Hydrogen-bond quenching of photodecarbonylation in the solid state and recovery of reactivity by co-crystallization†‡

Jing Zhang, Milan Gembicky, Marc Messerschmidt and Philip Coppens*

Intermolecular H-bonding between C=O (ketone) and HO (4′-hydroxyphenyl) quenches photodecarbonylation of 2,2,4,4-tetramethyl-1,3-di(4′-hydroxyphenyl)acetone 1 in the crystalline solid state, its reactivity is recovered by co-crystallization with the small organic molecule 4,4′-bicyclohexanone.

It is well established that solid-state photochemical processes are strongly affected by the details of the packing arrangement of the reactants, which can be manipulated by crystal modification.[1–5] In the case of photodecarbonylation of β-substituted cyclohexanones, for example, the absence or presence of the reaction has been shown to depend on the molecular conformation imposed by crystal packing requirements.[6] Unlike in solution, the radicals or radical pairs generated by photo-induced σ-bond breaking (Norrish type-I reaction) can not easily separate in the reaction cavity in solids, so decarbonylation can not always compete with triplet to singlet ISC which allows recombination of the unpaired spins.[7] A series of careful studies of the topochemical conditions for these reactions have been reported.[8,9]

In the current work, we show that intermolecular H-bonding between C=O (ketone) and HO (4′-hydroxyphenyl) quenches photodecarbonylation of 2,2,4,4-tetramethyl-1,3-di(4′-hydroxyphenyl)acetone 1 (**HOTMK**, Scheme 1) in the crystalline solid state inhibits reaction, and how the reactivity can be recovered by co-crystallization with the small organic molecule 4,4′ -bicyclohexanone in **1a** (**HOTMK·BCH**), which eliminates the interaction responsible for the quenching.

We chose 1 (**HOTMK**, Scheme 1) as subject for photodecarbonylation, for (1) the similar electron donating ability of OH and *p*-OMe in 3 (**MeOTMK**, Scheme 1), which was reported to exhibit high reactivity in this reaction;[9] (2) its synthetic versatility; (3) its low pK_a and oxidation potential, and strong hydrogen bonding

abilities. The analogue 2 (**MonoOHTMK**, Scheme 1), which has 4-hydroxy- and 4′-methoxy-phenyl substituents, is prepared by monomethylation of 1 with MeI in acetone. Crystalline solids of 1, 2 and 3 are obtained by recrystallization in chloroform, a mixture of ether and hexane (1 : 1) and ethanol, respectively.§

Even after 3 h no photoreactivity is observed when a powder sample of 1 is irradiated with a focused 200 W medium-pressure mercury lamp at RT, whereas under the same conditions 2 and 3 give the decarbonylated products in 30 and >95% yields, respectively, although the substituents have similar electronic donating ability (the Hammett σ⁺$_{p-OH}$ and σ⁺$_{p-MeO}$ values are −0.40 and −0.27, respectively[10]) and are all in the *para* position. The crystal structures of 1 (Fig. 1(a)) and 2 (Fig. S1, ESI†). show that the difference in reactivity can be traced to an OH···O=C hydrogen bond to the carbonyl oxygen of 1 (O···O = 2.72 Å), which is absent in 2 (Fig. S1, ESI†), in which hydrogen bonded chains are formed by the hydroxyl groups and the solvated water molecules (Table S1, ESI†), and rare in benzylketones.[11] In 1 hydrogen bonding between the hydroxyl groups extends the H-bonded network into two dimensions (Fig. 1).

To the best of our knowledge, quenching of decarbonylation by C=O···H–O hydrogen bonding has never been examined in crystalline solids, although it is important for solid-state photochemistry. It is well known that in the liquid phase the lowest n, π* state of aromatic ketones is capable of inter- and intramolecular hydrogen abstraction from hydrocarbon, arene and alcohol

Scheme 1 Chemical structures of 1–3 (1: R$_1$ = R$_2$ = H, **HOTMK**; 2: R$_1$ = H, R$_2$ = Me, **MonoOHTMK**; 3: R$_1$ = R$_2$ = Me, **MeOTMK**).

Department of Chemistry, State University of New York at Buffalo, Buffalo, New York, 14260-3000, USA. E-mail: coppens@buffalo.edu; Fax: (716)645-6948

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‡ The HTML version of this article has been enhanced with colour images.

Fig. 1 Hydrogen bonding in the structure of 1 which "turns off" the photodecarbonylation. Selected interatomic distances (Å): O1(carbonyl O)···O3A(phenyl O) 2.72, O3A(phenyl O)···O2(phenyl O) 2.77.

