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Ionizing Power of Aprotic Solvents

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Dedicated to Professor Masatomo Nojima on the occasion of his 70th birthday

Keywords: Kinetics / Reaction mechanisms / Solvent effects / Linear free energy relationships / Ion pairs / Heterolysis reactions

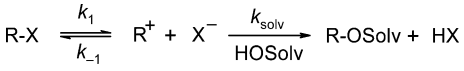
Rate constants for the heterolysis reactions (S_N1) of a series of chloro-diarylmethanes in aprotic solvents (dimethyl sulfoxide (DMSO), acetonitrile, carboxamides, etc.) have been determined conductometrically in the presence of amines or triphenylphosphane, which trap the intermediate ion-pairs and suppress ion recombination. The operation of S_N2 mechanisms can be excluded because the observed first-order rate constants become almost independent of the nature of the nucleophilic additive when a certain concentration of nucleophile is exceeded. The heterolysis rate constants are used to calculate nucleofugality parameters N_f and s_f for chloride in aprotic solvents according to the linear free-energy relationship $\lg k$ (25 °C) = $s_f(N_f + E_f)$. Ionizing powers Y_{BnCl} of these solvents were calculated according to the Winstein–Grunwald equation. Because the heterolysis rate constants in aprotic solvents correlate only poorly with dielectric constants or empirical solvent parameters such as Gutmann's acceptor numbers or E_T^N values, the most common solvent polarity parameters do not reliably predict ionization rates in aprotic solvents.

Introduction

In 1948, Winstein and Grunwald reported that the rates of the S_N1 solvolyses of neutral RX substrates in different solvents (Scheme 1) can be described by the linear free-energy relationship [Equation (1)][1]

$$\lg(k/k_0) = mY \quad (1)$$

where the solvent ionizing power Y ($Y = 0$ for 80% aqueous ethanol) is defined as the ratio of the solvolysis rates of *tert*-butyl chloride ($m = 1$) in a given solvent (k) and in 80% aqueous ethanol (k_0) at 25 °C.



Scheme 1. Simplified scheme for S_N1 solvolysis.

Initially assumed to be applicable to all types of S_N1 solvolyses, it was soon realized that deviations from Equation (1) were due to variable degrees of solvation of the developing carbocations, particularly of alkyl and aryl groups.[2–9] As a consequence, numerous Y scales of solvent ionizing power were later introduced for a more reliable prediction of the solvolysis rate constants for structurally related compounds.[3a,10–14] However, most of these scales were restricted to protic solvents such as alcohols, water, or mixtures of protic and aprotic solvents, where the intermediate carbocations may irreversibly be trapped, so that the course of the reactions can be followed by monitoring the formation of the acid HX. Only a few aprotic solvents have so far been investigated.[13] S_N1 reactivities of *tert*-butyl halides and adamantyl derivatives have been studied in moderately basic solvents, such as dimethylformamide and acetamide, which become alkylated by the intermediate, highly reactive carbenium ions.[15] The ionization rates of adamantyl arenesulfonates have been investigated in acetonitrile solutions by titrimetric determination of the consumption of added azide ions; under these conditions the intermediate adamantyl cations are either trapped directly by azide ions or are intercepted by the solvent to give *N*-adamantyl-nitrilium ions, which undergo 1,3-dipolar cycloadditions with the azide ions.[16a] By following the rate of development of toluenesulfonic acid from *p*-methoxyneophyl toluenesulfonate, Winstein and co-workers were able to compare the ionizing power of protic and aprotic solvents.[16b]

Heterolysis rate constants in aprotic solvents have also been determined by the so-called "verdazyl method" introduced by Dvorko and co-workers,[17] in which triphenylverdazyl radicals react with solvent-separated ion-pairs. The reaction rates are usually monitored spectrophotometrically

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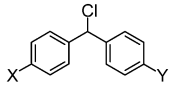
by following the decrease in the absorbance of the radical. We now report a more direct and general method to determine the ionizing power of aprotic solvents.

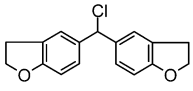
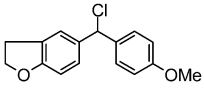
Recently, we have shown that amines and phosphanes can suppress common ion return in S_N1 solvolysis reactions of chloro-diarylmethanes in protic solvents (acetone/water and acetonitrile/water mixtures) without reacting by the S_N2 mechanism.[18] Because the intermediate carbocations are trapped quantitatively by formation of benzhydrylammonium ions, the ionization rate constants could be determined conductometrically by using conventional and stopped-flow techniques. This methodology has now been similarly employed to determine the ionization rates of the chloro-diarylmethanes **1a**–**f** (Table 1) in aprotic solvents. These rate constants will be used to include aprotic solvents into the previously established scales of solvent ionizing power and to calculate the nucleofugality parameters N_f and s_f of chloride ions in aprotic solvents according to the linear free-energy relationship [Equation (2)][19,20]

$$\lg k(25\ ^\circ\mathrm{C}) = s_f(N_f + E_f) \quad (2)$$

where the heterolysis rate constants k (s^{-1}) are expressed as a function of the solvent-independent electrofuge-specific parameter E_f and the nucleofuge-specific parameters s_f and N_f, which refer to combinations of leaving groups and solvents.

Table 1. Chloro-diarylmethanes **1a**–**f** and electrofugality parameters E_f[20] of the corresponding benzhydrylium ions **1a**$^+$–**f**$^+$.



