rate. In one case (4-MeOPhCH$_2$CN$^{\bullet+}$), the low efficiency of the DCA/BP system has not allowed us to detect the absorption due to the cation radical. Presumably, with respect to the other cation radicals, 4-MeOPhCH$_2$CN$^{\bullet+}$ may have a lower excitation coefficient or be formed in a smaller concentration, being the species with the highest reduction potential (vide infra).

The cation radicals were observed to decay (see insets in Figure 1) with a rate which is of first order in the CAN-promoted reactions and of mixed order in the DCA/BP system. The half-

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(4) (a) Gould, I. R.; Ege, D.; Moser, J. E.; Farid, S. *J. Am. Chem. Soc.* **1990**, *112*, 4290. (b) Herrmann, H.; Exner, M.; Zellner, R. *Ber. Bunsen-Ges. Phys. Chem.* **1991**, *95*, 598 and references therein.

(5) (a) Del Giacco, T.; Baciocchi, E.; Steenken, S. *J. Phys. Chem.* **1993**, *97*, 5451. (b) Baciocchi, E.; Del Giacco, T.; Murgia, S. M.; Sebastiani, G. V. *J. Chem. Soc., Chem. Commun.* **1987**, 1246. (c) Ito, O.; Akiho, S.; Iino, M. *J. Org. Chem.* **1989**, *54*, 2436.

(6) Aloisi, G. G.; Elisei, F.; Latterini, L. *J. Chem. Soc., Faraday Trans.* **1992**, *88*, 2139.

(7) A weak absorption band ($\Delta A < 0.03$) which decayed by first-order kinetics ($\tau \approx 34$ μs) was observed in the 450–550-nm region. This long-lived transient, produced within the laser pulse, was also detected by irradiating DCA in MeCN without additives; addition of BP, O$_2$, and substrate did not change its decay kinetics.

Table I. Absorption Maxima (λ_{max}) and Half-Life Values ($t_{1/2}$) of 4-$MeOPhCH_2X$ Cation Radicals

X	λ_{max} (nm)	$t_{1/2}$ (μs)	
		DCA/BP[a]	CAN[b]
CN			0.31
Cl	≤300, 450	2.1	1.5
OMe	≤300, 420	1.8	3.3
OH	≤300, 420	1.5	2.9
Ph	≤300, 440	2.0	10
4-MeOPh	330, 450	1.7	5.7
OAc	≤300, 460	1.9	4.3
Me	≤300, 430	1.6	12
H	≤300, 440	1.7	34

[a] Cation radicals generated in MeCN by irradiation in the presence of DCA/BP. [b] Cation radicals generated in MeCN by irradiation in the presence of CAN.

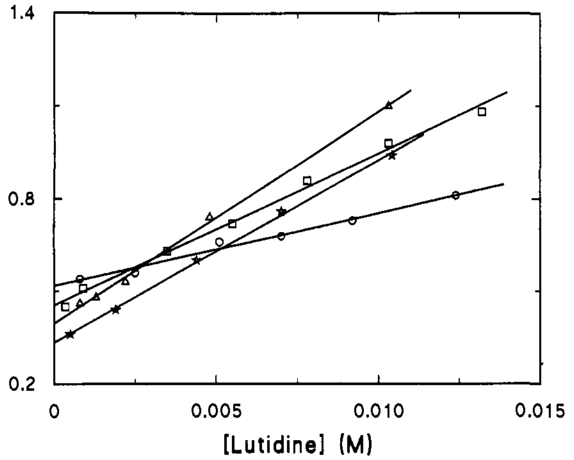

Figure 2. Decay rate constants of $(4\text{-}MeOPh)_2CH_2^{\bullet+}$ (triangles), 4-$MeOPhCH_2CH_3^{\bullet+}$ (stars), 4-$MeOPhCH_3^{\bullet+}$ (squares), and 4-$MeOPhCD_3^{\bullet+}$ (circles) produced in the DCA/BP system, in O_2-saturated MeCN, vs the concentration of 2,6-lutidine (λ_{exc} = 347 nm).

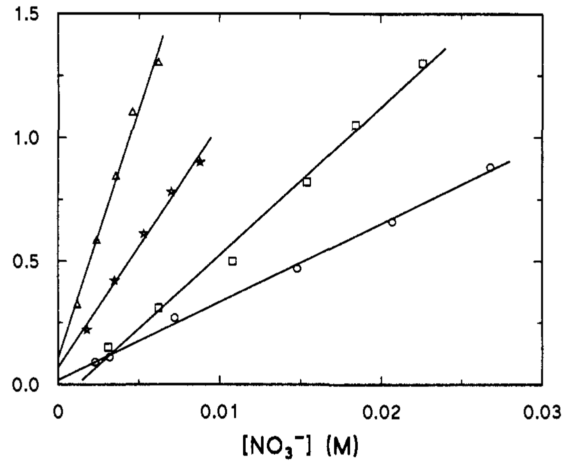

Figure 3. Decay rate constants of $(4\text{-}MeOPh)_2CH_2^{\bullet+}$ (triangles), 4-$MeOPhCH_2CH_3^{\bullet+}$ (stars), 4-$MeOPhCH_3^{\bullet+}$ (squares), and 4-$MeOPhCD_3^{\bullet+}$ (circles) produced by CAN in air-equilibrated MeCN vs the concentration of NO_3^- (λ_{exc} = 347 nm).

