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Applications of singlet oxygen reactions: mechanistic and kinetic investigations

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Abstract - Analytical tools and methods for mechanistic and kinetic investigations of singlet oxygen reactions are presented and their limitations discussed in view of their application in developmental work and complex biological and biomimetic systems.

INTRODUCTION

Photooxidation reactions are among the principal processes which lead to the degradation of organic material of all kind under the combined action of light and oxygen. In a large number of photooxidation reactions, the reactive intermediate is singlet oxygen, which is most often produced by sensitization, i.e. by energy transfer from an electronically excited sensitizer molecule to molecular oxygen.
Investigations on the noxious effect of light on biological systems, in the presence of a dye and of molecular oxygen (photodynamic effect), are reported since the beginning of this century (ref. 1), and, 40 years later, Tennent concluded that cell defects observed upon irradiation in the presence of different dyes must be due to a "photocompound", an active agent inducing the photodynamic effect (ref. 2). Kautsky suggested already in 1931 that the reactive intermediate of dye-sensitized photooxidations could be a metastable activated species of molecular oxygen, since the diffusion of some oxidizing agent was necessary in order to explain photooxidation when sensitizer and reactant were adsorbed separately on solid matrices (ref. 3).
Singlet oxygen was discovered by astrophysicists in 1924, but it was almost 40 years until the observed emission bands of the chemiluminescence of the reaction of hydrogen peroxide with sodium hypochlorite could be attributed to singlet oxygen (ref. 4,5). It remained then to demonstrate that the hydrogen peroxide/sodium hypochlorite system, the sensitized photooxidation and the oxidation by oxygen which has been excited in an electric discharge produced the same distribution of oxidation products for a given reactant (ref. 6,7).
The last 25 years have witnessed an extraordinary development of the research on singlet oxygen related photooxidations in most diverse areas (ref. 8), such as atmospheric physics, spectroscopy, organic, inorganic and polymer chemistry, as well as environmental chemistry. Important contributions originate from life sciences with research work on phototoxicity and photodynamic therapy.
Development work on sensitized photooxidations on a technical scale is necessarily based on a detailed knowledge of reaction mechanisms and, consequently, on a set of methods of specific and quantitative analysis. This specialization in the analysis of the intermediates of light induced oxidations has placed us on the crossroads of very diverse research topics, and some of them are taken as examples in order to demonstrate the state of research in this domain.

SINGLET OXYGEN PRODUCTION BY SENSITIZATION

The two lowest electronically excited states of molecular oxygen are singlet states, the two electrons in the $1\pi_g$ orbital having opposite spins (ref. 9,10). The energy difference between the triplet ground state and the first excited state ($^1\Delta_g$) is 94.2 kJ·mol^{-1}, and is 156.9 kJ·mol^{-1} between the second excited state ($^1\Sigma_g^+$) and the ground state. The electronic transitions between the triplet ground state and the excited singlet states are spin-forbidden transitions. Consequently, the corresponding molar absorption coefficients of molecular oxygen are extremely weak, and the production of singlet oxygen by direct excitation is of no importance.

Besides sensitization, some chemical reactions, electric discharge and the photolytic decomposition of ozone may be used for the production of singlet oxygen (ref. 8,10). Sensitization can be applied in almost any reaction system and is relatively easy to implement on a technical scale.

Equations (1), (2) and (3) summarize the sensitization mechanism.

$$\text{Sens} \xrightarrow{h\nu} {}^1\text{Sens}^* \qquad (1)$$

$${}^1\text{Sens}^* \xrightarrow{\text{isc}} {}^3\text{Sens}^* \qquad (2)$$

$${}^3\text{Sens}^* + O_2 \xrightarrow{\text{et}} \text{Sens} + {}^1O_2 \qquad (3)$$

The sensitizer (Sens) is excited by absorption of light (1). Given that the lifetimes of excited triplet states are much longer than the lifetimes of excited singlet states, sensitization in diffusion controled reactions generally takes place *via* the triplet state of the sensitizer (${}^3\text{Sens}^*$, (3)). Depending on the energy of ${}^3\text{Sens}^*$ (E_T), both excited singlet states of oxygen can be generated, and the sensitizer is deactivated without chemical alteration. In practice, the ${}^1\Sigma_g^+$ state is rapidly deactivated in solution (ref. 10), and in the following, we are only interested in the ${}^1\Delta_g$ state as the reactive intermediate, denoted ${}^1O_2$.

