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Nucleophilicities of Nitroalkyl Anions

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The kinetics of the reactions of eight nitroalkyl anions (nitronate anions) with benzhydrylium ions and quinone methides in DMSO and water were investigated photometrically. The second-order rate constants were found to follow a Ritchie constant selectivity relationship with slightly smaller selectivities than those observed previously for other carbanions and O or N nucleophiles. Evaluation of the kinetic data by the correlation equation log k (20 °C) $= s(N + E)$ yields the nucleophilicity parameters (N), which allow a comparison of the nucleophilicities of nitronates with those of other classes of compounds. Although the aliphatic nitronates **1a**−**c** are more nucleophilic than the aromatic representatives **1d**−**h** in DMSO, hydration reduces the nucleophilicities of aliphatic nitronates by a factor of 1 million, which is considerably greater than the reduction of the reactivities of the aromatic nitronates with the consequence that aromatic nitronates are more nucleophilic in water than aliphatic ones. The nucleophilic reactivities of nitronates are only slightly affected by substituent variation in DMSO and even less so in aqueous solution, which is considered to be the reason for the unusual rate equilibrium relationships, the so-called nitroalkane anomaly. Outer-sphere electron transfer does not occur in any of the reactions that were investigated.

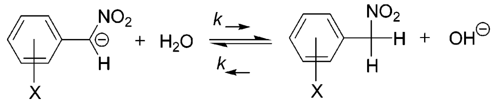
Introduction

Relationships between nucleophilicity and basicity belong to the fundamental concepts of the electronic theory of organic chemistry.[1,2] Thus, substituents R that increase the basicity of carbanions are generally assumed to also increase the nucleophilicity.[2,3]

$$R{-}CH_2^{\ominus} + EX \rightarrow R{-}CH_2E + X^{\ominus}$$

It has long been known, however, that acceptor groups in the *m*- and *p*-positions of phenylnitromethyl anions reduce basicity (as expected) but, at the same time, increase the rate of conversion of the nitroalkyl anions into the corresponding acids ($k_{\rightarrow}$ in Scheme 1).[4]

SCHEME 1. Protonation of Aryl Nitronates in Water



This and related phenomena are termed nitroalkane anomaly.[5] As a consequence, in contrast to common practices in preparative carbanion chemistry, pK_{aH} values cannot be employed for estimating the relative nucleophilicities of nitroalkyl anions, which are of great importance as reagents in organic synthesis.[6]

Previously, we have demonstrated that eq 1 can be used for developing a comprehensive nucleophilicity scale, including *n*-, π-, and σ-nucleophiles,[7] and we have suggested employing benzhydrylium ions and structur-

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[1] Brønsted, J. N.; Pedersen, K. *Z. Phys. Chem.* **1924**, *108*, 185−235.

[2] Bordwell, F. G.; Cripe, T. A.; Hughes, D. L. In *Nucleophilicity*; Harris, J. M., McManus, S. P., Eds.; American Chemical Society: Washington, DC, 1987.

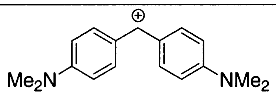
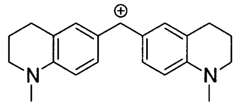
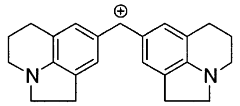
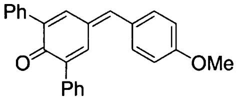
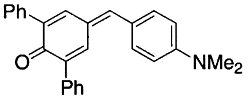
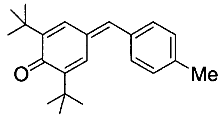
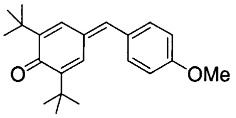
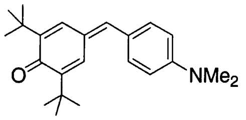
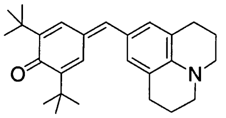
[3] (a) Bates, R. B.; Ogle, C. A. In *Carbanion Chemistry-Reactivity and Structure Concepts in Organic Chemistry*; Hafner, K., Lehn, J.-M., Rees, C. W., Schleyer, P. von R., Trost, B. M., Zahradnik, R., Eds.; Springer-Verlag: Berlin, 1983; Vol. 17. (b) Buncel, E.; Dust, J. M. *Carbanion Chemistry-Structures and Mechanism*; Oxford: New York, 2003. (c) Snieckus, V. *Advances in Carbanion Chemistry*; JAI: Greenwich, CT, 1992 and 1996; Vols. 1 and 2. (d) Heathcock, C. H.; Winterfeldt, E.; Schlosser, M. In *Modern Synthetic Methods-Topics in Carbanion Chemistry*; Scheffold, R., Ed.; VHCA and VCH: Basel, Switzerland, and Weinheim, Germany, 1992. (e) *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Pattenden, G., Eds.; Pergamon Press: Oxford, 1991; Vol. 3, Chapters 1.1−1.7.

[4] (a) Fukuyama, M.; Flanagan, P. W. K.; Williams, F. T., Jr.; Frainier, L.; Miller, S. A.; Shechter, H. *J. Am. Chem. Soc.* **1970**, *92*, 4689−4699. (b) Bordwell, F. G.; Boyle, W. J., Jr.; Yee, K. C. *J. Am. Chem. Soc.* **1970**, *92*, 5926−5932. (c) Bordwell, F. G.; Boyle, W. J., Jr. *J. Am. Chem. Soc.* **1975**, *97*, 3447−3452. (d) Bernasconi, C. F.; Wiersema, D.; Stronach, M. W. *J. Org. Chem.* **1993**, *58*, 217−223.

[5] (a) Bernasconi, C. F.; Ali, M.; Gunter, J. C. *J. Am. Chem. Soc.* **2003**, *125*, 151−157. (b) Yamataka, H.; Ammal, S. C. *Arkivoc* **2003**, 59−68. (c) Eliad, L.; Hoz, S. *J. Phys. Org. Chem.* **2002**, *15*, 540−543. (d) Yamataka, H.; Mustanir; Mishima, M. *J. Am. Chem. Soc.* **1999**, *121*, 10223−10224. (e) Beksic, D.; Betran, J.; Lluch, J. M.; Hynes, J. T. *J. Phys. Chem. A* **1998**, *102*, 3977−3984. (f) Erden, I.; Keefe, J. R.; Xu, F. P.; Zheng, J. B. *J. Am. Chem. Soc.* **1993**, *115*, 9834−9835. (g) Bernasconi, C. F.; Paschalis, P. *J. Am. Chem. Soc.* **1989**, *111*, 5893−5902. (h) Albery, W. J.; Bernasconi, C. F.; Kresge, A. J. *J. Phys. Org. Chem.* **1988**, *1*, 29−31. (i) Pross, A.; Shaik, S. S. *J. Am. Chem. Soc.* **1982**, *104*, 1129−1130. (j) Agmon, N. *J. Am. Chem. Soc.* **1980**, *102*, 2164−2167. (k) Keeffe, J. R.; Morey, J.; Palmer, C. A.; Lee, J. C. *J. Am. Chem. Soc.* **1979**, *101*, 1295−1297. (l) Kresge, A. J. *Can. J. Chem.* **1974**, *52*, 1897−1903. (m) Goumont, R.; Magnier, E.; Kizilian, E.; Terrier, F. *J. Org. Chem.* **2003**, *68*, 6566−6570. (n) Terrier, F.; Moutiers, G.; Pelet, S.; Buncel, E. *Eur. J. Org. Chem.* **1999**, 1771−1774. (o) Moutiers, G.; Peignieux, A.; Terrier, F. *J. Chem. Soc., Perkin Trans. 2* **1998**, 2489−2495. (p) Moutiers, G.; Thuet, V.; Terrier, F. *J. Chem. Soc., Perkin Trans. 2* **1997**, 1479−1486. (q) Marcus, R. A. *J. Am. Chem. Soc.* **1969**, *91*, 7224−7225.

10.1021/jo048773j CCC: $27.50

TABLE 1. Electrophilicity Parameters *E* and Ritchie Parameters (log k_0) of the Reference Electrophiles Employed for Determining the Nucleophilicities of Nitroalkyl Anions 1a–h

	electrophile	*E*	log k_0^a	λ_{max} (nm)
2a		-7.02^b	-2.64	604^a
2b		-8.22^b	-3.34	618^a
2c		-10.04^b	-4.44	630^a
2d		-12.18^c	–	420^d
2e		-13.39^c	–	533^d
2f		-15.83^c	–	371^e
2g		-16.11^c	–	393^e
2h		-17.29^c	–	486^e
2i		-17.90^c	–	521^e

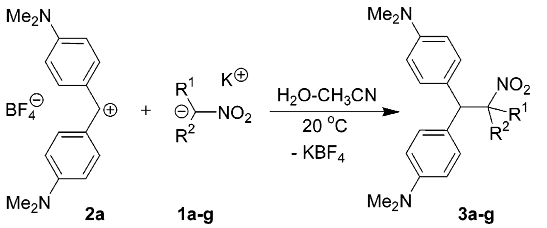
[a] In water, from ref 11. [b] From ref 8. [c] From ref 9. [d] In DMSO, from ref 12. [e] In DMSO, from ref 13.

ally related quinone methides as reference electrophiles[8–10] (Table 1)

$$\log k\ (20\ °\mathrm{C}) = s(N + E) \tag{1}$$

where k is the second-order rate constant in $M^{-1}\ s^{-1}$, s is the nucleophile-specific slope parameter, N is the nucleophilicity parameter, and E is the electrophilicity parameter.

