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Nucleophilicity Parameters for Carbanions in Methanol

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The kinetics of the reactions between eleven carbanions **2a**–**k** (nitronates and malonic acid derivatives) and benzhydrylium ions **1a**–**g** were investigated photometrically in methanol/acetonitrile (91:9, v/v) at 20 °C. Since the competing reactions of the benzhydrylium ions with methanol and methoxide ions are generally slower, the second-order rate constants of the reactions between the benzhydrylium ions **1a**–**g** and the carbanions **2a**–**k** can be determined with high precision. The second-order rate constants (log *k*) correlate linearly with the electrophilicity parameters *E* of the benzhydrylium ions, allowing us to determine the nucleophilicity parameters *N* and *s* of the carbanions in methanol/acetonitrile (91:9, v/v). The nucleophilic reactivities do not correlate with the acidity constants of the conjugate CH acids, and from the poor correlation of the reactivities of the substituted α-nitrobenzyl anions **2d**–**h** with Hammett's σ^- constants it can be inferred that the nucleophilic reactivities are strongly controlled by solvation.

Introduction

The three-parameter equation [Equation (1)] by which electrophiles are characterized by one parameter (electrophilicity *E*) and nucleophiles are characterized by two parameters (nucleophilicity *N* and slope *s*) has turned out to be applicable to a large variety of combinations of electrophiles with nucleophiles.[1,2]

$$\log k_{20\,^\circ\mathrm{C}} = s(E + N) \qquad (1)$$

While the electrophiles investigated so far include various types of carbocations, cationic heterocycles, and metal π complexes,[2] as well as ordinary Michael acceptors[3] and electron-deficient arenes,[4,5] nucleophiles demonstrated to follow Equation (1) include *n*-nucleophiles (amines,[6] alcohols,[7] alkoxides,[8] phosphanes,[9] inorganic anions[10–13]), σ-nucleophiles (C–H,[14] Si–H, Sn–H hydride donors[15,16]), and a large variety of π-nucleophiles[17] (for example alkenes, arenes, enol ethers, ketene acetals,[18] enamines,[19] allylelement compounds,[20] transition metal π complexes,[21] diazoalkanes,[22] and delocalized carbanions[23–25]). A comprehensive listing of previously published *N* and *E* parameters is available online.[26] It has been demonstrated that the rates of the reactions of cationic carbon electrophiles with neutral π-nucleophiles, which have mostly been investigated in dichloromethane solution, are only slightly dependent on solvent polarity; solvent effects on their *N* and *s* parameters can usually be neglected.[2] On the other hand, the reactivities of amines, alcohols, and anionic nucleophiles depend strongly on solvent, and *N* and *s* parameters for these nucleophiles have been defined with respect to particular solvents.[6,7,12,24,25] Recent studies have indicated that nucleophilicity parameters *N* and *s* that have been derived from the reactions between the corresponding nucleophiles and benzhydrylium ions or quinone methides as reference electrophiles[1] also reflect the order of nucleophilicities in S_N2-type reactions[7] and nucleophilic aromatic substitutions.[4]

Numerous rate constants for nucleophilic substitutions have been reported in the literature, often with reference to methanol as a solvent.[27–29] In order to make efficient use of these data for our correlations, we set out to determine the *N* and *s* parameters of a variety of carbanions in methanol.

In this paper we report on the nucleophilic reactivities of the nitro-, ester-, and cyano-substituted carbanions **2a**–**k** in methanol and compare their nucleophilicities with the corresponding reactivities in water and in DMSO.

Results

In previous works[1,23b] we have recommended benzhydrylium ions and structurally analogous quinone methides as reference electrophiles (Table 1) for the determination of the reactivity parameters *N* and *s* as defined by Equation (1) for nucleophiles.

Since most of the reference electrophiles **1** listed in Table 1 react readily with methanol it was not possible to prepare solutions of these electrophiles in methanol and mix them with methanolic solutions of the carbanions in order to determine rate constants for the reactions of carb-

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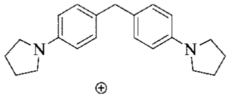
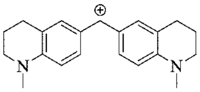
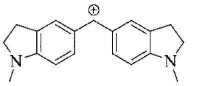
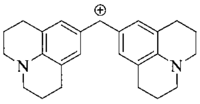
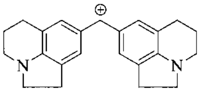
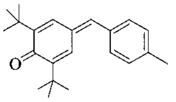
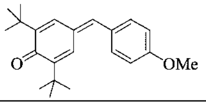
Supporting information for this article is available on the WWW under http://www.eurjoc.org or from the author.

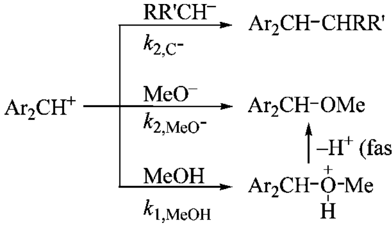
Table 1. Benzhydrylium ions and quinone methides employed in this work.