According to the scheme of equations (1) to (3), the quantum yield of singlet oxygen production (Φ_Δ) by a given sensitizer is equal to the product of the quantum yield of intersystem crossing (or triplet formation, Φ_{isc}) and the efficiency of the energy transfer to molecular oxygen (ϕ_{et}).

$$\Phi_\Delta = \Phi_{isc} \cdot \phi_{et} \qquad (4)$$

where $$\phi_{et} = k_{et}[O_2]/(k_{et}[O_2] + k'_{isc} + k_p + k_{rd}[O_2]) \qquad (5)$$

k'_{isc} and k_p being the rate constants of the non-radiative and radiative decay of ${}^3\text{Sens}^*$, respectively, and k_{rd} the rate constant of other possible processes involving ${}^3\text{Sens}^*$ and O_2 (e.g. superoxide anion formation, quenching of ${}^3\text{Sens}^*$ by O_2 leading to the ground state of both reactants).

In evaluating singlet oxygen sensitizers by their quantum efficiency of singlet oxygen production, the differentiation and specific determination of both factors, Φ_{isc} and ϕ_{et}, is important for the fundamental understanding of primary and secondary processes involved in sensitization and, consequently, for the development of new sensitizers for different domains of applications.

The intersystem crossing quantum yield (Φ_{isc}) may be determined by laser flash-photolysis experiments using either the partial saturation method (ref. 11) or the energy transfer method (ref. 12). Preparing applications in microheterogeneous or heterogeneous media, we have used preferably the first of these methods in order to avoid problems arising from large concentrations of quenchers needed for a quantitative quenching of triplet states.
The direct determination of ϕ_{et} by the energy transfer method (ref. 13) being rarely applied due to experimental difficulties, ϕ_{et} is usually calculated from separately determined Φ_{isc} and Φ_Δ values.

The evaluation of the photophysical parameters of the hematoporphyrin derivative (HPD) is an interesting example demonstrating different methods of analysis and their limits. HPD is still the most frequently used sensitizer in photodynamic therapy of tumors (ref. 14) and is taken as a standard in the development of new sensitizers designed for this application. This substance has no defined chemical structure but consists of several porphyrins exhibiting related chromophore characteristics (ref. 15). HPD (of Photofrin II quality (ref. 14)) exhibits a rather high quantum yield of singlet oxygen production in

methanol (Φ_Δ = 0.83). However, in physiological salt solution, HPD has a very limited solubility and is a rather poor singlet oxygen sensitizer: Φ_Δ has a value of 0.12 at a concentration of 0.06 $g \cdot l^{-1}$, and decreases as the HPD concentration increases (ref. 16). Maximum values of Φ_{isc} of about 0.5 in physiological salt solution and of 0.9 in methanol have been calculated on the basis of results obtained from the partial saturation method and assuming an average molecular weight of 598.7 $g \cdot mol^{-1}$ (ref. 17). Thus, the difference of Φ_Δ in methanol and in physiological salt solution reflects an important solvent dependence of Φ_{isc} and of ϕ_{et}. Parallel spectroscopic studies show a notable shift of the Soret band, an increase of its molar absorption coefficient, a more distinct profile of the Q bands and a steady increase of the relative quantum yield of fluorescence (by a factor of 6) for water/methanol mixtures containing from 0 to 100% methanol (ref. 17,18). These changes are due to a pronounced aggregation of the sensitizer in aqueous solution, which enhances internal conversion from the electronically excited singlet state and thus diminishes the efficiencies of both fluorescence and intersystem crossing.

As triplet states are efficiently quenched by molecular oxygen, many authors assumed a Φ_{isc} equal to Φ_Δ and, thus, an efficiency of the energy transfer to molecular oxygen (ϕ_{et}) equal to unity. For instance, based on an indirect determination of Φ_Δ of rose bengal, Φ_{isc} has been usually taken to be 0.76 in methanol (ref. 19) and 0.86 in ethanol (ref. 20). In fact, Φ_{isc} determined by the partial saturation method is, in both water and methanol, practically unity (ref. 21), hence, diminishing the efficiency of energy transfer, ϕ_{et}, to values of 0.76 in methanol and 0.75 in water.

