PROBLEMS ASSOCIATED WITH DISTINGUISHING BETWEEN SINGLET OXYGEN AND ELECTRON TRANSFER PHOTOOXYGENATION REACTIONS

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In the introduction a review is given of the various methods available for probing the mechanism of photooxygenation reactions. To illustrate the methodology, some new results on the the photooxygenation of α-ketocarboxylic acids and esters is given in which it is shown that these compounds sensitise singlet oxygen formation but are relatively unreactive to this oxidising species. Alternative mechanistic schemes are proposed.
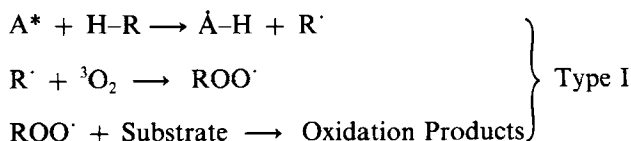
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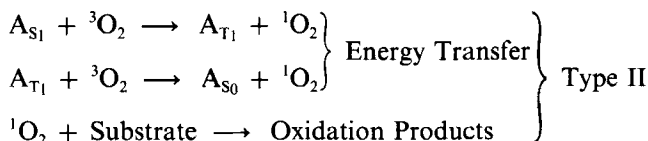
INTRODUCTION

A review of mechanistic aspects of photooxidation reactions

There are many aspects to the studies of photooxidation reactions. These include the breakdown of biologically significant compounds such as polyunsaturated acids, purine and pyrimidine bases and certain amino acids to name but a few. Other aspects include the use of photooxidation reactions in synthesis, and attempts to discover ways of suppressing the reactions since they often contribute to the mechanical failure of such synthetic materials as polymers (e.g. surface coatings, objects fabricated from polypropylene). In order to use photooxygenation reactions with the most benefit and also, where it is desired, to prevent such reactions an understanding of the mechanism or mechanisms involved is essential.

Photooxygenation reactions can be conveniently classified into two types — direct and photosensitised. In the former, the compound absorbing the light sensitises its own oxidative destruction and in the second, the material absorbing the light, generates *via its* electronically excited states species capable of interacting with *other ground state* species triggering off oxidation reactions. In both processes the nature of oxidising species is of great importance. Two principle types of reaction mode have been identified — Type I and Type II.[1] The essential difference between the two is that the Type I is an electron or atom transfer process and the Type II is singlet oxygen mediated.
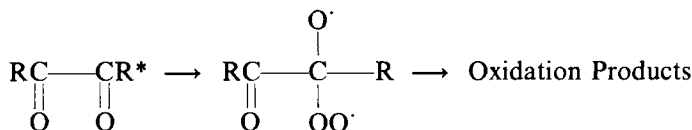
$$A^* + H\text{–}R \longrightarrow \dot{A}\text{–}H + R^{\cdot}$$

$$R^{\cdot} + {}^3O_2 \longrightarrow ROO^{\cdot}$$

$$ROO^{\cdot} + \text{Substrate} \longrightarrow \text{Oxidation Products}$$

Type I

* — indicates an electronically excited state.

$$A_{S_1} + {}^3O_2 \longrightarrow A_{T_1} + {}^1O_2$$

$$A_{T_1} + {}^3O_2 \longrightarrow A_{S_0} + {}^1O_2$$

Energy Transfer

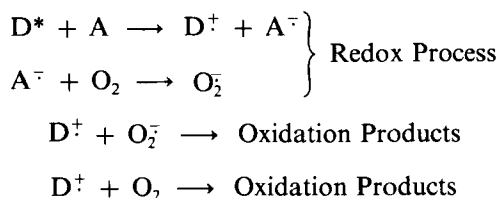$${}^1O_2 + \text{Substrate} \longrightarrow \text{Oxidation Products}$$

Type II

i.e. a Singlet Oxygen mediated process

Included in the Type I process is the possibility that the light absorbing species reacts directly with oxygen to give a peroxy species.[2]

$$\underset{\underset{O}{\|}}{RC}\text{—}\underset{\underset{O}{\|}}{CR^*} \longrightarrow \underset{\underset{O}{\|}}{RC}\text{—}\underset{\underset{OO^{\cdot}}{|}}{\overset{\overset{O^{\cdot}}{|}}{C}}\text{—}R \longrightarrow \text{Oxidation Products}$$

Such a mechanism is reminiscent of the mechanism first put forward by Schenck to explain the photosensitising properties of dyes.