SCHEME 2

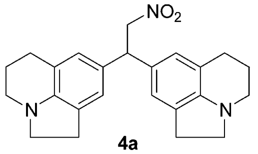


1a (R^1 = H, R^2 = H)	**3a** (86 %)
1b (R^1 = H, R^2 = CH_3)	**3b** (80 %)
1c (R^1 = CH_3, R^2 = CH_3)	**3c** (70 %)
1d (R^1 = H, R^2 = C_6H_5)	**3d** (93 %)
1e (R^1 = H, R^2 = 4-CH_3-C_6H_4)	**3e** (90 %)
1f (R^1 = H, R^2 = 4-NO_2-C_6H_4)	**3f** (92 %)
1g (R^1 = H, R^2 = 3-NO_2-C_6H_4)	**3g** (78 %)

Results

Preparative Investigations. As discussed by Seebach,[14] nitronate ions cannot be readily C-alkylated by ordinary alkyl halides. In contrast, good yields of the C-alkylation products (**3a**–**g**) were obtained when solid benzhydrylium tetrafluoroborate (**2a**-BF_4^-) was added to solutions of the potassium nitronates [(**1a**–**g**)-K^+] in aqueous acetonitrile (Scheme 2).

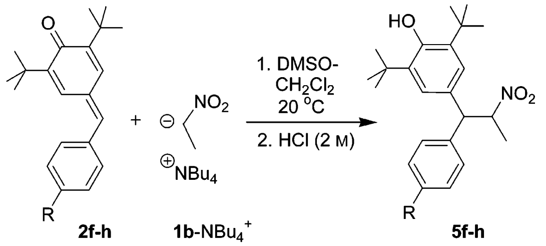
The less-electrophilic benzhydrylium tetrafluoroborate **2c**-BF_4^- was demonstrated to react analogously with **1a** to yield 87% of the addition product **4a**.



4a

Only moderate yields of products **5f**–**h** were isolated when **1b**-NBu_4^+ was combined with the quinone methides **2f**–**h** in DMSO (Scheme 3).[13]

SCHEME 3



2f (R = Me)	**5f** (19 %)
2g (R = OMe)	**5g** (55 %)
2h (R = NMe_2)	**5h** (43 %)

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(6) (a) *Nitro Compounds*; Feuer, H., Nielsen, A., Eds.; Wiley: New York, 1990. (b) Seebach, D.; Colvin, E. W.; Lehr, F.; Weller, T. *Chimia* **1979**, *33*, 1–18. (c) Ono, N. *The Nitro Group in Organic Synthesis*; Wiley-VCH: Weinheim, Germany, 2001. (d) Denmark, S. E.; Cotell, J. J. In *The Chemistry of Heterocyclic Compounds*; Padwa, A., Pearson, W. H., Eds.; Wiley: New York, 2002; Vol. 59, pp 83–167. (e) Torssell, K. B. G. In *Nitrile Oxides, Nitrones, and Nitronates in Organic Synthesis*; Feuer, H., Ed.; VCH: Weinheim, Germany, 1988; pp 129–270. (f) Tartakovsky, V. A.; Ioffe, S. L.; Dilman, A. D.; Tishkov, A. A. *Russ. Chem. Bull.* **2001**, *50*, 1936–1948. (g) Schlosser, M. In *Organometallics in Synthesis-A Manual*; Schlosser, M., Ed.; Wiley: Chichester, U.K., 2002; pp 1–352.

(7) Mayr, H.; Patz, M. *Angew. Chem.* **1994**, *106*, 990–1010; *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 938–957.

(8) Mayr, H.; Bug, T.; Gotta, M. F.; Hering, N.; Irrgang, B.; Janker, B.; Kempf, B.; Loos, R.; Ofial, A. R.; Remennikov, G.; Schimmel, H. *J. Am. Chem. Soc.* **2001**, *123*, 9500–9512.

(9) Lucius, R.; Loos, R.; Mayr, H. *Angew. Chem.* **2002**, *114*, 97–102; *Angew. Chem., Int. Ed.* **2002**, *41*, 91–95.

(10) Mayr, H.; Kempf, B.; Ofial, A. R. *Acc. Chem. Res.* **2003**, *36*, 66–77.

(11) Minegishi, S.; Mayr, H. *J. Am. Chem. Soc.* **2003**, *125*, 286–295.

(12) Remennikov, G.; Mayr, H., unpublished results.

(13) Lucius, R. *Kinetische Untersuchungen zur Nucleophilie stabilisierter Carbanionen*, Dissertation, Ludwig-Maximilians-Universität, München, Germany, 2001.

(14) (a) Seebach, D.; Lehr, F. *Helv. Chim. Acta* **1979**, *62*, 2239–2257. (b) On the ambident reactivity of nitronate anions, see also: Linton, B. R.; Goodman, M. S.; Hamilton, A. D. *Chem. Eur. J.* **2000**, *6*, 2449–2455.

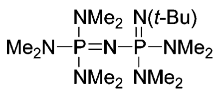
As shown in Schemes 2 and 3, product studies, including the full characterization of compounds **3a**−**g**, **4a**, and **5f**−**h** (see Supporting Information), were only performed for representative combinations of nitronate anions **1** and electrophiles **2** because variations of the remote aryl substituents were not expected to affect the types of products.

Kinetic Investigations

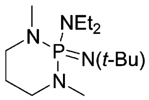
General. All of the reactions investigated in this work have been studied photometrically following the decay of electrophiles **2a**−**i** (absorption maxima at $\lambda_{\max} = 371$−630 nm). Nitroalkyl anions **1a**−**h** were generally employed in large excess over the electrophiles (see Tables S1−S49 in the Supporting Information). As a consequence, the concentrations of **1a**−**h** remained almost constant throughout the reactions and gave rise to pseudo-first-order kinetics with an exponential decay of the concentrations of the electrophiles **2** (eq 2).

$$-\mathrm{d}[\mathbf{2}]/\mathrm{d}t = k_{1\Psi}[\mathbf{2}] \tag{2}$$

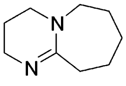
Kinetic Investigations in DMSO. Dimethyl sulfoxide solutions of nitroalkyl anions **1a**−**h** were generated by deprotonation of the corresponding CH acids with phosphazene bases P$_2$-*t*-Bu, BEMP, and DBU.[15]



P$_2$-*t*-Bu



BEMP



DBU

In previous work, we have shown that ion pairing or variable ion strengths did not affect the kinetics of the reactions of stabilized carbanions with quinone methides or benzhydrylium ions in DMSO.[9,16] This behavior was explained by the low values of the ion-pair association constants[17] in solvents of high permittivity ($\epsilon_{\mathrm{DMSO}} = 46$; from ref 18).

As shown in Figure 1 and for all other systems in the Supporting Information, plots of $k_{1\Psi}$ versus nitroalkyl anion concentration were generally linear, with almost zero intercepts. One can, therefore, conclude that the nature of the nucleophiles (free or paired ions) did not significantly change within the concentration range investigated. The slopes of these correlations gave the second-order rate constants (k_{2,C^-}) that are listed in Table 2.

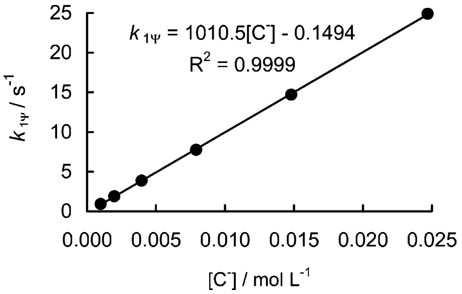
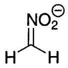
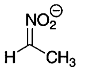
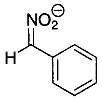
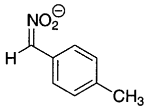
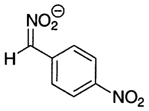
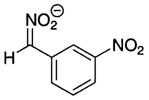
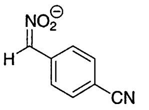


FIGURE 1. Determination of the second-order rate constant (k_{2,C^-}) for the reaction of **2f** with deprotonated nitromethane [**1a**-(P$_2$-*t*-Bu)-H$^+$] in DMSO at 20 °C.

TABLE 2. Second-Order Rate Constants (k_{2,C^-}) for the Reactions of Nitroalkyl Anions 1a−h with Quinone Methides or Benzhydrylium Tetrafluoroborates in DMSO at 20 °C

carbanion		pK_{aH}[a]	counterion[b]	electrophile	k_{2,C^-} ($\mathrm{M^{-1}\,s^{-1}}$)
1a		17.2[c]	(P$_2$-*t*-Bu)-H$^+$	**2d**	1.26×10^{5}
			(P$_2$-*t*-Bu)-H$^+$	**2e**	2.04×10^{4}
			(P$_2$-*t*-Bu)-H$^+$	**2f**	1.01×10^{3}
			(P$_2$-*t*-Bu)-H$^+$	**2i**	4.24×10^{1}
1b		16.7[d]	(P$_2$-*t*-Bu)-H$^+$	**2d**	6.18×10^{5}[e]
			(P$_2$-*t*-Bu)-H$^+$	**2e**	1.23×10^{5}[e]
			NBu$_4^+$	**2g**	2.06×10^{3}[f]
			NBu$_4^+$	**2h**	4.12×10^{2}[f]
			NBu$_4^+$	**2i**	2.00×10^{2}[f]
1c		16.8[d]	(P$_2$-*t*-Bu)-H$^+$	**2d**	5.81×10^{5}
			(P$_2$-*t*-Bu)-H$^+$	**2e**	9.50×10^{4}
			(P$_2$-*t*-Bu)-H$^+$	**2f**	1.85×10^{3}
			(P$_2$-*t*-Bu)-H$^+$	**2i**	7.29×10^{1}
1d		12.2[d]	(BEMP)-H$^+$	**2c**	8.52×10^{5}
			(BEMP)-H$^+$	**2e**	2.69×10^{3}
			(BEMP)-H$^+$	**2h**	5.54
1e		12.33[g]	(BEMP)-H$^+$	**2c**	2.23×10^{6}
			(BEMP)-H$^+$	**2e**	4.05×10^{3}
			(BEMP)-H$^+$	**2h**	6.82
1f		8.62[g]	(DBU)-H$^+$	**2b**	1.18×10^{6}
			(DBU)-H$^+$	**2c**	5.15×10^{4}
			(DBU)-H$^+$	**2f**	2.21
1g		10.04[g]	(DBU)-H$^+$	**2c**	7.66×10^{5}
			(DBU)-H$^+$	**2e**	9.03×10^{2}
			(DBU)-H$^+$	**2i**	1.85
1h		9.31[g]	(DBU)-H$^+$	**2c**	1.62×10^{5}
			(DBU)-H$^+$	**2e**	2.29×10^{2}
			(DBU)-H$^+$	**2h**	7.52×10^{-1}

[a] In DMSO. [b] For abbreviations, see ref 15. [c] From ref 17. [d] From ref 19. [e] From ref 20. [f] From ref 16. [g] From ref 21.