The observed solvent dependence of Φ_{isc} of HPD might originate from effects which concern only a limited number of the components involved and, due to aggregational effects, is an exception to a generally accepted rule that the quantum efficiencies of primary photochemical processes of simple sensitizer molecules do not vary to a great extent as far as the solvent change maintains the polar or apolar solvent character. A solvent dependence of Φ_Δ may, hence, be generally explained by variations of ϕ_{et}. Redmond and Braslavsky compared experimentally determined Φ_Δ values of a series of sensitizers with the already published Φ_{isc} of the same compounds (ref. 22). The calculated ϕ_{et} lead to a qualitative differentiation between energy transfers from $\pi\pi^*$ and $n\pi^*$ triplets to molecular oxygen, the former showing higher values of ϕ_{et}. Based on a reaction scheme which includes the spin statistical factors determining the dynamics of the quenching of $^3Sens^*$ by molecular oxygen (ref. 23), variations of ϕ_{et}, due to changes of the k_{et}/k_{rd} ratio ((4) and (5)), may be explained by the relative importance of the intersystem crossing between the two electronic configurations of the sensitizer-oxygen exciplexes with strong CT characteristics: $^1(Sens^{\delta+}\ldots{}^{\delta-}O_2)^*$ and $^3(Sens^{\delta+}\ldots{}^{\delta-}O_2)^*$ (ref. 22). The extent of this intersystem crossing may be qualitatively linked to the polarizability of the electronically excited sensitizer molecule which is generally assumed to be lower in $\pi\pi^*$ than in $n\pi^*$ triplet states. This interpretation cannot explain the strong solvent dependence of Φ_Δ of fluorenone (Φ_Δ(benzene)/Φ_Δ(methanol) ~ 20, ref. 22,24,25), unless the lowest triplet state of fluorenone has a strong $n\pi^*$ character in methanol, for which no experimental evidence has been given so far.

Among the many means of Φ_Δ determination, methods of direct and indirect analysis have to be distinguished. Methods of direct analysis make use of a physical quality of singlet oxygen which can be observed with an appropriate equipment; luminescence (ref. 26) and calorimetric (ref. 27) measurements are mostly used at present. Luminescence measurements at 1270 nm under continuous excitation are very convenient for technical evaluations of new sensitizers as well as for fundamental investigations. In the absence of a singlet oxygen quencher or acceptor, reactions (1) to (3) are followed by

$$^1O_2 \xrightarrow{k_e} O_2 + h\nu' \qquad (6)$$

$$^1O_2 \xrightarrow{k_d} O_2 \qquad (7)$$

The quantum yield of singlet oxygen luminescence, Φ_e, is then

$$\Phi_e = \Phi_\Delta \cdot \phi_e \qquad (8)$$

where $\phi_e = k_e/(k_e + k_d)$ (9)
is the luminescence efficiency, if the quenching of singlet oxygen by the sensitizer (24) is negligible. Note that $k_e << k_d$ (ref. 26).

For a given equipment, the emitted photon flux, P_e, is proportional to the observed signal S_e, thus,

$$\Phi_e = P_e/P_a = C\ S_e/P_a \qquad (10)$$

If measurements with sample (Sens) and reference (R) solutions are made using identical absorbances at the wavelength(s) of excitation (A), hence, ensuring identical absorption factors ($\alpha = P_a/P_0 = (1-10^{-A})$), the equipment specific proportionality factor C remains constant. Furthermore, k_e and k_d are respectively the same in experiments with Sens and R, if the same solvent is used. Consequently, the following equations can be applied:

- *for experiments with identical solvent, A and* λ_{exc}:

$$\Phi_\Delta = \Phi_\Delta^R\ S_e/S_e^R \qquad (11)$$

- for experiments with identical solvent and A, but different λ_{exc} for Sens and R:

$$\Phi_\Delta = \Phi_\Delta^R\ (S_e/S_e^R)\ (P_a^R/P_a) \qquad (12)$$

- *for experiments with identical A and* λ_{exc}, *but different solvents for Sens and* R:

$$\Phi_\Delta = \Phi_\Delta^R\ (S_e/S_e^R)\ (k_e^R/k_e)\ (\tau_\Delta^R/\tau_\Delta) \qquad (13)$$

where $\tau_\Delta = 1/(k_e + k_d)$ or $\tau_\Delta = 1/k_d$ (as $k_e << k_d$) (14)
is the lifetime of singlet oxygen in a given medium.