Table II. Kinetic and Thermodynamic Data for the Deprotonation of α-Substituted *p*-Methoxytoluene Cation Radicals in MeCN[a]

α-substituent	k_{2obs} (M^{-1} s^{-1})[b]		pK_a[c]	$E°$ (V)[d]
	NO_3^-[e]	2,6-lutidine		
CN	7.5×10^9		-7.9	1.76
Cl	1.2×10^9	1.1×10^8	-4.6	1.72
OMe	8.4×10^8	4.0×10^7	-5.4	1.67
OH	6.1×10^8	5.7×10^7	-5.4	1.67
Ph	1.6×10^8	7.1×10^6	-2.4	1.57
4-MeOPh	2.0×10^8	7.0×10^6	-1.6	1.52
OAc	1.4×10^8	3.5×10^7	-3.7	1.69
Me	9.9×10^7	6.0×10^6	-1.0	1.51
H	4.1×10^7[f]	3.0×10^6[f]	0.45	1.53
D	2.1×10^7[f]	1.5×10^6[f]		

[a] For the generation of the cation radicals, see text. The temperature is 22 ± 2 °C. [b] The average error is ca. 10%. [c] Calculated at 25 °C on the basis of a thermochemical cycle by the equation $pK_a = (1/1.37)[\Delta G°(ArCHX\text{-}H) + 23.06E°(H^\bullet/H^+) - 23.06E°(ArCH_2X)]$, where $\Delta G°(ArCHX\text{-}H)$ is the Gibbs energy for the cleavage of the ArCHX-H bond, given by the ArCHX-H bond dissociation energy (BDE) minus the entropy factor ($T\Delta S°$, taken in all cases as 8 kcal mol^{-1} at 298 K), $E°(H^\bullet/H^+)$ is the oxidation potential (-1.87 V vs SCE)[9] for the oxidation of $H^\bullet$ to H^+ in MeCN, and $E°(ArCH_2X)$ is the oxidation potential of the parent α-substituted *p*-methoxytoluene. The ArCHX-H bond dissociation energies (kcal mol^{-1}) used in these calculations were 87 [X = H, 1 kcal mol^{-1} less than the BDE (88 kcal mol^{-1})[10] of $PhCH_2$-H, since this is the difference between the BDEs of 4-MeOPhCH(CN)-H and PhCH(CN)-H[11]], 82.3 [X = OMe and OH, by assuming that the effect of OH or OMe on BDEs is the same as that found (4.7 kcal mol^{-1})[10] on going from $H—CH_2—CH{=}CH_2$ to $H—CH(OH)—CH{=}CH_2$], 84.4 [X = Me, by assuming that between 4-$MeOPhCH_2$-H and 4-$MeOPhCH(CH_3)$-H there is the same difference in the C-H BDE (2.6 kcal mol^{-1})[10] as between $PhCH_2$-H and $PhCH(CH_3)$-H], 84.7 (X = Cl, assumed equal to X = Me),[12] 81 (X = CN),[11] 83 [X = Ph, as above taken to be 1 kcal mol^{-1} less than the C-H BDE (84 kcal mol^{-1}) in diphenylethane[10]], 82 (X = 4-MeOPh, taken to be 1 kcal mol^{-1} less than for X = Ph), and 85 (X = OAc, by considering that the OCOPh group is 2 kcal mol^{-1} less effective than a methyl group in stabilizing the $-CH_2X$ radical[10] and that the difference should be somewhat less with a benzylic radical). [d] Oxidation potentials (vs SCE) of the parent substrate estimated from $h\nu_{CT}$ for the CT complexes between the *p*-methoxytoluenes and tetracyanoethylene, as described in the text. [e] The counterion is $(n\text{-}Bu)_4N^+$. [f] *k* values are statistically corrected for the difference in the number of α-hydrogen atoms.

life times ($t_{1/2}$) have been determined and collected in Table I together with the values of the absorption maxima. It can be noted that $t_{1/2}$ values are different for the two systems investigated, which indicates different decay paths. Presumably, the cation radicals react with the solvent in the CAN system, whereas reactions with $O_2^{\bullet-}$ are also possible in the DCA/BP system. We have not investigated this problem further but have focused our attention on the cation radical decays in the presence of added bases, i.e., under conditions where deprotonation should be the dominant reaction pathway of these species.

