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Reaction of Singlet Oxygen with Thioanisole in Ionic Liquid−Acetonitrile Binary Mixtures

Enrico Baciocchi,[†] Cinzia Chiappe,[‡] Chiara Fasciani,[§] Osvaldo Lanzalunga,[§,†] and Andrea Lapi*,[§,†]

Dipartimento di Chimica and Istituto CNR di Metodologie Chimiche-IMC, Sezione Meccanismi di Reazione c/o Dipartimento di Chimica, Università di Roma La Sapienza, P.le A. Moro 5, 00185 Rome, Italy, and Dipartimento di Chimica e Chimica Industriale, Università di Pisa, via Bonanno 33, 56126 Pisa, Italy

andrea.lapi@uniroma1.it

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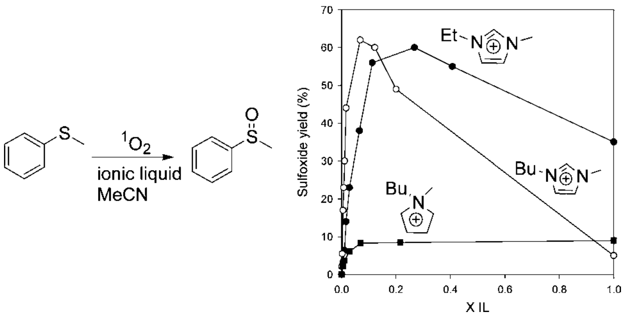
ABSTRACT



A study of the reaction of thioanisole with singlet oxygen in different ionic liquid−acetonitrile binary mixtures has shown that ILs are able to accelerate the thioanisole sulfoxidation when used as additives. With imidazolium ILs, the maximum efficiency is reached at x_{IL} ~ 0.1−0.2, whereas for the pyrrolidinium IL a plateau is reached. These results are discussed in terms of the ILs' tendency to form ionic aggregates and of differences in sulfoxidation reaction mechanism.

The use of singlet oxygen ($^1O_2$) as the terminal oxidant for sulfide oxidation has attracted a great amount of attention for its economical and environmental features. One of the peculiarities of sulfide oxidation by $^1O_2$ is the strong dependence of its efficiency as well as its kinetic behavior on substrate, temperature, and solvent.[1] In particular, higher efficiency was observed in protic media (e.g., MeOH) than in aprotic solvents where the reaction is sluggish[1a,2] and, in particular, aryl alkyl and diaryl sulfides appear practically unreactive, requiring the presence of (generally protic) additives to produce sulfoxides. The role of such additives (A in Scheme 1) is that of stabilizing the persulfoxide **2** (in most cases by hydrogen bonding on the peroxy appendage of **2**), the key intermediate in the consensus mechanism for the $^1O_2$-promoted sulfoxidation, thus favoring product formation with respect to the unproductive intersystem crossing (path b).[1]

In this respect, we have recently reported that, in contrast with the unreactivity exhibited in dipolar aprotic solvents, thioanisole (**1**) can be efficiently sulfoxidated by $^1O_2$ in ionic liquids (ILs), namely, imidazolium- and pyrrolidinium-based ILs.[3] Moreover, on the basis of product isotope effect and trapping experiments, evidence for a solvent-dependent mechanistic dichotomy was obtained showing that in pyr-

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[†] Istituto CNR di Metodologie Chimiche, IMC.

[‡] Università di Pisa.

[§] Università di Roma.

(1) (a) Liang, J. J.; Gu, C. L.; Kacher, M. L.; Foote, C. S. *J. Am. Chem. Soc.* **1983**, *105*, 4717. (b) Clennan, E. L. *Acc. Chem. Res.* **2001**, *34*, 875. (c) Clennan, E. L.; Pace, A. *Tetrahedron* **2005**, *61*, 6665.