From the most recent experiments, results of Φ_Δ determination of 1H-phenalen-1-one should be mentioned. Taking fluorenone as a standard in C_6D_6 or C_6H_6 (11) and rose bengal as a standard in CD_3OD (12), the same value of 0.98(±0.05) has been found for 1H-phenalen-1-one in both solvents, placing this ketone among the most efficient singlet oxygen sensitizers known (ref. 25).

Evidently, Φ_Δ determinations can also be made by time resolved luminescence measurements, but problems usually arise from an inferior signal/noise ratio, from the reproducibility of the incident photon flux and from difficulties with the measurement of the signal intensity at zero-time. However, good results can be obtained when well-investigated sensitizers are used as references (ref. 13). Moreover, time resolved luminescence measurements are necessary for an independent determination of τ_Δ in order to solve (13) for a given reaction medium.

Although, some authors have claimed k_e to be solvent independent (ref. 28,29), several research groups reported results which can only be interpreted with a considerable variation of k_e (ref. 30-32). For instance, Φ_Δ of rose bengal was determined by experiments where singlet oxygen is quantitatively trapped by 2-furfuryl alcohol (*vide infra*) to be 0.85 in acetonitrile (ref. 33), a high value indicating that this solvent is a reaction medium of preference for many preparative applications. In a similar experiment in methanol, the reference value (0.76, ref. 19) could be duplicated, and thus the ratio Φ_Δ(acetonitrile)/Φ_Δ(methanol) is 1.12. Parallel Φ_Δ determinations were made by luminescence measurements, and (13) was applied, taking rose bengal in CD_3CN as Sens and the same sensitizer in CD_3OD as R (ref. 34). A value of k_e(acetonitrile)/k_e(methanol) of 1.4 was calculated, a ratio which is definitely larger than 1. The combined use of different methods of analysis of singlet oxygen is based on the hypothesis that k_e remains constant for a solvent in its perhydrogenated and perdeuterated form, a hypothesis which is in

accord with the interpretation that k_e depends on the solvent polarizability (ref. 31,32).

Detecting the singlet oxygen luminescence at an angle of 90° with respect to the axes of the beam of the monochromatic incident light, the equipment specific proportionality factor C depends on the absorbance of the solution. An empirical function can be found in comparing the singlet oxygen luminescence initiated by the same sensitizer at different absorbances, keeping one absorbance value as reference (A^R). Referring to (10), we may write

$$\Phi_e = C\ S_e/\{P_0(1 - 10^{-A})\} = C\ S_e/\{P_0(1 - T)\} \qquad (15)$$

and then

$$S_e/S_e^R = (C^R/C)\ (\Phi_e/\Phi_e^R)\ \{(1 - T)/(1 - T^R)\} \qquad (16)$$

when the same incident photon flux (P_0) is applied. If Φ_e is independent of [Sens] as is the case for rose bengal and 1H-phenalen-1-one, a plot of $S_e/S_e^R = f\{(1 - T)/(1 - T^R)\}$ shows the proportionality function C^R/C (Fig. 1, ref. 35). If Φ_e depends on [Sens],the same plot includes the relative variation of Φ_e, and concentration effects on Φ_e can be demonstrated. This is for instance the case for methanol solutions of chloro aluminium(III) sulfonated phthalocyanine (AlSPC), another potential sensitizer for PDT applications (Fig. 1). This result coincides with earlier measurements, evaluating the solvent dependence of its Φ_Δ, for which a decrease from 0.3 in pH 10 buffered aqueous solution to 0.1 in methanol was found (ref. 36). We assume that both observations are due to an enhanced aggregation of the multiply charged compound in the organic solvent leading to a decrease of Φ_Δ and, thus, of Φ_e.