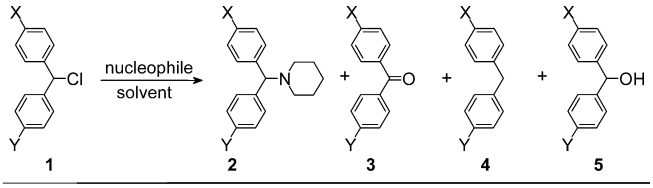
	X	Y	E_f
1a			1.07
1b			0.61
1c	OMe	OMe	0.00
1d	OMe	OPh	–0.86
1e	OMe	Me	–1.32
1f	OMe	H	–2.09

Results

Product Analysis

In the absence of additives, solutions of the chloro-diarylmethanes **1a**–**f** were stable in all solvents used for this study [CH_3CN, dimethyl sulfoxide (DMSO), dimethylacetamide (DMA), dimethylformamide (DMF), *N*-methylpyrrolidin-2-one (NMP), propylene carbonate (PC), $CHCl_3$, CH_2Cl_2, and acetone]. When piperidine or triphenylphosphane was added, the formation of **2**–**5** was observed by NMR or GC-MS analysis after aqueous workup (Table 2).

Table 2. Products of the reactions of **1** with piperidine or PPh_3 in different solvents at 20 °C.



Solvent	Substrate	Nucleophile	Crude products [%][a]	Yield [%][b]
CH_3CN	**1c**	piperidine	100 (**2c**)	80 (**2c**)
	1f	piperidine	100 (**2f**)	85 (**2f**)
DMSO	**1c**	piperidine	97 (**2c**), 3 (**3c**)	72 (**2c**)
	1f	piperidine	68 (**2f**), 32 (**3f**)	58 (**2f**), 28 (**3f**)
DMA	**1c**	piperidine	76 (**2c**), 9 (**3c**), 15 (**4c**)	60 (**2c**)
DMF	**1c**	piperidine	100 (**2c**)	80 (**2c**)
acetone	**1c**	piperidine	100 (**2c**)	84 (**2c**)
$CHCl_3$	**1c**	PPh_3	–	95 (**5c**)

[a] By GC-MS analysis after aqueous workup. [b] Isolated products after recrystallization or column chromatography.

Kinetics

As previously shown for the reactions of other halo-diarylmethanes in protic solvents and DMSO,[18,21] it is possible to follow the course of the reactions by conductivity measurements because ionic products are formed from covalent starting materials. Because the observed conductivities are directly proportional to the concentrations of the products, we were able to obtain rate constants k_{obs} by fitting the time-dependent conductivities G to the monoexponential function (3)

$$G = G_{max}\,(1 - e^{-k(obs)t}) + const. \quad (3)$$

A typical example for such experiments is illustrated in Figure 1 for the reaction of chloro-(2,3-dihydro-5-benzofuranyl)-(4-methoxyphenyl)methane (**1b**) with variable concentrations of piperidine in acetonitrile.

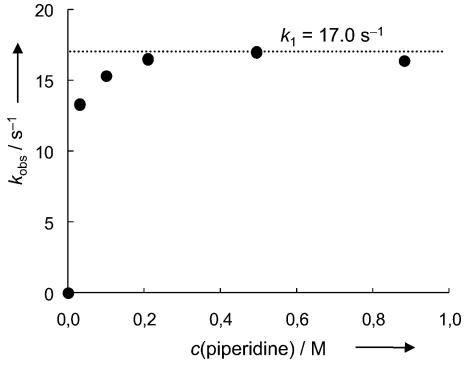
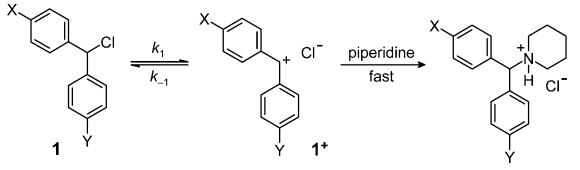


Figure 1. Plot of the observed rate constants k_{obs} vs. c(piperidine) for the reaction of chloro-(2,3-dihydro-5-benzofuranyl)-(4-methoxyphenyl)methane (**1b**) with piperidine in acetonitrile at 25 °C.

As mentioned above, **1b** is stable in pure acetonitrile in the absence of piperidine, and there is no observable change of conductivity. In the presence of a low concentration of piperidine [c(piperidine) = 0.03 M] a change in conductivity is observed, the time dependence of which can be fitted to

Equation (3) to yield a rate constant k_{obs} = 13.3 s^{-1}. As depicted in Figure 1, the observed rate constants increase with increasing piperidine concentrations. A maximum rate constant of $k_{obs,max}$ = 17.0 s^{-1} is finally observed at *c*(piperidine) = 0.50 M, and at higher piperidine concentrations the rate constants decrease slightly.

The observation that the rate constants k_{obs} increase with increasing piperidine concentrations, until a plateau is reached at a certain concentration of piperidine, indicates the operation of an S_N1 mechanism (Scheme 2). If the reactions proceeded by S_N2 mechanisms, k_{obs} would increase linearly with the piperidine concentrations. A detailed discussion will be given below.



Scheme 2. Heterolyses of chloro-diarylmethanes in the presence of piperidine.

The situation described in Figure 1, i.e., increase of k_{obs} with increasing piperidine concentration until a plateau is reached, has been observed for numerous reactions of chloro-diarylmethanes **1a**–**f** with piperidine in different aprotic solvents (see the Supporting Information). When pyridine was used to trap the intermediate carbocations, a somewhat lower plateau was observed (for **1c** in acetonitrile $k_{max,piperidine}/k_{max,pyridine}$ = 1.6, see Figure 2).

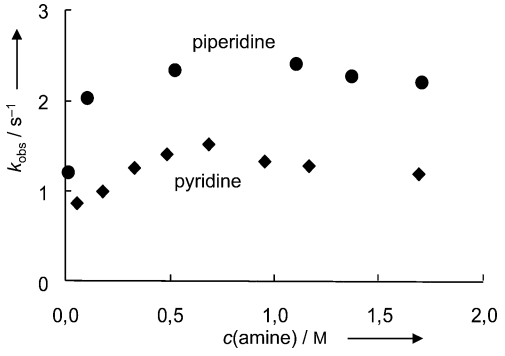


Figure 2. Plot of the observed rate constants k_{obs} vs. *c*(amine) for the reactions of chloro-bis(4-methoxyphenyl)methane (**1c**) with piperidine (circles) and pyridine (diamonds) in pure acetonitrile.

