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## Heterogeneous Photocatalytic Oxidation of Hydrocarbons on Platinized TiO<sub>2</sub> Powders

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The photodecomposition of hydrocarbons in oxygen-containing solutions at platinized TiO<sub>2</sub> yields predominantly CO<sub>2</sub> as the reaction product, with intermediate production of hydroxylated compounds. A mechanism for the reaction based on photogeneration of hydroxyl radicals at the TiO<sub>2</sub> surface is proposed.

### Introduction

Recent investigations from this laboratory have described the application of platinized titanium dioxide powders (Pt/TiO<sub>2</sub>) to heterogeneous photocatalytic and photosynthetic processes, such as the photo-Kolbe reaction, in which aliphatic mono-<sup>1</sup> and dicarboxylic<sup>2</sup> acids are decomposed to give the corresponding alkane as the main product, as well as other reactions.<sup>3</sup> These investigations have clearly demonstrated the usefulness of Pt/TiO<sub>2</sub> in photoelectrochemical experiments and the potential for accomplishing reactions requiring highly oxidizing conditions. In previous works we found that the decarboxylation of benzoic acid at Pt/TiO<sub>2</sub> involved the preceding hydroxylation of the benzene ring to form hydroxylated benzoates as reaction intermediates.<sup>2</sup> However, the main product of this reaction was CO<sub>2</sub>, suggesting that photodecomposition of hydrocarbon intermediates was possible. Thus in this paper we extend these studies to the photocatalyzed decomposition of hydrocarbons at Pt/TiO<sub>2</sub>. Phenol is shown to be a reaction intermediate for the photodecomposition of benzene, with the final product CO<sub>2</sub>. This unusual and efficient photocatalyzed breakdown of benzene at room temperature to yield CO<sub>2</sub> thus provides a possible pathway in the decarboxylation mechanism proposed for the photooxidation of benzoic acid.<sup>2</sup> We also describe the photodecomposition of several aliphatic hydrocarbons, in which alcohols have been detected as intermediates.

### Experimental Section

**Materials.** Benzene (reagent grade, Matheson Coleman and Bell (MCB)), hexane (MCB, 99+ mol %), cyclohexane (spectrophotometric grade, MCB), heptane (reagent grade, Eastman), nonane and decane (Fisher Certified), barium hydroxide (reagent grade, MCB), and phenol (reagent grade, Fisher) were used without further purification. Decanol, nonanol, heptanol, hexanol, and cyclohexanol (reagent grade, Eastman) were used as received for standards in GC-mass spectroscopic analysis. The kerosene was extracted repeatedly with distilled water before illumination to simplify subsequent analysis of the aqueous phase. All solvents and other chemicals were reagent or spectrophotometric grade and were used without further purification. The platinized TiO<sub>2</sub> powders were prepared by photodecomposition of hexachloroplatinic acid onto TiO<sub>2</sub> powders (reagent grade, MCB, 125-250 μm) and contained 10% platinum by weight.<sup>4</sup>

**Apparatus.** The irradiation source for the photodecomposition of aliphatic hydrocarbons was an Atlas Weatherometer, Model 6000, equipped with a 6000-W Xe lamp. The described experiments were performed at an unfocused power output of 5000 W, which corresponds to a total radiant intensity of ~35 mW/cm<sup>2</sup> at the location of the reaction cell. The Xe lamp was jacketed with a water cooling cell to remove infrared irradiation. A constant reaction temperature was maintained with a large water bath fitted with a coil for water cooling. A 2500-W