The bases chosen were 2,6-lutidine for the photolysis experiments in the presence of DCA/BP and NO_3^- for those in the presence of CAN. NO_3^- is the only base compatible with the CAN system, whereas the use of a sterically hindered pyridine base, like 2,6-lutidine, is due to the need for avoiding the possibility that the cation radical could undergo ring nuclear attack besides deprotonation.[8] On addition of these bases, the lifetimes of the cation radicals were significantly reduced, as expected. Under both the conditions used, the decay rates of the cation radicals always followed clean first-order kinetics and a linear correlation was found between the first-order rate constants (k_1) and the base concentration (some examples are reported in Figures 2 and 3). From the slopes of these plots, the observed second rate constants (k_{2obs}) were calculated for the decay processes (Table II), which are reasonably attributed to the occurrence of the deprotonation reactions described in eqs 7 and 8.

$$4\text{-}MeOPhCH_2X^{\bullet+} + Lut \rightarrow 4\text{-}MeOPhCHX^\bullet + LutH^+ \tag{7}$$

$$4\text{-}MeOPhCH_2X^{\bullet+} + NO_3^- \rightarrow 4\text{-}MeOPhCHX^\bullet + HNO_3 \tag{8}$$

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(8) Schlesener, C. I.; Kochi, J. K. *J. Org. Chem.* **1984**, *49*, 3142.

(9) Griller, D.; Martinho Simões, J. A.; Mulder, P.; Sim, B. A.; Wayner, D. D. M. *J. Am. Chem. Soc.* **1989**, *111*, 7872.

(10) McMillen, D. F.; Golden, D. M. *Annu. Rev. Phys. Chem.* **1982**, *33*, 493.

(11) Xhang, X.; Bordwell, F. G. *J. Org. Chem.* **1992**, *57*, 4163.

(12) Russel, G. A. In *Free Radicals*; Kochi, J. K., Ed.; Wiley and Sons: New York, 1973; p 283.

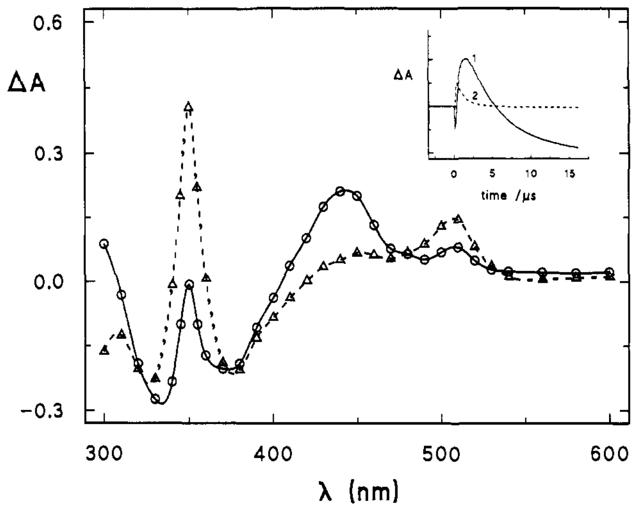

Figure 4. Time-resolved absorption spectra of the CAN/(4-MeOPh)$_2$CH$_2$ system in Ar-saturated MeCN in the presence of 3.6 × 10^{-3} M NO$_3^-$ recorded 0.3 (circles) and 1.5 (triangles) μs after the laser pulse (λ_{exc} = 308 nm). The negative absorption is due to the depletion of the ground state of CAN. Inset: decay kinetics recorded at 350 (1) and 450 (2) nm.

In the case of (4-MeOPh)$_2$CH$_2^{\bullet+}$, it was also possible to observe the deprotonation product, (4-MeOPh)$_2$CH$^\bullet$, which has absorption maxima at 350 and 510 nm. This result is shown in Figure 4, where the time-resolved absorption spectra, obtained by irradiating the CAN/(4-MeOPh)$_2$CH$_2$ system in Ar-saturated MeCN in the presence of 3.6 × 10^{-3} M NO$_3^-$, are displayed. A similar check was not possible for the other substrates as the absorption of the produced benzyl radicals lies at wavelengths shorter than 300 nm, which is the lower limit of our experimental setup.

To test the reliability of the deprotonation rate constants under our reaction conditions, we have also generated the hexamethylbenzene cation radical from the parent hydrocarbon using the DCA/BP system and studied its deprotonation induced by pyridine. A rate constant of 2.8 × 10^7 M^{-1} s^{-1} was obtained, which agrees very well with the value (2.1 × 10^7 M^{-1} s^{-1}) obtained by Kochi and co-workers[13] for the same reaction, but with the hexamethylbenzene cation radical formed by irradiation of hexamethylbenzene in the presence of C(NO$_2$)$_4$.

