

## Photochemical Reduction of 1,2-Diketones in the Presence of TiO<sub>2</sub>

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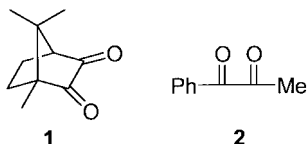
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1,2-Diketones, camphorquinone and 1-phenyl-1,2-propanedione, are converted to the corresponding  $\alpha$ -hydroxyketones in moderate to good yields by TiO<sub>2</sub>-catalyzed photochemical reactions in deoxygenated alcoholic media. The reduction yield for 1-phenyl-1,2-propanedione is considerably increased by addition of water or triethylamine

**Keywords :** Photoreduction, Titanium dioxide, 1,2-Diketone.

### Introduction

Photochemical reactions mediated by semiconducting particles have drawn a great amount of interest in solar energy conversion and storage,<sup>1</sup> photochemical clean-up of organic pollutants,<sup>2</sup> and functional group transformation of organic compounds.<sup>3</sup> TiO<sub>2</sub> is the most studied semiconductor due to its uv-vis absorption and chemical stability. Irradiation of TiO<sub>2</sub> promotes one electron from the valence band to the conduction band. A reactant that receives the electron from TiO<sub>2</sub> conduction band is reduced, while a reactant that donates an electron to the hole of TiO<sub>2</sub> valence band is oxidized. Though numerous examples of photo-oxidation of organic substrates catalyzed by TiO<sub>2</sub> have been reported, the photocatalytic reductions are less frequently encountered presumably due to low reducing power of the conduction electron. However, this makes the reduction process more selective and suitable for organic synthesis. The TiO<sub>2</sub>-catalyzed photochemical reduction of pyruvate to lactate,<sup>4</sup> organic nitro-<sup>5</sup> and nitroso-compounds<sup>6</sup> to amines, bis(2-dipyridyl)-disulfide to 2-mercaptopyridine,<sup>7</sup> and aldehydes to alcohols<sup>8</sup> have been reported. Here, we report the TiO<sub>2</sub>-catalyzed photochemical reduction of 1,2-diketones to  $\alpha$ -hydroxyketones. The 1,2-diketones used in this work are ( $\pm$ )-camphorquinone **1** and 1-phenyl-1,2-propanedione **2**, which are prototype 1,2-diketones and widely used as photosensitizers in photopolymerization reactions due to facile cleavage of the compounds by direct photochemical reactions.<sup>9</sup>



$\alpha$ -Hydroxyketones are versatile organic intermediates and a variety of methods have been developed for their preparation.<sup>10-16</sup> Non-photochemical reduction of 1,2-diketones to  $\alpha$ -hydroxyketones has been accomplished by various methods

such as baker's yeast,<sup>11</sup> carbonyl reductase,<sup>12</sup> Zn-salt-EtOH,<sup>13</sup> HI,<sup>14</sup> TiCl<sub>3</sub>,<sup>15</sup> and TiI<sub>4</sub>.<sup>16</sup> However, the search for an alternative method without the problem of over-reduction is still worthwhile. This work demonstrates that the photochemical reactions of 1,2-diketones in the presence of TiO<sub>2</sub> give the corresponding  $\alpha$ -hydroxyketones in moderate to good yields, while without the catalyst photoirradiation results in mostly decomposition products.

### Results and Discussion

The photochemical reactions of camphorquinone in the presence as well as in the absence of TiO<sub>2</sub> yield four isomeric ( $\pm$ )- $\alpha$ -hydroxycamphors, which exhibit different characteristic <sup>1</sup>H NMR peaks: the *CHOH* protons of 2-endo-, 2-exo-, 3-endo- and 3-exo-hydroxycamphor appear at  $\delta$  3.87 (s), 3.58 (s), 4.28 (d, *J* = 5 Hz), and 3.72 (s), respectively.<sup>10a,12,17</sup> The yield and ratio of each isomer were easily determined from the integration values of the corresponding peaks and were found to be comparable with those determined from <sup>1</sup>H NMR spectra of crude product mixture using the external standard. The results are summarized in Table 1.

