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Nucleophilic substitution of chlorobis(4-methoxyphenyl)methane: reactivity of carbenium ions in ILs-trifluoroethanol mixtures

Riccardo Bini,[a] Cinzia Chiappe,[a,*] Daniela Pieraccini,[a]
Paolo Piccioli[a] and Christian Silvio Pomelli[*,b]

[a]Dipartimento di Chimica Bioorganica e Biofarmacia, via Bonanno 33, 56126 Pisa, Italy
[b]Dipartimento di Chimica e Chimica Industriale, via Risorgimento, 56126 Pisa, Italy

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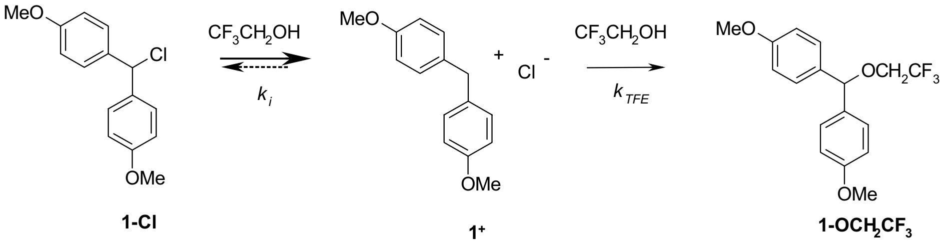
Abstract—The ionization of chlorobis(4-methoxyphenyl)methane (**1-Cl**) was performed in 1:1 mixtures of TFE/ILs (ILs = [emim][Tf$_2$N], [bmim][Tf$_2$N], [bpy][Tf$_2$N]), and TFE/CH$_3$CN. The decay of the immediately formed carbenium ion **1**$^+$ was followed by stopped flow, showing that the lifetime of this intermediate significantly decreases on going from CH$_3$CN to [emim][Tf$_2$N]. Ab initio calculations suggest an increase in the electrophilicity of the carbenium ion in ILs.

Ionic liquids (ILs) are a fascinating class of compounds with unique properties, which have recently attracted the attention of a wide number of researchers. Numerous works have been published in the last 2–3 years reporting the possibility to perform several organic reactions and catalyzed processes in these new media.[1] Despite of the frenetic activity in this field, however, little is known about how the solvent properties of ionic liquids are able to affect reactivity.[2,3]

Nucleophilic substitutions represent one of the most important classes of organic reactions. Although the bimolecular process (S$_N$2) in ILs has been recently investigated both from synthetic[4] and mechanistic point of view,[3] only few data have been reported on substitution reactions occurring through carbenium ions (S$_N$1).[5] To better investigate this latter reaction we have examined the kinetic of the solvolysis of chlorobis(4-methoxyphenyl)methane (**1-Cl**) in mixtures IL/TFE.[6]

Colorless solutions of **1-Cl** in the ionic liquids [emim][TF$_2$N], [bmim][TF$_2$N], and [bpy][TF$_2$N] (where emim = 1-ethyl-3-methylimidazolium, bmim = 1-butyl-3-methylimidazolium, bpy = butylpyridinium, and Tf$_2$N = bis(trifluoromethanesulfonyl)imide) have been mixed 1:1 at 20 °C with TFE (dried by distillation over CaSO$_4$) in a stopped-flow apparatus equipped with a diode-array detector.[7] By comparison, the reaction in a 1:1 mixture CH$_3$CN/TFE was carried out under identical conditions. All reactions were characterized by the



Keywords: Ionic liquids; Carbenium ions; S$_N$1.

* Corresponding author. Tel./fax: +39 (0)50 221 9669; e-mail: cinzia@farm.unipi.it

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Table 1. Kinetic constants of the solvolysis of **1-Cl** or $\mathbf{1^+BF_4^-}$ in TFE/IL mixtures at 20 °C

	CH_3CN (%)	TFE (%)	IL (%)	IL	k_{TFE}[a] (s^{-1})	$t_{1/2}$ (ms)
1-Cl	50	50	—		16.4 (12.4)[b]	18
1-Cl	—	50	50	[emim][Tf_2N]	198[c]	3.5
1-Cl	10	40	50	[emim][Tf_2N]	133	5.2
1-Cl		50	50	[bpy][Tf_2N]	85	8.1
1-Cl		50	50	[bmim][Tf_2N]	124	5.5
$\mathbf{1^+BF_4^-}$		50	50	[bmim][Tf_2N]	112	6.2

[a] Standard deviations in the values of k_{TFE} were always less than 10%.

[b] From Ref. 6.