Discussion

The rate constants, k_{2obs}, for the deprotonation reactions of 4-MeOPhCH$_2$X$^{\bullet+}$ and 4-MeOPhCD$_3^{\bullet+}$, induced by 2,6-lutidine and NO$_3^-$, are reported in Table II. For the reason given above, it was not possible to study the deprotonation of 4-MeOPhCH$_2$CN$^{\bullet+}$ by 2,6-lutidine in the DCA/BP system. Thus, the investigated reactivity span is 10^2 for the reactions with NO$_3^-$, where the rate almost reaches the diffusion-controlled limit with X = CN, but only about 20 for those with 2,6-lutidine. Surprisingly, deprotonations induced by NO$_3^-$ (pK_a = 8.9)[14] were always faster than the corresponding ones induced by 2,6-lutidine (pK_a = 14),[14] in spite of the higher basicity of the latter base. It is possible that steric effects play some role in the reactions promoted by 2,6-lutidine.

In Table II, the pK_a values of the cation radicals, calculated by a thermochemical cycle,[15] from the C–H bond dissociation energies and the oxidation potentials of the parent substrates, are also reported. Due to the great difficulty of obtaining reversible cyclic voltammograms, the oxidation potentials have been estimated by the frequency values of the charge-transfer (CT) bands of the complexes between 4-MeOPhCH$_2$X and tetracyanoethylene, using the correlation (eq 9)established for a series

$$E°(\text{V vs SCE}) = 0.862(h\nu)_{\text{CT}} - 0.271 \qquad (9)$$

of methyl- and alkylbenzenes.[16] The validity of this approach is shown by the fact that it has allowed us to calculate an $E°$ value of 1.53 V (vs SCE) for *p*-methoxytoluene which compares very well with the value (1.56 V) experimentally measured.[8] In spite of this good agreement, there is no doubt that the pK_a values in Table II are subject to a significant error (up to ±2 pK_a units), also in consideration of the uncertainty in the values of the bond dissociation energies. However, it should be noted that the error in the relative values of pK_a is probably smaller and, therefore, we feel that the following discussion on the dependence of the deprotonation rates upon pK_a values is warranted.

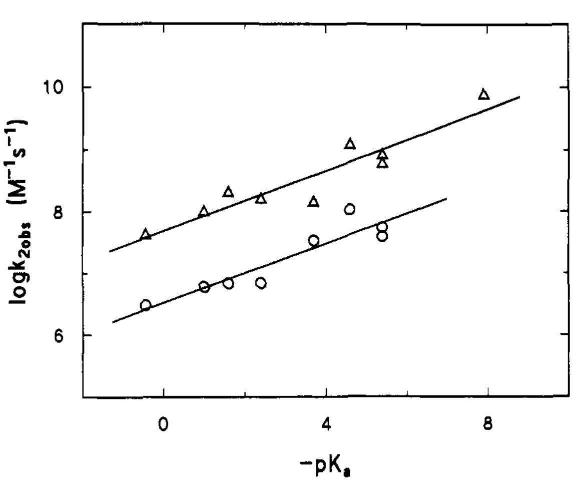

Figure 5. Brönsted plots for the deprotonation of 4-MeOPhCH$_2$X$^{\bullet+}$ by NO$_3^-$ (triangles) and 2,6-lutidine (circles).

The first observation, in this respect, is that the deprotonation rates appear to parallel, quite regularly, the thermodynamic acidity. Indeed, the plot of log k_{2obs} vs pK_a (Brönsted plot) for both of the deprotonation reactions is satisfactorily linear (Figure 5). The α value (0.24) is the same for the two reactions and is quite small. As far as we know, these are the first examples of Brönsted plots for the deprotonation of alkylaromatic cation radicals, obtained by changing the structure of the carbon acid. Interestingly, very similar Brönsted coefficients (between 0.24 and 0.27) have been determined by Kochi and co-workers in the deprotonation of some polymethylbenzene cation radicals, by changing, however, the structure of the pyridine bases.[17] This similarity speaks in favor of the reliability of the pK_a values in Table II (or at least of the relative values) and suggests that no significant charge imbalance should exist in the transition state of these deprotonations.[18]

Clearly, the small α values indicate a transition-state structure very close to that of the reactants, as expected for exergonic reactions and in agreement with previous conclusions.[17] A very small positive charge must reside at the α-carbon in the transition state, in view of the small rate effects observed when the α-substituent is OH or OMe, as well as of the almost identical effect on the rate exhibited by the α-phenyl and the α-methoxyphenyl substituents. Likewise, the small, but certainly primary, deuterium kinetic isotope effects measured by comparing the reactivities of 4-MeOPhCH$_3^{\bullet+}$ and 4-MeOPhCD$_3^{\bullet+}$ (k_H/k_D = 2.0 with NO$_3^-$ and 2.1 with 2,6-lutidine) can be interpreted on the basis of a greatly asymmetric transition state with a very small degree of C–H bond cleavage. Finally, an insignificant role of the base with respect to the transition-state structure is

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(13) Masnovi, J. M.; Sankararaman, S.; Kochi, J. K. *J. Am. Chem. Soc.* **1989**, *111*, 2263.