Another form of the Type I process which has recently received a lot of attention is the ELECTRON TRANSFER SENSITISED REACTION[3]

$$D^* + A \longrightarrow D^+ + A^{\cdot-}$$

$$A^{\cdot-} + O_2 \longrightarrow O_2^{\cdot-}$$

Redox Process

$$D^+ + O_2^{\cdot-} \longrightarrow \text{Oxidation Products}$$

$$D^+ + O_2 \longrightarrow \text{Oxidation Products}$$

D* — indicates an electronically excited state.

In this process an electron, rather than a hydrogen atom, is transferred to the sensitiser and this is subsequently followed by other electron transfer processes such as the generation of the superoxide ion. When such reactions occur in aqueous media it is also possible (because of the low pKa for the process $HO_2^{\cdot} \rightarrow O_2^{\cdot-} + H^+$, pKa ~ 4.6) that this type of reaction can also generate hydroperoxy radicals which in turn trigger off oxidation reactions.

In the Type II process that oxidising species singlet oxygen, is generated by an energy transfer process. Excited singlet states can act as sensitisers provided their $S_1–T_1$ energy gap is greater than the energy of singlet oxygen, ${}^1\Delta g\, O_2$ (23 kcal/mole).[4a,b] Energy transfer from triplet states is particularly common since the triplet energies for many compounds are greater than that of singlet oxygen (${}^1\Delta g\, O_2$). The efficiency of the energy transfer process has only recently been studied with any thoroughness. Thus if there is a vast difference between the triplet energies of the sensitiser and that of singlet oxygen, transfer may become inefficient. Transfer has to occur to a singlet

TABLE I

Methods available for detecting the participation of singlet oxygen in reactions

Method	Reliability of method	References
Use of singlet oxygen quenchers e.g. DABCO, β-carotene.	The quenchers of singlet oxygen can also quench the excited states of the sensitiser. Hence, very low concentrations of quenchers must be used. Sodium azide is not a reliable quencher. Quenching of singlet oxygen by β-carotene can be detected by laser flash photolysis.	Quenching of singlet oxygen by DABCO[6] and β-carotene[7]. Necessity for controlling concentration of quenchers.[8] Use of laser flash photolysis using β-carotene.[9]
Kinetic Solvent Isotope Effect	The occurrence of the Type I process and interference by reaction product leads to values lower than expected on the basis of measured lifetimes of singlet oxygen. The quenching of singlet oxygen by the sensitisers and effect of the isotopic content of solvent upon the photophysics of the sensiter can also lead to erroneous conclusions.	Demonstration of kinetic solvent isotope effect.[10] Interference by products. Quenching of singlet oxygen by sensitisers.[11] Isotope effect upon photophysics of sensitisers.[12]
Time resolved experiments, e.g. bleaching of diphenylisobenzofuran (DPBF) sensitised cis- trans isomerisation of β- carotene. Follow decay of singlet oxygen by its luminescence at 1.27 μm	Bleaching of DPBF by singlet oxygen — an indirect method. Similar remark applies to sensitised isomerisation of β-carotene. Following decay of singlet oxygen via its luminescence offers a direct way to obtain rate constants for quenching singlet oxygen and for determining yields of singlet oxygen.	Bleaching of DPBF.[13] Sensitised isomerisation of β-carotene.[9] Use of emission produced by decay of singlet oxygen.[14]

state of oxygen possessing considerable vibrational energy and consequently the Franck–Condon factor for transfer mitigates against the process. Some carbonyl compounds appear to fall into this category.[5a,b,c]

For a particular reaction, distinguishing between the mechanistic pathways and in some cases assessing the extent to which each of the pathways participate is a complicated and in some cases intractable problem. In Table I we show some of the ways used for detecting the participation of singlet oxygen in reactions.