Plateaus of similar, but not identical heights had also been observed when different amines or triphenylphosphane were used to trap benzhydrylium ions, which were reversibly generated from chloro-diarylmethanes in aqueous acetone or acetonitrile.[18] The small differences in the plateaus obtained with different nucleophiles can again be explained by the fact that diffusion-limited trapping reactions will partially occur at the ion-pair stage. In the case of piperidine, its weak hydrogen-bond donating abilities may also contribute.

The dependence of the heights of these plateaus on the nature of the trapping nucleophiles is negligible compared to the influence of the solvent and the substituents X and Y on the magnitude of k_{max}. Therefore, k_{max} values obtained with different trapping reagents are jointly listed as k_1 in Table 3. Whereas piperidine was the preferred trapping agent in most solvents, it reacts with dichloromethane, chloroform,[22] and propylene carbonate, and therefore cannot be employed in these solvents. For that reason, piperidine was replaced by PPh_3 in CH_2Cl_2 and $CHCl_3$, and by pyridine in propylene carbonate, in which PPh_3 is poorly soluble.

Table 3. Conductometrically measured rate constants (k_1, 25 °C) of the reactions of the chloro-diarylmethanes **1a**–**f** with different trapping reagents.

Solvent[a]	Substrate	Electrofugality E_f	k_1 [s^{-1}]
CH_3CN[b]	**1a**	1.07	9.51×10^1
	1b	0.61	1.70×10^1
	1c	0.00	2.40
	1d	–0.86	1.47×10^{-1}
	1e	–1.32	3.77×10^{-2}
	1f	–2.09	3.60×10^{-3}
DMSO[b]	**1a**	1.07	8.85×10^1
	1b	0.61	1.57×10^1
	1c	0.00	2.46
	1d	–0.86	1.89×10^{-1}
	1e	–1.32	5.03×10^{-2}
	1f	–2.09	6.78×10^{-3}
DMA[b]	**1a**	1.07	2.35
	1b	0.61	4.81×10^{-1}
	1c	0.00	7.86×10^{-2}
	1d	–0.86	6.66×10^{-3}
	1e	–1.32	1.37×10^{-3}
DMF[b]	**1a**	1.07	1.44×10^1
	1b	0.61	2.55
	1c	0.00	3.69×10^{-1}
	1d	–0.86	2.73×10^{-2}
	1e	–1.32	6.02×10^{-3}
NMP[b]	**1a**	1.07	1.45
	1b	0.61	2.94×10^{-1}
	1c	0.00	5.32×10^{-2}
	1d	–0.86	4.16×10^{-3}
	1e	–1.32	1.04×10^{-3}
PC[c]	**1a**	1.07	4.63×10^1
	1b	0.61	8.47
	1c	0.00	1.22
	1d	–0.86	1.05×10^{-1}
	1e	–1.32	2.47×10^{-2}
$CHCl_3$[d]	**1a**	1.07	1.54×10^1
	1b	0.61	3.17
	1c	0.00	4.98×10^{-1}
	1d	–0.86	5.82×10^{-2}
CH_2Cl_2[d]	**1a**	1.07	4.84
	1b	0.61	1.02
	1c	0.00	1.72×10^{-1}
	1d	–0.86	1.54×10^{-2}
	1e	–1.32	4.00×10^{-3}
Acetone[b]	**1a**	1.07	1.40
	1b	0.61	2.71×10^{-1}
	1c	0.00	3.49×10^{-2}
	1d	–0.86	3.31×10^{-3}
	1e	–1.32	6.12×10^{-4}

[a] For acronyms see Table 4. [b] Piperidine as trapping reagent. [c] Pyridine as trapping reagent. [d] Triphenylphosphane as trapping reagent.

Figure 3 shows that the heterolysis rate constants of 2-chloro-2-phenylpropane (cumyl chloride) in aprotic solvents, which were determined by Dvorko's verdazyl technique,[17] correlate roughly (slope of 1.11) with those of chloro-bis(4-methoxyphenyl)methane (**1c**), which were determined by the "amine method" described in this work.

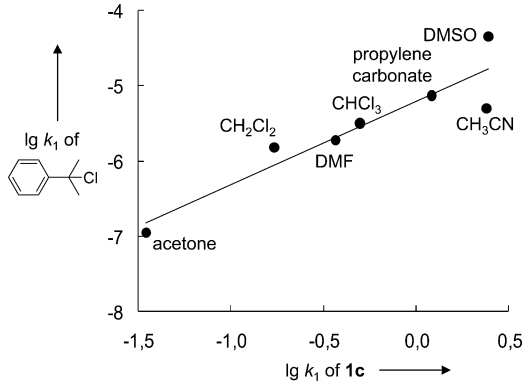
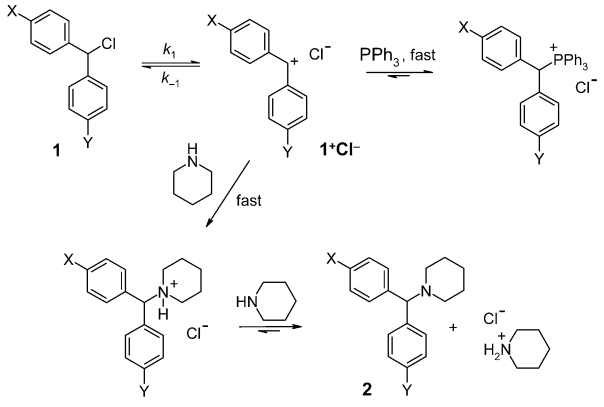


Figure 3. Correlation of the heterolysis rate constants lgk_1 of 2-chloro-2-phenylpropane (by verdazyl method[17]) with those of chloro-bis(4-methoxyphenyl)methane (**1c**) in various aprotic solvents.

