Photoproduction of remarkably stable benzylic radicals in cyclodextrin inclusion complexes

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Abstract

Photolysis of cyclodextrin inclusion complexes of diastereomers of α,α'-dimethyldibenzyl ketone in the solid state resulted in stable benzylic radicals at room temperature. These radicals were characterized by their electron spin resonance (ESR) signals, emission and excitation spectra.

1. Introduction

It has been known for a considerable time that cyclodextrins form inclusion complexes with a variety of organic molecules, both in aqueous solution and in the solid state, provided that the cavity dimensions of the cyclodextrins and the size and the shape of the organic molecules are comparable [1]. While the extensive studies of cyclodextrin complexes in aqueous solution derive in part from their similarity to enzymatic systems [2], the growing interest in the utilization of cyclodextrin solid state complexes can be attributed to their promise as reaction media to induce novel chemistry or selectivity in chemical reactions [3]. In general, cyclodextrin solid state complexes can be prepared by precipitation from saturated cyclodextrin–water solutions containing the guest organic molecule. Such precipitates contain the guest accommodated within the cavity of the cyclodextrin, and are often characterized as polycrystalline inclusion complexes on the basis of X-ray powder diffraction patterns [4], solid state nuclear magnetic resonance (NMR) spectra [5], Fourier transform IR (FTIR) spectra [4], melting point [6], etc.

In the context of photochemistry, these solid complexes have received the most recent attention [3]. Our earlier investigations in conjunction with Ramamurthy's studies demonstrate that cyclodextrins play a significant role in controlling and modifying Norrish type I and type II reactions by imposing constraints on the conformations of guest molecules and on the translational and rotational motions of the photochemically generated intermediates [3, 6, 7]. In this connection, any spectroscopic studies directed towards the monitoring of the photochemical transients generated in the solid state cyclodextrin inclusion complexes will be of value in understanding the inclusion effects on photochemical reactions. In this report, we present a novel stabilization of benzylic

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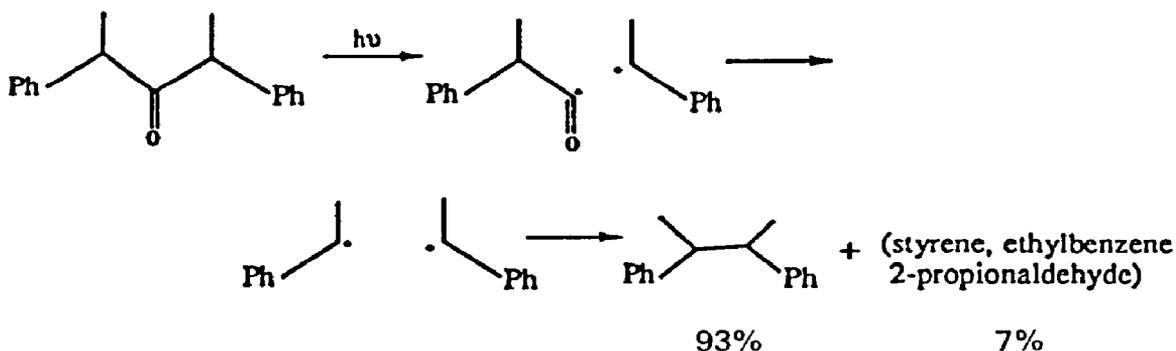
Scheme 1.

radicals generated photochemically from α,α'-dimethyldibenzyl ketone (DMDBK) adsorbed in a β-cyclodextrin cavity.

On excitation in organic solvents, DMDBK undergoes type I reaction from its triplet state to produce a geminate triplet radical pair [8]. This radical pair can undergo either recombination to give the starting ketone or decarbonylation to yield transient benzylic radicals which, in solution, undergo recombination to give a 1:1 mixture of 2,3-diphenylbutanes as major products (93%); the minor products (7%), styrene and ethylbenzene, result from the disproportionation process (Scheme 1). The objective of this study is to monitor these transient intermediates within the cyclodextrin inclusion complex.

