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# Catalysis by the Fe(III) Complex of *N*-Dodecyl-3,4-dihydroxybenzamide in the Hydroxylation of Anisole with Hydrogen Peroxide*

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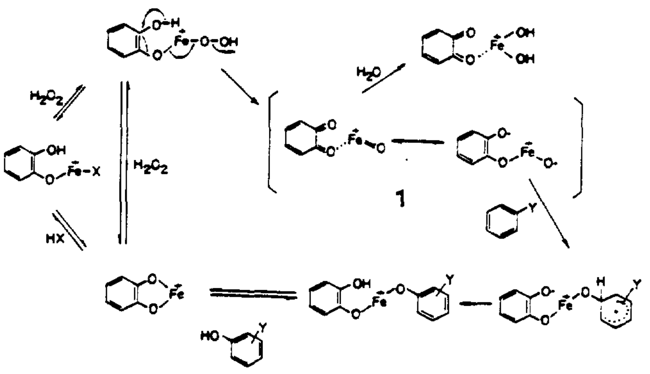
Hydroxylation of anisole with $H_2O_2$ was investigated by employing Fe (III) ion and *N*-dodecyl-3,4-dihydroxybenzamide (DDHB) as a catalyst. The study was aimed at obtaining an insoluble catalyst with a long catalytic life, in view of the inactivation of the catechol portion of the catalyst during the reaction. The rate of decomposition of $H_2O_2$ under various conditions indicated that the reaction proceeds through the catalytic participation of Fe(III)·DDHB. Yield of the hydroxylation products under various conditions revealed that Fe (III)·DDHB is not inactivated during the reaction.

Hydroxylation of aromatic compounds with Fenton reagent (Fe(II) + $H_2O_2$) has been subjected to extensive mechanistic and synthetic studies.[1] Addition of enediols such as ascorbic acid, hydroquinone, or catechol enhances the rate and yield of Fe (III) or Fe (II) ion-catalyzed hydroxylation of aromatic compounds with $H_2O_2$.[2,3] The proposed mechanism[3,4] of the Fe (III)·catechol-catalyzed aromatic hydroxylation is summarized in Scheme 1. Inactivation of the catalyst by the water attack at catalytic intermediate 1 has been proposed to occur as the reaction proceeds.[3,4] Thus, the reaction stops when all of the catalyst is destroyed and the relative rates of the attack at 1 by water and by the aromatic substrate affect the yield.

In an attempt to immobilize the Fe (III)· catechol catalyst and in an attempt to provide hydrophobic environment to the catalytic center so that the water attack at 1 is suppressed, a polystyrene-supported catechol (2) was prepared previously.[5] Catechol 2, however, was inactivated during the hydroxylation reaction.[6] In the present study, *N*-dodecyl-3,4-dihydroxybenzamide (DDHB) was employed as the insoluble hydrophobic catechol. The Fe(III)·DDHB-catalyzed hydroxylation of anisole with $H_2O_2$ proceeded without appreciable destruction of the catechol moiety, as will be reported in this paper.



Scheme 1

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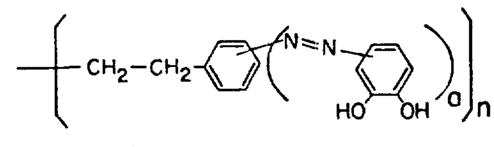

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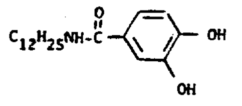

(DDHB)

## Results and Discussion

DDHB was hardly soluble even in boiling water. All of the reactions in the present study were conducted in water, and, therefore, were heterogeneous. The amounts of Fe (III) ion adsorbed on DDHB are illustrated in Figure 1. Analysis with Langmuir isotherm of single layer adsorption[5] did not produce a satisfactory theoretical curve for the data of this figure, implicating that a multilayer scheme is needed to account for the adsorption of Fe (III) on DDHB.