Discussion

Reaction Mechanism

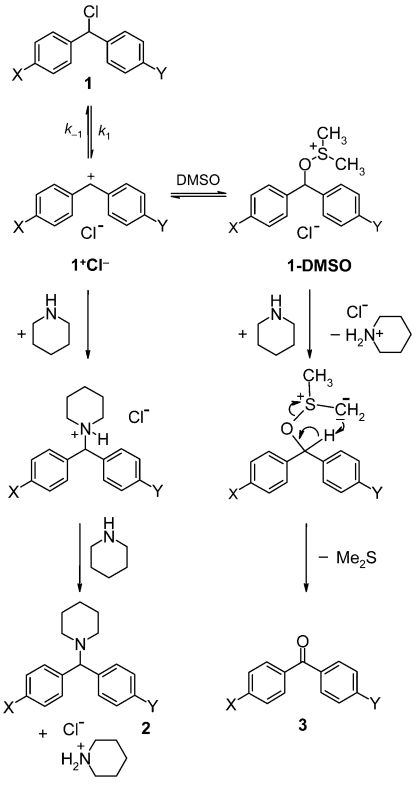
The reactions of the chloro-diarylmethanes **1a**–**f** with piperidine or triphenylphosphane in acetonitrile, DMF, acetone, $CHCl_3$, or CH_2Cl_2 give rise to the formation of 1-benzhydrylpiperidines **2** or benzhydryl phosphonium salts (Scheme 3). As pointed out above, the non-linearity of the plots of k_{obs} vs. the concentration of the trapping reagents, and the plateaus in these plots (Figures 1, 2 and the Supporting Information) suggest that the reactions proceed through the S_N1 mechanism; after ionization of **1**, the intermediate carbocation is rapidly trapped by either piperidine or triphenylphosphane.



Scheme 3. Heterolyses of chloro-diarylmethanes in the presence of piperidine or triphenylphosphane.

In the absence of nucleophiles, the chloro-diarylmethanes **1a**–**f** are stable in all solvents listed in Table 3, indicating that the covalent chloro-diarylmethanes **1** are favored in the dynamic ionization equilibria **1** ⇄ **1**$^+$**Cl**$^-$. In the presence of low concentrations of the trapping reagents, ion recombination is accompanied by the reactions of the ions or ion-pairs with triphenylphosphane or piperidine, yielding benzhydrylphosphonium salts or 1-benzhydryl-piperidines **2**, respectively. When the concentrations of the trapping reagents are increased, the observed rate constants increase due to the fact that ion recombination (k_{-1}) becomes increasingly suppressed. At a certain concentration, independence of the rate constant $k_{obs,max}$ of the nucleophile concentration is observed, indicating that ion recombination is completely suppressed and that the ionization of **1** has become rate-determining. Under these conditions, the observed rate constants $k_{obs,max}$ correspond to the ionization rate constants k_1 defined in Scheme 1 and Scheme 3. The slight decrease of reactivity at high concentrations of amines can be explained by a change of solvent polarity.

The situation is different in DMSO solution because this solvent is a stronger O-nucleophile than water and ordinary alcohols.[21] When **1** is dissolved in pure DMSO, a reversible ionization leads to **1**$^+$**Cl**$^-$, which is reversibly attacked by DMSO to form **1-DMSO** (Scheme 4). As conductivity does not change, one can conclude that in these equilibria the covalent chloro-diarylmethanes **1** are the dominating species. In contrast, the corresponding bromo-diarylmethanes have been observed to react with DMSO also in the absence



Scheme 4. Heterolyses of chloro-diarylmethanes in DMSO in the presence of piperidine.

of amine.[21] When piperidine is present, two reaction pathways are possible: The left path shown in Scheme 4 is identical to that shown in Scheme 3, where the intermediate carbocation is trapped by piperidine to form 1-benzhydrylpiperidines **2**. Alternatively (right path in Scheme 4) an oxysulfonium ion **1-DMSO** is formed, which yields a sulfur ylide by deprotonation at a methyl group. Eventually, a proton shift and cleavage of the O–S bond yields the benzophenones **3** (Kornblum oxidation).[23]

The question can be asked: Why does one obtain a much higher percentage of benzophenone with **1f** than with **1c** in DMSO/piperidine (Table 2)? As previously shown,[24] Equation (4) can be used to calculate the rate constants of the reactions of carbocations with a large variety of nucleophiles, including amines,[25] halide ions,[26] and solvents.[27]

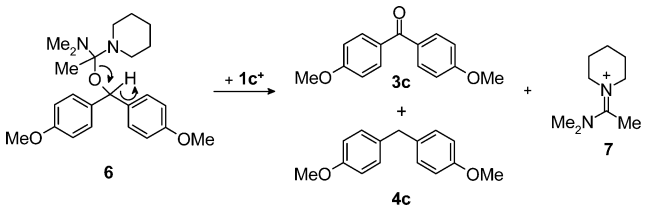
$$\lg k = s_N(E + N) \quad (4)$$

In Equation (4) k is a second-order ($M^{-1} s^{-1}$) or first-order (s^{-1}, for reactions with solvents) rate constant, s_N and N are empirical, nucleophile-specific parameters (s_N has previously been called s), and E is an empirical electrophilicity parameter.