TABLE I: Photocatalytic Oxidation of Benzene on Platinized Anatase or Anatase Powders<sup>a</sup>

expt no.	catalyst	time of illumination, h	conditions	CO <sub>2</sub> generated, mmol	phenol generated, mmol
1	10% platinized anatase	4	illuminated, O <sub>2</sub> saturated	0.13	0.10
2	10% platinized anatase	18.5	illuminated, O <sub>2</sub> saturated	0.72	0.41
3	10% platinized anatase	40	illuminated, O <sub>2</sub> saturated	1.85	
4	none	72	illuminated, O <sub>2</sub> saturated	0.03	
5 <sup>b</sup>	10% platinized anatase	19	illuminated, O <sub>2</sub>	0.10	
6	10% platinized anatase	43	illuminated, deoxygenated	0.15	
7	anatase	14	illuminated, O <sub>2</sub> saturated	0.38	

<sup>a</sup> If not otherwise mentioned, the solution was composed of 5 mL of benzene suspended in 20 mL of H<sub>2</sub>O; 100 mg of catalyst was employed. <sup>b</sup> Benzene (25 mL) was used as the reacting solution.

Xe lamp (Model UF 30 KK, Christie Electric Corp., Los Angeles, CA) operated at 1600 W was used as the light source for all preparative runs in the photodecomposition of benzene. The reaction cell with a flat window for irradiation and the water bath were both of Pyrex. A 450-W Xe lamp with Model 6242 power supply (Oriental Corp., Stamford, CT) served in the photoelectrochemical measurements. Mass of GC-mass spectra of reaction gases were obtained with an automated gas chromatograph/EI-CI mass spectrometer system (Finnigan, Model 2000). UV-visible spectra were recorded with a Cary Model 14 spectrophotometer. Electrochemical experiments were performed by using a PAR Model 173 potentiostat (Princeton Applied Research, Princeton, NJ) and a PAR Model 173 universal programmer.

**Product Analysis. Aliphatic Hydrocarbons.** In a typical experiment, 200 mg of the photocatalyst powder was suspended by magnetic stirring in a two-phase system composed of 5 mL of water and 5 mL of the hydrocarbon. The reaction cell was maintained at  $36 \pm 1$  °C. The sweep gas, N<sub>2</sub> or O<sub>2</sub>, was first passed through Ba(OH)<sub>2</sub> to remove any traces of CO<sub>2</sub> in the cylinder gas and then into the reaction cell. The gas was then passed through a large-volume cell cooled at -56 °C to condense volatile organic chemicals and then into a Ba(OH)<sub>2</sub> solution for determination of CO<sub>2</sub> as precipitated BaCO<sub>3</sub>. Solar experiments were conducted in a Pyrex flask with a liquid surface area of ~700 cm<sup>2</sup> by using 1.0 g of the photocatalyst. The condensed volatile organic chemicals were analyzed by a GC-mass spectrometer. For hydrocarbon analysis, the columns used were a 6-m capillary of OVI and a 36-cm OVI column. Relative concentrations of trace impurities were compared by intergration of ion current peaks and calibrated with standard samples. Investigation of the more polar constituents was performed with a Carbowax column. Identification of intermediate products was based on comparison of retention times and mass spectra of sample and standards. A detection limit of 2 ppm (equivalent to ~12 μM) was established for heptanol under these conditions.

The gas products not condensed at -56 °C were collected in a gas buret and were analyzed by a mass or GC-mass spectrometer.

**Fenton's Reagent Reaction of Heptane.** Five milliliters of heptane suspended in 100 mL of 0.64 M FeSO<sub>4</sub> was purged with N<sub>2</sub> to remove CO<sub>2</sub>. H<sub>2</sub>O<sub>2</sub> (5 mL) was added while the system was swept with N<sub>2</sub>. After 12 h, an additional 3 mL of H<sub>2</sub>O<sub>2</sub> was added to ensure complete reaction. The evolved CO<sub>2</sub> was precipitated as BaCO<sub>3</sub> from a saturated Ba(OH)<sub>2</sub> solution.