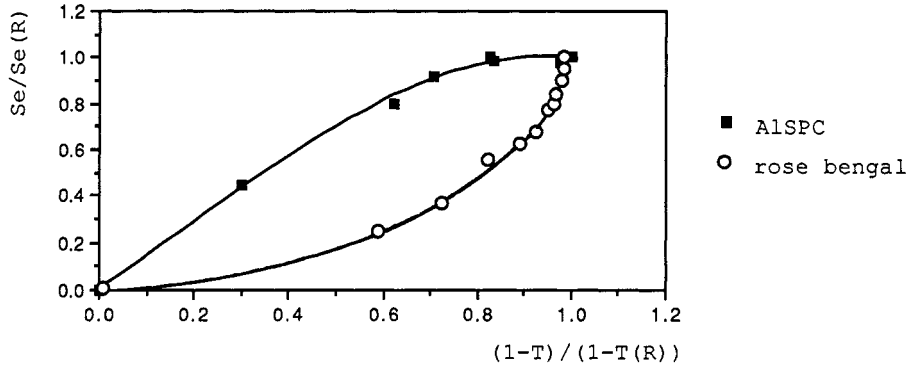


Fig. 1. - Plot of $S_e/S_e^R = f\{(1 - T)/(1 - T^R)\}$, (see (16) and text).

Methods of indirect singlet oxygen analysis make use of its chemical reactivity, and, in using specific acceptors, the decrease of both the concentration of the acceptor A and the concentration of the dissolved molecular oxygen may be determined ((3) and (17)).

$$^1O_2 + A \xrightarrow{k_r} AO_2 \qquad (17)$$

The quantum yield of the chemical reaction of singlet oxygen, Φ_r, is defined as

$$\Phi_r = \Phi_\Delta \cdot \phi_r \qquad (18)$$

where $$\phi_r = k_r[A]/\{k_d + (k_r + k_q)[A]\} \qquad (19)$$

k_q being the rate constant of the physical quenching of $^1O_2$ by A (20).

$$^1O_2 + A \xrightarrow{k_q} O_2 + A \qquad (20)$$

In order to apply a singlet oxygen acceptor for quantitative analysis, the following conditions must be fulfilled:

- specific reaction with $^1O_2$,
- the stoichiometry of (17) is known and preferentially 1:1,
- $k_r[A]$ is the dominant rate of consumption of $^1O_2$, k_r being preferentially higher than 10^7 $l \cdot mol^{-1} \cdot s^{-1}$.

Changing (18) into

$$1/\Phi_r = \{(k_r + k_q)/(k_r \Phi_\Delta)\} + \{k_d/(k_r \Phi_\Delta)\} (1/[A]) \quad (21)$$

the experimentally determined Φ_r (22) can be plotted as $1/\Phi_r = f(1/[A])$, yielding $1/\Phi_\Delta$ from the origin if $k_r >> k_q$, and k_r from the slope as k_d is known for the reaction medium used. For a 1:1 stoichiometry of (17), we can write

$$\Phi_r = (1/P_a) (d[A]/dt) = (1/P_a) (d[O_2]/dt) \quad (22)$$

Spectrophotometric analysis of the acceptor concentration is most convenient, but only in the last few years, water soluble acceptors which change their absorption spectrum in (17) have been published. They permit to extend this kind of analysis to a larger range of organic solvents and water (ref. 37). Among the acceptors cited, 1,3-diphenylisobenzofuran (DPBF) is one of the least specific, as this compound is known to react readily with radical species which might be present in the reaction mixture (ref. 38), and Φ_r determined on the basis of DPBF reactivity are usually overestimated.

The indirect singlet oxygen analysis is the method of choice for Φ_r determinations in non-homogeneous reaction systems. For [Sens] dependent Φ_Δ, luminescence measurements might lead to an erroneous result due to the difficulties in establishing C (*vide supra*), and corresponding experiments should be checked by singlet oxygen trapping. For example, Φ_Δ decreases by a factor of 2, as [HPD] is increased from 0.06 to 0.6 $g \cdot l^{-1}$ in aqueous solution (ref. 16), a concentration effect which would be very difficult to quantify by luminescence measurements.