From the electrophilicity parameters for the benzhydrylium ions[24] **1c**$^+$ ($E = 0.00$) and **1f**$^+$ ($E = 2.11$) and the nucleophile-specific parameters for piperidine in DMSO ($N = 17.19$, $s_N = 0.71$)[28] one can calculate $k > 5 \times 10^9$ $M^{-1} s^{-1}$ for the reactions of both benzhydrylium ions with piperidine, i.e., trapping of **1c**$^+$ and **1f**$^+$ is diffusion limited. Assuming a second-order rate constant of $k_2 = 5 \times 10^9$ $M^{-1} s^{-1}$ for the diffusion-limited reaction of a carbocation with a neutral nucleophile, multiplication with c(piperidine) = 0.5 M yields pseudo-first-order rate constants of $k_{obs} = 2.5 \times 10^9$ s^{-1} for the reactions of **1c**$^+$ and **1f**$^+$ with piperidine. This value is significantly larger than the first-order rate constant ($k_1 = 2.30 \times 10^8$ s^{-1}) calculated by using Equation (4) for the reaction of DMSO ($N_1 = 11.3$, $s_N = 0.74$)[21] with **1c**$^+$ ($E = 0.00$). In line with this calculation, the main product of the reaction of **1c** with piperidine in DMSO is the 1-benzhydryl-piperidine **2c**, and only traces (GC-MS: 3%) of the benzophenone **3c** can be detected.

From the reactivity parameters for DMSO ($N_1 = 11.3$, $s_N = 0.74$) and **1f**$^+$ ($E = 2.11$)[24] one can calculate a first-order rate constant of 8×10^9 s^{-1}, which is in the same order of magnitude as the pseudo-first-order rate constant for the diffusion-limited reaction of **1f**$^+$ with piperidine ($c = 0.5$ M). The formation of comparable quantities of **2f** and **3f** (Table 2) can thus be explained.

When **1c** was dissolved in DMA or NMP in the presence of piperidine, dimethoxybenzophenone (**3c**) and bis(4-methoxyphenyl)methane (**4c**) were formed as minor products, in addition to formation of **2c** as the major product (GC-MS: ≥75% yield). At present, it is not clear how **3c** and **4c** are formed under these conditions. A conceivable mechanism may involve attack of the solvent and piperidine at the dimethoxybenzhydrylium ion (**1c**$^+$) with formation of **6**. Hydride abstraction from **6** by a second dimethoxybenzhydrylium ion (**1c**$^+$) may then lead to formation of **3c** and **4c**. Hydrolysis during aqueous workup of the concomitantly generated amidinium ion **7** (Scheme 5) might regenerate the starting materials.



Scheme 5. Possible hydride transfer during the heterolysis reaction of **1c** in DMA in the presence of piperidine.

Hammett Correlation

From the plots of $\lg k_1$ (i.e., $k_{obs,max}$) vs. $\Sigma\sigma^+$, the Hammett reaction constants of $\rho \approx -4$ can be derived for the heterolysis reactions of the chloro-diarylmethanes **1a**–**f** in various aprotic solvents, as exemplified for acetonitrile, DMF, and DMA in Figure 4 (for Hammett correlations of the other solvents in this study see the Supporting Information).

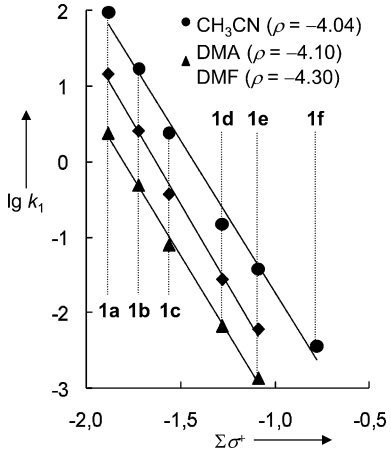


Figure 4. Plots of $\lg k_1$ (= $\lg k_{obs,max}$) of the heterolysis reactions of benzhydryl chlorides **1a**–**1f** in different solvents vs. Hammett's substituent constants $\Sigma\sigma^+$ (σ^+ from ref.[29]).

The excellent linear correlations and the magnitude of the reaction constants ρ suggest transition states in which the positive charge of the carbocations is fully developed. The Hammett plots thus support the conclusion from the kinetic data that $k_{obs,max}$ corresponds to the ionization step of an S_N1 reaction and not to an S_N2-type attack of the amine at the chloro-diarylmethanes. These results are in line with previous findings for the reactions of bromo-diarylmethanes with amines in DMSO, showing that only the first-order rate constants k_1 (S_N1 reaction) and not the second-order rate constants k_2 (S_N2 reaction) correlate with the substituent constants σ^+.[21]

Nucleofugality of Chloride in Different Solvents

In previous work,[19,20] we have demonstrated that Equation (2) can be used to calculate the heterolysis rate constants k_1 of benzhydryl derivatives in various solvents. Plots of $\lg k_1$ (i.e., the maximum observed first-order rate constants $k_{obs,max}$) vs. the electrofugality parameters E_f of the benzhydrylium ions (see Table 1) are linear, as exemplified in Figure 5 for the heterolyses of the chloro-diarylmethanes **1a**–**f** in DMSO, CH_2Cl_2, and acetone. Analogous correlations have been observed in acetonitrile, DMA, DMF, NMP, PC, and $CHCl_3$ (see the Supporting Information). From these correlations, one can extract the nucleofugality parameters N_f of chloride in these solvents as the negative intercepts on the abscissa (E_f axis) and the s_f parameters as the slopes (Table 4).