**Benzene.** In a Pyrex cell, a stirred suspension of 100 mg of Pt/TiO<sub>2</sub> in an emulsion of 5 mL of benzene and 20 mL of distilled water held at  $27 \pm 1$  °C was illuminated under oxygen with white light from a 2500-W Xe lamp (operated at 1600 W). The gases produced during the irradiation

were collected in a mercury-containing gas volumetric apparatus, as reported previously.<sup>1</sup> After termination of photolysis, the mixture in the gas buret was transferred to an evacuated gas sample cell which attached to the mass spectrometer for gas analysis. The average rate of CO<sub>2</sub> evolution was determined gravimetrically in another preparative run. The reaction gases were swept out of the reaction vessel with a stream of oxygen and were bubbled through a saturated solution of Ba(OH)<sub>2</sub> in 0.2 M sodium hydroxide. The precipitated BaCO<sub>3</sub> was filtered off, washed with distilled water, dried at 120 °C, and weighed. The colorless reaction mixture after filtering off the photocatalyst powders was analyzed by UV-visible absorption.

## Results

**Photocatalytic Decomposition of Benzene on Platinized TiO<sub>2</sub> Powders.** Illumination of suspensions of platinized TiO<sub>2</sub> powders in aqueous benzene mixtures in the presence of oxygen produced observable evolution of gaseous CO<sub>2</sub>. After illumination, the gaseous products were analyzed by mass spectrometry. The mass spectra (*m/e* (relative intensity)) consisted of signals of CO<sub>2</sub> (44 (44.9) and 16 (11.5)) with background signals due to O<sub>2</sub> (32 (100)), N<sub>2</sub> (28 (28)), benzene (78 (12)), and water (18 (5)). Thus the only significant gaseous product of photooxidation of benzene in water was CO<sub>2</sub>. The yield of CO<sub>2</sub> determined gravimetrically in another series of experiments is shown in Table I. The UV spectrum of the colorless reaction mixture showed absorption maxima at 2390, 2720, and 2780 Å with a shoulder at 2670 Å. The product was identified as phenol by comparing its UV spectrum with that of a standard phenol solution. The concentration of phenol given in Table I was determined by UV spectroscopy. The results of some control experiments are also summarized in Table I. As shown in experiment 4, the photodecomposition of benzene requires the presence of catalyst. Platinized anatase has a higher efficiency than plain anatase powder (see experiments 2 and 7). The results shown in experiments 3 and 6 show that the presence of oxygen promotes the photodecomposition of benzene. Particularly interesting, the addition of water, compared to a system containing only benzene, promotes the photodecomposition of benzene (see experiments 2 and 5). As shown in experiments 1 and 2, substantial amounts of phenol were isolated as an intermediate product. These results suggest that the photooxidation of benzene on platinized TiO<sub>2</sub> powders suspended in H<sub>2</sub>O probably proceeds via the hydroxylation of benzene to form phenols as the intermediate.<sup>5,6</sup> Moreover, the results are different from those for the electrolysis of aqueous benzene solutions in which *p*-benzoquinone is the predominant product.<sup>7-9</sup> No *p*-benzoquinone or *p*-hydroquinone was obtained in the present experiments.

**Photocatalytic Decomposition of Aliphatic Hydrocarbons on Pt/TiO<sub>2</sub> Powders.** Illumination of a suspension

TABLE II: Photocatalytic Oxidation of Aliphatic Hydrocarbons on Platinized Anatase Powders

alkane	powder wt, g	time of illumination, h	CO <sub>2</sub> production rate, $\mu\text{mol/h}$	oxidation rate, $\mu\text{mol/h}$	alcohol generated, $\mu\text{mol}$
hexane	0.199	24	53.7	8.95	
	0.200	12	30.9	5.2	0.55
	0.200	24	65.2	10.9	
cyclohexane	0.200	24	86.4	14.4	$6 \times 10^{-5}$
	0.200	48	60.4	8.6	0.650
heptane	0.201	24	61.1	8.7	
	0.201	24	45.3	6.5	
	0.0 <sup>a</sup>	18	14.4	2.1	
	0.200	24	41.4	4.6	0.220
nonane	0.200	46	65.6	7.3	
	1.430 <sup>b</sup>	24	54.6	6.1	
	0.200	67	14.8	1.5	
decane	0.201	291	34.1	3.4	0.105
	0.0 <sup>c</sup>	30	0.0	0.0	
	0.200 <sup>d</sup>	24	0.0	0.0	
	0.200 <sup>e</sup>	6	75.0	7.5	
kerosene	0.200	72	17.2		