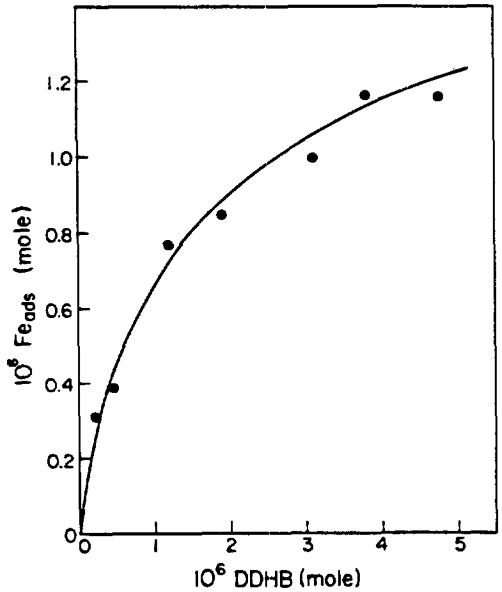

**Figure 1.** The amount of Fe (III) adsorbed on DDHB at pH 4.3 and 25 °C plotted against the total amount of DDHB. This amount of DDHB, however, does not represent the amount of the molecules exposed on the surface, but the two quantities are proportional to each other Total amount of Fe (III) and the total volume of the buffer solution were $2.39 \times 10^{-6}$ mole and 10 *ml*, respectively. The results of this experiment (e.g. ca. $0.9 \times 10^{-6}$ mole/10 *ml* Fe (III) adsorbed on $1.5 \times 10^{-6}$ mole/ 10 *ml* DDHB) indicate that a substantial portion of DDHB molecules located on the surface would be bound to Fe (III) ion under the conditions (Table 1) of hydroxylation of anisole.

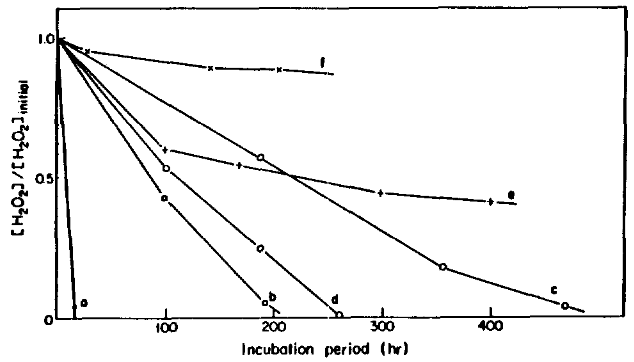

**Figure 2.** Decomposition of $H_2O_2$ in the presence of $1.5 \times 10^{-4}$ mole/l DDHB, $8 \times 10^{-5}$ *M* Fe (III) ion, and 0.01 *M* anisole; a, pH 3.6; b, pH 2.9; c, pH 2.4; d, pH 4.3; e, pH 4.3 without DDHB and anisole (with Fe (III) only); f, pH 4.3 without anisole (with Fe (III) and DDHB).

Decomposition of $H_2O_2$ was measured under various conditions and the results are illustrated in Figure 2. Slower rates at low pHs are attributable to the less favorable formation of Fe (III)·DDHB due to the suppressed ionization of the phenol groups of DDHB. On the other hand, the formation of hydroxo complexes of Fe (III) would also inhibit the formation of Fe (III)·DDHB at high pHs.

At pH 4.3, about 50% of $H_2O_2$ was decomposed in 200 h when only Fe (III) was present (Figure 2, line *e*), while only about 10% is decomposed when DDHB is added (line *f*). This can be attributed to the formation of insoluble Fe (III)·DDHB, and the consequently decreased [Fe(III)]. Although the insoluble Fe(III)·DDHB alone does not decompose $H_2H_2$, the cooperative action of Fe (III)·DDHB and anisole leads to efficient decomposition of $H_2O_2$ (line *d*).

The results of the hydroxylation of anisole in the presence of Fe(III)·DDHB are summarized in Table 1. The yield and product distribution were measured after the decomposition of $H_2O_2$ was complete.