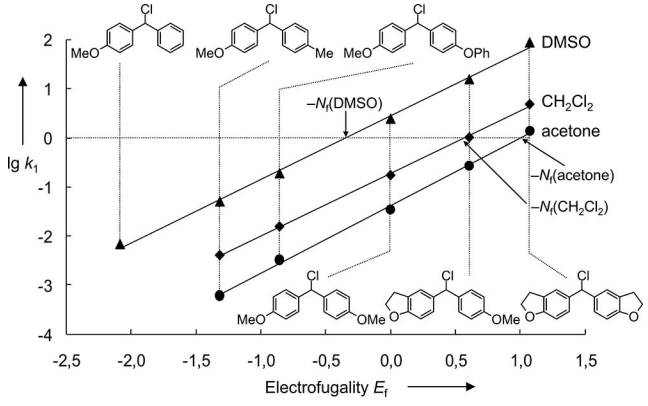


Figure 5. Plots of the first-order rate constants $\lg k_1$ ($k_{obs,max}$) of the heterolyses of chloro-diarylmethanes **1a**–**f** in different solvents in the presence of trapping reagents against the electrofugality parameters E_f.

Table 4. Nucleofugality parameters N_f and s_f of chloride in different solvents.

Solvent	N_f	s_f
DMSO (dimethyl sulfoxide)	0.35	1.30
CH_3CN	0.30	1.39
PC (propylene carbonate)	0.10	1.35
$CHCl_3$	–0.18	1.25
DMF (dimethylformamide)	–0.28	1.39
CH_2Cl_2	–0.57	1.28
DMA (diemthylacetamide)	–0.82	1.33
NMP (*N*-methylpyrrolidin-2-one)	–0.98	1.31
Acetone	–1.00	1.38

As shown in Table 4, the s_f parameters of chloride in the aprotic solvents are substantially higher ($1.25 \leq s_f \leq 1.39$) than the corresponding s_f parameters in protic solvents (usually $0.85 \leq s_f \leq 1.11$).[20] How can these differences be explained?

Substitution of the nucleophilicity parameters N and s of chloride in acetonitrile ($N = 17.20$, $s_N = 0.60$)[26] and the electrophilicity parameters E of the benzhydrylium ions $\mathbf{1a}^+$–$\mathbf{f}^+$ ($-1.36 < E < 2.11$)[24] into Equation (4) yields the second-order rate constants $k > 3 \times 10^9$ $M^{-1} s^{-1}$ for the reactions of these benzhydrylium ions with Cl^-, i.e., all ion recombinations are diffusion-limited or at least very close to the diffusion limit in acetonitrile and, therefore, proceed without activation energy. Because the other solvents used in this study are of similar or lower polarity than acetonitrile, the combinations of these carbocations with Cl^- will also proceed without barriers in these solvents. From the principle of microscopic reversibility, one can now derive that there is no energy maximum between reactants and ionic intermediates in the ionization process ($\mathbf{1} \rightarrow \mathbf{1}^+ + Cl^-$) in these solvents, i.e., the activation free energies of the ionization (heterolysis) step (k_1) equal the differences between the free energies of the ions $\mathbf{1}^+ + Cl^-$ and their precursors **1**.

The same line of reasoning can now be used for the ionization of chloro-diarylmethanes **1a**–**f** in protic solvents. Direct measurements of the rates of the reactions of these carbocations with Cl^- in protic solvents have shown that these reactions are not diffusion-limited, i.e., there is a barrier for ion combination.[26] As a consequence, the carbocationic character is not yet fully developed in the transition state of the ionizations of these chloro-diarylmethanes in protic solvents, which results in smaller values of s_f. Furthermore, the different magnitudes of s_f may also be due to the fact that the differences in the Gibbs free energies between covalent precursors **1** and ion-pairs $\mathbf{1}^+\mathbf{Cl}^-$ are somewhat attenuated in more polar solvents such as alcohols and water.

With the newly determined nucleofugality parameters N_f and s_f (Table 4) it now becomes possible to directly compare the leaving group ability of chloride in protic and aprotic solvents (Figure 6).

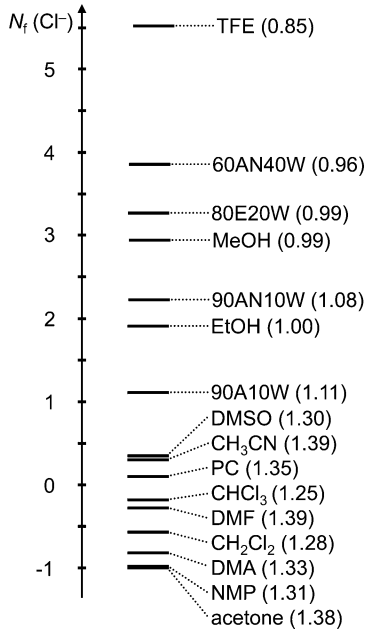


Figure 6. Comparison of the nucleofugality parameters N_f (s_f parameter in parentheses) of chloride in various protic and aprotic solvents (data from this work and ref.[20]). Mixtures of solvents are given (v/v); A = acetone, AN = acetonitrile, E = ethanol, TFE = 2,2,2-trifluoroethanol, W = water.

As mentioned above, the s_f parameters of chloride in aprotic solvents are exceptionally high. Thus, for a precise comparison with other nucleofuges with smaller s_f parameters, s_f should not be neglected. However, the N_f parameters given in Figure 6 show the qualitative trend of the leaving group ability (S_N1 reactivity) of chloride in aprotic and protic solvents. The nucleofugality of chloride in the aprotic solvents studied in this work is in the range $-1 < N_f < 0.5$. DMSO, the aprotic solvent with the highest ionizing power of this series, is about 1.5 orders of magnitude less ionizing than ethanol. The leaving group ability of chloride decreases by more than 6.5 orders of magnitude from 2,2,2-trifluoroethanol (TFE) to acetone, which fall at the extremes of this scale. Thus, whereas the half-life of chloro-(4-methoxyphenyl)-phenylmethane (**1f**) in acetone in the presence of a trapping agent is about 3.5 h, it is less than 1 ms in TFE.[20]

Determination of the Solvent Ionizing Power *Y* for Aprotic Solvents

In the Winstein–Grunwald[1] relationship [Equation (1)], the solvent ionizing power is expressed by the empirical parameter *Y*.[1–14] As most readers will be familiar with the *Y* scale, the information given by the N_f scale in Figure 6 was converted into Winstein–Grunwald *Y* values.