Electrophile			$E^{[a]}$
1a	$(pyr)_2CH^+$		–7.69
1b	$(thq)_2CH^+$		–8.22
1c	$(ind)_2CH^+$		–8.76
1d	$(jul)_2CH^+$		–9.45
1e	$(lil)_2CH^+$		–10.04
1f	tolQM		–15.83
1g	aniQM		–16.11

[a] From ref.[1,23b]

anions (Table 2) with **1** in pure methanol. However, the kinetics could be measured in methanol/acetonitrile mixtures (91:9, v/v), obtained in a stopped-flow instrument by mixing 10 parts of a methanolic solution of the CH acidic compound and methoxide with 1 part of a solution of benzhydrylium tetrafluoroborate Ar_2CH^+ BF_4^- (**1**) in acetonitrile.

As illustrated in Scheme 1 and expressed by Equation (2) and Equation (3), the photometrically observed pseudo-first-order rate constants k_{obs} for the consumption of the colored benzhydrylium ions reflect the sums of the reactions of benzhydrylium ions with carbanions, methoxide, and methanol. As reported in previous articles,[24,25] all carbanions studied in this work are attacked at carbon by the electrophiles **1a**–**g**.



Scheme 1. Parallel reactions between benzhydrylium ions and carbanions, methoxide, and methanol in methanol.

$$d[Ar_2CH^+]/dt = -k_{obs}[Ar_2CH^+] \quad (2)$$

$$k_{obs} = k_{2,C^-}[C^-] + k_{2,MeO^-}[MeO^-] + k_{1,MeOH} \quad (3)$$

The constancy of $[C^-]$ and $[MeO^-]$ throughout the reactions was warranted because in all experiments the carbanion concentrations were much larger than the electrophile concentrations ($[C^-] > 10[Ar_2CH^+]$) and any consumed MeO^- was rapidly regenerated by proton transfer processes.

Carbanions were generated from the CH acidic compounds in methanol by treatment with sodium methoxide.

From Equations (4), (5), (6), (7), and (8) it is possible to calculate $[C^-]$ and $[MeO^-]$ if either the equilibrium constants (K_{CH}) or the pK_{aH} values of the CH acids, as well as the total base concentrations, are known (see details in Supporting Information).

$$CH + MeO^- \overset{K_{CH}}{\rightleftharpoons} C^- + MeOH \quad (4)$$

$$K_{CH} = [C^-]/([CH][MeO^-]) \quad (5)$$

$$pK_{aH} = -\log\{([C^-][H^+])/[CH]\} \quad (6)$$

$$pK_{MeOH} = -\log([MeO^-][H^+]) = 16.92 \text{ (at 20 °C)}^{[30]} \quad (7)$$

$$\text{Then } K_{CH} = K_{aH}/K_{MeOH} \quad (8)$$

For some CH acids, such as phenylnitromethane (**2d**-H), (*p*-tolyl)nitromethane (**2e**-H), and (*p*-cyanophenyl)nitromethane (**2h**-H), neither the pK_{aH} nor the K_{CH} values in

Table 2. Carbanions investigated in this work and pK_{aH} values of the corresponding CH acids in methanol, water, and DMSO.

Carbanion		pK_{aH} in MeOH	K_{CH} [M^{-1}] in MeOH, Equation (4)	pK_{aH} in H_2O	pK_{aH} in DMSO
2a	$CH_2=NO_2^-$	15.60[a]	$2.20\cdot10^{1}$[a]	10.22[h]	17.20[h]
2b	$MeCH=NO_2^-$	14.20[a]	$5.00\cdot10^{2}$[a]	8.60[h]	16.70[h]
2c	$(Me)_2C=NO_2^-$	13.19[b]	$5.37\cdot10^{3}$[f]	7.74[h]	16.80[h]
2d	$C_6H_5CH=NO_2^-$	12.62[c]	$2.00\cdot10^{4}$[c]	6.88[h]	12.20[h]
2e	$(4\text{-}MeC_6H_4)CH=NO_2^-$	13.02[c]	$8.01\cdot10^{3}$[c]	7.11[h]	12.33[h]
2f	$(4\text{-}NO_2C_6H_4)CH=NO_2^-$	10.50[d]	$2.63\cdot10^{6}$[f]	5.89[h]	8.62[h]
2g	$(3\text{-}NO_2C_6H_4)CH=NO_2^-$	10.90[d]	$1.05\cdot10^{6}$[f]	6.30[h]	10.04[h]
2h	$(4\text{-}CNC_6H_4)CH=NO_2^-$	11.99[c]	$8.61\cdot10^{4}$[c]	6.17[h]	9.31[h]
2i	$EtO_2C(CN)CH^-$	15.53[e]	$2.40\cdot10^{1}$[e]	11.20[i]	13.10[i]
2j	$(MeO_2C)_2CH^-$	17.27[e]	$4.50\cdot10^{-1}$[e]	13.00[j]	15.90[k]
2k	$(CN)_2CH^-$	14.10[a]	$6.00\cdot10^{2}$[g]	11.20[i]	11.10[i]

[a] From ref.[27] [b] From ref.[31] [c] This work. [d] From ref.[32] [e] From ref.[28] [f] Calculated from the corresponding pK_{aH} values. [g] From ref.[33] [h] From references quoted in ref.[24] [i] From references quoted in ref.[25] [j] From ref.[34] [k] From ref.[35]

methanol have been reported; so these values were determined in this work by spectrophotometry through the UV absorptions of the nitronate anions. When the CH acids were added to solutions of methoxide in methanol, the absorbances of the generated carbanions increased steadily and reached constant values at certain $[CH]_0/[MeO^-]_0$ ratios, as shown for (*p*-cyanophenyl)nitromethane (**2h**-H) in Figure 1. From the end absorbances A_{end} and the absorbances A at certain points in the titration it is possible to calculate the K_{CH} values of the CH acids in methanol if the validity of the Beer–Lambert law is assumed.