(2) (a) Clennan, E. L.; Greer, A. *J. Org. Chem.* **1996**, *61*, 4793. (b) Bonesi, S. M.; Albini, A. *J. Org. Chem.* **2000**, *65*, 4532.

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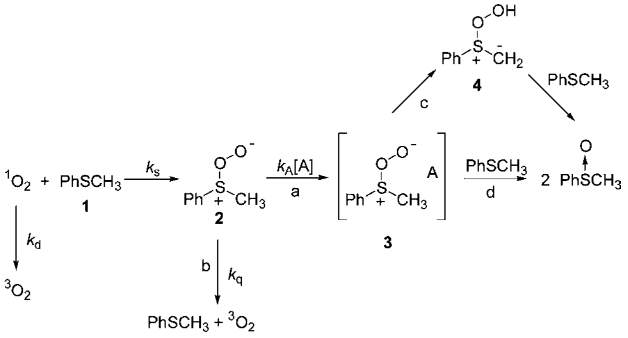
Scheme 1. Mechanistic Scenario for the Reaction of Singlet Oxygen with Thioanisole in Ionic Liquids



rolidinium ILs sulfoxide formation follows path c in Scheme 1 involving the formation of a hydroperoxysulfonium ylide (**4**) from the persulfoxide intermediate **2**. In imidazolium ILs, instead path d is followed as it occurs in protic media due to the hydrogen bond donating ability of the hydrogen atom in the 2 position of the imidazolium ring. In both cases, the role of ILs is that of stabilizing the persulfoxide intermediate, thus favoring product formation.

As a further development of this study, we now wish to present results showing that ILs can also promote the $^1O_2$-induced sulfoxidation of thioanisole not only as neat solvents but also when used as additives in acetonitrile and that, very interestingly, in imidazolium ILs but *not* in the pyrrolidinium IL the sulfoxidation efficiency at relatively low IL concentrations is higher than in the neat IL. Quantitative information on the ILs' efficiency is also presented and compared with that of methanol.

Both imidazolium and pyrrolidinium ILs were used (Figure 1). In all cases, the anion is the bistrifluoromethanesulfonylimide.[4] As already mentioned, thioanisole is unreactive toward $^1O_2$ in acetonitrile, so that any reactivity observed in this solvent is due to the presence of the additive.

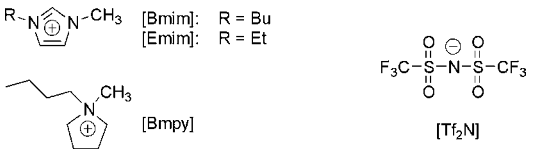


Figure 1. Structures of the ions forming the ionic liquids under investigation.

In a typical reaction, a 2 mL oxygen-saturated solution of thioanisole (5×10^{-2} M) and methylene blue (5×10^{-4} M) in an IL−acetonitrile mixture was irradiated for 15 min (400−600 nm) at 25 °C. After the addition of an internal standard, the mixture was analyzed by GC and GC-MS (comparison with authentic specimens). For comparison, the same reaction was carried out, under the same conditions, in the presence of methanol. Blank experiments, carried out under the same reaction conditions but in the absence of methylene blue or oxygen, showed the absence of any detectable amount of products. In all cases, the mass balance was >97%. The sulfoxide yields (with respect to the starting thioanisole) were plotted against the concentration of IL expressed as molarity or mole fraction (Figure 2).

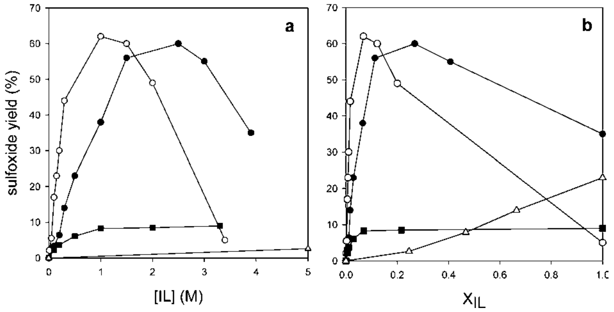


Figure 2. Methyl phenyl sulfoxide yield vs additive concentration (a) and mole fraction (b) after 15 min irradiation. (○) [Bmim][Tf_2N], (●) [Emim][Tf_2N], (■) [Bmpy][Tf_2N], (Δ) MeOH.