2. Experimental details

2.1. Materials

β-Cyclodextrin (β-CD), obtained from Aldrich, was used after recrystallization from distilled water. A diastereomeric mixture of DMDBK was prepared by following a reported procedure [8]. Methylation at α and α' positions was carried out on dibenzylketone by generating a dianion with potassium hydride and butyl lithium, followed by quenching with two equivalents of methyl iodide. The meso and d,l isomers thus obtained were separated on a Whatman Magnum 9 ODS-3 high performance liquid chromatography (HPLC) column (9.0 cm × 50.0 cm, 15% water in methanol). The structures of the diastereomers were established from their spectral characteristics and by comparison with authentic samples. Their deuterated derivatives were also synthesized using the same procedure with deuterated methyl iodide in place of methyl iodide.

2.2. Preparation and characterization of solid β-CD–DMDBK complexes

To an aqueous saturated solution of β-CD (0.3 M) was added an equimolar amount of *meso*- or *d,l*-DMDBK. The solutions were magnetically stirred for 24 h at room temperature. The white precipitate that formed was filtered and dried at 50 °C for 5 h. These precipitated inclusion complexes were characterized by their melting points (m.p.) (*meso*-DMDBK–CD complex, m.p. 263 ± 1 °C; *d,l*-DMDBK–CD complex, m.p. 255 ± 1 °C) and solid state emission and excitation spectra. The host to guest ratio was determined by gas chromatography (GC) analysis. The amount of ketone present in a known amount of the complex was determined from integration of the peak with respect to the added internal standard (deoxy benzoin) and by weighing

the extracted ketone. The host to guest ratios thus calculated were in the range of 1:0.9–1.2.

2.3. Electron spin resonance (ESR) and solid state emission spectra

Electron spin resonance measurements of the degassed solid inclusion complexes were carried out using a Bruker 100D ESR X-band spectrometer interfaced with an IBM 9002 microcomputer. Irradiations in the ESR cavity were carried out with an Oriel 6141 1000 W Hg–Xe lamp with aqueous $NiSO_4$ or $CoSO_4$ filters. The emission and excitation spectra of the irradiated samples were obtained using a Spex-Fluorolog spectrophotometer with a datamate computer. Both emission and excitation spectra were collected using a front-face arrangement (45°).

2.4. Solid state photolysis and product analysis

Photolysis of microcrystalline inclusion complexes was carried out using a Hanovia 450 W medium pressure mercury arc lamp. Samples were degassed and irradiated for 1 h. Samples were rotated continuously during the irradiation to ensure uniform exposure. After photolysis, the irradiated complexes were dissolved in warm water and extracted with ether. The products of photolysis, meso and d,l-diphenylbutane (meso- and d,l-DPB), styrene, ethylbenzene and phenyl propionaldehyde, were analyzed by GC and were identified by comparison with the retention times of authentic samples.

3. Results and discussion

The addition of the meso or d,l isomers of DMDBK to saturated solutions of β-CD caused a white solid to precipitate. (Similar attempts to prepare complexes of DMDBK with α-CD failed to yield solid inclusion complexes; complex preparation with γ-CD was not attempted.) This solid was washed with an excess of water and dried at 50 °C to yield the solid inclusion complexes. The presence of DMDBK in the precipitated solid was confirmed by its solid state emission and excitation spectra (vide infra). Based on the sharp melting points of these precipitated solids (meso-DMDBK–CD complex, m.p. 263 ± 1 °C; d,l-DMDBK–CD complex, m.p. 255 ± 1 °C), in contrast with the uncomplexed β-CD which decomposes above 298–300 °C, it was inferred that the precipitated solids were true inclusion complexes and not simple mechanical mixtures [6]. The amount of guest present in a weighed sample of the complex was determined by GC using an internal standard after extracting the guest ketone with diethyl ether. An approximate 1:1 ketone to β-CD ratio was observed for both the meso- and d,l-DMDBK–CD complexes, consistent with a structure having one DMDBK molecule per CD cavity.