Methods for determining whether reactions involve electron transfer sensitisation are even less direct than those for detecting the intermediacy of singlet oxygen. In some cases the products formed in singlet oxygen mediated and electron transfer sensitised reactions can be distinguished, e.g. in the oxidation of cyclohexa-1,3-diene,[15a,b] and 1,4-dimethylnaphthalene.[16] In those cases where the photoredox reaction between the donor and acceptor is thermodynamically favourable and the substrate is known to be relatively or totally unreactive towards singlet oxygen then

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the observation of chemical reaction is best rationalised in terms of radical ion intermediates, e.g. the oxidation of stilbene by 9,10-dicyanoanthracene.[15a] The intermediacy of the superoxide ion can be shown by studying the effect of added benzoquinones.[17] The latter have lower reduction potentials than the superoxide ion which is consequently scavenged by the redox process:

$$O_2^- + BQ \longrightarrow {}^3O_2 + BQ^-$$
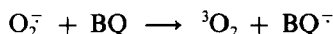
As a consequence added quinone should, and does, reduce the rate of photooxidation of stilbene in the presence of 9,10-dicyanoanthracene. This indirect test may not be totally infallable however, due to the ubiquitous ability of benzoquinone to scavenge electron deficient species.

Occasionally the products of the reaction are such that it is only reasonable to invoke the intermediacy of radical ions, e.g. in the 9,10-dicyanoanthracene sensitised oxidation of 1,1-di(4-methoxyphenyl)ethene the peroxide produced [1] is most likely to be formed via the ethene radical cation.[18]
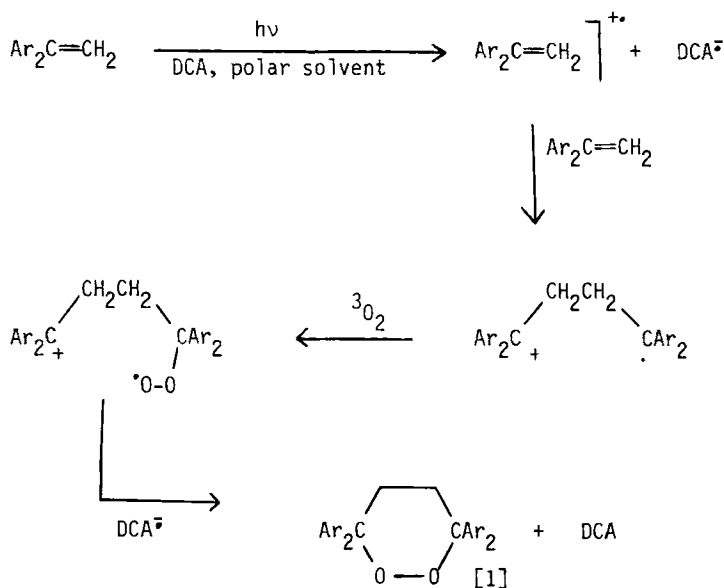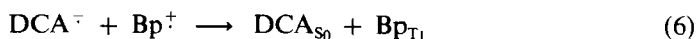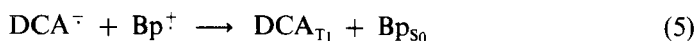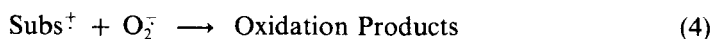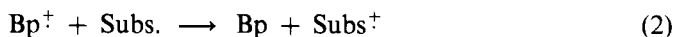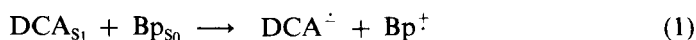