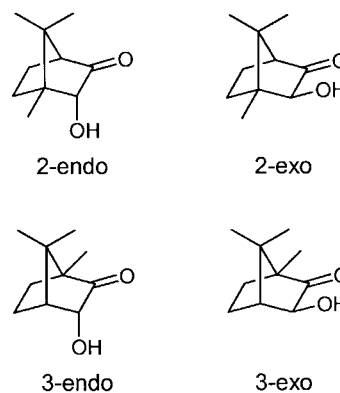


Table 1 shows clearly that camphorquinone has low photochemical reactivity in deoxygenated alcoholic media under direct irradiation and the yields of the reduction products are low (entry 1 and 2). This is consistent with an earlier report.<sup>18</sup> TiO<sub>2</sub> catalyzes the photochemical reduction

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**Table 1.** Product distribution obtained from photochemical reduction of ( $\pm$ )-camphorquinone (CPQ)<sup>a</sup>

Entry	Solvent	Reaction time, h	TiO <sub>2</sub>	Conversion of CPQ, %	Yields of $\alpha$ -hydroxycamphor, %				
					3-endo	2-endo	3-exo	2-exo	Total
1	CH <sub>3</sub> OH	24	no	91	9	12	2	1	24
2	4:1 CH <sub>3</sub> OH:H <sub>2</sub> O	24	no	93	17	18	2	1	38
3	CH <sub>3</sub> OH	2	yes	95	30	37	10	6	83
4	2-PrOH	2	yes	97	19	26	6	9	60
5	4:1 CH <sub>3</sub> OH:H <sub>2</sub> O	2	yes	100	46	35	1	2	84
6	9:1 2-PrOH:H <sub>2</sub> O	2	yes	98	37	34	1	1	73

<sup>a</sup>Yields were calculated from <sup>1</sup>H NMR spectra using the integral values of the corresponding -CHOH peaks of the isomeric  $\alpha$ -hydroxycamphors.<sup>17</sup>

**Table 2.** Product distribution obtained from photochemical reduction of 1-phenyl-1,2-propanedione(PPD)<sup>a</sup>

Entry	Solvent	Reaction time, h	TiO <sub>2</sub> /TEA <sup>b</sup>	Conv. of PPD, %	Yields of products, %					
					3 <sup>c</sup>	4 <sup>c</sup>	5 <sup>c</sup>	6 <sup>c</sup>	7 <sup>c</sup>	6+7
1	CH <sub>3</sub> OH	3	none	95	33	11	7	1	<sup>d</sup>	1
2	9:1 CH <sub>3</sub> OH:H <sub>2</sub> O	3	none	94	22	5	16	1	<sup>d</sup>	1
3	CH <sub>3</sub> OH	2	TEA	85	52	5	<sup>d</sup>	7	<sup>d</sup>	7
4	CH <sub>3</sub> OH	2	TiO <sub>2</sub>	82	13	2	14	16	3	19
5	9:1 CH <sub>3</sub> OH:H <sub>2</sub> O	2	TiO <sub>2</sub>	95	8	1	7	45	6	51
6	CH <sub>3</sub> OH	2	TiO <sub>2</sub> /TEA <sup>b</sup>	94	<sup>d</sup>	<sup>d</sup>	<sup>d</sup>	56	4	60

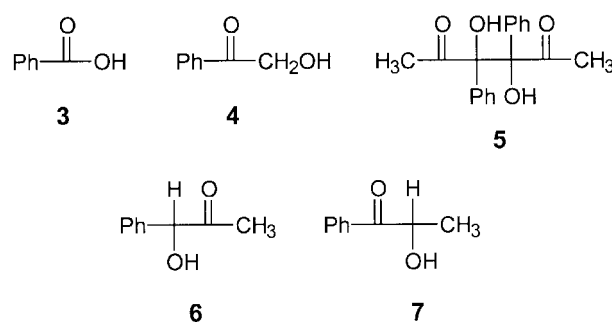
<sup>a</sup>Yields were calculated from <sup>1</sup>H NMR spectra using the integral values of the corresponding peaks of each product. <sup>b</sup>Concentration of TEA (triethylamine) was 0.5 M. <sup>c</sup>3, benzoic acid; 4, 2-hydroxyacetophenone; 5, 3,4-dihydroxy-3,4-diphenyl-2,5-hexanedione; 6, 1-hydroxy-1-phenyl-2-propanone; 7, 2-hydroxy-1-phenyl-1-propanone. <sup>d</sup>not detected in NMR spectra.

of camphorquinone: the presence of TiO<sub>2</sub> not only speeds up the reaction, but also increases the yields of  $\alpha$ -hydroxycamphors 2-4 fold. The Table also indicates that endo-hydroxycamphors are formed much more favorably than exo products, but there is little selectivity between 2 and 3 positions. Methanol solvent gives better yields of  $\alpha$ -hydroxycamphor than isopropanol. The addition of water increases the photochemical reactivity of camphorquinone and the yields of reduction products for both direct and TiO<sub>2</sub>-catalyzed photochemical reactions of the diketone.