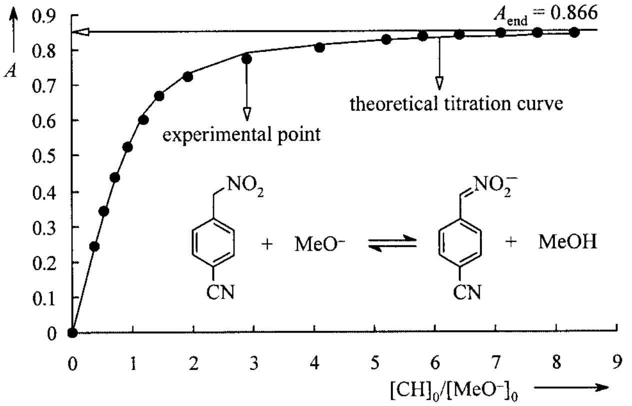


Figure 1. Deprotonation of (*p*-cyanophenyl)nitromethane (**2h**-H) by methoxide (20 °C, in methanol), detected by the absorbance at 340 nm.

The K_{CH} values for phenylnitromethane (**2d**-H), (*p*-tolyl)nitromethane (**2e**-H), and (*p*-cyanophenyl)nitromethane (**2h**-H), which are presented in Table 2, were obtained by least-squares fitting, which optimizes the end absorbances and the individually calculated K_{CH} values (for more details see Supporting Information). The pK_{aH} values (Table 2) were then calculated from K_{CH} as in Equation (8). It was also shown for the titration of **2h**-H with methoxide that the equilibrium constants in pure methanol and in MeOH/MeCN (91:9, v/v)[36] agree within experimental error, justifying the use of pK_{aH} values relating to pure methanol also for reactions in MeOH/MeCN (91:9, v/v).

In general, the competing reactions of MeO^- have to be considered. Since the rate constants k_{2,MeO^-} for the reactions between methoxide anion and the reference electrophiles used in this work in MeOH/MeCN (91:9, v/v) and in pure MeOH have recently been reported (Table S1 in Supporting Information),[8] the terms responsible for the reactions of the carbanions and methanol [Equation (9), right] with the reference electrophiles can be derived by rearranging Equation (3) to Equation (9).

$$k_{1\Psi} = k_{obs} - k_{2,MeO^-}[MeO^-] = k_{2,C^-}[C^-] + k_{1,MeOH} \quad (9)$$

The second-order rate constants k_{2,C^-} are then obtained as the slopes of plots of $k_{1\Psi}$ vs. $[C^-]$ as shown for the reaction between $(thq)_2CH^+$ (**1b**) and the nitroethyl anion (**2b**) in Figure 2. The intercepts of these correlations correspond to the reactions between the electrophiles and the solvent methanol $\{k_{1\Psi} = k_{1,MeOH}$ for $[C^-] = 0$; see Equation (9)$\}$. Since the intercepts are usually small and are the products of long-range extrapolations, the $k_{1,MeOH}$ values determined in this way are of much lower accuracy than the directly determined rate constants for the reactions with the solvent.[7a] A typical deviation between the intercepts of $k_{1\Psi}$ vs. $[C^-]$ correlations and directly determined values of $k_{1,MeOH}$ is given in the caption of Figure 2.

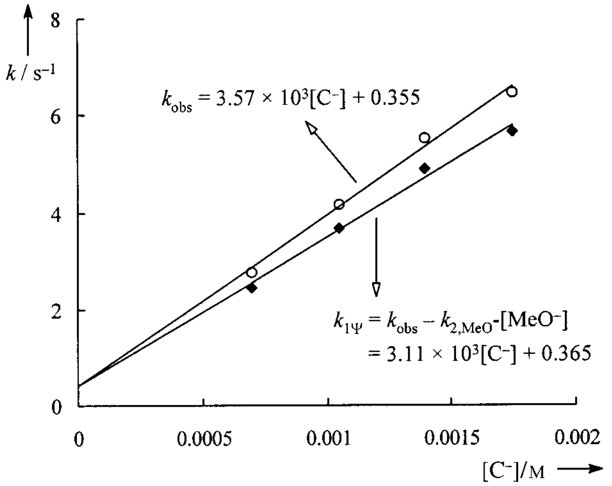


Figure 2. Determination of the second-order rate constant $k_{2,C^-} = (3.11 \pm 0.22)\times 10^3\ M^{-1}\ s^{-1}$ for the reaction between $(thq)_2CH^+$ (**1b**) and nitroethyl anion (**2b**) in MeOH/MeCN (91:9, v/v) at 20 °C [for the competing reaction of **1b** with methanol: $k_{1,MeOH} = (3.65 \pm 2.84)\times 10^{-1}\ s^{-1}$, which has to be compared to the more accurate value $k_{1,MeOH} = 2.17\times 10^{-1}\ s^{-1}$ determined directly from the reaction between **1b** and methanol (ref.[7])].