Kinetic Investigations in Water. In the reactions of nitroalkyl anions **1a**−**h** in water, competing reactions of the benzhydrylium ions with hydroxide and water have to be considered. The observed pseudo-first-order rate constants ($k_{1\Psi,\mathrm{obs}}$) reflect the sum of the reactions of the

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(15) Schwesinger, R.; Schlemper, H.; Hasenfratz, C.; Willaredt, J.; Dambacher, T.; Breuer, T.; Ottaway, C.; Fletschinger, M.; Boele, J.; Fritz, H.; Putzas, D.; Rotter, H. W.; Bordwell, F. G.; Satish, A. V.; Ji, G.-Z.; Peters, E.-M.; Peters, K.; von Schnering, H. G.; Walz, L. *Liebigs Ann. Chem.* **1996**, 1055−1081. P$_2$-*t*-Bu: 1-(*tert*-butylimino)-1,1,3,3,3-pentakis(dimethylamino)-1λ^5,3λ^5-diphosphazene, pK_{BH^+} = 21.4 (in DMSO), CAS Registry No. 111324-03-9. BEMP: (2-*tert*-butylimino-1,3-dimethyl-2λ^5-[1,3,2]diazaphosphinan-2-yl)diethylamine, p$K_{\mathrm{BH}^+} \approx$ 16.5 (in DMSO), CAS Registry No. 98015-45-3. DBU: 1,8-diazabicyclo-[5.4.0]undec-7-ene, p$K_{\mathrm{BH}^+} \approx$ 13.9 (in DMSO), CAS Registry No. 6674-22-2.

(16) Lucius, R.; Mayr, H. *Angew. Chem.* **2000**, *112*, 2086−2089; *Angew. Chem., Int. Ed.* **2000**, *39*, 1995−1997.

(17) Olmstead, W. N.; Bordwell, F. G. *J. Org. Chem.* **1980**, *45*, 3299−3305.

(18) Reichardt, C. *Solvents and Solvent Effects in Organic Chemistry*, 3rd ed.; Wiley-VCH: Weinheim, Germany, 2003.

TABLE 3. Influence of the Concentration of Hydroxide on the Second-Order Rate Constants k_2 of the Reactions of 2b-BF_4^- with the Potassium Salt of Nitromethane (1a)

entry	[**2b**-BF_4^-]$_0$ (M)	[OH^-]$_0$ (M)	[CH_3NO_2]$_0$ (M)	[**1a**-K^+] (M)	$k_{1\Psi}$ (s^{-1})	k_2 (M^{-1} s^{-1})
1	2.34×10^{-5}	7.76×10^{-5}	8.13×10^{-4}	6.35×10^{-5}	8.29×10^{-3}	
2	2.55×10^{-5}	2.11×10^{-4}	2.21×10^{-3}	1.95×10^{-4}	2.11×10^{-2}	
3	2.53×10^{-5}	4.19×10^{-4}	4.39×10^{-3}	4.02×10^{-4}	4.11×10^{-2}	
4	2.31×10^{-5}	7.66×10^{-4}	8.02×10^{-3}	7.49×10^{-4}	7.85×10^{-2}	
5	2.48×10^{-5}	1.23×10^{-3}	1.29×10^{-2}	1.21×10^{-3}	1.29×10^{-1}	
6	2.20×10^{-5}	1.46×10^{-3}	1.53×10^{-2}	1.44×10^{-3}	1.52×10^{-1}	1.05×10^{2} [a]
7	9.79×10^{-6}	2.54×10^{-3}	3.66×10^{-4}	3.40×10^{-4}	3.44×10^{-2}	
8	9.79×10^{-6}	2.54×10^{-3}	5.48×10^{-4}	5.07×10^{-4}	4.93×10^{-2}	
9	9.79×10^{-6}	2.54×10^{-3}	7.31×10^{-4}	6.71×10^{-4}	6.77×10^{-2}	
10	9.79×10^{-6}	2.54×10^{-3}	9.14×10^{-4}	8.33×10^{-4}	8.49×10^{-2}	
11	9.79×10^{-6}	2.54×10^{-3}	1.37×10^{-3}	1.22×10^{-3}	1.22×10^{-1}	
12	9.79×10^{-6}	2.54×10^{-3}	1.83×10^{-3}	1.56×10^{-3}	1.60×10^{-1}	1.03×10^{2} [b]
13	9.79×10^{-6}	5.07×10^{-3}	3.66×10^{-4}	3.54×10^{-4}	2.90×10^{-2}	
14	9.79×10^{-6}	5.07×10^{-3}	5.48×10^{-4}	5.29×10^{-4}	4.58×10^{-2}	
15	9.79×10^{-6}	5.07×10^{-3}	7.31×10^{-4}	7.04×10^{-4}	6.14×10^{-2}	
16	9.79×10^{-6}	5.07×10^{-3}	9.14×10^{-4}	8.79×10^{-4}	7.73×10^{-2}	
17	9.79×10^{-6}	5.07×10^{-3}	1.37×10^{-3}	1.31×10^{-3}	1.22×10^{-1}	
18	9.79×10^{-6}	5.07×10^{-3}	1.83×10^{-3}	1.74×10^{-3}	1.64×10^{-1}	9.78×10^{1} [c]

[a] Calculated from the slopes of plots of $k_{1\Psi}$ (eq 4) vs [**1a**] for entries 1−6. [b] Calculated from the slopes of plots of $k_{1\Psi}$ (eq 4) vs [**1a**] for entries 7−12. [c] Calculated from the slopes of plots of $k_{1\Psi}$ (eq 4) vs [**1a**] for entries 13−18.

benzhydrylium ions with the nitroalkyl anion ($k_{1\Psi,\mathrm{C^-}}$), OH^- ($k_{1\Psi,\mathrm{OH^-}}$), and water ($k_{1\Psi,\mathrm{W}}$) (eq 3).

$$k_{1\Psi,\mathrm{obs}} = k_{1\Psi,\mathrm{C^-}} + k_{1\Psi,\mathrm{OH^-}} + k_{1\Psi,\mathrm{W}} \quad (3)$$
$$= k_{2,\mathrm{C^-}}[\mathrm{C^-}] + k_{2,\mathrm{OH^-}}[\mathrm{OH^-}] + k_{1\Psi,\mathrm{W}}$$

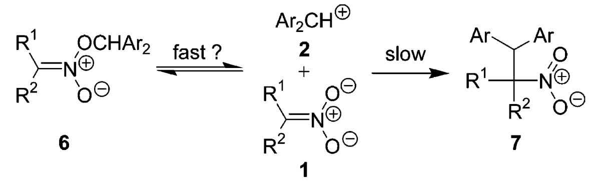
[C^-] is the concentration of the nitroalkyl anion, which was generated from the CH acid with KOH. The concentrations of the nitroalkyl anions [C^-] and of the hydroxide [OH^-] are calculated[22] from [OH^-]$_0$, [CH acid]$_0$, and pK_{aH}, as described in the Supporting Information. With the published $k_{2,\mathrm{OH^-}}$ values[11] and the calculated concentrations [OH^-], the partial pseudo-first-order rate constants, $k_{1\Psi,\mathrm{OH^-}} = k_{2,\mathrm{OH^-}}[\mathrm{OH^-}]$, can be calculated.

$$k_{1\Psi} = k_{1\Psi,\mathrm{obs}} - k_{2,\mathrm{OH^-}}[\mathrm{OH^-}] = k_{2,\mathrm{C^-}}[\mathrm{C^-}] + k_{1\Psi,\mathrm{W}} \quad (4)$$

According to eq 4, the slopes of the plots of $k_{1\Psi}$ versus [C^-] correspond to the second-order rate constants $k_{2,\mathrm{C^-}}$. As explicitly shown in the Supporting Information, the intercepts, which correspond to the reactions of the benzhydrylium ions with water, are negligible, in accord with their directly measured reactivities toward water.[11]

To explicitly determine the influence of the hydroxide concentration on the reactivities of the nitroalkyl anions, the reaction of $H_2CNO_2^-$ (**1a**) with **2b** was studied in detail. In a first series of experiments (entries 1−6, Table 3), the benzhydrylium salt, **2b**-BF_4^- (~0.02 mM), was combined with variable amounts of **1a** (~0.06−1.4 mM), while the ratio of nitromethane/KOH was kept constant at 10.5. In a second and third series of experiments, the concentration [**2b**-BF_4^-] was kept at 9.79×10^{-3} mM and at a constant of [OH^-]$_0$ = 2.54 (entries 7−12) and 5.07 mM (entries 13−18), respectively, while the nitromethane concentration was varied from 0.37 to 1.83 mM. The resulting second-order rate constants agree within ±3% (last column in Table 3), which reflects the error limits of our experiments.

SCHEME 4. C- and O-Alkylation of Nitronates



Though the products that were isolated from the combination of benzhydrylium ions with nitroalkyl anions (Scheme 2) show the formation of carbon−carbon bonds, one cannot exclude a priori the initial attack of benzhydrylium ions at the oxygen of the nitro group and the successive rearrangement into the nitro compound, as illustrated in Scheme 4.

Initial O-alkylation with the intermediate accumulation of the nitronates of **6** was definitely ruled out for the reaction of nitroalkyl anion **1f** with benzhydrylium ion **2a** (Figure 2).