(14) Izutsu, K. *Acid-Base Dissociation Constants in Dipolar Aprotic Solvents*; IUPAC Chemical Data Series No. 35; Blackwell: Oxford, U.K., 1990; pp 21, 24. We have assumed that 2,6-lutidine has the same pK_a as 2,4-lutidine.

(15) Nicholas, A. M. de P.; Arnold, D. R. *Can. J. Chem.* **1982**, *60*, 2165.

(16) Fukuzumi, S.; Kochi, J. K. *J. Org. Chem.* **1981**, *46*, 4116.

(17) Schlesener, C. I.; Amatore, C.; Kochi, J. K. *J. Am. Chem. Soc.* **1984**, *106*, 7472.

(18) Bernasconi, C. F. *Acc. Chem. Res.* **1992**, *25*, 9.

Scheme I

$$\mathrm{AH + B} \overset{(1)}{\rightleftarrows} \mathrm{(AH\ B)} \overset{(2)}{\rightleftarrows} \mathrm{(A\ HB)} \overset{(3)}{\rightleftarrows} \mathrm{A + HB}$$

also suggested by the identical Brönsted coefficients exhibited by such structurally different bases as 2,6-lutidine and NO_3^-.

Further insight into the nature of the deprotonation process has been obtained by treating the kinetic data in terms of the Marcus equation[19] (eq 10). $\Delta G^{\ddagger}$ is the activation free energy for

$$\Delta G^{\ddagger} = w_r + \Delta G_0^{\ddagger}[1 + (\Delta G^\circ - w_r + w_p)/4\Delta G_0^{\ddagger})]^2 \qquad (10)$$

the proton transfer which is thought to occur inside the encounter complex (step 2 in Scheme I, where charges are omitted for the sake of simplicity); $\Delta G_0^{\ddagger}$ is the intrinsic barrier for this process, that is, the energy expended for bond and solvation reorganization during the proton transfer; w_r and w_p are the energies associated with the formation (step 1) and separation (step 3), respectively, of the encounter pairs; and ΔG° is the free energy of the overall acid–base reaction.

By considering that $\Delta G^{\ddagger} = 2.3RT(\log Z - \log k)$, where Z is 6×10^{11} s^{-1} and that k, the rate constant for step 2, is related to the observed rate constants in Table II by eq 11, with k_d as the diffusional rate constant,[20] eq 10 becomes eq 12, which

$$1/k_{2\mathrm{obs}} = 1/k + 1/k_d \qquad (11)$$

$$\log k_{2\mathrm{obs}} = -\log\{1/Z \exp[-w_r/RT - (\Delta G_0^{\ddagger}/RT)(1 + \Delta G^\circ/4\Delta G_0^{\ddagger} - w_r/4\Delta G_0^{\ddagger})^2] + 1/k_d\} \qquad (12)$$

correlates the observed deprotonation rates to the free energy changes. The values of ΔG° (in kcal mol^{-1}) are calculated at 25 °C by eq 13, where $pK_a(AH)$ and $pK_a(BH)$ are the pK_a values

$$\Delta G^\circ = 1.37[pK_a(AH) - pK_a(BH)] \qquad (13)$$

of the cation radical (Table II) and of the base. In the reaction with NO_3^-, w_r is given by the electrostatic interaction between the anion and the cation (−1.6 kcal mol^{-1}, taking r = 1.89 and 3.5 Å for NO_3^- [21] and the cation radical,[22] respectively, $D_{\mathrm{MeCN}} = 37.5$[23]). Reasonably, w_r can be neglected in the reactions of 2,6-lutidine, as well as w_p for both the deprotonation reactions.[24]

In Figure 6, the result of a nonlinear least squares curve fitting of $\log k_{2\mathrm{obs}}$ and $[pK_a(BH) - pK_a(AH)]$ values to eq 12 is shown, using $\Delta G_0^{\ddagger}$ as the adjustable parameter. The fit is quite good and values of 12.2 (± 0.5) and 15.2 (± 0.3) kcal mol^{-1} have been calculated for the intrinsic barrier of the reactions with NO_3^- and 2,6-lutidine, respectively. It is noteworthy that the barrier for the latter reaction is almost identical to that calculated for the deprotonation of polymethylbenzene cation radicals by substituted pyridines (15.4 kcal mol^{-1}).[17,25] The above intrinsic barriers are also comparable with those generally observed for acid–base reactions involving carbon acids,[19b] as well as with the barriers determined by Saveant for the deprotonation of cation radicals of NADH analogues.[3]