Only for the combination of the quinone methide **1f** with the ethyl cyanoacetate anion (**2i**) was the term $k_{2,C^-}[C^-]$ smaller than $0.5k_{obs}$, which implies the risk of high error propagation due to uncertainties in $k_{2,MeO^-}[MeO^-]$.

In all other cases, the term $k_{2,C^-}[C^-]$ corresponds to 60 to 100% of k_{obs}; that is, the rate constants k_{2,C^-} listed in Table 3 are as precise as other reported second-order rate constants (±5%), because the contributions of the parallel reactions of MeO^- and of MeOH with the reference electrophiles are small in relation to those of the reactions of the carbanions.

The case illustrated in Figure 2, for example, shows that the rate constant for the reaction with the solvent is not used for the evaluation of the kinetics, but results as the intercept. The difference in the slopes (3574 for k_{obs} and 3111 for $k_{1\Psi}$) is due to the parallel reaction with methoxide. Since this is only a correction by 13%, it is possible to calculate that even a 25% error in the methoxide term would affect k_{2,C^-} by only 3%. Errors introduced by any inaccurate values of pK_{aH} are not included in this consideration. Since previous work has shown that the reactivities of the carbanions **2a**–**k** in polar solvents do not depend on the counterion,[23b,24,25] we consider the rate constants k_{2,C^-} determined in this work to be those for the free carbanions.

For the reasons discussed above, most of the kinetic data reported in this work have been determined not in pure methanol, but in methanol/acetonitrile (91:9, v/v). However,

Table 3. Second-order rate constants k_{2,C^-} (± 5%) for the reactions between benzhydrylium ions and carbanions in methanol/acetonitrile (91:9, v/v) at 20 °C.

Carbanion		k_{2,C^-} [M^{-1} s^{-1}]						
		(pyr)$_2$CH$^+$	(thq)$_2$CH$^+$	(ind)$_2$CH$^+$	(jul)$_2$CH$^+$	(lil)$_2$CH$^+$	tolQM	aniQM
2a	$CH_2{=}NO_2^-$	$7.37\cdot10^3$	$2.96\cdot10^3$	$1.51\cdot10^3$	$5.65\cdot10^2$	$2.70\cdot10^2$		
2b	$CH_3CH{=}NO_2^-$	$7.53\cdot10^3$	$3.11\cdot10^3$	$1.19\cdot10^3$	$4.60\cdot10^2$	$1.95\cdot10^2$		
2c	$(CH_3)_2C{=}NO_2^-$	$1.68\cdot10^3$	$6.52\cdot10^2$	$2.49\cdot10^2$	$9.60\cdot10^1$			
2d	$C_6H_5CH{=}NO_2^-$	$1.53\cdot10^3$	$7.95\cdot10^2$	$2.97\cdot10^2$				
2e	4-$MeC_6H_4CH{=}NO_2^-$	$5.35\cdot10^3$	$2.70\cdot10^3$	$1.12\cdot10^3$				
2f	4-$NO_2C_6H_4CH{=}NO_2^-$		$1.72\cdot10^4$	$5.35\cdot10^3$	$2.31\cdot10^3$	$7.49\cdot10^2$		
2g	3-$NO_2C_6H_4CH{=}NO_2^-$		$4.45\cdot10^4$	$1.63\cdot10^4$	$6.32\cdot10^3$	$2.12\cdot10^3$		
2h	4-$CNC_6H_4CH{=}NO_2^-$		$1.74\cdot10^4$	$5.24\cdot10^3$	$2.05\cdot10^3$	$7.25\cdot10^2$		
2i	$EtO_2C(CN)CH^-$		$5.02\cdot10^6$	$2.23\cdot10^{6}$[a]	$1.16\cdot10^6$	$4.87\cdot10^5$	$5.93\cdot10^1$	$4.13\cdot10^1$
2j	$(MeO_2C)_2CH^-$		$2.73\cdot10^6$	$1.29\cdot10^6$	$4.92\cdot10^5$	$1.80\cdot10^5$		
2k	$(CN)_2CH^-$		$6.95\cdot10^6$	$2.57\cdot10^6$	$1.14\cdot10^6$	$4.35\cdot10^5$	$3.90\cdot10^1$	$2.93\cdot10^1$

[a] Because of a large negative intercept in the plot of $k_{1\Psi}$ vs. [C$^-$] this number is to be treated with caution.

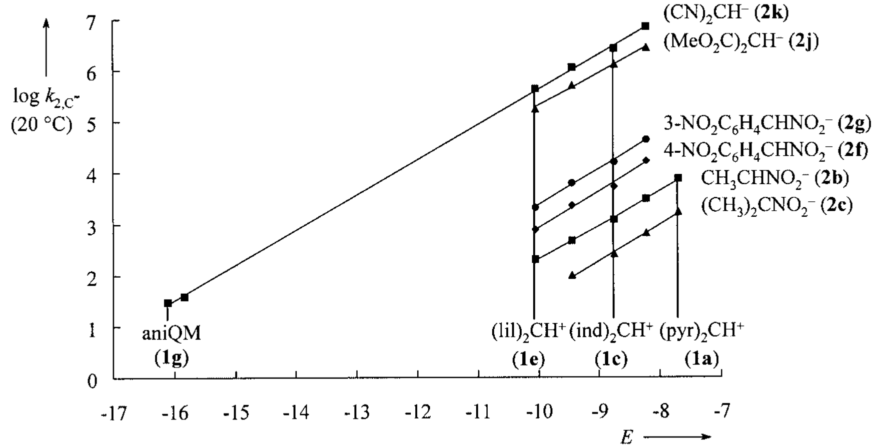


Figure 3. Correlation of logk_{2,C^-} (from Table 3) with the electrophilicity parameters *E* of the corresponding benzhydrylium ions and quinone methides.