A combination of equimolar amounts of **1f** and **2a** in water resulted in a decay of the absorptions of **1f** ($\lambda_{\max}$ = 380 nm, log ϵ = 4.14)[23,24] and **2a** ($\lambda_{\max}$ = 604 nm)[11] and the appearance of a new absorption at $\lambda_{\max}$ = 261 nm. The eventual intermediate (**6f**) possesses a chromophore similar to that of **8f**, the UV spectrum of which has been reported in the literature.[25]

Figure 2 shows the absence of a peak between 300 and 350 nm throughout the reaction. For that reason, one can exclude the formation of significant concentrations of **6f**, which successively rearranges to **3f**. While this experiment proves that the rate constants, $k_{2,\mathrm{C^-}}$ (Table 4), refer to the C−C bond-forming reactions, we cannot exclude

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(19) Bordwell, F. G.; Satish, A. V. *J. Am. Chem. Soc.* **1994**, *116*, 8885−8889.
(20) Lemek, T.; Mayr, H. *J. Org. Chem.* **2003**, *68*, 6880−6886.
(21) Keeffe, J. R.; Morey, J.; Palmer, C. A.; Lee, J. C. *J. Am. Chem. Soc.* **1979**, *101*, 1295−1297.
(22) Bug, T.; Mayr, H. *J. Am. Chem. Soc.* **2003**, *125*, 12980−12986.
(23) Bernasconi, C. F.; Ni, J. X. *J. Am. Chem. Soc.* **1993**, *115*, 5060−5066.
(24) Moutiers, G.; Thuet, V.; Terrier, F. *J. Chem. Soc., Perkin Trans. 2* **1997**, 1479−1486.
(25) Kornblum, N.; Brown, R. A. *J. Am. Chem. Soc.* **1964**, *86*, 2681−2687.

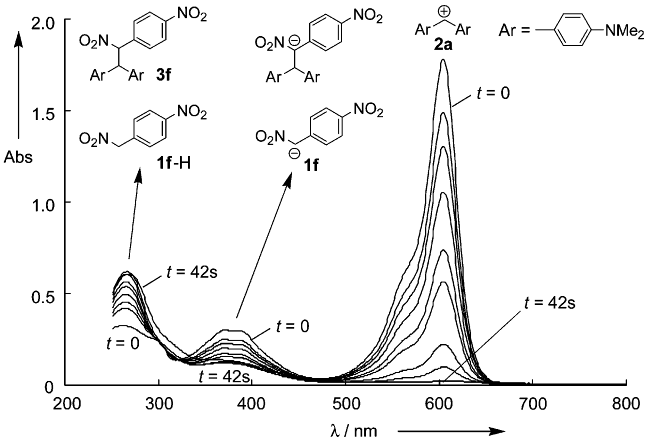
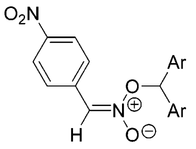
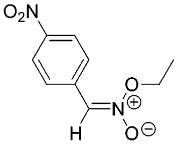


FIGURE 2. Online UV−vis monitoring of the reaction of nitroalkyl anion **1f** with benzhydrylium ion **2a** (in water at 20 °C, reaction conditions: **2a**/KOH/**1f**-H = 1/5/1).

the fast reversible formations of low concentrations of the O-alkylated intermediates **6**.



6f



8f

λ_{max} (log ε):
240 nm (3.97),
337 nm (4.25)

Discussion

Ritchie Correlations. Thirty years ago, Ritchie demonstrated that many combinations of stabilized carbocations with various types of nucleophiles follow the constant selectivity relationship (eq 5)

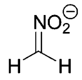
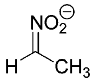
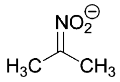
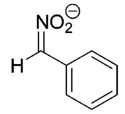
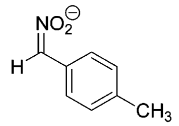
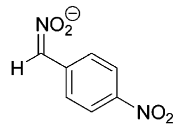
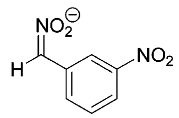
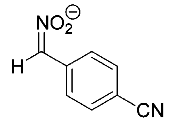
$$\log(k/k_0) = N_+ \qquad (5)$$

where nucleophiles are characterized by a single electrophile-independent parameter (N_+), and log k_0 represents the nucleophile-independent electrophile reactivities.[29]

Because cyanide was the only carbon nucleophile characterized by Ritchie, we have recently investigated carbanions that are stabilized by two keto, ester, or cyano groups and reported that their reactivities toward carbocations also follow the constant selectivity relationship (eq 5).[22]

Least-squares fitting of the rate constants in Table 4, according to eq 5 using the previously published log k_0 parameters[11] of benzhydrylium ions, shows systematic deviations from the correlation lines, which were derived from the reactions of benzhydrylium ions with O and N nucleophiles (Figure 3). It should be noted that the deviation of the data points for **2a** and **2c** from the drawn correlation lines is not an artifact. Of course, one might draw correlation lines going through these points implying that the secluded data set described in this work follows a constant selectivity relationship. However, this would be different from the constant selectivity relationship reported in refs 11 and 22. In Figure 3, the majority of rate constants for the most-reactive electrophile (**2a**) are below the correlation line, while the rate constants for the least-reactive electrophile (**2c**) are above the previously determined correlation line. It is thus indicated that nitroalkyl anions in water are, in general, slightly less selective toward carbenium ions than O and N nucleophiles[11] and most ester- and keto-substituted carbanions.[22]

TABLE 4. Second-Order Rate Constants (k_{2,C^-}) for the Reactions of the Potassium Salts of Nitroalkyl Anions 1a−h with the Tetrafluoroborate Salts of Benzhydrylium Ions 2a−c (in H_2O, at 20 °C)

carbanion		pK_{aH}	electrophile	k_{2,C^-} / M^{-1} s^{-1}
1a		10.22[a]	**2a**	5.14×10^2
			2b	1.05×10^2
			2c	1.23×10^1
1b		8.60[a]	**2a**	1.65×10^2
			2b	3.17×10^1
			2c	4.43
1c		7.74[a]	**2a**	1.21×10^2
			2b	2.19×10^1
			2c	2.41
1d		6.88[b]	**2a**	3.94×10^2
			2b	1.26×10^2
			2c	1.06×10^1
1e		7.11[c]	**2a**	1.13×10^3
			2b	2.54×10^2
			2c	3.45×10^1
1f		5.89[b]	**2a**	2.73×10^3
			2b	6.57×10^2
			2c	7.16×10^1
1g		6.30[b]	**2a**	2.17×10^3
			2b	5.72×10^2
			2c	8.77×10^1
1h		6.17[c]	**2a**	1.56×10^3
			2b	4.83×10^2
			2c	4.30×10^1

[a] In water, from ref 26. [b] In water, from ref 27. [c] Calculated from increments as described in ref 28. Since **1e** and **1h** are considerably less basic than OH^-, errors in pK_{aH} values by 1−2 units do not affect the calculated concentrations of the carbanions.

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(26) Turnbull, D.; Maron, S. H. *J. Am. Chem. Soc.* **1943**, *65*, 212−218.

(27) Bordwell, F. G.; Boyle, W. J., Jr. *J. Am. Chem. Soc.* **1972**, *94*, 3907−3911.

(28) From *SciFinder Scholar 2002*: calculated using Advanced Chemistry Development (ACD) Software Solaris V4.67 (© 1994−2003 ACD).

(29) (a) Ritchie, C. D. *Acc. Chem. Res.* **1972**, *5*, 348−354. (b) Ritchie, C. D. *Can. J. Chem.* **1986**, *64*, 2239−2250.

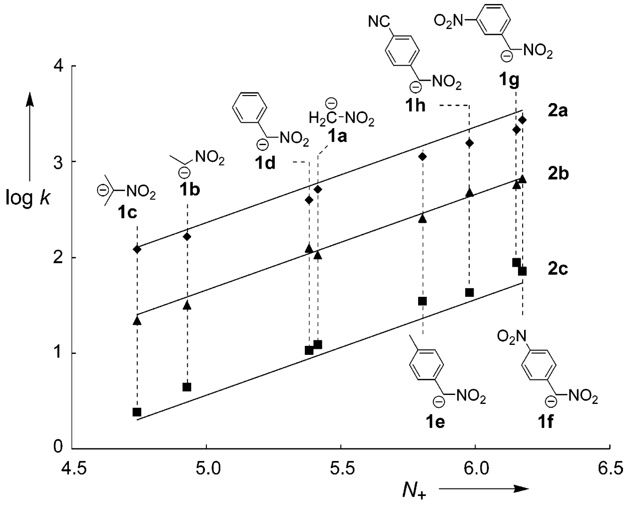


FIGURE 3. Analysis of the rate constants of the reactions of nitroalkyl anions **1a**−**h** with benzhydrylium cations **2a**−**c** in water (20 °C) according to the Ritchie formalism (eq 5). The drawn correlation lines are derived from the reactions of benzhydrylium ions **2a**−**c** with O and N nucleophiles in ref 11.