[c] Standard deviation is around 20%, the k_{TFE} value is in this case at the limit of determination for the stopped-flow technique.

immediate formation of the carbenium ion $\mathbf{1}^+$, having a strong absorption band centered around 500 nm. The same UV spectrum (characterized by identical values of absorbance) and the same kinetic behavior were registered also dissolving an equimolar amount of the corresponding salt, benzhydrylium tetrafluoroborate ($\mathbf{1^+BF_4^-}$), in the IL. Although the extremely high reaction rates prevented an accurate evaluation of the percentage of conversion of **1-Cl** in the carbenium ion $\mathbf{1}^+$, the similarity of the absorptions of this latter intermediate with those of the carbenium ion $\mathbf{1^+BF_4^-}$, registered under identical conditions, suggested a high ionization percentage of **1-Cl** in IL/TFE 1:1 mixtures. The absorbance of the carbenium ion $\mathbf{1}^+$ generated from **1-Cl** or $\mathbf{1^+BF_4^-}$ in IL/TFE (1:1, v/v) decayed following a first order rate law, the kinetic constants (k_{TFE}) are reported in Table 1.[8]

The values of the kinetic constants significantly increase on going from CH_3CN to ILs, corresponding to a significant decrease in the lifetime of the ionic intermediate; the highest value of k_{TFE} characterizes the IL having the lowest viscosity, [emim][Tf_2N].

The decreased lifetime of $\mathbf{1}^+$ in ILs may be attributed to an increased electrophilicity of the carbenium ion $\mathbf{1}^+$ or to a higher nucleophilicity of TFE in the mixtures with ILs. The Kamlet–Taft parameters[9] for CH_3CN, TFE, [bmim][Tf_2N], and their 1:1 mixtures, determined using three solvatochromic dyes (Reichardt'dye, *N*,*N*-diethyl-4-nitroaniline, and 4-nitroaniline), are reported in Table 2.

The comparison of the data related to the two 1:1 solvent mixtures showed that the substitution of acetonitrile with [bmim][Tf_2N] gives a medium characterized by an increased dipolarity/polarizability, whereas both hydrogen bond donor (α) and acceptor ability (β) are slightly lower. The higher dipolarity/polarizability (π^*) of the mixture IL/TFE should favor the C–Cl bond cleavage and the formation of the corresponding ion pair, $\mathbf{1^+Cl^-}$. Furthermore, although in molecular solvents the ionization gives contact ion pairs, in equilibrium with solvent separated ion pairs and free ions, in ILs, a sphere of oppositely charged solvent ions always surrounds the ions arising by heterolytic bond cleavage ($\mathbf{1}^+$ and Cl^-) and the metathesis reaction is extremely fast. This latter feature has been recently evidenced in the glycosidation reaction of glucopyranosyl fluoride and in the fluorodediazoniation reaction.[10] The high dipolarity and the extremely fast metathesis reaction render the return of the formed ions pairs unimportant, in agreement with the observation that identical kinetic constants have been found starting from **1-Cl** and $\mathbf{1^+BF_4^-}$. The carbenium ion intermediates behave in the investigated ILs analogously to a free ion in molecular solvents, although in ILs they are surrounded by oppositely charged ions.

Table 2. Kamlet–Taft parameters

Solvent	π^*	α	β
CH_3CN	0.66	0.12	0.40
TFE	0.73	1.51	0.00
CH_3CN/TFE (1:1)	0.88	1.22	0.27
[bmim][Tf_2N][a]	0.98	0.62	0.24
[bmim][Tf_2N]/TFE (1:1)	1.10	1.06	0.13

[a] The water amount in [bmim][Tf_2N], determined by Karl Fisher technique, was 90 (±15) ppm.

Ab initio calculations,[11] at B3-LYP/CEP-121G(d,p) and B3LYP/6-311++G(d,p) level, have been carried out on the parent system, chlorodiphenylmethane, to obtain information about the different ability of CH_3CN and ILs to interact with carbenium ion intermediates. The energy values for the hypothesized complexes, arising from the interaction of the positive charge of the carbenium ion with acetonitrile or the anion of the IL, are reported in Table 3. Both level of calculations lead to the same trend of stability for the ionic pairs.

The bond distances between the carbenium ion carbon and the nitrogen atom of the solvent in the complexes ($d_{C\text{–}N}$, in Table 3) indicate that there is a significant interaction. This is confirmed by the NBO analysis showing that the occupation of the bond orbital is greater than 1.97 in all the investigated complexes.

However, it is noteworthy that whereas acetonitrile is able to interact with positively charged intermediate to give a 'relatively' stable species ($[Ph_2CH\text{–}CH_3CN]^+$), the bis(trifyl)imino anion is not able to give this stabilizing contribute (see Fig. 1 and Table 3).