<sup>a</sup> Performed with Fenton's reagent; see Experimental Section. <sup>b</sup> Solar experiment. <sup>c</sup> Control experiment, no catalyst added. <sup>d</sup> N<sub>2</sub> substituted for O<sub>2</sub>. <sup>e</sup> Emulsifying agent added (0.25 mL of Igepal-560).

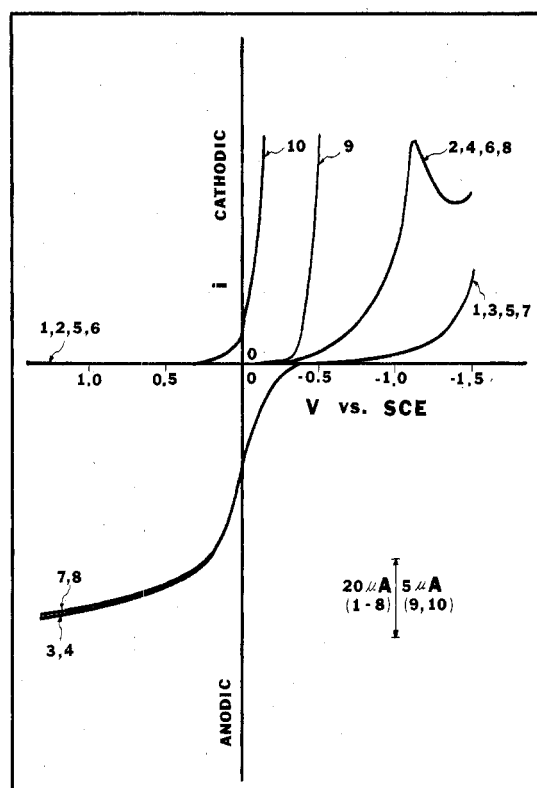
of Pt/TiO<sub>2</sub> in aqueous aliphatic hydrocarbon mixtures in the presence of oxygen also leads to the observable evolution of CO<sub>2</sub>. The yields of CO<sub>2</sub>, which was the only significant gaseous product (not condensed at -56 °C), are shown in Table II.

Extensive analysis for intermediates revealed a detectable level of only the alcohols (see Table II), except in the case of decane, where trace amounts of 2-, 4-, and 5-decanone were identified. The concentrations of lower molecular weight hydrocarbon impurities remained essentially unchanged before and after reaction, demonstrating that the cleavage of the alkanes does not result in the formation of shorter-chain hydrocarbons.

The reduction in the rate of photocatalytic oxidation with increasing molecular weight is coincident with an increase in the viscosity of the hydrocarbons. An exception to this trend is cyclohexane; however, in this case an emulsion of the three phases (photocatalyst powder, H<sub>2</sub>O, and hydrocarbon) occurs. Addition of an emulsifying agent, Igepal-560 (nonionic nonylphenoxypoly(oxyethyleneethanol), GAF Corp.) to a suspension of decane was found to increase the rate of CO<sub>2</sub> production from 34.0 to 75.0  $\mu\text{mol/h}$ , confirming that the enhanced rate for cyclohexane oxidation is probably due to improved phase mixing.

The reaction between heptane and Fenton's reagent, which produces hydroxyl radicals, also produced a considerable amount of CO<sub>2</sub> (Table II). This demonstrates the possibility that, at least in the initial stages of the photodecomposition process, the attack of  $\cdot\text{OH}$  on hydrocarbons and intermediates occurs.