Figure 2 clearly shows that with imidazolium ILs the sulfoxide yield rapidly increases by increasing the IL concentration up to a maximum value which is significantly higher than that observed in neat ionic liquids. In contrast, the pyrrolidinium-containing IL [Bmpy][Tf_2N] shows a much more modest increase in sulfoxide yield on increasing IL concentration up to reach a plateau at ca. 1 M concentration. The above behaviors contrast with that of MeOH (by far the least effective additive) which exhibits a regular increase of the sulfoxide yield by increasing its concentration.

Very interestingly, when we consider the dependence of the efficiency upon mole fraction (Figure 1b), it can be noted that the maximum sulfoxide yield is reached for both the imidazolium ILs at around $x_{IL} \sim 0.1{-}0.2$. This is an important observation in the light of the finding that binary mixtures of imidazolium ILs with molecular solvents (among which are binary mixtures of both [Bmim][Tf_2N] and [Emim][Tf_2N] with acetonitrile) show a nonmonotonous variation of conductivity in terms of IL mole fraction with a maximum value just at $x_{IL} \sim 0.1{-}0.2$.[5] This so remarkable

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(3) Baciocchi, E.; Chiappe, C.; Del Giacco, T.; Fasciani, C.; Lanzalunga, O.; Lapi, A.; Melai, B. *Org. Lett.* **2009**, *11*, 1413.

(4) Particular care must be taken on the ILs purity grade since the presence, at trace levels, of impurities able to rapidly quench $^1O_2$ dramatically reduces the efficiency of the process. Accordingly, in some commercially available ILs we observed a drastically reduced reactivity when compared to that in ILs prepared by us. Moreover, laser flash photolysis experiments (phenazine irradiation in the presence of $^3O_2$) showed the absence of the $^1O_2$ emission at 1270 nm in these commercial ILs thus suggesting an efficient quenching exerted by some ILs impurities.

(5) (a) Stoppa, A.; Hunger, J.; Buchner, R. *J. Chem. Eng. Data* **2009**, *54*, 472. (b) Del Pòpolo, M. G.; Mullan, C. L.; Holbrey, J. D.; Hardacre, C.; Ballone, P. *J. Am. Chem. Soc.* **2008**, *130*, 7032. (c) François, Y.; Zhang, K.; Varenne, A.; Gareil, P. *Anal. Chim. Acta* **2006**, *562*, 164. (d) Jarosik, A.; Krajewski, S. R.; Lewandowski, A.; Radzimski, P. *J. Mol. Liq.* **2006**, *123*, 43. (e) Comminges, C.; Barhdadi, R.; Laurent, M.; Troupel, M. *J. Chem. Eng. Data* **2006**, *51*, 680.

similarity suggests that as for the conductivity variation,[5b,c] the sulfoxide yield decrease observed at higher x_{IL} can be due to a sharp increase in ion association, to form ion pairs or more complex aggregates, that reduces the ion availability in solution.[6] On the other hand, it is well-known that neat imidazolium ILs appear as continuous highly ordered three-dimensional supermolecular polymeric networks of anions and cations linked by hydrogen bond, electrostatic, and $\pi-\pi$ interactions,[7] whereas at very low dilution, the ILs must be necessarily solvated by molecular solvent as free ions or, if the anion−cation interactions are enough strong, as discrete ion pairs. Evidence in favor of a change in imidazolium ILs' self-aggregation in binary mixtures also comes from an experimental and computational study on a [Bmim][PF_6]−naphthalene mixture showing a marked change of IL coordination and bonding (at $x_{IL} \sim 0.2$).[5b] More recently, a molecular dynamic simulation of a [Bmim][PF_6]−acetonitrile binary mixture, carried out at different compositions, showed the first formation of isolated ionic aggregates at $x_{IL} \approx 0.06$.[8]

