Pure & Appl. Chem., Vol. 62, No. 2, pp. 261–264, 1990.
Printed in Great Britain.

Nitroxide radicals in studies of correlation between molecular mobility and chemical reactivity

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Abstract - The use of nitroxide radicals for studying the correlation between molecular mobility and chemical reactivity by EPR methods is discussed.

The majority of studies in the domain of chemical physics have the final aim of understanding connections between physical and chemical properties of molecules. In connection with the condensed state, it is proper to speak of physical properties of the multimolecular kinetic cage, which includes the reacting molecules together with surrounding molecules affecting the chemical reactivity. One of the fundamental properties of such a cage is its mobility as manifested by the rotational, conformational, etc. mobility of the individual molecule included in the cage. This makes it reasonable to search for a correlation between chemical reactivity and molecular mobility starting from the idea that the given mobility is responsible for significant differences between the rate constants of the same reactions in ideal, nonviscous solutions and in the real, solid-like (but noncrystalline) media including glasses, amorphous polymers, liquid crystal and biological structures. Molecular mobility may be estimated well from line shape or relaxation parameters of the EPR spectra of nitroxides, especially if newer EPR techniques are applied such as pulse EPR or EPR at extremely high frequencies. Meanwhile, the same nitroxides (or other spin probes) are fortunately not totally stable but may be involved in chemical reactions such as electron or proton transfer, isomerisation, etc., and as a result of reaction changes in EPR intensity or line shape may also occur. Nitroxides present unique possibility for studying in parallel both the physical and the chemical dynamics of free radicals (in the same sample and with the same spectrometer).

While in principle different types of paramagnetic centers may be used, all the attempts till now were performed using nitroxides (ref. 1). In this case, the physical dynamic is studied using the well-developed spin probe or spin label techniques. In addition to standard X-band EPR, we used 2mm-band EPR which increases the informational capacity of method and provides fine details of the molecular motion (ref. 2).

As the most interesting example we shall consider the reaction between nitroxides and tetranitromethane (ref. 3). The reaction was carried out in homogeneous water-t-butanol solution and in micellar system based on non-ion surfactants such as "triton X100", "triton X1339". X100 at 0.02 M forms micelles with a size of 60-80 Å while for X1339 it reaches 120-150 Å. Micelle dimensions were determined by light scattering techniques. We believe that the micellar triton systems have fairly high molecular organisation and may be considered simplified models of biological membranes.

For the reaction, we used nitroxides with a long hydrophobic hydrocarbon chain which is easily incorporated into the micelles. To define the region of nitroxide localization, we used the EPR hyperfine splitting $2A_{iso}$ which depends on the polarity of medium. For micellar solutions, $2A_{iso}$ is exactly the same as in pure surfactants and supports localization of the radicals in the micelles. Observation of spin-exchange between radicals and $K_3(Fe(CN)_6)$ in water-alcohol and micellar solution gave an order of magnitude difference indicating that nitroxide probes are localized inside rather than at the surface of micelles.

Rotational correlation times τ_c were determined mostly by standard X-band EPR techniques at 0-50 °C temperature range. Some of the experiments were made with 2mm EPR, and showed, in particular, that the rotational anisotropy remains the same in pure surfactants and micelles. The absolute values of τ_c increase dramatically in micellar solution, as seen from (Fig. 1).

The oxidation process itself is supposed to follow a two stage mechanism

$$C(NO_2)_4 + R_2NO \xrightarrow{k} R_2NO^+ + C(NO_2)_3^- + NO_2^{\cdot}$$

$$R_2NO^{\cdot} + NO_2^{\cdot} \rightarrow R_2NO^+ + NO_2^-$$

the first stage being the limiting one.

Rate constants were determined with excess tetranitromethane by EPR and spectrophotometric methods.

For micellar solution, rate constants appeared to be much larger but it may arise from two different reasons: by micellar catalysis, that is, by concentration of the reagents in micelles; and by the mobility effect, that is, a change of radical mobility in micelles. In order to account for the micellar effect and to find the true rate constants, one needs the partition coefficient for tetranitromethane in micellar solution. We have obtained it by comparing oxidation rates of the hydrophillic reagent $FeSO_4$ by $C(NO_2)_4$ in water solution and micellar solutions. The rate constants drop in the latter case due to inclusion of part of the $C(NO_2)_4$ molecules into micelles and from this the true concentration of $C(NO_2)_4$ in micelles may be calculated.

The true rate constants determined as described above were compared with τ_c by plotting 1/k vs τ_c as shown in Fig.2. Experimental data show rather good correlation between the oxidation rate and radical mobility, the true rate constant in micelles appearing actually to be much lower than in solution in accordance with the fact that mobility (at the same temperature) is lower.