Evidently, all indirect methods of analysis quantify singlet oxygen which is available for diffusion controled chemical reaction with a chosen acceptor. Sensitizer molecules might themselves be efficient quenchers or acceptors of singlet oxygen ((23) and (24)), hence competing with an added acceptor ((17) and (20)). k'_q (24) can be easily determined by time-resolved luminescence measurements; for the determination of k'_r (23), indirect analysis of self-sensitized oxidation is possible if conditions of total absorbance can be ensured during irradiation time.

$$^1O_2 + \text{Sens} \xrightarrow{k'_r} \text{Sens}O_2 \quad (23)$$

$$^1O_2 + \text{Sens} \xrightarrow{k'_q} O_2 + \text{Sens} \quad (24)$$

In many evaluations involving very complex sensitizer systems, investigations usually focus on a determination of (relative) Φ_r. Surface waters are known to be media where light induced oxidative degradation of dissolved or dispersed organic pollutants occurs, a process in which singlet oxygen, sensitized by humic substances, might participate. These substances are polychromophoric macromolecules of unknown detailed structure and molecular weight, in which inner and outer areas of complexation and, hence, of quenching (ref. 39,40) can be differentiated. Interferences of the absorption spectra of sensitizer and singlet oxygen acceptor call for the analysis of dissolved molecular oxygen, a technique which has been developed in detail in our laboratory. This method uses 2-furfuryl alcohol as a specific singlet oxygen acceptor (ref. 40,41) for which the 1:1 stoichiometry of (17) has also been established (ref. 42). For a series of aqueous humic and fulvic acids, values of Φ_r in the range of 0.02 to 0.04 have been found (ref. 43), results which are for technical reasons not yet reproducible by luminescence measurements.

Rather important series of (relative) Φ_r determinations have been made in the course of the development of insoluble singlet oxygen sensitizers (ref. 10,44,45,46). Luminescence measurements are only of restricted use for immobilized sensitizer particles and extended surfaces and yield S_e values which are difficult to interpret due to large differences in surface structure

and support reactivity (ref. 47). Again, because of the heterogeneity of the reaction systems, we prefer Φ_r determinations using an oxygen electrode. As anticipated, the results show maximum efficiencies for insoluble sensitizers of colloidal size (ref. 45): insoluble sensitizers consisting of 2% of rose bengal chemically bound to functionalized SiO_2 surfaces show an efficiency of approximately 50% of the standard sensitizer in solution.

Laser spectroscopic investigations on deaerated suspensions of the same insoluble sensitizers show the known T-T absorption spectrum of rose bengal, but also the spectrum of the radical cation of the sensitizer (ref. 21,45). This spectrum becomes dominant in aerated suspensions indicating a very competitive electron transfer reaction to oxygen (25).

$$^3\text{Sens} + O_2 \xrightarrow{\text{elt}} \text{Sens}^{+\cdot} + O_2^{-\cdot} \qquad (25)$$

The observed decrease of Φ_r for insoluble sensitizer might therefore, at least partially, be due to electron transfer reaction, which in turn is favored by a high local sensitizer concentration. A decrease of Φ_r can also be observed, when rose bengal sensitized oxidations are carried out in W/O microemulsions, where the local concentration of rose bengal is increased due to the restricted volume of the aqueous phase (ref. 48). A further development of insoluble sensitizers should then also be focussed on the preparation of sensitizers with more dilute surface occupation, the surface functionalization not acting as a singlet oxygen quencher.

SINGLET OXYGEN REACTIVITY

Singlet oxygen is a rather specific reagent whose typical reactions are classified as ene-reactions, (2+4) cycloadditions, (2+2) cycloadditions and sulfoxidations (ref. 8,10).
Improvements in preparative applications of some of these reactions may be possible in using new sensitizers and different solvents or solvent mixtures, or in introducing new reactor geometries.
Development of sensitized photooxidations on a technical scale is always based on Φ_r determinations for which substrate, product and oxygen analysis may be used. On the other hand, published tables of k_r, but also of k_q values (ref. 49), might help to evaluate Φ_r for reaction systems of known sensitizers and solvents. The simultaneous measurements of oxygen concentration and absorbed photon flux yield excellent results as long as periods of irradiation remain within the time limits of the stability of oxygen electrodes (ref. 50).