The distribution of *o*- and *p*-isomers of methoxyphenol obtained at pH 4.3 is very similar to that observed in the hydroxylation catalyzed by Fe (III)·catechol or Fe (III)·**2** at pH 4.2 (Table 2). The isomer distribution, however, is markedly different from that ($o/p = 8$) measured in the absence of any catechol derivative. Although virtually no hydroxylation was observed at pH 2.9 in the present study, the Fe(III)-catalyzed hydroxylation of anisole in the absence of catechol proceeded with 13% yield.[7] The outcome of the catalysis by the insoluble Fe (III)·DDHB is, therefore, distinctly different from that by

**TABLE 1: Hydroxylation of Anisole with $H_2O_2$ in the presence of Fe (III) and DDHB.[a]**

| Exp. | pH[b] | DDHB[c] | Fe (III) | $H_2O_2$ | yield[d] | Isomer distribution(%)[e] | |
|---|---|---|---|---|---|---|---|
| | | ($10^{-4}$ mole/*l*) | ($10^{-4}$ *M*) | ($10^{-3}$ *M*) | (%) | *ortho* | *Para* |
| 1 | 4.3 | 1.5 | 0.8 | 2 | 9 | 58 | 42 |
| 2 | 4.3 | 1.5 | 0.8 | 2 | 8 | 67 | 33 |
| 3 | 4.3 | 1.5 | 0.8 | 4 | 10 | 63 | 37 |
| 4 | 4.3 | 1.5 | 0.8 | 6 | 10 | 65 | 35 |
| 5 | 4.3 | 1.5 | 1.2 | 2 | 10 | 61 | 39 |
| 6 | 4.3 | 3.0 | 0.8 | 2 | 7 | 60 | 40 |
| 7 | 3.6 | 1.5 | 0.8 | 2 | 10 | 76 | 24 |
| 8 | 3.6 | 1.5 | 0.8 | 4 | 9 | 74 | 26 |
| 9[f] | 3.6 | 1.5 | 0.8 | 2 | 7 | 79 | 21 |
| 10 | 3.2 | 1.5 | 0.8 | 2 | 10 | 83 | 17 |
| 11 | 2.9 | 1.5 | 0.8 | 2 | <0.1[g] | | |
| 12 | 2.4 | 1.5 | 0.8 | 2 | ~0 | | |

[a] 25°C, 0.01 *M* anisole; [b] 0.05 *M* acetate buffer for pH 2.9–4.3 and 0.05 *M* chloroacetate buffer for pH 2.4; [c] DDHB was insoluble in the reaction mixture; [d] Moles of products divided by moles of $H_2O_2$ added initially. [e] Small amounts of the meta isomer are not included; [f] DDHB used for the hydroxylation at pH 4.3 was recovered and then used in this experiment. [g] Product distribution was not measured due to the small yield.

**TABLE 2: Hydroxylation of Anisole Catalyzed by Other Fe (III)·Catechol Complexes**[a]

| Catechol derivative | Fe (III) ($10^{-4}$ *M*) | $H_2O_2$ ($10^{-3}$ *M*) | yield (%) | Isomer distribution[b] *ortho* | *para* |
|---|---|---|---|---|---|
| catechol[c], 0.15 mM | 0.8 | 2 | 55 | 66 | 34 |
| *2*[d], <0.46 mmole/l[e] | 0.4 | 2 | 92 | 67 | 33 |
| *2*[d], <0.46 mmole/l[e] | 0.4 | 4 | 47 | 70 | 30 |

[a] pH 4.2, [anisole] = 0.01 *M*. Yield was calcualted as indicated in Table 1; [b] Small amounts of the meta isomer are not included. [c] Ref. 3; [d] Ref. 5,6; [e] The upper limit is calculated assuming that each monomer of the polystyrene backbone of *2* contains one catechol residue.

free Fe (III) ion.