In a semiempirical way, the connection between k and τ_c may be approximated as follows (ref. 1):

$$\frac{1}{k} \approx \frac{1}{k_f} + \alpha\tau_c \qquad (1)$$

where $k_f = k_f^0 \exp(-E_f/RT)$ is the rate constant in the ideal solution, $\alpha = \alpha_0 \exp(E_f/2KT)$ with α_0 being the number reflecting ratio of frequ-

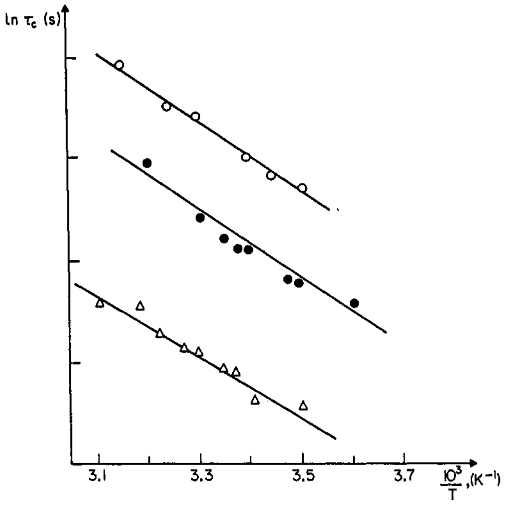


Fig.1 Temperature dependences of rotational correlation times for nitroxides in homogenous water-t-butanol 1:1 solution (o), micellear triton X100 (Δ) media.

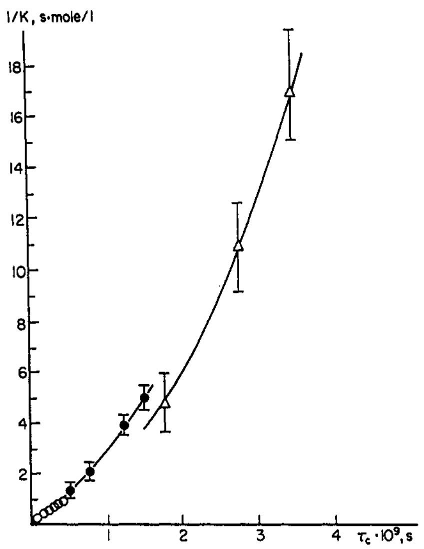


Fig.2 Reactivity (1/k) vs rotational correlation time (τ_c) relationship for nitroxide oxidation (for identification of points see Fig.1).

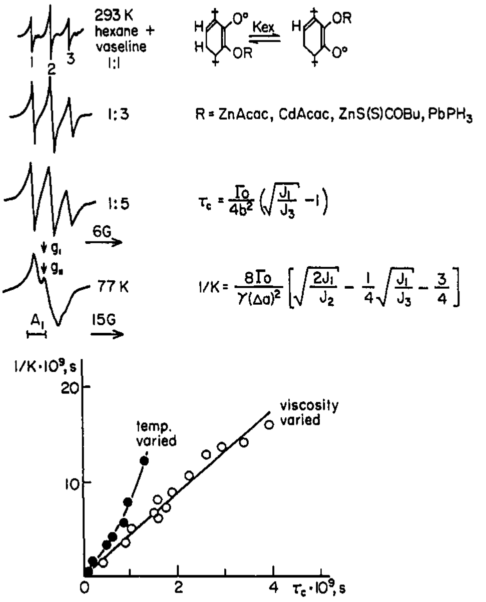


Fig.3 Reactivity (τ_{ex}) vs rotational correlation time (τ_c) relationship for intramolecular transfer. At the top typical changes of EPR spectra and equations determining τ_c and τ_{ex} are exhibited.

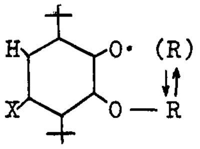
I - intensities of hyperfine components, Γ_0 - line width of central line, b - anisotropy parameter, Δa - diference of isotropic hyperfine splitings for two ring protons.

encies of motion along the reaction coordinate and of motion modulating EPR spectrum. The slight nonlinearity of the 1/k- τ_c dependence in Fig.2 may be related to the approximate character of eqn.(1), see (ref. 1). But the main and the most striking result of experiment is that knowledge of the spin probe mobility allows the prediction almost exactly, of chemical reactivity even for such a complex system as micellar solutions.

The above-discussed example is far from being the only observation of astonishingly good correlation between motional parameters and chemical reactivity. Much earlier linear correlation of type of (1) was observed for H atom transfer between phenols and nitroxides in polymer matrices (ref. 4).

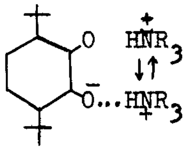
Of late, similar results were for the first time obtained for a number of monomolecular reactions including spin exchange in nitroxy biradicals (ref. 5) and intermolecular transfer of electron, hydrogen and more complex groups (ref. 6,7).

The typical process studied looks like follows:

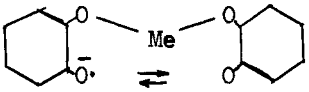


with several different R and X (Fig. 3).

Other examples are hydrogen bond transfer:



and electron transfer:



with Me = Sn, Zn, Si.

The chemical exchange in these cases modulates the isotropic hyperfine splitting at para- and meta-protons, while physical reorientation modulates anisotropic magnetic interactions. Hence a system of equations may be derived which connects the two parameters desired (τ_c and k) with two experimental ratios of intensities of three hyperfine lines (Fig. 3).

It looks remarkable that in all cases investigated till now the correlation equation (1) has been confirmed. It supports our hope that studies of spin probes and spin labels may be developed as an effective way of predicting chemical reactivity of free radicals in amorphous solids. On the other hand , the same results may be considered as a starting point to develop microscopic models of chemical reactions in the condensed media.

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