The concentration of the acceptor may be an important parameter in the optimization of a sensitized photooxidation. However, maximum limits might be imposed by potential sensitizer-substrate interactions (e.g. (28), ref. 37). In this respect, sulfoxidation is particularly interesting, since in its sequence of product formation ((26) and (27)) a second molecule of substrate is involved. In fact, the concentration dependence of the overall sulfoxidation is the principal argument for the proposed sequence (ref. 51).

$$^1O_2 + \text{RSR}' \xrightarrow{k_r} \text{RSO}_2\text{R}' \qquad (26)$$

$$\text{RSO}_2\text{R}' + \text{RSR}' \xrightarrow{\text{ro}} 2\ \text{RSOR}' \qquad (27)$$

$$^3\text{Sens}^* + \text{RSR}' \longrightarrow \text{Sens} + {}^3\text{RSR}' \qquad (28)$$

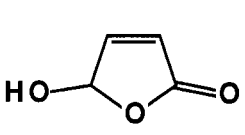
Microemulsions have been used in order to ensure important differences in concentration. In the case of N-methyl phenothiazine (MPT), the sensitizer-substrate interaction is of importance, although (28) must be a very inefficient process (E_T(MPT) ~ 60 kcal·mol^{-1}, ref. 52). Quenching of the sensitizer triplet by MPT and the corresponding rate constant k_t could be determined by a Stern-Volmer analysis of singlet oxygen luminescence (ref. 48), and the quenching is most probably due to an electron transfer reaction (29).

$$^3\text{Sens}^* + \text{RSR}' \xrightarrow{k_t} \text{Sens}^{-\cdot} + \text{RSR}'^{+\cdot} \qquad (29)$$

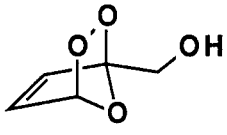
Research on light stability of macromolecules and, more recently, on the photodynamic effects linked to phototoxicity reemphasized the search and evaluation of new physical quenchers of singlet oxygen. Time-resolved and steady-state singlet oxygen luminescence measurements are used in many laboratories for the determination of k_q (20). This method of analysis is, however, only applicable, when the quencher has no competitive chemical reactivity. If k_q and k_r are of the same order of magnitude, the combined use of luminescence measurements and indirect analysis by singlet oxygen trapping is advantageous, the first yielding *via* Stern-Volmer analysis ($k_q + k_r$), the second determining k_r.

Analytic and kinetic investigations as mentioned above help to understand the mechanisms of singlet oxygen production and reactions and permit to draw conclusions for the development of more efficient sensitizers, reaction systems or quenchers. These investigations, however, do not follow the reaction up to the final product, although much of the developmental work in preparative chemistry is concerned with the reactivity of the intermediates (e.g. peroxides) and, hence, with the optimization of the subsequent thermal reactions.

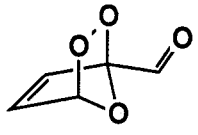
The specificity of these reactions may be checked in using $^1(^{17}O_2)$ followed by ^{17}O-NMR analysis of the final product(s). For instance, 2-furfuryl alcohol is not only used as a specific singlet oxygen acceptor (*vide supra*), but seemed also a potential substrate for the production of 5-hydroxy-2(5H)-furanone-2 (A, ref. 45). Earlier, the same product was isolated from the sensitized photooxidation of 2-furfuryl aldehyde (ref. 53), and this procedure has been patented since (ref. 54). ^{17}O-NMR analysis reveals that the endoperoxide of furfuryl alcohol (B_1) can undergo S_N2 as well as S_N1 reactions with the solvent, finally producing A and the hydroperoxide C, respectively. The same method of analysis showed that the S_N1 reaction cannot be observed with the endoperoxide of 2-furfuryl aldehyde (B_2), probably due to the destabilization of the carboniumion in α position of the carbonyl group. Consequently, A is formed specifically by both S_N2 and fragmentation reactions of B_2 (ref. 55).



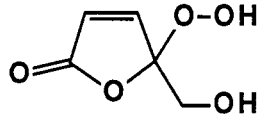
A



B_1



B_2



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OUTLOOK

This overview of todays current analytical methods in the domain of singlet oxygen chemistry demonstrates that tools are available for a detailed mechanistic investigation on the generation, chemical reaction and physical deactivation of singlet oxygen. Considerable research efforts are still needed for the development of analytical methods and tools designed to be applied in microheterogeneous and heterogeneous media, particularly in photobiochemistry. Besides the technical evaluation of singlet oxygen sensitizers, our work in this domain is focussed on the differentiation of type I and II reactions of surface bound sensitizers (ref. 56).

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