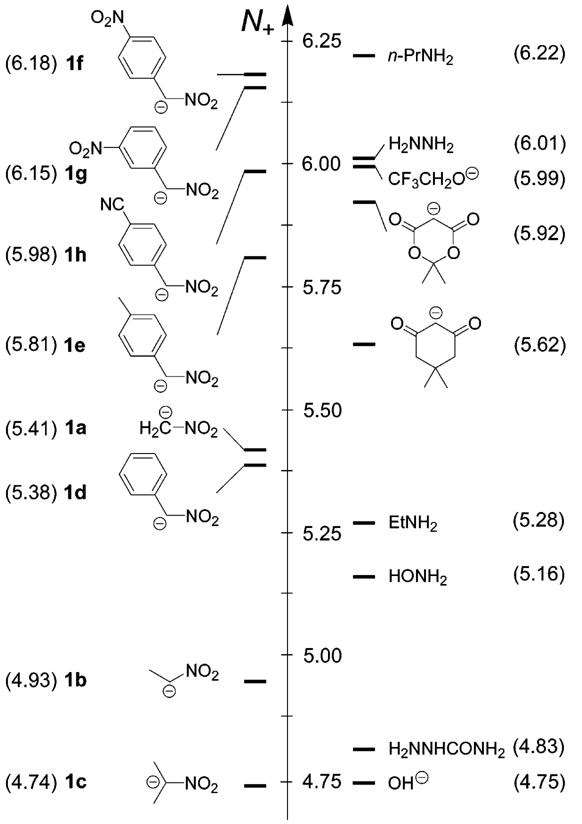


FIGURE 4. Comparison of the Ritchie N_+ values for nitroalkyl anions **1a**−**h** in water with those of other nucleophiles: N_+ of OH^-, $H_2NNHCONH_2$, $HONH_2$, $CF_3CH_2O^-$, and n-$PrNH_2$ from ref 11, N_+ of dimedone and Meldrum's acid from ref 22, and N_+ of $EtNH_2$ and H_2NNH_2 from ref 29b.

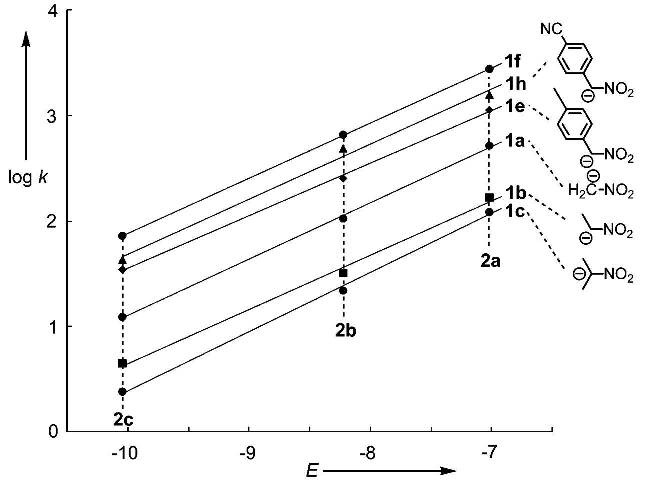


FIGURE 5. Correlation of the rate constants (20 °C) for the reactions of nitroalkyl anions **1a**−**h** with the benzhydrylium tetrafluoroborates (**2a**−**c**)-BF_4^- in water toward the electrophilicity parameters E (data for **1d** and **1g** not plotted).

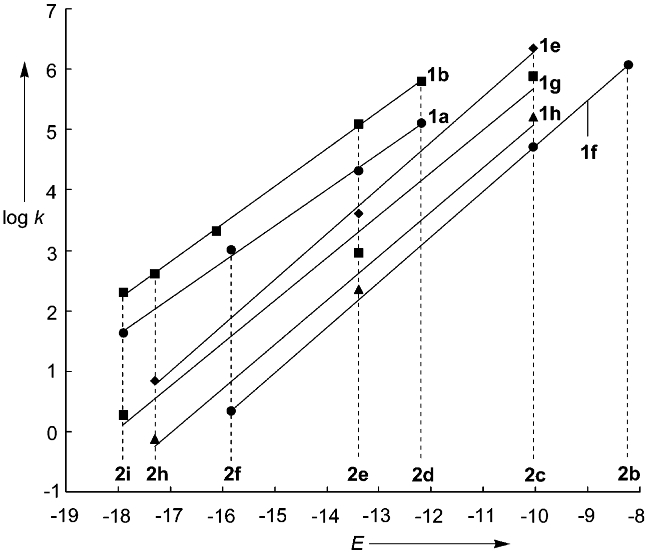
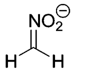
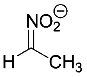
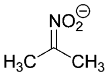
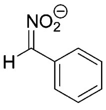
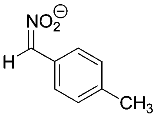
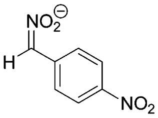
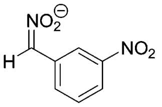
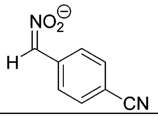


FIGURE 6. Correlation of the rate constants (20 °C) for the reactions of nitroalkyl anions **1a**−**h** with the electrophiles **2** in DMSO toward the electrophilicity parameters E (data for **1c** and **1d** not plotted).

While the lower selectivities of nitroalkyl anions **1a**−**h** can quantitatively be treated by the slope parameter of eq 1 (see below), the deviations from the Ritchie correlation (eq 5, Figure 3) are small enough that the calculation of approximate N_+ parameters appears to be justified. Figure 4, which compares the nucleophilic reactivities of nitroalkyl anions in water with those of amines, hydroxide, and other carbanions in water, reveals a remarkable phenomenon. The nucleophilic reactivities of all nitroalkyl anions in water that were investigated in this work are within 1.5 logarithmic units, comparable to those of hydroxide ions and primary aliphatic amines. The phenomenon that the aryl-substituted nitroalkyl anions are slightly more nucleophilic than the alkyl-substituted representatives, in contrast to the expectations on the basis of pK_{aH} values, will be discussed below.

Correlations with log *k* (20 °C) = *s*(*N* + *E*). A more comprehensive comparison of nucleophilic reactivities can be based on eq 1, which differs from Ritchie's correlation (eq 5) by the additional nucleophile-dependent slope parameter s.[7−10] Figures 5 and 6 plot the rate constants (log k) of the reactions of representative nitroalkyl anions with reference electrophiles (benzhydrylium ions and

TABLE 5. Comparison of the Reactivity Parameters *N* and *s* for Nitroalkyl Anions 1a−h in Water and DMSO

carbanion		*N* / *s*	
		in water	in DMSO
1a		12.06 / 0.53	20.71 / 0.60
1b		11.25 / 0.52	21.54 / 0.62
1c		10.69 / 0.56	20.61 / 0.69
1d		12.05 / 0.53	18.29 / 0.71
1e		13.09 / 0.50	18.31 / 0.76
1f		13.58 / 0.52	16.29 / 0.75
1g		14.25 / 0.46	18.06 / 0.71
1h		13.23 / 0.52	16.96 / 0.73

quinone methides) in water and DMSO, respectively, against the corresponding *E* parameters.

Evaluation of the correlation lines shown in Figures 5 and 6 according to eq 1 yields the *N* and *s* parameters for nitroalkyl anions **1a**−**h** in water and DMSO, as listed in Table 5.

Table 5 indicates that the slopes *s* are generally somewhat greater in DMSO than in aqueous solution. The differences in *s* are so small, however, that a detailed analysis of the slope parameters does not appear to be meaningful at present. The small values of *s* (0.46−0.56) for the nitroalkyl anions in water, which are smaller than those of most other nucleophiles so far investigated, reflect the previously discussed deviations of the data points from the Ritchie correlations in Figure 3.

Structure−Reactivity Relationships. Though the relative reactivities of the nitroalkyl anions slightly depend on the nature of the electrophile because of the differences in *s*, some general trends can be derived from Figure 7.

In DMSO, aromatic nitroalkyl anions **1d**−**h** are less nucleophilic than the aliphatic ones (**1a**−**c**), which may be explained by delocalization of the negative charge into the aromatic ring. In line with this argument, acceptor substituents in the aromatic ring lead to a reduction of nucleophilicity.

In water, all nitronate anions are considerably less nucleophilic than in DMSO. However, the decrease in nucleophilicity strongly depends on the nature of the nitronate. While the *N* values of the aliphatic nitronate ions are 9−11 units smaller in water than those in DMSO, corresponding to a reduction in the rate constants by roughly 1 million (depending on the reference electrophile), the solvent effect on the aromatic nitronates is much smaller ($\Delta N = 3-6$). As a consequence, the aliphatic nitronate ions, which are the stronger nucleophiles in DMSO, are the weaker nucleophiles in water. Solvation of the more localized charges in **1a**−**c** by hydrogen bridging in water may account for this finding.

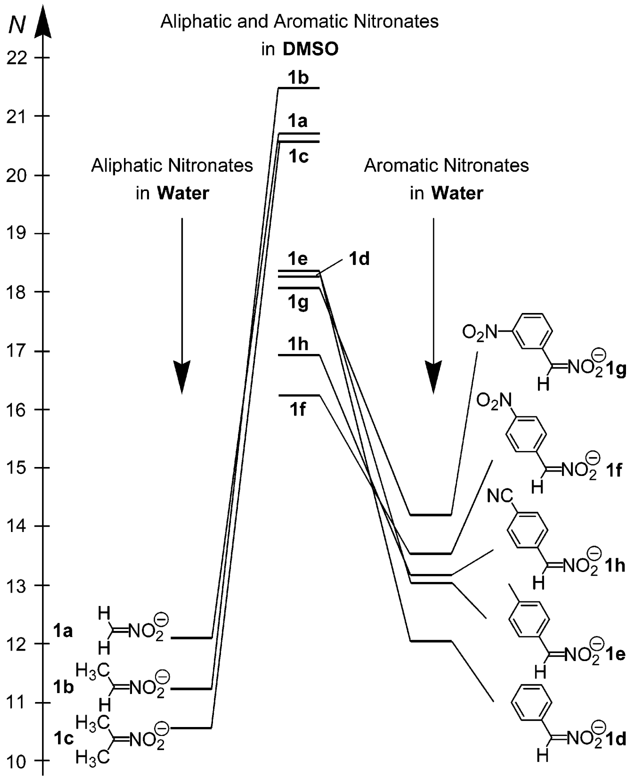


FIGURE 7. Comparison of the nucleophilicities of nitroalkyl anions **1a**−**h** in water and DMSO.

Hammett Correlations. Nucleophilic reactivities of phenolate and benzyl anions usually correlate with the Hammett−Brown parameter, σ^- (direct conjugation of the lone pair at the reaction center with the variable substituents).[30] Accordingly, the reactions of carbanions **1d**−**h** with various electrophiles in DMSO follow the Hammett σ-correlations with small negative reaction constants ($\rho \approx -1.0$), though with low correlation coefficients, indicating that only a small part of the negative charge in the nitronates is delocalized by the aromatic ring (Figure 8).