**Electrochemical and Photoelectrochemical Measurements.** The photocatalytic activities of suspended platinized anatase powders were correlated with the behavior of TiO<sub>2</sub> single crystal electrodes in photoelectrochemical (PEC) measurements as shown in Figure 1. The current-potential behavior of a rutile single crystal electrode was examined in an aqueous solution containing 1 M NaClO<sub>4</sub> as the supporting electrolyte. In the dark, only a very small anodic current was observed on a TiO<sub>2</sub> electrode both in deoxygenated and oxygen-saturated solutions, with or without benzene. In oxygen-saturated solution, however, the TiO<sub>2</sub> electrodes showed a reduction peak at -1.16 V vs. SCE (curve 2); this peak can be attributed to the reduction of oxygen, since it disappeared when the solution was thoroughly deoxygenated (curve 1).



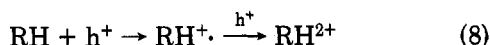
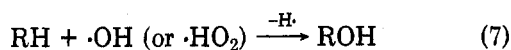
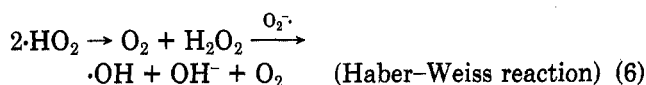
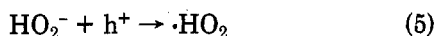
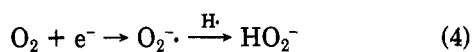
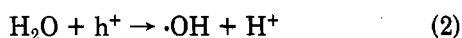
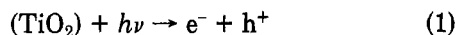
**Figure 1.** Voltammetric curves at platinum and single crystal rutile electrodes in solution containing 1 M NaClO<sub>4</sub> as the supporting electrolyte. Scan rate, 100 mV/s. Initial potential at the positive extremes. Curve 1: In the dark; on TiO<sub>2</sub>; under N<sub>2</sub>; solution without containing benzene. Curve 2: In the dark; on TiO<sub>2</sub>; oxygen saturated; without benzene. Curve 3: Under illumination; on TiO<sub>2</sub>; under N<sub>2</sub>; without benzene. Curve 4: Under illumination; on TiO<sub>2</sub>; under O<sub>2</sub>; without benzene. Curve 5: In the dark; on TiO<sub>2</sub>; under N<sub>2</sub>; benzene-saturated solution. Curve 6: In the dark; on TiO<sub>2</sub>; oxygen- and benzene-saturated solution. Curve 7: Under irradiation; on TiO<sub>2</sub>; under N<sub>2</sub>; benzene-saturated solution. Curve 8: Under irradiation; on TiO<sub>2</sub>; oxygen- and benzene-saturated solution. Curve 9: On Pt; under N<sub>2</sub>; benzene saturated. Curve 10: On Pt; oxygen and benzene saturated.

These voltammetric curves were essentially unaffected by saturating the solution with benzene (curves 5 and 6). Under illumination, an appreciable anodic current was observed. The onset photopotential,  $V_{\text{on}}$  was essentially unaffected by the presence of oxygen or benzene and was -0.35 V vs. SCE for all cases. The presence of oxygen did

not change the magnitude of the photocurrent; however, the presence of benzene caused a slight reduction in the photocurrent (curves 7 and 8), probably due to the absorption of some of the incident light by benzene and phenols generated. On the other hand, proton reduction on a platinum electrode in the presence of benzene occurred at potentials more negative than  $-0.4$  V vs. SCE (curve 9). However, oxygen reduction on platinum occurred at potentials much more positive than either the onset photopotential or the reduction potential of oxygen on  $\text{TiO}_2$  (curve 10). Thus, the presence of platinum on the  $\text{TiO}_2$  powder could promote the photocatalytic activity of  $\text{TiO}_2$  compared to  $\text{TiO}_2$  alone. Also, the photocatalytic activity of platinized  $\text{TiO}_2$  powder would be substantially enhanced by the presence of oxygen. These results at a rutile electrode are thus qualitatively consistent with the powder results. The role of oxygen in PEC and the accompanying photocatalytic reactions on  $\text{TiO}_2$  have also been demonstrated by Korsunovskii.<sup>10</sup>