Irradiation of degassed, room temperature samples of the solid meso-DMDBK–CD complex with a 1000 W Xe–Hg lamp (aqueous $NiSO_4$ or $CoSO_4$ filter) in the ESR cavity leads to the stable ESR spectrum shown in Fig. 1(a). The ESR signal persists after the light is turned off and remains as long as oxygen is excluded. In the presence of oxygen, the signal slowly decays. Similar photolysis of the d,l-DMDBK–CD complex in the ESR cavity produces the ESR spectrum shown in Fig. 1(b). The ESR spectra produced from the d,l and meso isomer complexes are clearly different; that obtained from the d,l isomer complex seems to have more fine structure. Curiously, if the irradiated meso-DMDBK–CD complex is allowed to remain 3 days in the absence of oxygen, it begins to develop the fine structure evident in the irradiated d,l-DMDBK–CD complex spectrum (Fig. 1(c)). Irradiation of α,α'-di(trideuteromethyl)dibenzyl-
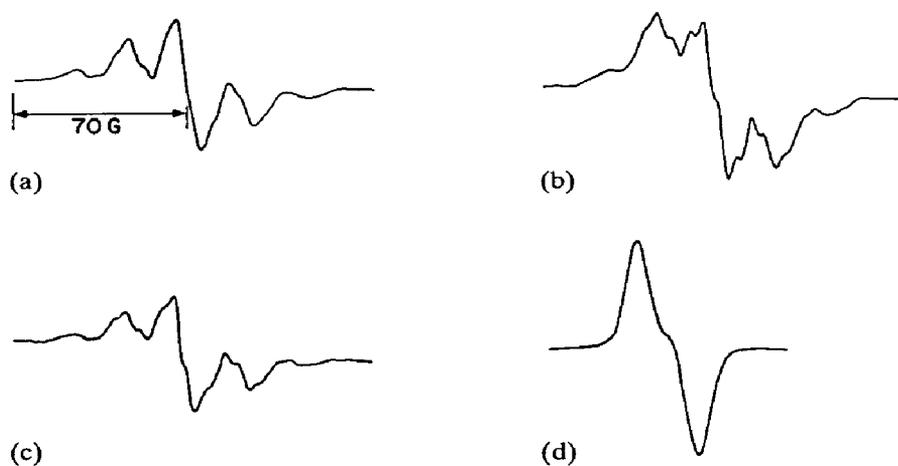
Fig. 1. ESR spectra of the irradiated DMDBK–β-CD complexes: (a) *meso*-DMDBK–CD; (b) *d,l*-DMDBK–CD; (c) *meso*-DMDBK–CD, spectrum recorded 72 h after irradiation; (d) *d,l*-di(trideuteromethyl)dibenzylketone–CD.

ketone–CD complexes produces the ESR spectrum shown in Fig. 1(d). The decreased spectral width and the absence of fine structure indicate that the methyl groups are strongly coupled to the unpaired electron. Assuming normal hyperfine interactions, this provides evidence that the radical detected derives from DMDBK and not β-CD. The difference between the ESR spectra of the *meso*- and *d,l*-DMDBK–CD complexes suggests a possible radical pair interaction. However, no half-field transition is observed for any of the irradiated samples. We interpret these spectra to indicate the presence of non-reacting benzylic radicals within the solid complexes.

Additional corroboration that benzylic radicals are present in the solid comes from emission and excitation studies (Fig. 2). From Fig. 2(a), it is evident that the emission spectrum before photolysis corresponds to the starting ketone DMDBK. It is also evident that the emission spectra of the inclusion complex before and after irradiation are clearly different. After irradiation with the Hg–Xe lamp (aqueous $NiSO_4$ or $CoSO_4$ filter), the emission spectrum exhibits new broad emissions centered at around 470 nm and 510 nm. These new emission bands are irreversibly quenched by exposure of the irradiated sample to oxygen, suggesting that the ground state of the emitting species reacts with oxygen. This observation is analogous to the ESR results described above. The excitation spectra, given in Fig. 2(b), demonstrate that the emission bands at 510 nm and 470 nm derive from a species which has an absorption maximum at 320 nm. After correcting and subtracting the excitation and emission spectral contributions due to the starting ketone, the resultant spectrum of the photoinduced species is shown in Fig. 2(c). These spectral features are highly characteristic of benzylic radicals reported in solution [9].