In line with previous reports,[30] the heterolysis rates ($\lg k_1$) of the chloro-diarylmethanes **1a**–**f** correlate well with the solvent ionizing power *Y* derived from secondary benzyl derivatives such as the Y_{BnCl} scale (Figure 7).[10]

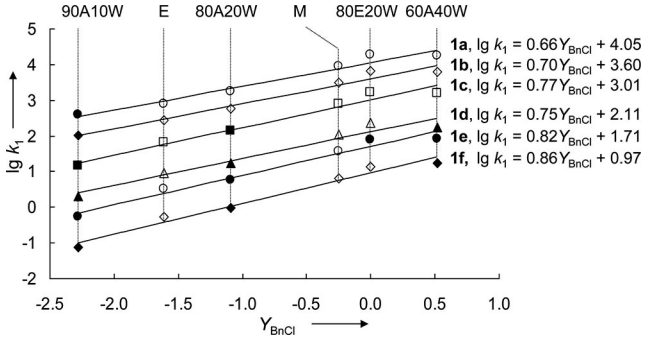


Figure 7. Plot of the first-order rate constants $\lg k_1$ for the solvolyses of **1a**–**f** in different solvents [filled symbols: experimental values from ref.[20]; open symbols: calculated by using Equation (2)] against the solvent ionizing power Y_{BnCl} [mixtures of solvents are given (v/v); A = acetone, E = ethanol, M = methanol, W = water].

As the stopped-flow conductivity technique is only applicable to solvent mixtures where a solution of the substrate in an inert aprotic solvent is mixed with the protic solvent, it was not possible to determine k_1 experimentally for all heterolysis reactions of **1a**–**f** plotted in Figure 7. The reliability of Equation (2) for predicting benzhydryl solvolysis rate constants (see Figure 5) allowed us, however, to supplement missing experimental rate constants in Figure 7 by calculated values (N_f, s_f, and E_f from ref.[20]), which are identified by open symbols.

Substitution of the heterolysis rate constants k_1 of the chloro-diarylmethanes **1a**–**f** in aprotic solvents (Table 3) into the correlation equations in Figure 7 allows the solvent ionizing powers Y_{BnCl} to be calculated for aprotic solvents, which are listed in Table 5 (see also the correlation on page 5 of the Supporting Information). As the correlations of the solvolysis rate constants of the chloro-diarylmethanes **1a**–**f** in protic solvents with other *Y* scales, such as Y_{OTs}, are of lower quality, we have not attempted to determine Y_{OTs} for aprotic solvents from the rate constants in Table 3. It should be noted, however, that previously published Y_{OTs} values for CH_3CN, DMF and DMA (–3.21, –4.14, and –4.99, respectively)[13] show the same ordering; the Y_{OTs} values for these solvents are approximately 0.5 units less negative than the Y_{BnCl} values determined in this work (Table 5).

The ionizing powers Y_{BnCl} of different aprotic solvents in this study differ by almost 2.5 units, ranging from the least ionizing solvent, acetone (Y_{BnCl} = –5.96), to best ionizing solvent, DMSO (Y_{BnCl} = –3.52). Although aprotic solvents generally have a smaller ionizing power than protic solvents, Figure 8 shows that protic solvents such as 2-pro-

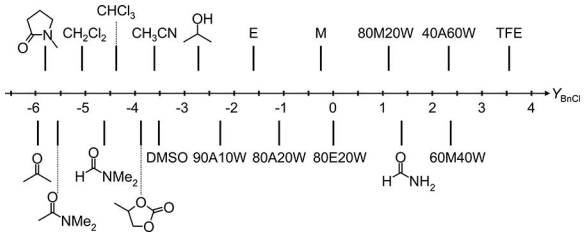


Figure 8. Y_{BnCl} scale for protic and aprotic solvents [this work and from ref.[10b]; mixtures of solvents are given (v/v); A = acetone, E = ethanol, M = methanol, TFE = 2,2,2-trifluoroethanol, W = water].

Table 5. Calculated solvent ionizing power Y_{BnCl} for aprotic solvents.

Solvent	**1f**	**1e**	**1d**	**1c**	**1b**	**1a**	Average Y_{BnCl}[a]
DMSO	–3.65	–3.67	–3.78	–3.40	–3.43	–3.19	–3.52 (±0.22)
CH_3CN	–3.97	–3.82	–3.92	–3.42	–3.39	–3.14	–3.61 (±0.34)
PC		–4.05	–4.12	–3.80	–3.82	–3.61	–3.88 (±0.21)
$CHCl_3$			–4.46	–4.30	–4.43	–4.34	–4.38 (±0.07)
DMF		–4.79	–4.89	–4.47	–4.56	–4.38	–4.62 (±0.22)
CH_2Cl_2		–5.01	–5.23	–4.90	–5.13	–5.10	–5.07 (±0.13)
DMA		–5.58	–5.72	–5.34	–5.60	–5.57	–5.56 (±0.14)
NMP		–5.72	–5.99	–5.56	–5.90	–5.89	–5.81 (±0.17)
Acetone		–6.00	–6.12	–5.80	–5.95	–5.91	–5.96 (±0.12)

[a] Standard deviations in parentheses.

panol or 90% aqueous acetone are only one unit higher on the Y_{BnCl} scale than DMSO and acetonitrile.

Comparison with Other Solvent Polarity Scales

It is well-recognized that there is no universal solvent polarity scale,[31] and, even worse, the term "polarity" itself is "rather ill-defined" as noted in the IUPAC Gold Book.[32] Figure 9 compares the suitability of different solvent polarity parameters for predicting the S_N1 rates of a typical chloro-diarylmethane (e.g., **1c**).