The results of Table 1 reveal that the low yields are not due to the destruction of DDHB during the reaction.[8] The yields are based on the amount of added $H_2O_2$. When the amount of $H_2O_2$ is varied from 2 to 6 mM at pH 4.3, the change in yield was small, with the amount of product being almost proportional to that of $H_2H_2$. If the reaction stops due to the oxidation of the DDHB by the water attack at *1* as proposed in Scheme 1, the amount of product would be determined by the amount of DDHB and independent of the amount of the excessively added $H_2O_2$. Since the amount of product increased linearly with the amount of added $H_2O_2$, DDHB is not destroyed during the decomposition of *ca.* 40-fold molar excess $H_2O_2$. This is further supported by the result of Exp. 6 in which an increase in the amount of DDHB did not improve the yield. If DDHB is inactivated during the reaction, the yield should be proportional to the amount of added DDHB. Furthermore, when DDHB was used for the hydroxylation at pH 4.3 and then used again at pH 3.6 (Exp. 9), the hydroxylation was as efficient as that with fresh DDHB.

When 2 was the catalyst (Table 2), the amount of product was not affected when the amount of $H_2O_2$ was doubled, indicating that 2 is inactivated during the reaction. The different behavior of the two immobilized catechol derivatives, 2 and DDHB, could be related to the differences in the hydrophobicity of the microenvironment of the catalytic site or/and to the different electronic effects exerted by the diazo and amido substituents of the catechol ring.

The catalytic system of Fe (III)·DDHB is associated with a long catalytic life, but with a small yield. From the view point of economy involved in aromatic hydroxylation reactions, however, the longer catalytic life is much more important than the yield based on the amount of added hydrogen peroxide. Efforts are continuously made in this laboratory to increase both the catalytic life and the yield[8] by varying the hydrophobicity and the electronic properties of the catalyst.

## Experimental Section

*N-Dodecyl-3,4-dihydroxybenzamide* (*DDHB*). To a stirred solution of 3,4-dihydroxybenzoic acid (0.97g) and *N*-hydroxysuccinimide (0.73 g) in 35 m*l* 4:3 dioxane-acetone at 4°C, *N,N'*-dicyclohexylcarbodiimide (1.3 g) was added, and the mixture was kept at 4°C for 24 h. After filtration of the *N,N'*-dicyclohexylurea, dodecylamine (1.2 g) was added at room temperature. The white material (DDHB) which precipitated was washed with acetone and recrystallized from benzene, mp 107-9°. DDHB was hardly soluble in boiling water, but readily dissolved in chloroform. DDHB was thoroughly pulverized prior to the use in the hydroxylation studies.

*Measurements.* Quantitation of $H_2O_2$ was performed colorimetrically with potassium iodide according to the literature.[9] The amount of Fe (III) ion unadsorbed on DDHB was measured colorimetrically according to the reported procedures.[10]

For the hydroxylation of anisole, DDHB was suspended in a buffer solution containing ferric chloride and anisole. After the mixture was stirred for 1 hr under a nitrogen atmosphere, $H_2O_2$ was added to the suspension, which was stirred on a laboratory magnetic stirrer until $H_2O_2$ decomposed completely. The methoxyphenols obtained from the hydroxylation reaction were methylated with dimethyl sulfate according to the literature.[3] The dimethoxybenzenes thus obtained were extracted with benzene and analyzed by gas chromatography (Yananco G180 FID gas chromatograph).

Absorbance readings in colorimetric determination of Fe (III) ion and $H_2O_2$ were measured on a Beckman Model 25 spectrophotometer. pH measurements were performed with a Chemtrix type 60A pH meter. Constant temperature for the incubation of the hydroxylation mixture was maintained with a Haake E12 circulator.

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(8) Although efficient decomposition of $H_2O_2$ requires anisole,[2,7] only a part of $H_2O_2$ is utilized in the hydroxylation of anisole (Table 1, 2). The yield of hydroxylation catalyzed by Fe (III)·DDHB at pH 2.9 is especially small (Table 1), in spite of the fast decomposition $H_2O_2$ (Figure 1.). In this regard, it is noteworthy that a reaction path has been proposed in the Fe(II)-catalyzed reaction[7] in which anisole is regenerated from a catalytic intermediate with participation of specific or general acids.

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