H-donors.[12,13] In the case of substituted dibenzyl ketones hydrogen abstraction and photodecarbonylation can both occur.[12] It has been argued that stabilization of the n-orbital by H-bond formation to the carbonyl oxygen may lead to the non-reactive triplet p, p* state being lower in energy than the n, p* excited state.[14] To examine the nature of the excited state, absorption and emission spectra of 1–3 were recorded at 298 K (Fig. S3, ESI†) and at 77 K (Fig. S4, emission only, ESI†), using 350 nm light for excitation. The emission spectra of the three compounds are essentially identical. Corresponding excited state lifetimes are less than 200 ns for all three compounds. The similarity of the emission spectra and lifetimes indicates that no inversion of the n, π^* to π, π^* state energy levels occurs on hydrogen bonding. Evidence presented by Turro and co-workers indicates the hydrogen abstraction, which is very rapid, to occur from the excited singlet state.[12] In the confined space in the crystal the initial hydrogen abstraction may be reversed rapidly when the excited state decays, leading to the quenching of the α-cleavage reaction. Alternatively, the hydrogen bond to the carbonyl oxygen may interfere with escape of the CO group after initial α-cleavage leading to recombination of the geminate radical pairs.

To obtain additional evidence for the effect of C=O hydrogen bonding on the photo-reactivity we synthesized the related co-crystals **1a** and **2a** with 4,4′-biscyclohexanone (**HOTMK·BCH** and **2MonoHOTMK·BCH**, respectively). In neither of these, nor in the previously reported 2,2,4,4-tetramethyl-1,3-diarylacetones[9] is the keto group involved in hydrogen bonding, and all are reactive. Co-crystals **1a** contain linear chains of alternating **1** and 4,4′-biscyclohexanone molecules connected by hexanone C=O···H–O hydrogen bonds (Table S1, ESI†). No hydrogen bonding to the keto group of the diaryl ketone occurs (Fig. 2). 2 : 1 cocrystals **2a** of **2** with **BCH** showing similar C=O···H–O hydrogen bonding can also be grown (Fig. S2, ESI†). In the IR spectra carbonyl stretching frequencies of compounds **2**, **3**, **1a** and **2a** occur at 1679–1698 cm^{-1}, whereas for **1** they are shifted to 1659 cm^{-1} in accordance with the carbonyl hydrogen bonding observed in the crystal structure (Table S2, ESI†).

Irradiation of powdered samples for 60 min under the conditions described above yielded the decarbonylation products of **1a** and **2a** in yields of 60 and 69%, respectively. ^{1}H NMR analysis of **1a** dissolved in d^6-DMSO after different irradiation times exhibits a smooth progression upon increasing exposure (Fig. 3(a) and (b)). Small amounts of an unidentified side product
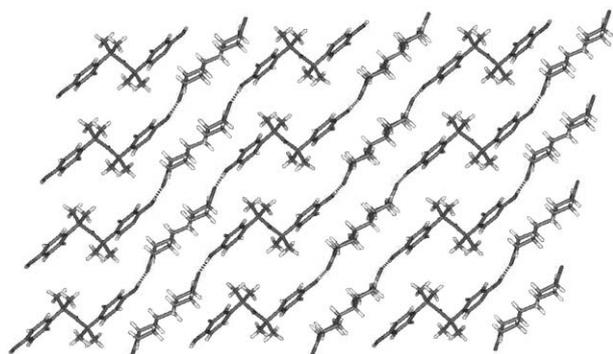
Fig. 2 Hydrogen bonding in the structure **1a**. Selected interatomic distances (Å): O2···O5A 2.74, O3···O4 2.76.
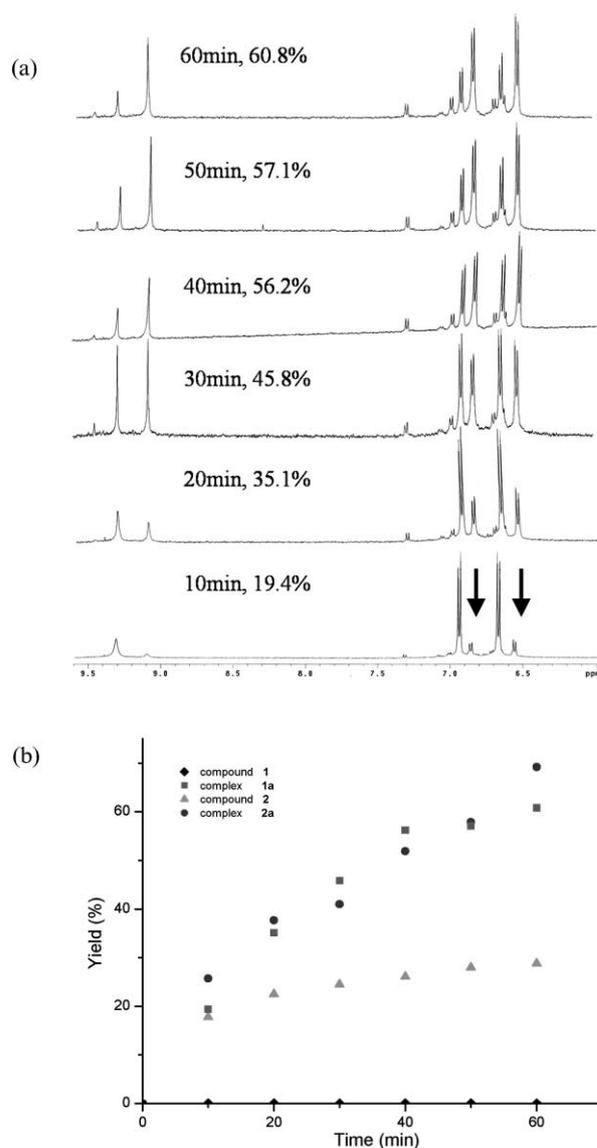
Fig. 3 (a) ^{1}H NMR of the phenyl group hydrogens in a d^6-DMSO (500 MHz) solution after room-temperature irradiation of crystalline powders of **1a** for different lengths of time. Arrows indicate photoinduced signals. (b) Product formation of **1**, **1a**, **2** and **2a** as a function of irradiation time.