The most striking observation from the above results is that the transient benzylic radicals produced in the photolysis of DMDBK are stabilized by CD inclusion to such an extent that they can be characterized using steady state spectroscopic techniques at room temperature. At this juncture, it is important to compare our observations with those reported by Bartlett and McBride [10], Griller and coworkers [11] and Hollingsworth *et al.* [12]. In the photodecomposition of azo-diphenylbutanes, Bartlett and McBride observed stable ESR signals in the irradiated frozen benzene solution of azobis-2-phenyl-3-methylbutane at −196 °C. Assuming that the signal at half-field
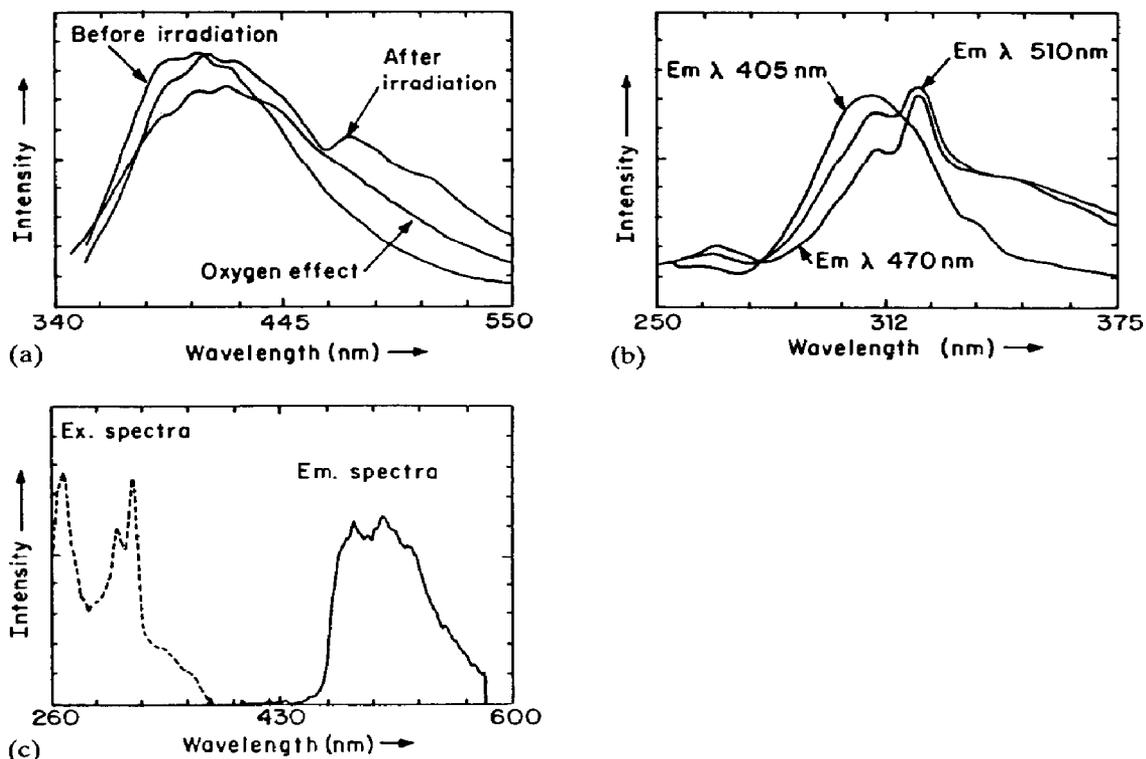
Fig. 2. Excitation and emission spectra of *meso*-DMDBK–CD complex in the solid state before and after irradiation: (a) emission spectra of the complex; (b) excitation of the complex; (c) excitation and emission spectra of the β-CD-stabilized α-methyl benzylic radical after correction.

corresponds to the transition with $\Delta M = 2$, they attributed the ESR signals to the triplet radical pair resulting from the photo-elimination of a nitrogen molecule. Griller and coworkers [11] and Hollingsworth *et al.* [12] have studied independently the photodecomposition of long-chain diacyl peroxides trapped in channels within urea clathrates and zeolites. ESR spectra of radical pairs of long-chain peroxides in single crystals of urea clathrates show that the alkyl radicals respond to the CO_2 stress field by recoiling along the channel. The rotational mobility and exceptional kinetic stability of the radicals can be attributed to relaxation of stress and the lack of a convenient escape pathway for the trapped carbon dioxide molecules. It is interesting to note that the photolysis of long-chain peroxides intercalated in silicate channels, yields isolated radicals, but not radical pairs, at temperatures down to 20 K.