Since only the anion of the IL may in these media stabilize the carbenium ion intermediate, we have tried to perform the reaction in [bmim][$N(CN)_2$]. This ionic liquid presents a less congested anion, which should be more prone to interact with the carbenium ion intermediate. Furthermore, it is characterized by a sufficiently

Table 3. Energetic and geometric data for the complexes under investigation

Run	Molecular system	B3-LYP/CEP-121G(d,p)			B3LYP/6-311++G(d,p)		
		E+ZPE (hartrees)	Δ(E+ZPE) (kcal/mol)	$d_{C–N}$ (Å)	E+ZPE (hartrees)	Δ(E+ZPE) (kcal/mol)	$d_{C–N}$ (Å)
1	Ph_2CH^+	−79.713677			−501.785899		
2	$[N(CN)_2]^-$	−41.112562			−240.553219		
3	$[Tf_2N]^-$	−250.545985			−1827.553190		
4	CH_3CN	−22.966227			−132.751055		
5	$[Ph_2CH–CH_3CN]^-$	−102.675120	3.00	1.49	−634.537449	−0.31	1.48
6	$Ph_2CH–NTf_2$	−330.246721	8.12	1.59	−2329.332183	4.34	1.70
7	$Ph_2CH–NCNCN$	−120.849945	−14.88	1.46	−742.385350	−29.02	1.43
8	$Ph_2CH–N(CN)_2$	−120.840616	−9.03	1.55	−742.374476	−22.20	1.52

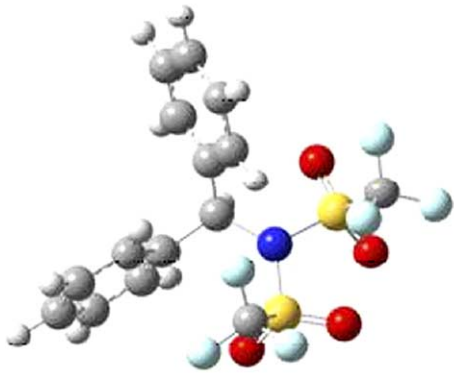

Figure 1. Equilibrium geometry of the $Ph_2CH–NTf_2$ complex.

low viscosity[12] to be investigated using the stopped-flow technique. In this case, however, the substrate **1-Cl** reacted during the dissolution process with the IL to give a mixture of products arising from the incorporation of the anion.

Ab initio calculations are in agreement with this behavior; the energies of the two adducts, arising from the reaction of diphenylcarbenium ion with $[N{\equiv}C–N–C{\equiv}N]^-$ on the external and internal N atom, are both sufficiently low (runs 7–8, Table 3). The differences among the adducts of the diphenylcarbenium ion and the anions $[N(CN)_2]^-$ and $[Tf_2N]^-$ are of steric nature. Both the linear and 'Y' shaped complex of $[N(CN)_2]^-$ are not sterically hindered. At variance, this feature is relevant in the $[Tf_2N]^-$ complex. The acetonitrile complex is similar, from the steric point of view, to the linear $[N(CN)_2]^-$ complex. An index for the steric hindering in the complexes is the bond distance, $d_{C–N}$. As shown in Table 3, the shorter distances characterize the complexes of the carbenium ion with acetonitrile and the linear complex with $[N(CN)_2]^-$, followed by the Y shaped complex with $[N(CN)_2]^-$ and finally the complex with $[Tf_2N]^-$. For complexes having a similar nature, such as those between the investigated carbenium ion and the IL anions, the bond length scale is coherent with the energetic scale.

In conclusion, the data reported in this communication show that the $[Tf_2N]^-$ based ILs, having a high ionizing power but a very low ability to interact with the formed carbenium ions, make these latter intermediates highly reactive species. The lifetime of the dimethoxy benzhydrylium cation in the investigated ionic media is shorter than in acetonitrile, a typical aprotic dipolar solvent.

Studies are in progress to evaluate how the structures of the substrate and IL affect this parameter, and in which measure ILs are able to influence the nucleophilicity of some typical nucleophiles.

Acknowledgements

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8. Solutions **1-Cl** in [emim][Tf_2N], [bmim][Tf_2N], and [bpy][Tf_2N] were stable at room temperature for at least 30 min. When these solutions were mixed in a NMR tube (using a coaxial system) with equal volumes of TFE, we immediately observed the appearance of a new signal at 5.5 ppm, attributable to the benzylic CH proton of the reaction product, $\mathbf{1\text{-}OCH_2CF_3}$. The same signal appeared after addition of TFE to a solution of **1-Cl** in CH_3CN. This product, however, underwent a slow decomposition both in IL/TFE and CH_3CN/TFE mixture, which could be evidenced also by the progressive darkening of the solution.
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