The easy access to endo- $\alpha$ -hydroxycamphor adds some value to the photocatalytic reduction of camphorquinone. When carbonyl group of the 7,7-dimethyl-bicyclo[2.2.1]-heptane ring system is reduced with hydride-type reducing agent such as NaBH<sub>4</sub>,<sup>18</sup> the exo-alcohol is usually obtained as a major product, due to the steric effect of 7-methyl group.

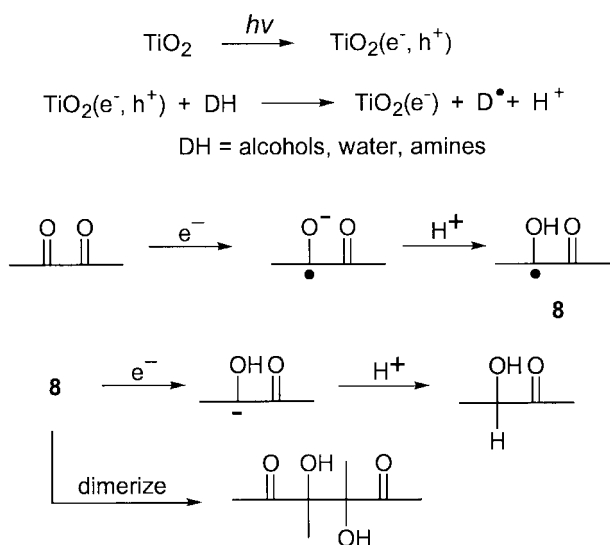
Photoirradiation of 1-phenyl-1,2-propanedione **2** was found to produce a mixture of benzoic acid (**3**), 2-hydroxyacetophenone (**4**), 3,4-dihydroxy-3,4-diphenyl-2,5-hexanedione (**5**), 1-hydroxy-1-phenyl-2-propanone (**6**), and 2-hydroxy-1-phenyl-1-propanone (**7**). Each product, **3-7** was separated from the reaction mixture and characterized firmly by comparison with authentic sample and/or <sup>1</sup>H NMR spectra and elemental analysis. The yields for the photochemical reduction of 1-phenyl-1,2-propanedione **2** under various conditions are summarized in Table 2.

It is evident from Table 2 that in the absence of TiO<sub>2</sub> photocleavage of 1-phenyl-1,2-propanedione leading to the formation of **3** and **4** is the main pathway and the reduction to  $\alpha$ -hydroxyketones **6-7** is almost negligible. Addition of



water depressed the photodecomposition both in the presence and absence of TiO<sub>2</sub>, which was also observed in the photoirradiation of camphorquinone **1**. The best yield of  $\alpha$ -hydroxyketones **6-7** was obtained in the presence of TiO<sub>2</sub> in methanol containing 0.5 M triethylamine (TEA). The high preference for 1-hydroxy-1-phenyl-2-propanone **6** over 2-hydroxy-1-phenyl-1-propanone **7** is noteworthy: the regioselectivity of 14 : 1 was obtained in TiO<sub>2</sub>-catalyzed photo-reaction in methanol/TEA medium. The selectivity for **6** is much higher than that reported in the chemical reduction of **2** by Zn-salt-EtOH,<sup>13</sup> HI,<sup>14</sup> or TiCl<sub>3</sub>.<sup>15</sup> The reduction of **2** with baker's yeast<sup>11b-d</sup> or TiI<sub>4</sub><sup>16</sup> was reported to give **7** as a major product.

To check the possibility of further reduction of  $\alpha$ -hydroxyketones,  $\alpha$ -hydroxycamphors, 1-hydroxy-1-phenyl-2-propanone **6**, and 2-hydroxy-1-phenyl-1-propanone **7** were subjected to the TiO<sub>2</sub>-catalyzed photochemical reduction: most of the starting materials were recovered and the corresponding diol products were not detected. This indicates that the reduction potential of the  $\alpha$ -hydroxyketones is well above the conduc-



**Scheme 1.**  $\text{TiO}_2$ -catalyzed photochemical reduction of 1,2-diketone. The electrons ( $e^-$ ) are provided from conduction electron of hole-trapped.

tion band energy of  $\text{TiO}_2$ , (-0.85 eV vs SCE).<sup>20</sup>

Based on the data in Table 1 and 2, we can speculate the mechanism for the photochemical reaction of 1,2-diketones (Scheme 1).