If the interpretation of the plots for imidazolium ILs in terms of changes in aggregation state is correct, it would appear that some kind of aggregation is present also at relatively low concentrations where it is more important for [Emim][Tf_2N] than for [Bmim][Tf_2N], whereas the inverse should hold at higher concentration, which causes the relative efficiency of the imidazolium-based ionic liquids to drastically depend on concentration. For example, at 1 M concentration, [Bmim][Tf_2N] is clearly much more efficient than [Emim][Tf_2N], but at higher concentrations, an opposite situation holds.[9] This peculiar behavior of the two ILs may be tentatively justified. Accordingly, a number of studies on neat imidazolium ILs have shown a decrease in ionicity by increasing the alkyl chain length and attributed such a decrease to an augmented van der Waals interaction between the alkyl chains.[10] On the other hand, a more important ionic association with [Emim][Tf_2N] than with [Bmim][Tf_2N] at low concentration might be due to the smaller hindrance of the ethyl group with respect to butyl.[11]

Coming to the different behavior of [Bmpy][Tf_2N], it might depend on its nonaromaticity since, as suggested by a quite recent study, in binary mixtures with MeCN nonaromatic ILs should not form specific local structures, but only uniform mixtures, at any molar ratio.[12] In this case, as we will see later on, the observed reaching of a plateau is expected.

A further deeper and quantitative insight on the role of ILs as dilute additives in comparison with MeOH can be obtained by using the same kinetic approach followed by Albini for the $^1O_2$-promoted sulfoxidation of diethyl sulfide in the presence of protic additives[2b] (under the reasonable assumption that the mechanism reported in Scheme 1 also holds for **1** sulfoxidation in IL−acetonitrile mixtures).[3] On the basis of the mechanism reported in Scheme 1 and using Foote's formalism,[1a] the concentration of sulfoxide formed at a given irradiation time is provided by eq 1 where [A] is the IL or MeOH concentration and K is the formal concentration of all the $^1O_2$ produced during the irradiation time. Moreover, since neither K nor k_s and k_d change significantly with varying [A] up to 1 M,[2a,b] at lower IL concentrations eq 1 can be simplified to eq 2 where K' is constant for the whole series of experiments and represents the formal concentration of all **2** formed during the irradiation.[13]

$$[\text{sulfoxide}] = K\frac{k_s[\text{sulfide}]}{k_d + k_s[\text{sulfide}]}\frac{2k_A[A]}{k_q + k_A[A]} \qquad (1)$$

$$[\text{sulfoxide}] = K'\frac{2k_A[A]}{k_q + k_A[A]} \qquad (2)$$

$$[\text{sulfoxide}]^{-1} = \frac{1}{2K'}\left(1 + \frac{k_q}{k_A}[A]^{-1}\right) \qquad (3)$$

By rearranging eq 2, eq 3 is obtained from which a linear doubly reciprocal plot for [sulfoxide] vs the additive concentration is expected with a slope value of ($k_q/2K'k_A$). Very rewardingly, as shown in Figure 3, very good linear relationships ($r^2 \geq 0.98$) were found with all ILs and MeOH when 1/[PhSOMe] was plotted vs 1/[A] ([A] < 1 M). However, eq 3 predicts that the linear plots should have the same intercept ($1/2K'$), as would seem to be the case for imidazolium ILs and MeOH but not for [Bmpy][Tf_2N] which exibits a significantly higher value.[14]