since the rate of the reaction of (lil)$_2$CH$^+$ (**1e**) with methoxide in pure methanol is only 1.4 times faster than the corresponding reaction in methanol/acetonitrile (91:9, v/v),[8] one can consider the data in Table 3 also to be representative for the reactions in pure methanol.

Table 4. Nucleophilicity parameters of carbanions in different solvents.

	Carbanion	*N*/*s*		
		in H_2O[a]	in MeOH[b]	in DMSO[c]
2a	$CH_2{=}NO_2^-$	12.06/0.53	14.02/0.605	20.71/0.60
2b	$CH_3CH{=}NO_2^-$	11.25/0.52	13.41/0.673	21.54/0.62
2c	$(CH_3)_2C{=}NO_2^-$	10.69/0.56	12.20/0.710	20.61/0.69
2d	$C_6H_5CH{=}NO_2^-$	12.05/0.53	12.51/0.666	18.29/0.71
2e	4-$MeC_6H_4CH{=}NO_2^-$	13.09/0.50	13.58/0.636	18.31/0.76
2f	4-$NO_2C_6H_4CH{=}NO_2^-$	13.58/0.52	14.05/0.720	16.29/0.75
2g	3-$NO_2C_6H_4CH{=}NO_2^-$	14.25/0.46	14.75/0.710	18.06/0.71
2h	4-$CNC_6H_4CH{=}NO_2^-$	13.23/0.52	13.92/0.736	16.96/0.73
2i	$EtO_2C(CN)CH^-$	15.57/0.58	18.59/0.654	19.62/0.67
2j/2j′	$(RO_2C)_2CH^-$	16.15/0.66	18.24/0.644	20.22/0.65
2k	$(CN)_2CH^-$	19.50/0.55	18.21/0.686	19.36/0.67

[a] Data for the carbanions **2a**–**h** from ref.[24], for the carbanions **2i**, **2j′** (R = Et), and **2k** from ref.[25] [b] This work, for carbanion **2j** (R = Me). [c] Data for the carbanions **2a**–**h** from ref.[24], for the carbanions **2i**, **2j′** (R = Et), and **2k** from ref.[23b]

Plots of logk_{2,C^-} (from Table 3) vs. the electrophilicity parameters *E* of the corresponding benzhydrylium ions[1] and quinone methides[23b] show linear correlations (Figure 3), from which *N* and *s* parameters of the carbanions according to Equation (1) were derived (Table 4). For the sake of clarity, only some of the kinetic data of Table 3 are shown graphically in Figure 3 (see the Supporting Information for the other logk_{2,C^-} vs. *E* correlations).

Figure 3 and the analogous plots in the Supporting Information show that the correlations are generally of high quality, which implies that rate constants calculated from the parameters given in Table 4 are generally accurate within ±10%. Because errors in *N* and *s* parameters compensate each other, we have refrained from assigning individual errors to the parameters listed in Table 4.

Discussion

The almost parallel correlation lines shown in Figure 3, which are reflected in the closely similar values of *s* in the middle column of Table 4, imply that the relative nucleophilicities of the carbanions **2a**–**h** in methanol depend only slightly on the electrophilicity of the reaction partner. As a consequence, the *N* parameters by themselves are good approximations of the relative reactivities of these carbanions toward benzhydrylium electrophiles in general. The same is true for the nucleophilic reactivities of these carbanions in DMSO and in water. Figure 4 shows that the correlation line for the reaction between **2f** and benzhydrylium ions is somewhat flatter for aqueous solution than for methanol and DMSO solutions. As a consequence, the reactivity ratios $k_{\mathrm{DMSO}}/k_{\mathrm{H_2O}}$ and $k_{\mathrm{MeOH}}/k_{\mathrm{H_2O}}$ will slightly increase with increasing electrophilicity of the reaction partners. Similar behavior can be expected for several other carbanions because Table 4 shows that *s* is in most cases somewhat smaller in water than in methanol or DMSO.

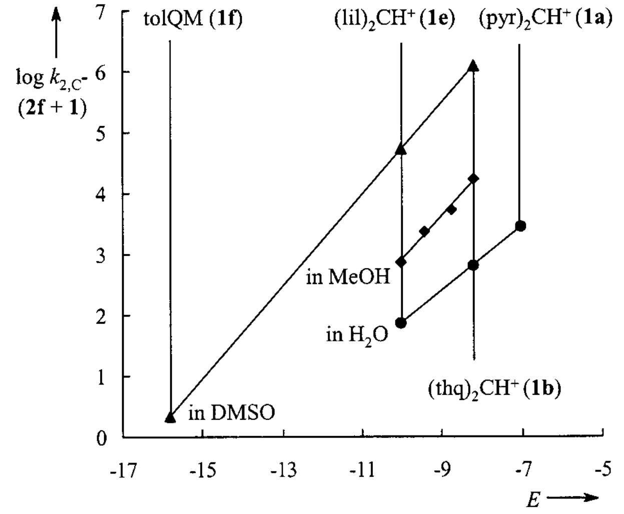


Figure 4. Rate constants for the reactions between the (*p*-nitrophenyl)nitromethyl anion (**2f**) and the reference electrophiles **1** in different solvents.