Figure 9 shows that the reactivities of the nitronate anions in water also correlate poorly with σ^-. The small differences in reactivity between the differently substituted nitronates (**1d**−**h**), which even give rise to positive Hammett reaction constants (ρ), indicate that the transition states of these reactions do not reflect the partial cancellation of conjugation between the aryl group and the carbanionic reaction center.

The correlations with positive ρ values, shown in Figure 9, imply that the nitroalkane anomaly[5] also turns

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[30] Exner, O. *Correlation Analysis of Chemical Data*; Plenum Press: New York, 1988.

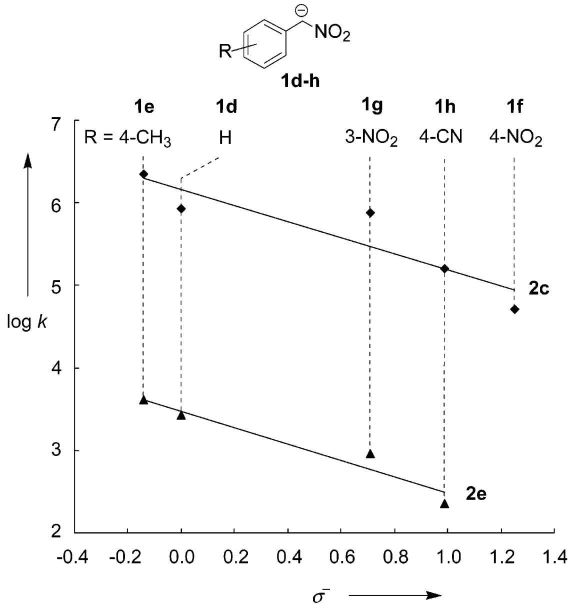


FIGURE 8. Correlations between log *k* of the reactions of aryl-substituted nitronates **1d**–**h** with electrophiles **2c** and **2e** in DMSO and the corresponding σ^- values (from ref 30). Correlation equations: (◆) $\log k = -0.97\sigma^- + 6.16$ ($r^2 = 0.8319$), (▲) $\log k = -0.99\sigma^- + 3.47$ ($r^2 = 0.9422$).

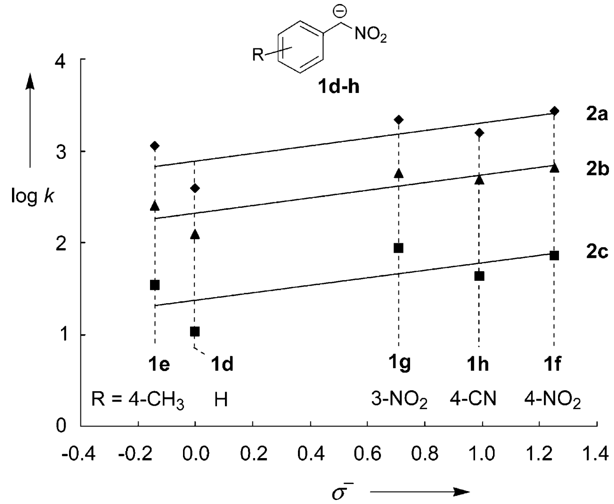


FIGURE 9. Correlations between log *k* for the reactions of aryl-substituted nitronates **1d**–**h** with **2a**–**c** in water and the corresponding σ^- values (from ref 30). Correlation equations: (◆) $\log k = 0.42\sigma^- + 2.89$ ($r^2 = 0.6038$), (▲) $\log k = 0.42\sigma^- + 2.32$ ($r^2 = 0.7424$), (■) $\log k = 0.41\sigma^- + 1.37$ ($r^2 = 0.4786$).

up in the reactions of aryl-substituted nitronate anions toward carbon electrophiles in water. A detailed discussion follows at the end of the next paragraph.

Correlations between Nucleophilicity and pK_{aH}. It is well-known that correlations between nucleophilic reactivities and pK_{aH} values only hold within narrow classes of compounds and completely fail when nucleophiles with different types of central atoms are compared.[2] The nitroalkane anomaly[5] was the most spectacular example, advising against the use of pK_{aH} for predicting nucleophilic reactivities even in case of structurally related compounds (nitronate anions).

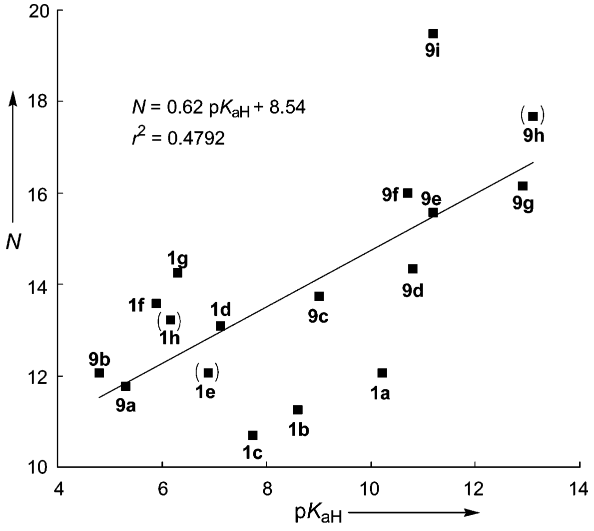


FIGURE 10. Plot of the nucleophilicity parameter *N* versus pK_{aH} of nitroalkyl anions **1a**–**h** and keto-, ester-, and cyano-stabilized carbanions **9a**–**i** (water, 20 °C). For **1a**–**h**, see Table 4 for pK_{aH} values and Table 5 for *N* values. For **9a**–**i**, pK_{aH} and *N* values are from ref 22. Points referring to uncertain pK_{aH} values are in parentheses.

To examine whether nitronate anions systematically differ from other types of carbanions in nucleophilicity–basicity correlations, we will now combine the kinetic data for nitronate anions **1a**–**h** with those for carbanions **9a**–**i**.

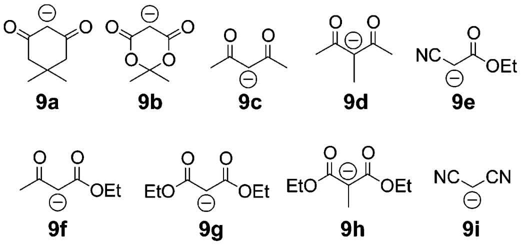


Figure 10 shows that the reactivities of most carbanions in water correlate moderately with pK_{aH}. Four points deviate significantly (**1a**–**c** and **9i**). The high intrinsic reactivity of the malodinitrile anion **9i** has recently been discussed.[22] We now find that aliphatic nitronate anions **1a**–**c** are 2 orders of magnitude less reactive than expected on the basis of pK_{aH}, indicating high intrinsic barriers for the reactions of the aliphatic nitronate anions.

The problem of using pK_{aH} for predicting nucleophilic reactivities in water is most impressively demonstrated by the comparison of the methyl nitronate **1a** and the malodinitrile anion **9i** (Figure 10). Though both species have comparable pK_{aH} values, their nucleophilic reactivities differ by a factor of 10^4 [**9i**/**1a**: $\Delta\log k = 0.54(19.50 - 12.06) = 4.02$].

The correlation between nucleophilic reactivities and pK_{aH} is considerably better in DMSO solution (Figure 11), but even in this dipolar aprotic medium, the pK_{aH} values do not render a reliable prediction of nucleophilicity. One can see, however, that in DMSO solution, nitronate ions **1a**–**h** do not differ significantly from other types of carbanions.

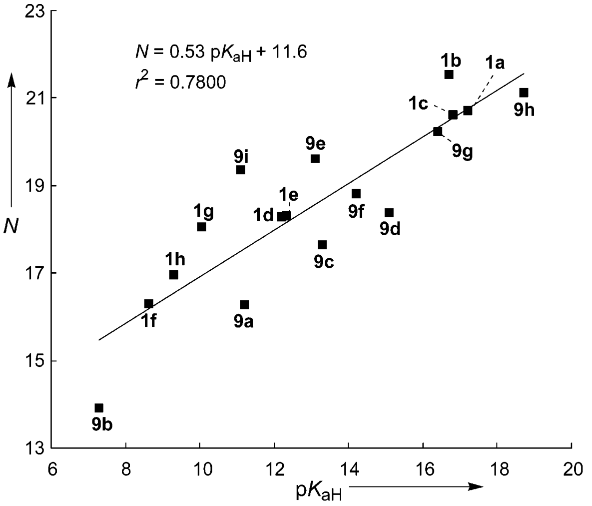


FIGURE 11. Plot of the nucleophilicity parameter *N* versus pK_{aH} of nitroalkyl anions **1a**−**h** and keto-, ester-, and cyano-stabilized carbanions **9a**−**i** (DMSO, 20 °C). For pK_{aH} values of **1a**−**h**, see Table 2; for *N* values, see Table 5. For pK_{aH} and *N* values of **9a**−**i**, see ref 22.

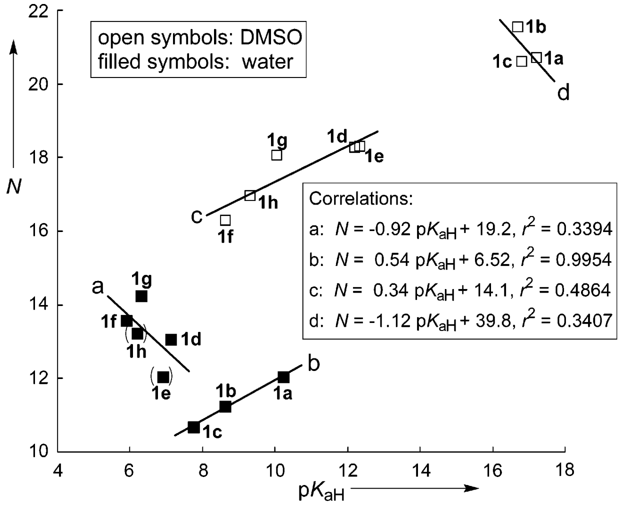


FIGURE 12. Questionable attempts to derive relationships between nucleophilicities and basicities of nitronate anions.