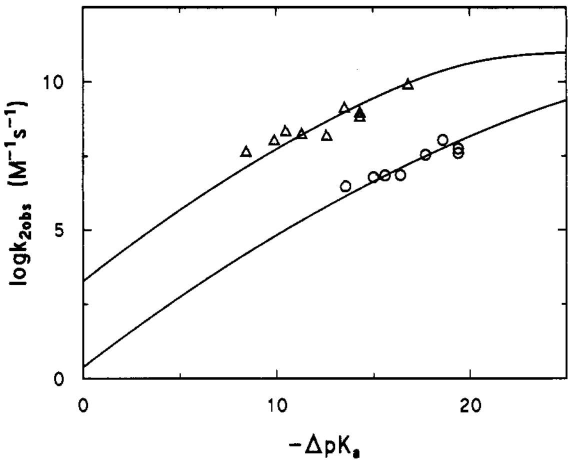

Figure 6. Marcus plots for the deprotonation of $4\text{-}MeOPhCH_2X^{\bullet+}$ by NO_3^- (triangles) and 2,6-lutidine (circles). The points are the experimental data, and the curves have been calculated using eq 12 with $\Delta G_0^{\ddagger}$ values of 12.2 (NO_3^-) and 15.2 (2,6-lutidine) kcal mol^{-1}.

Clearly, these values indicate that there must be significant charge and solvent reorganization in the proton transfer from an alkylaromatic cation radical, a conclusion which appears somewhat surprising in view of the reactant-like transition state of this process. The finding that the intrinsic barrier is smaller in the deprotonations induced by NO_3^- than in those promoted by 2,6-lutidine is in line with the faster rates observed for the former reactions. As already mentioned, steric effects might play some role in the reactions with 2,6-lutidine. In addition, stabilization by hydrogen bond formation (certainly more important with NO_3^- than with 2,6-lutidine) might play a role. It has recently been recognized that this stabilization can also be important in the deprotonation of carbon acids.[27]

Data in Table II also show that all α-substituents increase the deprotonation rate with respect to X = H, both with NO_3^- and 2,6-lutidine, as also observed in the deprotonation of α-substituted *p*-xylenes.[2a] However, in the $4\text{-}MePhCH_2X^{\bullet+}$ series, the relative deprotonation rates (with respect to X = H) were >100 (X = OMe and OH), 14 (X = Me), and 9 (X = CN).[28] Thus, there is some discrepancy between the effects of α-substituents in the two sets of cation radicals, which seems difficult to trace back to the different reaction conditions used for the two systems (in the *p*-xylene series, the solvent was AcOH or AcOH/MeCN and only relative reactivity data were obtained by a product distribution study). In particular, this discrepancy mainly concerns the fact that α-substituents of the +R type (OH, OMe, and to a less extent Me) have a much larger kinetic effect in the deprotonation of $4\text{-}MePhCH_2X^{\bullet+}$ than in that of $4\text{-}MeOPhCH_2X^{\bullet+}$; the contrary instead occurs with a −I or −R α-substituent like the CN group. A quite noteworthy consequence is that, for example, $4\text{-}MePhCH_2OMe^{\bullet+}$ is deprotonated at a significantly faster rate (more than 15 times) than $4\text{-}MePhCH_2CN^{\bullet+}$, whereas the reverse holds (see Table I) in the case of the corresponding *p*-methoxy compounds.

It is interesting to look at these different behaviors in light of the model recently proposed by Saveant and his associates for the deprotonation of NADH analogue cation radicals.[3] According to this model, the dynamics of the deprotonation process are dominated by the C–H homolytic bond dissociation energy in the cation radical, BDE($RH^{\bullet+}$). Now, there is little doubt that, with *p*-xylene cation radicals, the effect of α-substituents, at least qualitatively, is in agreement with this model. Indeed, in this system, the α-substituents of the +R type, which decrease the

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[19] (a) Marcus, R. A. *J. Phys. Chem.* **1968**, *72*, 891. (b) Cohen, A. O.; Marcus, R. A. *Ibid.* **1968**, *72*, 4249. (c) Kresge, A. *J. Chem. Soc. Rev.* **1973**, *2*, 475.

[20] k_d has been calculated as 1.1×10^{11} M^{-1} s^{-1} in the reaction with NO_3^- and as 1.9×10^{10} M^{-1} s^{-1} in the reaction with 2,6-lutidine (Cannon, R. D. *Electron Transfer Reactions*; Butterworths: London, 1988; p 100).

[21] Waddington, J. C. *Adv. Inorg. Chem. Radiochem.* **1959**, *1*, 180.

[22] Schlesener, C. J.; Amatore, C.; Kochi, J. K. *J. Am. Chem. Soc.* **1984**, *106*, 3567.

[23] Murov, S. L. *Handbook of Photochemistry*; Dekker: New York, 1973.

[24] Calculations have also been performed using both w_r and $\Delta G_0^{\ddagger}$ as independent parameters. In this case $\Delta G_0^{\ddagger}$ is 9.4 kcal mol^{-1} for NO_3^- (w_r = 1.8 kcal mol^{-1}) and 12.4 kcal mol^{-1} for 2,6-lutidine (w_r = 3.2 kcal mol^{-1}).