Because of the differences in *s*, discussions of structure–reactivity relationships can only be based on *N* when large differences in *N* are considered. Figure 5 shows that aliphatic (**2a**–**c**) and aromatic nitronates (**2d**–**h**) have similar nucleophilicities in methanol, comparable to the situation in water. The tremendous reduction of the nucleophilic reactivities of the aliphatic nitronates **2a**–**c** by hydrogen-bond donor solvents, which has been discussed for the change from DMSO to aqueous solution[24] is also found in methanol. A change from DMSO to methanol reduces the nucleophilicities of aliphatic nitronates **2a**–**c** much more than the nucleophilicities of aromatic nitronates **2d**–**h**.

Figure 5 furthermore shows that the ester- and cyano-substituted carbanions **2i**–**k** are considerably more nucleophilic in methanol than the nitronates **2a**–**h**. While in water the anions **2i**–**k** are also more nucleophilic than the nitronates **2a**–**h**, in DMSO the aliphatic nitronates **2a**–**c** are most nucleophilic, followed by **2i**–**k** and the even less reactive aromatic nitronates **2d**–**h**.

Comparison of the malononitrile anion **2k** in the three solvents shows that the slope *s* cannot be neglected when

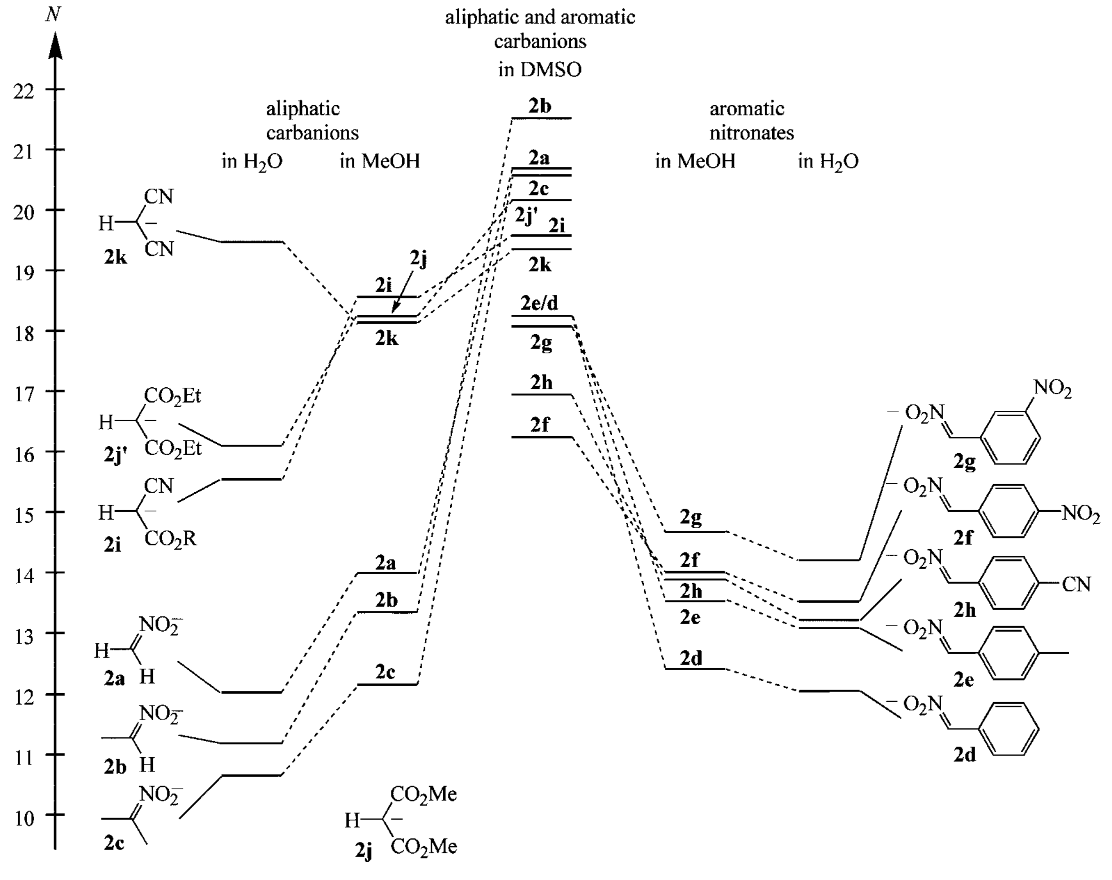


Figure 5. Comparison of the nucleophilic reactivities of carbanions in different solvents (data from Table 4).

small differences in N are compared. Although the nucleophilicity parameter N of **2k** is smaller in MeOH than in water and DMSO, the reactivity of **2k** toward $(lil)_2CH^+$ (**1e**) increases slightly from water to MeOH and DMSO ($k_{rel} \approx$ 1:3:12).[23b,25]

In previous work we had already found that the correlation between nucleophilic reactivities and pK_{aH} parameters is poor in DMSO solution and even worse in water.[23b,24,25] Figure 6 shows an analogous situation in methanol: the nucleophilicity parameters N correlate only poorly with pK_{aH}. Figure 7 demonstrates that the lacking correlation is not an artifact due to the use of N: the directly determined second-order rate constants for the reactions between the carbanions **2a**–**h** and the benzhydrylium ion **1b** also correlate poorly with pK_{aH}, showing that relative nucleophilic reactivities, even within a series of closely related structures, cannot be derived from the corresponding pK_{aH} values.