In the presence of  $\text{TiO}_2$ , most of irradiated light is absorbed by  $\text{TiO}_2$ , generating conduction electron ( $e^-$ ) and hole ( $h^+$ ) pair. Alcohols, water, and amines (abbreviated as DH) are good electron donors and trap holes giving surface-bound  $\text{D}^\bullet$  radical and adsorbed proton, and thus prevent electron-hole recombination.<sup>3a</sup> The reduction of 1,2-diketone proceeds *via* single conduction electron transfer followed by proton transfer giving ketyl radical **8**. Further reduction of the radical **8** to  $\alpha$ -hydroxyketone by another electron-proton transfer competes with the dimerization. Because of molecular geometry, the ketyl radical from camphorquinone **1** is hard to dimerize. Apparently, water and TEA suppresses the dimerization, presumably because they are better hole scavengers than alcohols.<sup>21</sup>

For direct photochemical reaction, it is believed that the triplet state of the diketones is involved in the reaction. The triplet state either undergoes the homolytic cleavage of C-C bond between the two carbonyl groups or abstracts hydrogen atom from solvent forming ketyl radical which dimerizes or transforms to  $\alpha$ -hydroxyketone through another hydrogen atom abstraction.

In conclusion, the photochemical reduction of camphorquinone and 1-phenyl-1,2-propanedione in the presence of  $\text{TiO}_2$  gives  $\alpha$ -hydroxycarbonyl compounds in moderate to good yields. The photoreduction provides a mild and convenient method for preparation of endo- $\alpha$ -hydroxycamphor and 1-hydroxy-1-phenyl-2-propanone from the respective starting materials. This work also demonstrates a promise for developing selective and environmentally friendly processes for the transformation of organic compounds using  $\text{TiO}_2$  as a photocatalyst.

## Experimental Section

**Photochemical Reactions of 1 and 2.** A reaction mixture of 0.200 g of diketone with or without 0.100 g of  $\text{TiO}_2$  (Degussa P-25) in 50 mL of appropriate solvent was added into a water-jacketed 25  $\times$  500 mm Pyrex vessel and was irradiated with 350 nm mercury lamp using RPR-100 photochemical reactor. The solution was continuously purged with  $\text{N}_2$  gas and 28  $^\circ\text{C}$  water was circulated through the jacket. After the reaction,  $\text{TiO}_2$  was removed by centrifuge, the solvent was evaporated off under reduced pressure and the residue was vacuum-dried to give crude products. A certain amount of the crude product was dissolved in  $\text{CDCl}_3$  together with a specific amount of an external standard, benzophenone for **1** and 4-methoxybenzophenone for **2**, and  $^1\text{H}$  NMR spectra were taken. Based on the peak integration and the added amount of the standard material, the yield and molar ratio of the products were determined.

**Purification of Photoreaction Products of 1.** The crude solid residue obtained from the photoirradiation of camphorquinone **1** was subjected to column chromatography eluting with 3 : 2 *n*-hexane : ethyl acetate to provide a mixture of isomeric ( $\pm$ )- $\alpha$ -hydroxycamphors separated from the unreacted starting material and other byproducts. The four isomeric  $\alpha$ -hydroxycamphors were identified from different characteristic  $^1\text{H}$  NMR peaks of the  $-\text{CHOH}$  protons,<sup>10a,12,17</sup> and their molar ratios were determined from the integral values of the corresponding peaks.

**Separation and Identification of Photoreaction Products of 2.** The crude residue of the reaction product of **2** was treated with methanol, and undissolved material was filtered, and then recrystallized from methanol to give 3,4-dihydroxy-3,4-diphenyl-2,5-hexanedione **5**. The filtrate obtained from the treatment of the crude residue with methanol was concentrated to dryness and was triturated with hot hexane. Filtration of the undissolved material followed by recrystallization yielded benzoic acid **3**. The hexane filtrate was concentrated and subjected to silica gel column chromatography eluting with 9 : 1 chloroform : ethyl acetate to get 2-hydroxyacetophenone **4**, 1-hydroxy-1-phenyl-2-propanone **6**,<sup>10c</sup> and 2-hydroxy-1-phenyl-1-propanone **7**<sup>10c</sup> as separate fractions.

Data for **5**: mp 126-128  $^\circ\text{C}$ ;  $^1\text{H}$  NMR ( $\text{CDCl}_3$ , 250 MHz)  $\delta$  2.26 (s, 3H,  $\text{CH}_3$ ), 5.50 (s, 1H, OH, exchangeable with  $\text{D}_2\text{O}$ ), 6.96-7.23 (m, 5H, Ph); MS (EI)  $m/z$  255 ( $\text{M}-\text{CH}_3\text{CO}$ )<sup>+</sup>. Anal. Calcd for  $\text{C}_{18}\text{H}_{18}\text{O}_4$ : C, 72.47; H, 6.08. Found: C, 72.24; H, 6.16.

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