[25] This values has been calculated by Saveant and his associates[3] using the data of ref 26. However, in ref 26, a value of $\Delta G_0^{\ddagger}$ (6.5 kcal mol^{-1}) is reported.

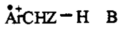
[26] Schlesener, C. J.; Amatore, C.; Kochi, J. K. *J. Phys. Chem.* **1986**, *90*, 3747.

[27] Bednar, R. A.; Jencks, W. P. *J. Am. Chem. Soc.* **1985**, *107*, 7117.

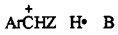
[28] These relative reactivities refer to cation radicals generated by anodic oxidation in AcOH/MeCN. Similar values are obtained when the oxidant is cerium(IV) ammonium nitrate.

BDE($RH^{\bullet+}$) to the largest extent, are also those exerting the largest enhancing effect upon the deprotonation rate. The same does not hold, however, for the cation radicals studied in the present paper, since we observe that, whereas the homolytic C–H bond dissociation energy is ca. 24 kcal mol^{-1} lower in 4-$MeOPhCH_2OMe^{\bullet+}$ than in 4-$MeOPhCH_2CN^{\bullet+}$,[29] the rate of deprotonation is ca. 10 times higher in the latter than in the former cation radical.

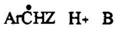
We can attempt an explanation of the small kinetic effect of +R α-substituents on the deprotonation rate of 4-$MeOPhCH_2X^{\bullet+}$, as compared to the very large effect that these substituents exert on the homolytic C–H BDE, based on the reasonable suggestion that the transition state for the deprotonation of an alkylaromatic cation radical may be described by the resonating structures **1**–**3**.


$\overset{\bullet+}{Ar}CHZ-H\quad B$

1


$Ar\overset{+}{C}HZ\quad H^{\bullet}\quad B$

2


$Ar\overset{\bullet}{C}HZ\quad H^{+}\quad B$

3

In structure **1**, the charge is still almost completely located in the aromatic ring, whereas structures **2** and **3** represent the homolytic and the heterolytic C–H bond cleavages, respectively. However, if the homolytic bond dissociation energy is the dominant factor in the dynamics of the deprotonation, it is very likely that **1** and **2** are the structures which best describe the transition state. Thus, the kinetic effect of α-substituents might also depend upon the relative importance of the two structures, since this should determine the extent of positive charge located on the α-carbon in the transition state.

In an alkylaromatic cation radical, the buildup of positive charge at the α-carbon requires extensive charge delocalization from the aromatic ring, and it is, therefore, possible that, when ring substituents very effective in stabilizing a positive charge (i.e., the MeO group in 4-$MeOPhCH_2X^{\bullet+}$)[31] are present, only a very small fraction of this charge is localized at, or has been transferred to, the benzylic carbon in the transition state. This fraction can, however, become significantly larger when the ring methoxy group is replaced by the methyl group (*p*-xylenes series), which is a weaker electron donor. In other words, in the deprotonation of 4-$MeOPhCH_2OR^{\bullet+}$, the expected favorable kinetic effect of the α-OMe substituent, related to its capacity of weakening the BDE($RH^{\bullet+}$) might be partially offset by the reduced charge delocalization at the benzylic carbon, due to the presence of the ring *p*-OMe group. The same phenomenon could explain the low rate enhancements observed for the other +R α-substituents (phenyl, 4-methoxyphenyl, and methyl) in the deprotonation of 4-$MeOPhCH_2X^{\bullet+}$.

This type of reasoning may, of course, also be applied to the kinetic effect of the α-CN group, which, as said before, is much larger in the deprotonation of 4-$MeOPhCH_2X^{\bullet+}$ than in that of 4-$MePhCH_2X^{\bullet+}$. The α-CN group is expected to somewhat decrease the BDE($RH^{\bullet+}$)[33] and therefore to increase the deprotonation rate. However, this time, the effect is felt less in the reaction of 4-$MePhCH_2X^{\bullet+}$ due to the counteracting action of the larger fraction of positive charge residing, in this case, on the benzylic carbon, in the transition state.

In conclusion, it is quite reasonable that α-substituents increase the deprotonation rate of an alkylaromatic cation radical as they generally also decrease the BDE($RH^{\bullet+}$). However, substantial deviations from the expected reactivity orders for different series of compounds are possible, probably due to differences in the amount of positive charge which develops at the C_α-H carbon in the respective transition states. The presence of ring substituents with different capacities of delocalizing a positive charge may play a crucial role in this respect.