The intercept value represents the reciprocal of the sulfoxide yield expected at infinite additive concentration ($2K'$), i.e., when $k_A[A] \gg k_q$ and all **2** is converted to **3** and then to products. However, this is valid only under the assumption that, once formed, **3** exclusively undergoes

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(6) (a) The conductivity decrease at high x_{IL} was also suggested to be due to a counterbalancing effect of the rapidly rising viscosity on ion mobility.[5a] This hypothesis could, in principle, be applied also to the sulfoxide yield decrease at high x_{IL} since a reduced ion mobility can reasonably make the persulfoxide coordination less competitive with respect to the unproductive isc process. However, the role of viscosity should not be very important in sulfoxidation as we note that with [Bmpy][Tf_2N] (85 mPa s)[6b] the sulfoxide yield remains constant from 1 M to neat liquid. (b) Zhang, S.; Sun, N.; He, X.; Lu, X.; Zhang, X. *J. Phys. Chem. Ref. Data* **2006**, *35*, 1475.

(7) Chiappe, C. *Monatsh. Chem.* **2007**, *138*, 1035, and references therein.

(8) Shimizu, K.; Costa Gomes, M. F.; Pàdua, A. A. H.; Rebelo, L. P. N.; Canongia Lopes, J. N. *J. Mol. Struct. Theochem.* **2010**, *946*, 70.

(9) It is noteworthy that above ca 1.5 M the concentration increase so strongly depresses the efficiency of [Bmim][Tf_2N] that it makes it the least efficient IL for sulfoxidation of thioanisole as neat solvent, also less efficient than the pyrrolidinium IL (vide infra).

(10) Tokuda, H.; Hayamizu, K.; Ishii, K.; Susan, M. A. B. H.; Watanabe, M. *J. Phys. Chem. B* **2005**, *109*, 6103. For a microreview, see: Ueno, K.; Tokuda, H.; Watanabe, M. *Phys. Chem. Chem. Phys.* **2010**, *12*, 1649.

(11) A conductometric study on a series of [$C_n$mim]Br in different molecular solvents showed that, at low concentrations, the ionic association constant decreases with increasing alkyl chain length. Wang, H.; Wang, J.; Zhang, S.; Pei, Y.; Zhuo, K. *Chem. Phys. Chem.* **2009**, *10*, 2516.

(12) Iwata, K.; Kakita, M.; Hamaguchi, H.-o. *J. Phys. Chem. B* **2007**, *111*, 4914.

(13) For what concerns the ILs, it should be pointed out that, from the k_s and k_d values measured in MeCN and in the ILs used in the present work,[3] it results that the k_s[PhSMe]/(k_d + k_s[PhSMe]) ratio (ca. 0.9) does not significantly change on passing from neat MeCN to neat ILs.

(14) Even though, different from the slope's values, the intercept values are subject to very high errors (especially for the plots having larger slopes), we observed that those for MeOH and imidazolium ILs lie within the same error interval (95% confidence interval), whereas that for [Bmpy][Tf_2N] is clearly outside it. For details, see Table S2 in SI.

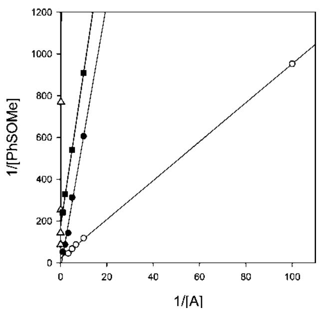

Figure 3. Doubly reciprocal plot for the methyl phenyl sulfoxide concentration (M) vs the concentration of ionic and molecular additives (M). (○) [Bmim][Tf_2N], (●) [Emim][Tf_2N], (■) [Bmpy][Tf_2N], (Δ) MeOH.

sulfoxide formation as is the case of protic additives and imidazolium ILs. Thus, the higher intercept value obtained with [Bmpy][Tf_2N] may be interpreted by suggesting that with this IL the complex **3** does not entirely proceed to products but may undergo some isc to $^3O_2$ in competition with product formation.[15]