Similarly oxygenation of cyclopropanes, sensitised by 9,10-dicyanoanthracene, in which the cyclopropane ring is destroyed are most readily explained by invoking the intermediacy of radical cations.[19] When the reactions being studied can occur by both singlet oxygen and electron transfer processes, mechanistic interpretation of the chemical processes becomes singularly difficult. Several important facts need to be borne in mind. Firstly, many of the highly fluorescent powerful electron acceptors, e.g. 9,10-dicyanoanthracene, are efficient sensitisers for singlet oxygen production.[4b,20] Secondly, many photoinduced charge transfer processes lead to the generation of triplet states and these can then act as progenitors for singlet oxygen.[21] Thirdly, the efficiency with which a charge transfer process competes with an energy transfer

process is dependent upon the concentrations of the various reactants and upon solvent polarity.[22] The formation of solvent separated ion pairs only occurs in highly polar solvents and consequently the use of such solvents favours the electron transfer process. Furthermore the efficiency with which excited states are quenched via a charge transfer process is often increased by a change from a non-polar to a polar solvent. Experience has taught us that in those cases where electron transfer reactions between the sensitiser and substrate are inefficient and the products obtained are consistent with singlet oxygen being an intermediate, this is the most likely explanation, e.g. in the oxidation of allenes sensitised by 9,10-dicyanoanthracene,[23] reaction of simple alkenes sensitised by 9,10-dicyanoanthracene[24] or 3,7,9,10-tetracyanoanthracene.[25]

Since the efficiency of some photoinduced redox processes is solvent dependent it is not surprising that a change of solvent from a non-polar to a polar solvent can lead to a change in mechanism from singlet oxygen mediated to electron transfer mediated. This has been shown to be the case for the oxidation of *cis* and *trans*-$\alpha\alpha'$-dimethylstilbenes, sensitised by 9,10-dicyanoanthracene in which the reaction of oxygen occurs exclusively via singlet oxygen in carbon tetrachloride and via singlet oxygen and electron transfer pathways in acetonitrile solution.[26]

An interesting and important aspect of electron transfer mediated reactions is the fact that certain aromatic hydrocarbons (particularly biphenyl) appear to be able to act as 'relays' in such reactions.[27] e.g.

$$DCA_{S_1} + Bp_{S_0} \longrightarrow DCA^{\cdot-} + Bp^{\cdot+} \tag{1}$$

$$Bp^{\cdot+} + Subs. \longrightarrow Bp + Subs^{\cdot+} \tag{2}$$

$$DCA^{\cdot-} + {}^3O_2 \longrightarrow DCA_{S_0} + O_2^{\cdot-} \tag{3}$$

$$Subs^{\cdot+} + O_2^{\cdot-} \longrightarrow \text{Oxidation Products} \tag{4}$$

$$DCA^{\cdot-} + Bp^{\cdot+} \longrightarrow DCA_{T_1} + Bp_{S_0} \tag{5}$$

$$DCA^{\cdot-} + Bp^{\cdot+} \longrightarrow DCA_{S_0} + Bp_{T_1} \tag{6}$$

The substrates used in the original investigations were aryl substituted oxiranes. The peculiar feature of the reactions, if the proposed mechanism is correct, is that the relay (biphenyl) accelerates the reaction via an endothermic process (Reaction 2). However, the endothermicity may be offset by the fact that the substrate radical cation undergoes rapid ring opening thereby driving the reaction to the right hand side.[28] Evidence in favour of the intermediacy of radicals in these reactions includes the fact that the addition of salts (which aid the formation of solvent separated ion pairs) has a beneficial effect.[29] It should not be forgotten that singlet oxygen can be produced in these reactions, via energy transfer from triplet states (generated in reactions (5) and (6)) to ground state oxygen.[30] Indeed laser flash photolysis studies have shown that the triplet produced is not that possessing the lowest triplet energy but the one of highest energy, i.e. the biphenyl triplet.

As an example of a recent mechanistic study, we describe our work upon the photooxidation of α-ketocarboxylic acids and related compounds.

MATERIALS AND METHODS

The α-ketocarboxylic acids and related esters were of the same origin as previously reported.[31,32] Laser flash photolysis experiments were carried out using the third harmonic of a J.K. Lasers, System 2000, Nd-YAG laser. Detection of the emission produced by decay of singlet oxygen was carried out with an E.O.S.S. Inc., G-050, 5 mm^2 germanium diode in association with appropriate filters (to protect the detector from scattered incident laser radiation).[5] Solutions of the acids and esters (optical density 0.5) were excited in oxygenated benzene solution.