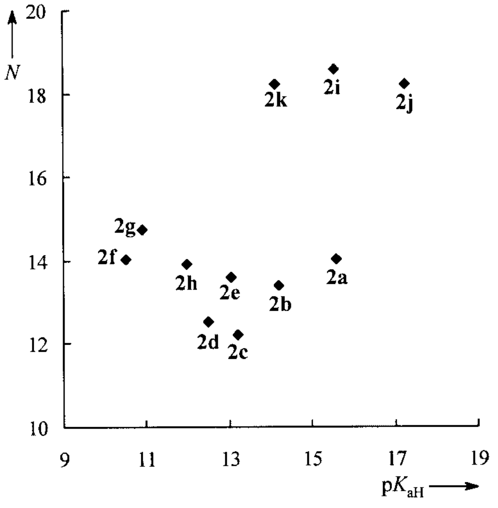


Figure 6. Plot of the nucleophilicity parameters N of the carbanions **2a**–**k** vs. pK_{aH} of the corresponding CH acids (MeOH, 20 °C).

As previously reported for aqueous solution, the unsubstituted α-nitrobenzyl anion **2d** is also the weakest nucleophile among the aromatic nitronates **2d**–**h** in methanol, while the 3-nitro derivative **2g** is the strongest nucleophile of this series. As shown in Figure 8 for the reactions with the benzhydrylium ions **1b** and **1c**, there is no correlation between the nucleophilic reactivities of the aromatic nitronates and Hammett's σ^- constants.[37] The fact that acceptor-substituted α-nitrobenzyl anions react more rapidly than the unsubstituted and *p*-methyl-substituted derivatives is another manifestation of the nitroalkane anomaly,[38] which implies that reactivity is controlled more by solvation than by intrinsic properties (e.g., basicities) of the anions.

At present we feel unable to rationalize the reasons for the poor correlations between nucleophilicity and basicity, which are strongly affected by solvation. Systematic investigations of the intrinsic barriers of these reactions will be needed to elucidate the factors that control these relationships. We are currently pursuing such investigations and also intend to employ the N and s parameters described in this work for analyzing nucleophilic aromatic and aliphatic substitutions.[7b]

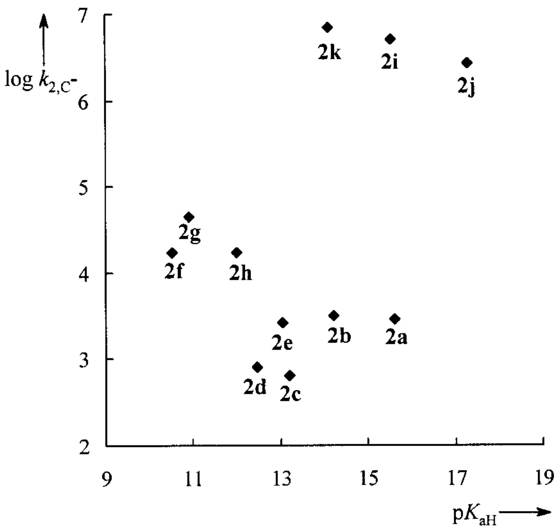


Figure 7. Plot of $\log k_{2,C^-}$ of the reactions between the carbanions **2a**–**k** and $(thq)_2CH^+$ (**1b**) vs. pK_{aH} values for the corresponding CH acids (MeOH, 20 °C).

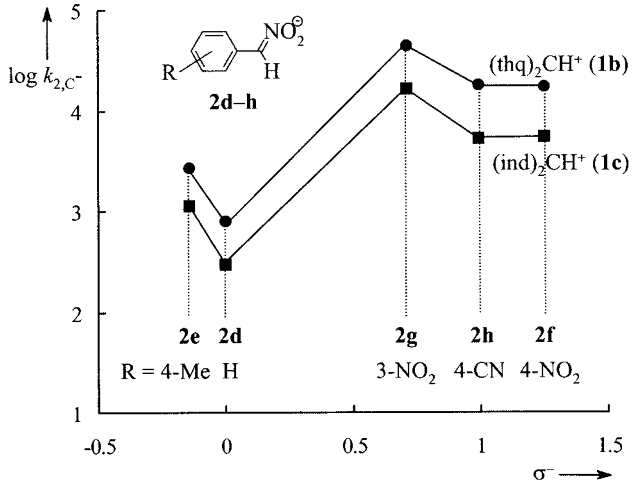


Figure 8. Correlations between $\log k_{2,C^-}$ for the reactions between aryl-substituted nitronates **2d**–**h** and $(thq)_2CH^+$ (**1b**) and $(ind)_2CH^+$ (**1c**) in methanol and the corresponding σ^- values (from ref.[37]).