This hypothesis is in line with another important observation: eq 2 predicts that by increasing the additive concentration a plateau in the sulfoxide yield should be reached when $k_A[A] \gg k_q$ where the yield should become practically equal to twice the concentration of all **2** produced during the experiment. This plateau is not reached for the imidazolium ILs, which can be reasonably justified by the aggregation problems already discussed, and for MeOH due to the extremely low value of k_A. It is instead clearly reached with [Bmpy][Tf_2N], but the maximum sulfoxide yield turns out to be much lower than the maximum yield reached with imidazolium ILs. This is a further indication that when A is [Bmpy][Tf_2N] the complex **3** proceeds to products only partially being in competition with isc, which might also explain the much lower efficiency of [Bmpy][Tf_2N] with respect to the imidazolium ILs. On the other hand, a different nature of **3** with [Bmpy][Tf_2N] with respect to that with imidazolium ILs may not be surprising if one takes into account the already mentioned different reaction mechanisms operating with the two ILs. Accordingly, with [Bmpy][Tf_2N] **3** is not directly converted to the sulfoxide; however, it is first converted to the ylide **4** and then to the product, whereas with the imidazolium ILs (and MeOH), **3**, is able to react with another molecule of sulfide to directly form the sulfoxide.[3] As previously suggested, the different mechanism for the latter ILs is probably due to their capacity to stabilize the persulfoxide intermediate, like MeOH, by hydrogen bonding through their acidic 2-C−H bond.

Moreover, for the three additives for which eq 1 is valid (complete conversion of **3** to sulfoxide), the slope value ratio for a given couple of additives provides their k_A ratio, i.e., a quantitative comparison of their catalytic efficiency in relatively dilute solutions (see Table S2 in SI where the k_A/k_{MeOH} values for the two imidazolium ILs are reported). Under these reaction conditions ([IL] = 0.01−1 M), [Bmim][Tf_2N] ($k_A/k_{MeOH} = 473$) turns out to be almost 1 order of magnitude more efficient than [Emim][Tf_2N] ($k_A/k_{MeOH} = 69$). Most probably, such a difference is only due to the fact that, as already discussed, [Emim][Tf_2N] exhibits, at low concentration, a larger aggregation state than [Bmim][Tf_2N]. This observation is very important as it indicates that the aggregation state can be a fundamental factor in determining the relative efficiency of ILs as catalysts. Thus, some caution should be exerted when interpreting the catalytic efficiency of ILs for a given reaction in terms of their intrinsic molecular properties: opposite behaviors might be obtained simply by changing ILs' concentration.

Finally, the high k_A/k_{MeOH} ratio obtained for [Bmim][Tf_2N] and [Emim][Tf_2N] confirms the importance of electrostatic interactions in the persulfoxide stabilization by ILs in addition to the capability of hydrogen bond formation.[16]

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Supporting Information Available: Experimental details, complete results, and kinetic treatment for [Bmpy][Tf_2N]. This material is available free of charge via the Internet at http://pubs.acs.org.

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[15] From the kinetic equation that takes into account the possibility of an isc process also on **3** (see SI), it results that also in this case a $[\text{sulfoxide}]^{-1}$ vs $[A]^{-1}$ linear plot is expected with an intercept value of $1/2fK'$ where f is the fraction of **3** undergoing product formation. Since for MeOH and imidazolium ILs $f = 1$, the highest intercept value is reached.

[16] In fact, from the Kamlet−Taft α values for MeOH (1.05) and [Bmim][Tf_2N] (0.617), it would appear that, for the persulfoxide **2** stabilization, the electrostatic interactions are more important than the capability of hydrogen bond formation: Crowhurst, L.; Mawdsley, P. R.; Perez-Arlandis, J. M.; Salter, P. A.; Welton, T. *Phys. Chem. Chem. Phys.* **2003**, *5*, 2790.