RESULTS

Excitation of various α-ketocarboxylic acids and esters in oxygenated solution was found to produce singlet oxygen. The latter was detected via its emission at 1.27 μ. Values for ϕ_Δ are shown in Table II. These were calculated by reference to benzophenone which has a ϕ_Δ value of 0.29.[5] In the case of t-butyl pyruvate the S_Δ value (0.2) was obtained using the following relationship:

$$\phi_\Delta = \phi_T \times S_\Delta$$

ϕ_T = Quantum yield for triplet production.
S_Δ = Energy transfer efficiency, i.e. fraction of quenching acts leading to $^1\Delta g$ O_2 production.

The quantum yield of triplet production was found to be 0.8 (± 0.1) by laser flash photolysis. Solutions of benzophenone and the t-butyl-pyruvate having similar optical densities (0.5) were excited with a Nd-YAG laser. The transient absorptions were extrapolated back to zero time in order to obtain the optical density for the triplet species at zero time. From a knowledge of the extinction coefficients of the triplet

TABLE II

Yields of singlet oxygen (ϕ_Δ) obtained by direct excitation of α-keto-carboxylic acids, and esters in benzene solution*

Compound	ϕ_Δ
Pyruvic acid	0.18
Phenylpyruvic acid	0.26
α-Ketobutyric acid	0.23
α-Ketooctanoic acid	< 0.04
Methyl pyruvate	0.20
Ethyl pyruvate	0.14
n-Butyl pyruvate	0.15
t-Butyl pyruvate	0.16
Benzyl pyruvate	< 0.07
Methyl α-ketooctanoate	0.00
2-(2-Naphthyl)ethyl pyruvate	0.27

*Optical densities of all solutions = 0.5, at the excitation wavelength where solubility allowed. The ϕ_Δ values have been corrected for any difference in optical density and variation in laser power, and optical densities were extrapolated to $t = 0$.

species and using a value of unity for the quantum yield for triplet production from benzophenone, the triplet yield of t-butyl pyruvate was obtained.[33]

DISCUSSION

After the early reports that the dye sensitised photooxygenation of α-ketocarboxylic acids involved singlet oxygen,[34] chemical evidence[35] and later indirect evidence from laser flash photolysis studies[36] refuted this claim. Many α-ketocarboxylic acids and their esters undergo photooxidation upon irradiation in certain oxygenated solutions.[37] Chemical studies suggested that these reactions did not involve singlet oxygen nor was direct α-cleavage to give acyl radicals an important process.[37] We suggested that the oxygenation process was triggered off by an electron transfer process.[31]

$$RCO\text{--}CO_2Me \xrightarrow{h\nu} |RCOCO_2Me|^{\dot{+}} + RCO\,CO_2Me|^{\dot{-}}$$

It was postulated that the radical ions form a biradical [1] which may also be produced via other routes.[2,31]
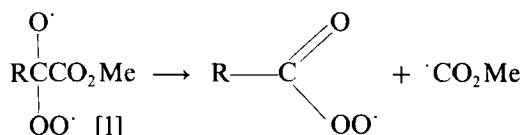
The results shown in Table II leave one in no doubt that the majority of α-ketocarboxylic acids and esters can sensitise singlet oxygen formation. However, it was found that singlet oxygen (generated by energy transfer from triplet protoporphyrin dimethyl ester in benzene solution) was not quenched at a measurable rate by t-butyl pyruvate. This puts an upper limit on the rate constant for quenching singlet oxygen by α-keto-carboxylates of $2 \times 10^5 M^{-1}s^{-1}$. This result confirms our earlier finding.[36]

We therefore conclude that the direct photooxidation of α-ketocarboxylic acids and esters does not involve attack of singlet oxygen upon the ground state carboxylic acid or ester. However, the majority of acids and esters sensitise singlet oxygen with similar efficiency to other triplet carbonyl compounds. The very low yield of singlet oxygen from α-ketooctanoic acid and its methyl esters may be attributed to the ease with which these compounds undergo the Norrish Type II process. This reduces the triplet lifetime to such an extent that a bimolecular reaction with oxygen at a concentration of around $5 \times 10^{-3}M$, would be very inefficient. Currently we are not sure whether this is the reason for the low sensitising ability of benzyl pyruvate.

Acknowledgements

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