Let us now turn to the origin of the nitroalkane anomaly by considering *N* versus pK_{aH} correlations of nitronates in water and in DMSO. Figure 12 shows that it is impossible to find a reasonable single correlation for all data in both solvents. If we follow the typical procedure, which led to the postulate of the nitroalkane anomaly, and look at correlations for a certain group of compounds in a certain solvent, we might arrive at the four correlation lines, a−d, drawn in Figure 12.

When considering the correlation lines for aromatic nitronates **1d**−**h** (correlations a and c in Figure 12), one would come to the conclusion that aromatic nitronates show an increase of nucleophilicity with increasing basicity in DMSO but a decrease of nucleophilicity with increasing basicity in water. We might thus corroborate previous statements that solvation by hydrogen bonding is responsible for the nitroalkane anomaly.[5,31]

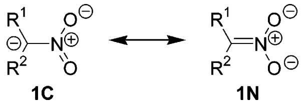
A different conclusion might be drawn from the correlation lines for aliphatic nitronates (correlations b and d in Figure 12). While **1a**−**c** in water show an increase of nucleophilicity with increasing basicity (i.e., normal behavior, no anomaly!), **1b** is somewhat more nucleophilic than **1a** and **1c** in DMSO (depending on the electrophile). Since it is not obligatory to treat aromatic and aliphatic nitronates separately, these examples show that the interpretation of rate equilibrium relationships within such small groups of compounds is highly questionable, particularly, since the slopes of the correlations depend on the choice of the group members.

TABLE 6. Comparison of pK_{aH} Values in DMSO and Water

R	$R{-}CH_2{-}NO_2$	$R{-}CH_2{-}CN$
	pK_{aH} in DMSO	
H	17.2[a]	31.3[b]
CH_3	16.7[c]	32.5[b]
$4\text{-}NO_2{-}C_6H_4$	8.62[d]	12.3[e]
	pK_{aH} in Water	
H	10.22[f]	28.9[g]
CH_3	8.60[f]	30.9[g]
$4\text{-}NO_2{-}C_6H_4$	5.89[h]	12.62[i]

[a] From ref 17. [b] From ref 32. [c] From ref 19. [d] From ref 21. [e] From ref 33. [f] From ref 26. [g] From ref 34. [h] From ref 27. [i] From ref 35.

The appearance of anomalous rate equilibrium relationships in nitronate chemistry[5] may be explained by the great importance of the nitronate resonance structure **1N** compared with the carbanion resonance structure **1C**.



1C **1N**

Because of the minor contribution of **1C**, variation of R^1 and R^2 (H, alkyl, or 4-nitrophenyl) affects pK_{aH} in DMSO by only 8.5 units and nucleophilicity by a factor of approximately $10^{3.5}$ ($\Delta N \approx 5$, $s \approx 0.7$). Because of this relatively small range, other factors (e.g., steric effects or differential solvation of ground and transition states) become dominant. Therefore, the correlation between *N* and pK_{aH}, including all nitronates **1a**−**h** in DMSO, is of low quality though the slope is in the expected order.

In aqueous solution, differential solvation becomes so important that the pK_{aH} values of nitronate anions **1a**−**h** differ by only 4 units and the nucleophilic reactivities differ by a factor of less than 10^2 ($\Delta N \approx 3.5$, $s \approx 0.5$) despite of the large structural variety of these nitronates. These small differences must arise from partial compensation of opposing effects, and depending on the choice of groups of compounds, one may arrive at completely different rate equilibrium relationships.

Nitronates thus differ substantially from other types of carbanions (e.g., cyano-substituted systems) because of the insignificance of the carbanion resonance structure. Table 6 shows that variation of R from H via CH_3 to 4-nitrophenyl in DMSO affects the pK_{aH} values of nitronates only half as much as those of cyano-substituted carbanions. In aqueous solution, the same substituent variation reduces the basicities of nitronates by

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(31) Keeffe, J. R.; Gronert, S.; Colvin, M. E.; Tran, N. L. *J. Am. Chem. Soc.* **2003**, *125*, 11730−11745.

TABLE 7. One-Electron Oxidation Potentials ($E°_{Ox}$) of Nitroalkyl Anions 1a−d, Free Energies of Electron Transfer ($\Delta G°_{ET}$), and Experimental Activation Free Energies for the Electrophile−Nucleophile Combinations (DMSO, 20 °C)

nitronate	$E°_{Ox}$ (DMSO)[a]	electrophile	$E°_{Red}$ (CH_3CN)[b]	$\Delta G°_{ET}$ (kJ mol^{-1})	$\Delta G^{\ddagger}$ (kJ mol^{-1})
1a	0.533	**2f**	−1.12	159.5	54.6
		2i	−1.29	175.9	62.3
1b	0.302	**2g**	−1.13	138.2	52.9
		2h	−1.26	150.7	56.8
		2i	−1.29	153.6	58.6
1c	0.096	**2f**	−1.12	117.3	53.1
		2i	−1.29	133.7	61.0
1d	0.220	**2h**	−1.26	142.8	67.3

[a] Relative to SCE; the oxidation potentials relative to Fc/Fc$^+$ reported in ref 19 were converted into $E°$ values relative to SCE using the equations $E°_{SCE} = E°_{NHE} - 0.241$ (ref 39) and $E°_{NHE} = E°_{Fc/Fc^+} + 0.750$ (ref 40). [b] From ref 38.

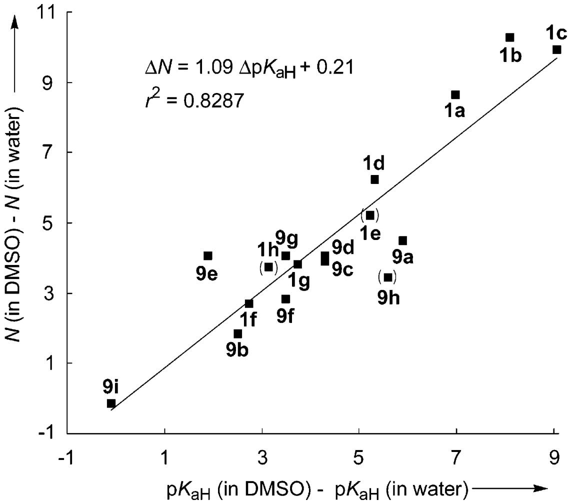


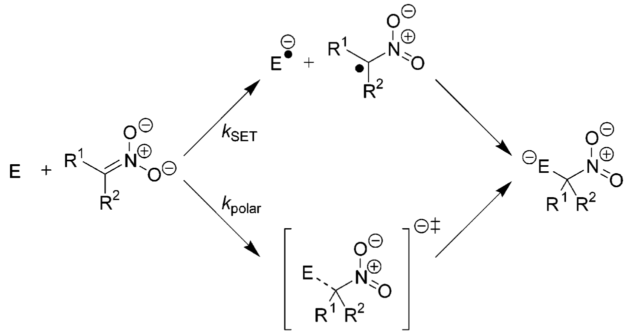
FIGURE 13. Effects of differential solvation on nucleophilicities and basicities of carbanions. Points referring to uncertain pK_{aH} values are in parentheses.

<5 units, while the corresponding cyano-substituted carbanions differ by more than 20 units in their pK_{aH} values.

Figure 13 indicates that aqueous solvation reduces nucleophilicities and basicities of carbanions proportionally. This phenomenon has previously been reported by Gilbert for S_N2 reactions.[36]

Is Outer-Sphere Electron Transfer Involved? Since Kornblum's pioneering investigations, it is well-known that nucleophilic substitutions with nitronate anions may proceed via SET processes.[37] Therefore, the question arises of whether the rate constants reported in this paper refer to polar reactions or to SET processes (Scheme 5). Let us analyze this situation for the reactions of nitronate anions with the quinone methides. In the molecule reactions, Coulomb interactions can be neglected because neither in the SET process nor in the polar reaction will charge separation be created or destroyed.

SCHEME 5. Single Electron (SET) and Polar Mechanism in the Reaction of Nitroalkyl Anions with Electrophiles



The free enthalpy for electron transfer can be calculated by eq 6 from the oxidation potentials of nitronate anions **1a**−**h** and the reduction potentials of quinone methides **2d**−**i**.

$$\Delta G°_{ET} = F(E_{Ox} - E_{Red}) \qquad (6)$$

While reduction potentials of the quinone methides have been reported in acetonitrile solution,[38] oxidation potentials for four of the nitronate anions have been determined in DMSO[19] (Table 7). Because solvent effects (in a comparison between acetonitrile and dichloromethane) on the reduction potentials of the structurally related benzhydrylium ions **2a**−**c** have been reported to be small,[38] we can directly connect the redox potentials determined in CH_3CN and in DMSO and calculate the free energy of electron transfer ($\Delta G°_{ET}$) by eq 6.

Comparison of the calculated $\Delta G°_{ET}$ values with the experimental activation free energies for the electrophile−nucleophile combinations (last column of Table 7 and Figure 14) reveals that in all cases, $\Delta G^{\ddagger} \ll \Delta G°_{ET}$ (i.e., none of the reactions investigated in this work can proceed via outer-sphere electron transfer).

Conclusions

Nitronates react with stabilized carbocations and Michael acceptors as C-nucleophiles. The rate constants for these reactions follow the linear free energy relationship (eq 1), which allows us to directly compare the

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(32) Bordwell, F. G.; Bares, J. E.; Bartmess, J. E.; Drucker, G. E.; Gerhold, J.; McCollum, G. J.; Van Der Puy, M.; Vanier, N. R.; Matthews, W. S. *J. Org. Chem.* **1977**, *42*, 326−332.

(33) For F. G. Bordwell's pK_a list, see http://www.chem.wisc.edu/areas/reich/pkatable/.