### Discussion

In the presence of oxygen, several n-type semiconductor powders have been shown to behave as photocatalysts and promote the oxidation of substrates. Irradiation of a semiconductor with light of energy higher than the band gap results in the creation of holes in the valence band and electrons in the conduction band of the semiconductor. These charge carriers can recombine, or the holes can be scavenged by oxidizable species (for example,  $\text{H}_2\text{O}$ ,  $\text{H}_2\text{O}_2$ , or hydrocarbons (RH)), and electrons by reducible species (for example,  $\text{O}_2$  or  $\text{H}^+$ ) in the solution.



The electrochemical and photoelectrochemical measurements suggest that the reduction of  $\text{H}^+$  on Pt and the reduction of  $\text{O}_2$  on  $\text{TiO}_2$  do not occur at an appreciable rate at the potentials where significant anodic photocurrent on  $\text{TiO}_2$  is observed. However, the reduction of  $\text{O}_2$  on Pt occurs at these potentials, and this represents a viable half-reaction at the photocatalyst particle. The role of the Pt for this reaction is thus to provide a site for the more efficient utilization of the photogenerated electrons in the reduction of  $\text{O}_2$  (e.g., eq 4), in agreement with the finding that the photooxidation of hydrocarbons in deoxygenated solutions does not occur to an appreciable extent (Tables I and II). It is also possible that intermediates formed during the reduction of  $\text{O}_2$  play an important role in the oxidation process, as suggested by reactions 4–6. Recent experiments involving spin trapping and electron spin

resonance spectroscopic detection of intermediates formed during irradiation of Pt/ $\text{TiO}_2$  in aqueous solutions have demonstrated the intermediacy of  $\cdot\text{OH}$  and  $\text{HO}_2\cdot$ .<sup>17</sup> The very slow rate of  $\text{CO}_2$  production in pure benzene (see experiment 5 in Table I), the lack of the intermediates other than hydroxylated compounds, and the dependence of the  $\text{CO}_2$  evolution rate on the degree of phase mixing (Table II) suggest that the photogenerated holes are scavenged by water (eq 2) rather than by hydrocarbons (eq 8). These would form  $\cdot\text{OH}$  or  $\cdot\text{HO}_2$  and lead to the hydroxylation of hydrocarbons and eventually the complete oxidation. The mode of the complete decomposition of the hydrocarbons has not been established. However, the detection of phenol for the case of benzene and of alcohols for the cases of aliphatic hydrocarbons suggests that attack by  $\cdot\text{OH}$  or  $\text{HO}_2\cdot$  radicals is a likely first step. The probable role of  $\cdot\text{OH}$  in these reactions is also supported by the reaction of benzoic acid<sup>2</sup> and hydrocarbons with Fenton's reagent.

Thus the heterogeneous photooxidation of hydrocarbons in suspensions with Pt/ $\text{TiO}_2$  can be explained by a mechanism similar to that invoked for benzoic acid; that is, the photooxidation proceeds via hydroxylated intermediates. In both experiments it is of importance that hydrocarbons, which are unattacked by most oxidizing agents, readily react with  $\cdot\text{OH}$  to form the final product  $\text{CO}_2$ . Since aliphatic hydrocarbons are themselves the products of the photo-Kolbe reaction,<sup>1,2</sup> their isolation in experiments involving the photodecomposition of organic acids suggests that they are capable of escaping from the powder surface. They then are swept from the reaction medium or react with  $\cdot\text{OH}$  less readily than the organic acid precursor. The destruction of hydrocarbons by the photocatalytic reaction described here might be useful in the treatment of waste streams or spills involving these materials.

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