Experimental Section

Materials: Reagent grade methanol (99.8%, Acros) was distilled from magnesium and iodine. Stock solutions of sodium methoxide were prepared by addition of freshly cut sodium metal, prewashed in methanol, to pure solvent maintained in an inert atmosphere of dry nitrogen. The solution was stored under nitrogen and analyzed immediately before use by titration with hydrochloric acid (0.1 M) to the phenolphthalein endpoint.

Nitromethane (≥99%), nitroethane (≥99%), 2-nitropropane (≥97%), dimethyl malonate (≥99%), ethyl cyanoacetate (99.5%), and malononitrile (≥99%) were purchased from commercial suppliers and distilled prior to use. Phenylnitromethane (**2d**-H), (*p*-

tolyl)nitromethane (**2e**-H), (*p*-nitrophenyl)nitromethane (**2f**-H), and (*m*-nitrophenyl)nitromethane (**2g**-H) were synthesized as previously reported.[24]

(*p*-Cyanophenyl)nitromethane (2h-H):[39] A mixture of *t*BuOK (6.78 g, 60.4 mmol) and 18-crown-6 (3.05 g, 11.5 mmol) in dry THF (200 mL) was cooled to –35 °C and a solution of 4-cyanotoluene (6.01 g, 51.3 mmol) in dry THF (40 mL) was slowly added. Subsequently, a solution of *n*-propyl nitrate (4.30 mL, 40.2 mmol) in dry THF (10 mL) was added with vigorous stirring. After the mixture had been stirred at –35 °C for 30 min, a solution of glacial acetic acid (8.5 mL) in dry THF (20 mL) was added. The mixture was stirred until it reached room temperature and was then poured into water (200 mL) and extracted with diethyl ether (3 × 100 mL). The combined organic phases were washed with water and dried (Na_2SO_4), and the solvent was evaporated to give the crude product as a light yellow solid (4.59 g, m.p. 93–95 °C). Crystallization gave **2h**-H as a colorless solid [4.25 g, 65%, m.p. 95–96 °C (from MeOH)]. ^1H NMR (300 MHz, $CDCl_3$): δ = 5.52 (s, 2 H, CH_2NO_2), 7.59 (d, J = 8.4 Hz, 2 H), 7.75 (d, J = 8.4 Hz, 2 H) ppm. ^{13}C NMR (75.5 MHz, $CDCl_3$): δ = 79.0 (t, CH_2NO_2), 114.1 (s, C-4), 117.8 (s, CN), 130.7 (d, C-2,6), 132.8 (d, C-3,5), 134.0 (s, C-1) ppm. $C_8H_6N_2O_2$ (162.15): C 59.26, H 3.73, N 17.28; found C 59.51, H 3.67, N 17.24.

Kinetic Measurements: Solutions of the carbanions were freshly generated prior to each kinetic measurement by mixing the CH acidic compounds with methoxide in methanol.

The reactions of the colored reference electrophiles with carbanions and with methoxide gave rise to colorless products, and the decays in the absorptions of the electrophiles were followed by UV/Vis spectroscopy.[6,19a,40,41] The temperature of the solutions during all kinetic studies was kept constant (20.0 ± 0.1 °C) by use of circulating bath thermostats.

In general, Hi-Tech SF-61DX2 stopped-flow spectrophotometer systems (controlled by Hi-Tech KinetAsyst2 software) with syringes set up for a 10:1 mixing ratio were used for investigation of the reactions between carbanions and reference electrophiles. Only the rates of the slow reactions between **2i** and quinone methides **1f** and **1g** were determined by use of 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) through fiber optic cables and standard SMA connectors.

The stopped-flow experiments were performed by mixing 10 volume parts of the solutions of the carbanions in methanol with 1 volume part of the solutions of the reference electrophiles in acetonitrile to yield 91:9 (v/v) mixtures of methanol and acetonitrile.

Carbanion concentrations were at least ten times higher than those of the electrophiles, resulting in pseudo-first-order kinetics with exponential decay of the electrophile concentrations. The pseudo-first-order rate constants k_{obs} (s^{-1}) were obtained by least-squares fitting of the single-exponential $A_t = A_0\exp(-k_{\text{obs}}t) + C$ to the time-dependent absorbance A of the electrophiles.

As defined in Equation (9), the terms $k_{2,\text{MeO}^-}[\text{MeO}^-]$ were calculated from the known k_{2,MeO^-} (from ref.[8]) and then subtracted from the pseudo-first-order rate constants k_{obs}. The obtained values $k_{1\Psi}$ (s^{-1}) were plotted against the concentrations of the carbanions, giving linear correlations with slopes corresponding to the second-order rate constants of the reactions of carbanions with the reference electrophiles k_{2,C^-} (M^{-1} s^{-1}). This method is analogous to the evaluation in references.[24,25]

Rate constants for the individual kinetic experiments are given in the Supporting Information.

Supporting Information (for details see the footnote on the first page of this article): Determination of the acidities of **2d**-H, **2e**-H, and **2h**-H in methanol; details of the kinetic experiments.

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