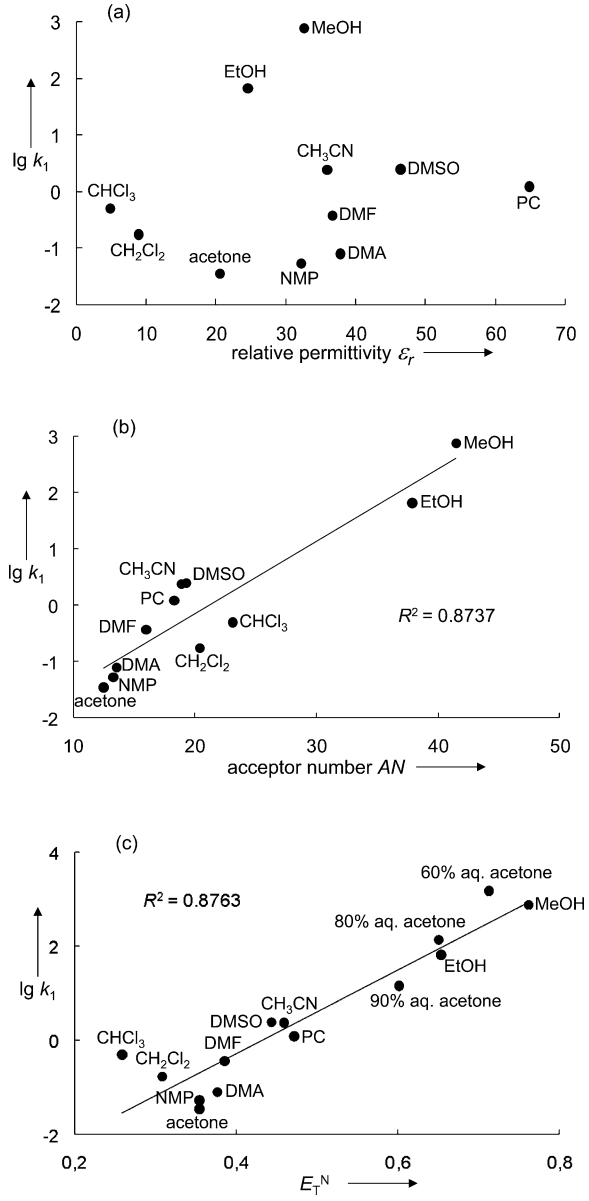


Figure 9. Plots of the first-order rate constants $\lg k_1$ for the solvolyses of **1c** in different solvents against (a) the relative permittivities ε_r, (b) acceptor number *AN*, and (c) E_T^N (constants from ref.[33], additional E_T^N values for acetone/water mixtures from ref.[34]).

Among the well-known solvent polarity scales, the correlation is worst with the relative permittivities (dielectric constants) ε_r (Figure 9a), in line with previous reports[33] that this macroscopic quantity is often a poor measure of solute–solvent interactions at the microscopic level. Whereas methanol and NMP have almost the same relative permittivities (ε_r = 32.7 and 32.2, respectively), **1c** is ionized about four orders of magnitude faster in methanol than in NMP.

Figure 9 (b, c) shows better correlations ($R^2 \approx 0.87$) between the ionization rates of **1c** with Gutmann's acceptor numbers *AN*[33,35] and the empirical solvent parameters E_T^N.[33,34,36] However, when only aprotic solvents are considered, the correlations with *AN* and E_T^N break down (R^2 = 0.47 and 0.32, respectively) as shown on page 4 of the Supporting Information. Thus, none of the common solvent polarity parameters are suitable for predicting the relative ionizing powers of aprotic solvents. Therefore, the method introduced in this work is recommended for a systematic investigation of ionization rates in aprotic solvents.

Experimental Section

General: Anhydrous solvents for the kinetic experiments were purchased (<50 ppm H_2O) and used without further purification.

Kinetic Experiments: The heterolysis rates of the chloro-diarylmethanes **1a**–**f** (Table 1) were monitored by following the increase of the conductivity of the reaction mixtures using a conventional conductometer (Tacussel CD 810, Pt electrode: WTW LTA 1/NS). The solvent (20 mL) containing a defined amount of trapping reagent (piperidine, pyridine or triphenylphosphane) was thermostatted (± 0.1 °C) at 25.0 °C for 5 min prior to adding the substrate. Typically, 10 to 80 mg of substrate was dissolved in 100 μL of the corresponding solvents, then injected into the solution of the trapping agent, and the conductance (*G*) was recorded at given time intervals. For the study of reactions with half lives of 10^{-2} s < $\tau_{1/2}$ < 10 s, a stopped-flow conductometer (Hi-Tech Scientific SF-61DX2, Pt electrodes, cell volume 21 μL, cell constant 4.24 cm^{-1}, minimum dead time 2.2 ms) was used. The temperature was kept constant at 25 °C in all experiments using a circulating water bath.

Typical Procedure for the Determination of the Reaction Products: The chloro-diarylmethanes (0.40 mmol) and piperidine (2.13 g, 25.0 mmol) or triphenylphosphane (6.56 g, 25.0 mmol) were dissolved in the corresponding solvent (50 mL) and stirred for at least 5 half-lives. Water (50 mL) was added, and the mixture was extracted with diethyl ether (2 × 30 mL) and dichloromethane (2 × 30 mL), then the organic layer was washed with water (2 × 30 mL) and brine (30 mL). The solvent was dried ($MgSO_4$) and evaporated under reduced pressure and the crude residue was either crystallized or purified by column chromatography to yield the products described in Table 2.

Supporting Information (see footnote on the first page of this article): Preparative procedures, details of the kinetic experiments, correlations of $\lg k$ vs. E_f and Hammett correlations for the heterolyses of chloro-diarylmethanes are available.

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