(34) Richard, J. P.; Williams, G.; Gao, J. *J. Am. Chem. Soc.* **1999**, *121*, 715−726.

(35) Bernasconi, C. F.; Hibdon, S. A. *J. Am. Chem. Soc.* **1983**, *105*, 4343−4348.

(36) Gilbert, H. F. *J. Am. Chem. Soc.* **1980**, *102*, 7059−7065.

(37) Kornblum, N. *Angew. Chem.* **1975**, *87*, 797−808; *Angew. Chem., Int. Ed. Engl.* **1975**, *14*, 734−745.

(38) Ofial, A. R.; Ohkubo, K.; Fukuzumi, S.; Lucius, R.; Mayr, H. *J. Am. Chem. Soc.* **2003**, *125*, 10906−10912.

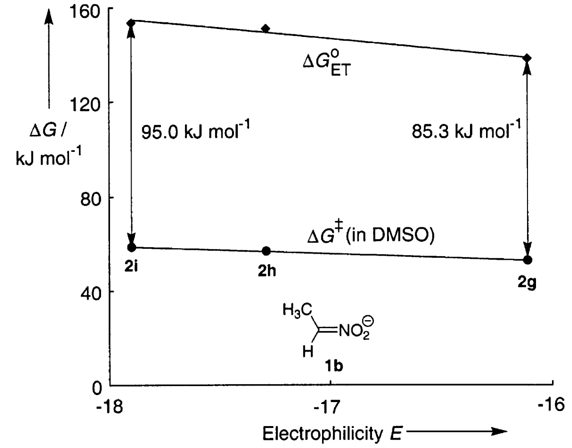

FIGURE 14. Comparison of the calculated free energies $\Delta G°_{ET}$ and the experimentally obtained $\Delta G^{\ddagger}$ for the reactions of the nitroethane anion (**1b**) with quinone methides in DMSO.

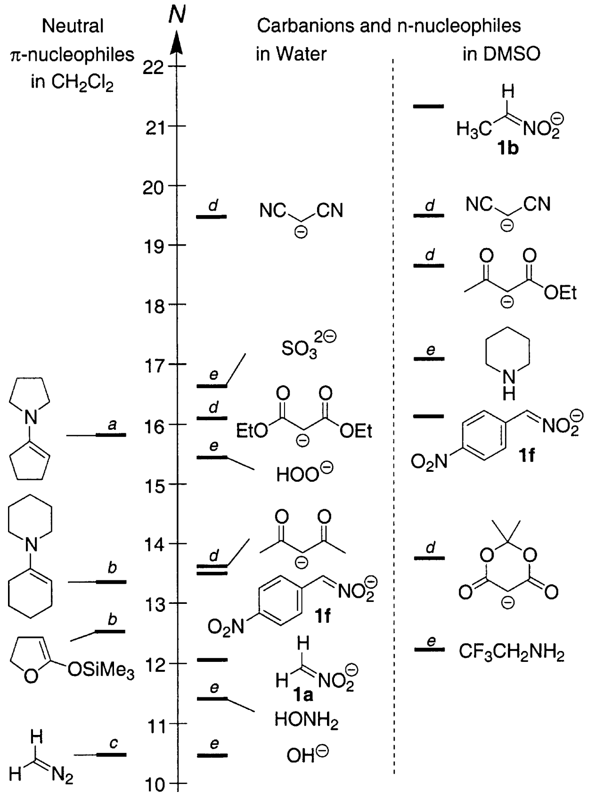

FIGURE 15. Comparison of the nucleophilicities of carbanions, *n*-nucleophiles, and neutral π-nucleophiles in different solvents. (*a*) From ref 41. (*b*) From ref 8. (*c*) From ref 42. (*d*) From ref 22. (*e*) From ref 11.

nucleophilic reactivities of nitronate anions with those of other charged and noncharged nucleophiles (Figure 15; for a collection of nucleophilicity parameters, see www.cup.uni-muenchen.de/oc/mayr). Because the nucleophilic reactivities of nitronate anions with wide structural variety differ by a factor of less than 10^2 in water, they cannot predominantly be controlled by polar substituent effects, resulting in curious rate equilibrium relationships.

Experimental Section

Materials. Benzhydrylium tetrafluoroborates[8] and quinone methides[13,43] were prepared as described in the literature. Potassium hydroxide was purchased from commercial suppliers as an aqueous solution [c = 0.1 M ± 0.1% and c = 0.5073 M (volumetric standard)]. Water was distilled and passed through a Milli-Q water purification system. Dimethyl sulfoxide (DMSO, puriss., stored over molecular sieve, $H_2O \leq 0.01\%$) and acetonitrile (for HPLC, ≥99.9%) were used without further purification.

Nitro Compounds. Nitromethane (≥99%), nitroethane (≥97%), and 2-nitro-propane (≥96%) were purchased from a commercial supplier and distilled before use. Compounds (**1d**–**g**)-H were synthesized from the corresponding benzyl bromides with $NaNO_2$ in DMF/urea as described in the literature.[44,45] 4-Cyanophenylnitromethane (**1h**-H) was synthesized from 4-cyanotoluene with KO^{t}Bu and n-$PrNO_2$ according to literature reports.[46]

Kinetics. The reactions of benzhydrylium ions with nitroalkyl anions were studied in aqueous solution and in DMSO, whereas the reactions of the quinone methides with nitroalkyl anions were only studied in DMSO. The rates of the reactions of colored electrophiles **2a**–**i** with nitroalkyl anions **1a**–**i** were measured photometrically under pseudo-first-order conditions using a large excess of **1a**–**i**. In aqueous solutions, all nitroalkyl anions were generated by the treatment of the corresponding acids with KOH.

For slow reactions ($\tau_{1/2}$ > 10 s), the decrease of the absorbances of the electrophiles was measured in a thermostated flask with an immersion UV–vis probe using a working station as already described.[47] This involves a J&M TIDAS diode array spectrophotometer which was controlled by Labcontrol Spectacle software and connected to a Hellma 661.502-QX quartz Suprasil immersion probe (5 mm light path) via fiber optic cables and standard SMA connectors. The temperature of the solutions during all of the kinetic studies was kept constant (20 ± 0.2 °C) by using a circulating bath thermostat and a thermocouple probe that was inserted into the reaction mixture.

Fast reactions ($\tau_{1/2}$ < 10 s at 20 °C) were studied with a stopped-flow instrument (Hi-Tech SF-61DX2 spectrophotometer controlled by Hi-Tech Kinet Asyst2 software) as described previously.[8,48] The experiments were initiated by mixing equal volumes of solutions of the nitroalkyl anion and the electrophile. Nitroalkyl anion concentrations that were higher than the electrophile concentrations were employed, resulting in pseudo-first-order kinetics with an exponential decay of the electrophile. First-order rate constants were obtained by the least-squares fitting of the single exponential $A_t = A_0 \exp(-k_{1\psi,\mathrm{obs}}t) + C$ to the absorbance data (averaged from at least four kinetic runs at each nucleophile concentration).

Because of the poor solubility of the benzhydrylium tetrafluoroborates in water, it was necessary to employ up to 1.6% (v/v) acetonitrile as a cosolvent for the kinetic investigations

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(39) Bard, A. J.; Faulkner, L. R. *Electrochemical Methods: Fundamentals and Applications*; Wiley: New York, 2001.

(40) Bordwell, F. G.; Cheng, J.-P.; Ji, G.-Z.; Satish, A. V.; Zhang, X. *J. Am. Chem. Soc.* **1991**, *113*, 9790–9795.

(41) Kempf, B.; Hampel, N.; Ofial, A. R.; Mayr, H. *Chem.—Eur. J.* **2003**, *9*, 2209–2218.

(42) Bug, T.; Hartnagel, M.; Schlierf, C.; Mayr, H. *Chem.—Eur. J.* **2003**, *9*, 4068–4076.

(43) Evans, S.; Nesvadba, P.; Allenbach, S. (Ciba-Geigy AG). EP 744392, 1996; *Chem. Abstr.* **1997**, *126*, 46968v.

(44) Kornblum, N.; Larson, H. O.; Blackwood, R. K.; Mooberry, D. D.; Oliveto, E. P.; Graham, G. E. *J. Am. Chem. Soc.* **1956**, *78*, 1497–1501.

(45) Kornblum, N.; Weaver, W. M. *J. Am. Chem. Soc.* **1958**, *80*, 4333–4337.

(46) (a) Shriner, R. L.; Parker, E. A. *J. Am. Chem. Soc.* **1933**, *55*, 766–770. (b) Boschan, R.; Merrow, R. T.; Van Dolah, R. W. *Chem. Rev.* **1955**, *55*, 485–510. (c) Fairbrother, D. M.; Skinner, H. A.; Evans, F. W. *Trans. Faraday Soc.* **1957**, *53*, 779–783.

(47) Dilman, A. D.; Ioffe, S. L.; Mayr, H. *J. Org. Chem.* **2001**, *66*, 3196–3200.

(48) Mayr, H.; Ofial, A. R. *Einsichten*: *Forschung an der LMU München* **2001**, *20*, 30–33.

in water. In previous work with other anionic nucleophiles, it has already been shown that the small amount of acetonitrile does not affect the observed rate constants.[11]

In some experiments with electrophile **2a** in water, small quantities of benzenesulfonic acid were added to avoid the reaction of **2a** with water prior to mixing the solutions of the reactants.

Acknowledgment. We thank the Alexander-von-Humboldt Foundation for a fellowship to T.L. and the Deutsche Forschungsgemeinschaft (Ma 673-17) and the Fonds der Chemischen Industrie for financial support. We are grateful to Clemens Schlierf and Dr. Binh Phan Thanh for experimental contributions and to Dr. Armin R. Ofial for valuable suggestions.

Supporting Information Available: Syntheses and characterization of products **3a**−**g**, **4a**, and **5f**−**h** and tables containing concentrations and rate constants of the individual kinetic experiments in DMSO and water. This material is available free of charge via the Internet at http://pubs.acs.org.

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