Experimental Section

Starting Materials. Cerium (IV) ammonium nitrate (Baker), tetra-*n*-butylammonium nitrate (Fluka), biphenyl (Carlo Erba RP), 4-methoxytoluene (Aldrich), and 4-methoxybenzyl alcohol (Aldrich) were commercial products, used as received. 4-Methoxybenzyl chloride, (4-methoxyphenyl)acetonitrile, and 2,6-lutidine were commercial products (Aldrich) purified by distillation. 9,10-Dicyanoanthracene (Kodak) was recrystallized from pyridine and MeCN. Using standard procedures, 4-methoxybenzyl methyl ether was prepared from 4-methoxybenzyl alcohol, 4-methoxyethylbenzene from 4-methoxyacetophenone (Aldrich), and (4,4′-dimethoxydiphenyl)methane from 4,4′-dimethoxybenzophenone. 4-Methoxytoluene-α,α,α-d_3 was synthesized by the procedure reported by Dewar and associates.[34] Spectrophotometric grade MeCN (Aldrich) was used.

Steady-State Photoreactions. (*a*) *With DCA/O$_2$.* An O_2-saturated MeCN solution (10 mL) containing DCA (4×10^{-4} M) and 4-$MeOPhCH_2X$ (4×10^{-2} M) was irradiated by a pyrex-filtered 500-W high-pressure mercury lamp under oxygen bubbling. The reaction mixture was worked up with aqueous HCl to remove the base and extracted with ethylic ether. The ether was removed after drying the extracts over anhydrous $MgSO_4$ and the residue analyzed by GC-MS and ^1H NMR (comparison with authentic samples) using bibenzyl as an internal standard.

(*b*) *With CAN.* A solution of 4-$MeOPhCH_2X$ (4×10^{-2} M) and CAN (8×10^{-2} M) in MeCN (12.5 mL) was irradiated with a 500-W high-pressure mercury lamp through pyrex. Workup and product analyses were as above. CAN concentration was determined by UV spectrophotometric analysis.

Laser Flash Photolysis. Excitation wavelengths of 308 and 347 nm from an excimer laser (Lambda Physik, LPX105) and a ruby laser (J.K., second harmonics) were used in nanosecond flash photolysis experiments (pulse width < 20 ns and energy < 10 mJ/pulse).[35] The decay of the cation radical, in the absence of added base, exhibited first-order kinetics when the irradiation was in the presence of CAN and mixed first–second-order kinetics in the presence of DCA/BP; in the absence of added base, regular first-order kinetics were observed in both cases. The transient spectra were obtained by a point-to-point technique, monitoring the optical density change (ΔA) values after the flash at intervals of 10 nm over the spectral range 300–700 nm and obtained by averaging at least 10 decays at each wavelength. All measurements were carried out at 22 ± 2 °C; the solutions were saturated by bubbling with oxygen or argon.

Charge-Transfer Complexes. The spectra of the charge-transfer complexes of tetracyanoethylene with 4-$MeOPhCH_2X$ have been recorded as previously described.[36] The λ_{max} value (nm) corresponding to the longer wavelength CT band have been the following: X = H, 562; X = Me, 567; X = OMe, 524; X = OAc, 518; X = CN, 502; X = Cl, 510; X = Ph, 550; X = 4-MeOPh, 565.

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[29] These values are calculated from the relationship BDE($RH^{\bullet+}$) = $23.06E°(R^{\bullet}/R^{+})$ + BDE(RH) − $23.06E°(RH/RH^{\bullet+})$. The oxidation potentials (V vs SCE) for the $R^{\bullet}/R^{+}$ couple are −0.51 (4-$MeOPhCHOMe^{\bullet}$) and 0.70 (4-$MeOPhCHCN^{\bullet}$).[30] The other data used in the calculations are from Table II.

[30] Wayner, D. D. M.; Sim, B. A.; Danneberg, J. J. *J. Org. Chem.* **1991**, *56*, 4853.

[31] That a large fraction of positive charge should be located on the ring methoxy group is shown by the high hyperfine coupling constant exhibited by the OCH_3 hydrogens in the anisole cation radical.[32]

[32] Neill, P. O.; Steenken, S.; Schulte-Frohlinde, D. *J. Phys. Chem.* **1975**, *79*, 2773. Dixon, W. T.; Murphy, D. *J. Chem. Soc., Perkin Trans. 2* **1976**, 1823.

[33] This is due to the fact that the α-CN group lowers the homolytic C–H BDE and increases the oxidation potential of the neutral substrate. The two effects overcome that of the destabilization of the benzyl carbocation, which acts in the opposite direction.

[34] Andrulis, P. J.; Dewar, M. J. S.; Dietz, R.; Hunt, R. L. *J. Am. Chem. Soc.* **1966**, *88*, 5473.

[35] (a) Romani, A.; Elisei, F.; Masetti, F.; Favaro, G. *J. Chem. Soc., Faraday Trans.* **1992**, *88*, 2147. (b) Görner, H.; Elisei, F.; Aloisi, G. G. *J. Chem. Soc., Faraday Trans.* **1992**, *88*, 29.

[36] Baciocchi, E.; Crescenzi, M.; Fasella, E.; Mattioli, M. *J. Org. Chem.* **1992**, *57*, 4684.