were also detected (<5% of total products). The initial product formation shows a levelling-off attributed to degradation of the crystal quality. The product yield for **2a** is twice that of **2** indicating the effect of dilution of the active species in the solid state.

Irradiation of single crystals of **2** and **3** at 90 K leads to reaction, but in neither case is the crystal structure preserved on irradiation. However, when **1a** is irradiated for 30 min at 90 K, no decarbonylation occurs and the crystal integrity is maintained, although small (<+1% in *a* and *c*, +1° in *β*, Table S2, ESI†) but significant changes in the unit cell dimensions occur. Fourier difference maps subtracting the after- from the before-irradiation densities clearly show a molecular shift of part of the molecules (∼30%) along the chain direction (Fig. 4), which is quantified by least squares as 0.6 Å, and is accompanied by slight rotations of the phenyl rings. The observations were reproduced in several
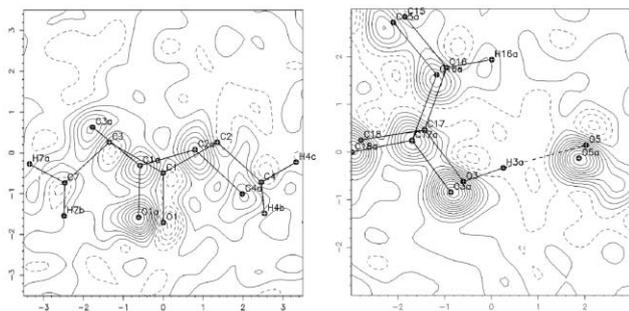
Fig. 4 (Left) Electron density change after 20 min exposure by 325 nm light of a crystal of **1a** (contour level 0.3 e Å^{-3}). Plane through the central atoms C1, C2, C3. The non-hydrogen atoms labelled 'a' belong to the displaced molecule. (Right) As left, in the intermolecular **HOTMK-BCH** H-bond region. Plane through the atoms C17, O3, O5.

successive experiments on different crystals. However when after exposure at 90 K the crystals were warmed to room temperature, the crystals did not remain transparent and turned into a white solid. Subsequent NMR analysis of a solution in d^6-DMSO indicates a low-concentration presence of the same products as obtained by room-temperature irradiation, *i.e.* that of combination of the secondary geminate pair (2,3-bis(*p*-hydroxyphenyl)-2,3-dimethylbutane), as well as a small amount of the unidentified side product. It is possible that these products are formed on or close to the surface of the crystal. The photoinduced structural changes in the crystals indicate that a photon-triggered process does occur, even though no changes were observed in atomic connectivity in the bulk of the crystals. Low-temperature EPR experiments would be most useful for further elucidation of these observations.

In summary, the evidence indicates that formation of an intermolecular H-bond between the carbonyl (C=O) and phenol (OH) groups of 2,2,4,4-tetramethyl-1,3-diarylacetone **1** in the solid state quenches the photodecarbonylation reaction. Chemical modification, such as substitution of one *p*-OH by *p*-OMe, leads to alternative crystal packing and allows the reaction to proceed. The reaction can also be turned on by co-crystallization with a hydrogen-bond acceptor such as 4,4′-biscyclohexanone, showing how solid-state reactivity can be manipulated by applying the methods of crystal engineering.

Notes and references

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