In the irradiated DMDBK–CD complexes, the observed data strongly support the formation of unpaired benzylic free radicals, but not radical pairs, whose formation is expected from the mechanism of this photoreaction. In the absence of detailed structural information for the inclusion complex, we propose that the constraints imposed by the CD may be limited enough to allow at least a few radicals to diffuse apart, whereas the rest react. Interestingly, the benzylic radicals generated from structurally similar unsubstituted dibenzylketone–CD complexes are not seen in the ESR spectra. This result suggests that the stabilization of benzylic radicals in β-CD complexes is strongly dependent on the detailed structural features of the system.

To understand the fate of these benzylic radicals stabilized by CD inclusion, we dissolved the irradiated inclusion complex in excess water and extracted the photoproducts

from CD. (Irrespective of whether the irradiation is carried out within the ESR cavity or outside the cavity, the photoproducts and their relative ratios obtained from the solid inclusion complexes are the same.) The products observed from the photolysis of DMDBK–CD inclusion complexes are the same as those resulting from irradiation in isotropic solvents. However, the relative ratios of the observed photoproducts are different from the solution photolyses. Irradiation of the *meso*-DMDBK complex results in *d,l*-DPB and *meso*-DPB in the ratio of 3:1. Similar irradiation of the *d,l*-DMDBK complex yields a ratio of 2:1. This observation may be related to the time evolution of the *meso*-DMDBK–CD ESR spectrum (*vide supra*). However, it is unclear what fraction of DPB products are formed prior, during and after extraction of the solid. No products derived from oxygen trapping of the benzylic radicals, resulting from α cleavage, were observed. While the diastereoselectivity in DPB formation can be partially attributed to the rotational and diffusional constraints imposed on the benzylic radicals by β-CD, the chiral nature of β-CD may be the driving force for the preferred *d,l*-DPB formation.

Acknowledgments

References

1 J. L. Atwood, J. E. D. Davies and D. D. MacNicol (eds.), *Inclusion Compounds*, Vols. 1–3, Academic Press, London, 1984.
2 D. W. Griffiths and M. L. Bender, *Adv. Catal.*, *23* (1973) 209.
   I. Tabushi and Y. Kuroda, *Adv. Catal.*, *32* (1983) 417.
   M. L. Bender and M. Komiyama, *Cyclodextrin Chemistry*, Springer, Berlin, 1978.
3 V. Ramamurthy and D. F. Eaton, *Acc. Chem. Res.*, *21* (1988) 200.
4 D. L. Wernick, Z. Savion and J. Levy, *J. Incl. Phenom.*, *6* (1988) 483.
5 J. A. Ripmeester, *J. Incl. Phenom.*, *6* (1988) 31.
6 B. N. Rao, M. S. Syamala, N. J. Turro and V. Ramamurthy, *J. Org. Chem.*, *52* (1987) 5517.
7 V. P. Rao and N. J. Turro, *Tetrahedron Lett.*, (1989) 4641.
   V. P. Rao, N. Han and N. J. Turro, *Tetrahedron Lett.*, (1990) 835.
8 B. H. Baretz and N. J. Turro, *J. Am. Chem. Soc.*, *105* (1983) 1309.
9 K. Tokumura, M. Udagawa, T. Ozaki and M. Itoh, *Chem. Phys. Lett.*, *141* (1987) 558.
10 P. D. Bartlett and J. M. McBride, *Pure Appl. Chem.*, *15* (1967) 89.
11 H. L. Casal, D. Griller, F. W. Hartstock, R. Kolt, D. J. Northcott, J. M. Park and D. D. M. Wayner, *J. Phys. Chem.*, *91* (1987) 2235.
12 M. D. Hollingsworth, K. D. M. Harris, W. Jones and J. M. Thomas, *J. Incl. Phenom.*, *5* (1987) 273.