

# The Role of Oxygen in the Hydroxylation Reaction of Benzene with Fenton's Reagent. $^{18}\text{O}$ Tracer Study

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**Abstract:** The role of oxygen in the hydroxylation of benzene with Fenton's reagent was studied in a 0.05 M  $\text{H}_2\text{SO}_4$  solution. The main products are phenol and benzoquinone in the molar ratio ca. 10:1. A precise determination of material balance with respect to benzene indicated that the selectivity of phenol is rather low, less than 50%. On the other hand, the conversion of  $\text{H}_2\text{O}_2$  into aromatic oxidation products including unidentified byproducts is unexpectedly high. Tracer study with  $(^{18}\text{O}_2)_2$  gas indicated that the isotope incorporation in phenol is ca. 20%, while the incorporation in benzoquinone is perfect. It was also shown that both oxygen and benzene were consumed in excess of  $\text{H}_2\text{O}_2$  during the reaction. To account for all of these results, regeneration of  $\text{H}_2\text{O}_2$  resulting from Dorfman's mechanism has been proposed. By the aid of computer simulation, the amount of  $\text{H}_2\text{O}_2$  regenerated was estimated to be around 20% of  $\text{H}_2\text{O}_2$  initially used. Factors affecting the isotope incorporation in phenol were also discussed.

## I. Introduction

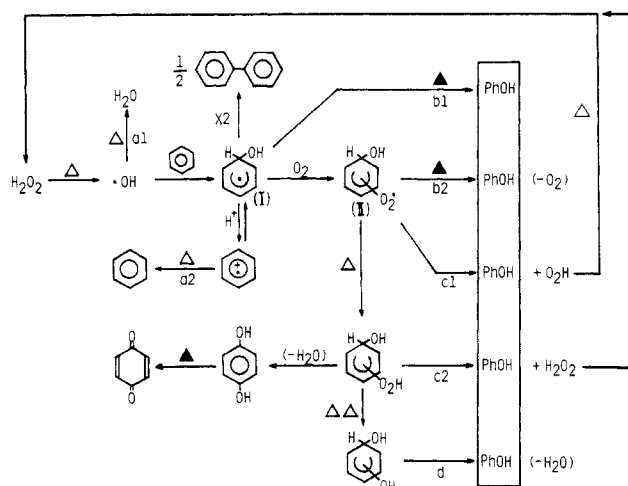
In the previous paper,<sup>1</sup> we studied the reaction mechanism of aerial oxidation of benzene in aqueous sulfuric acid solutions containing copper(I) chloride. The main products of this reaction were phenol and hydroquinone, and the active species responsible for these products was concluded to be hydroxyl radicals. The tracer study with use of  $(^{18}\text{O}_2)_2$  indicated that two hydroxyl groups of hydroquinone are introduced in two separate steps, and both phenol and hydroquinone are derived from the same intermediate, i.e., hydroxycyclohexadienyl radical. All the experimental results were consistent with the reaction mechanism of the Fenton reaction currently accepted.

Tracer study in the  $\text{Cu}/\text{O}_2$  system, however, had a limitation because the role of oxygen and hydrogen peroxide cannot be assigned separately. In order to see the role of oxygen, therefore, it is advantageous to study the reaction in the Fenton system, where the effect of oxygen can be studied independent of the effect of  $\text{H}_2\text{O}_2$  by using labeled oxygen and nonlabeled  $\text{H}_2\text{O}_2$  simultaneously. Although the reaction mechanism of the Fenton reaction occurring under a nitrogen atmosphere has been established in some detail,<sup>2-6</sup> there remain some uncertainties regarding the role of oxygen.

Almost all of the reaction mechanisms proposed in the past are summarized in Scheme I together with the regeneration mechanism which will be discussed in this paper.

It is well-known that, regardless of the method of generation, an OH radical once formed in aqueous media adds to an aromatic nucleus to form hydroxycyclohexadienyl radical (radical I).<sup>2-7</sup> The radical undergoes various fates depending upon the conditions of its surroundings. In the system having no particular oxidant, e.g., pulse radiolysis of aqueous benzene solution, biphenyl is the main product. According to Walling and his colleagues,<sup>2,3</sup> when a certain oxidant such as  $\text{Fe}^{3+}$  or  $\text{Cu}^{2+}$  ions is in the reacting system, radical I is readily oxidized to give phenol. The effect of oxygen is also drastic and, according to Dorfman,<sup>6</sup> radical I reacts with oxygen and forms peroxy radical (radical II) predominantly. Radical II thus formed is thought to give phenol by liberating  $\text{O}_2\text{H}$  radical (Dorfman mechanism). On the other hand, Narita and Tezuka<sup>7</sup> proposed a different mechanism operating

Scheme I<sup>a</sup>



<sup>a</sup> Triangular symbols stand for the reduction ( $\Delta$ ) and oxidation ( $\blacktriangle$ ) processes by  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$  ions, respectively. Double symbols are given for the two-electron process.

in nonaqueous solutions. They generated OH radicals by photodecomposition of an azohydroperoxide in a benzene solution in the presence of heavy oxygen and observed that the isotope content in phenol was at most 40% of the oxygen gas used. Their conclusion was that the peroxy radicals disproportionate to form diol intermediates which are finally dehydrated to give the phenol molecules, one-half of which are labeled. These studies are, in some sense, fragmentary, and no integrative understandings about the effect of oxygen on the fate of radical I has been established yet.

## II. Experimental Section

Procedures and apparatus employed were almost the same as described in the previous paper.<sup>1</sup> After the reaction was finished, residual benzene was extracted with hexane and analyzed by UV spectrometry. The products remaining in the extraction residue were analyzed by high-pressure liquid chromatography. Blank experiments ensured that more than 99% of benzene used was recovered without interfering in the analysis of phenolic products.  $\text{Fe}^{2+}$  ions were analyzed spectrophotometrically with *o*-phenanthroline.

**1. Tracer Study.** Benzene (30 mL) was placed in the reactor flask (500 mL) and frozen by external cooling. The reactor system was equilibrated with reacting gas containing heavy oxygen, and the flask was warmed up to room temperature. The reaction was started by feeding two solutions of 0.04 M  $\text{FeSO}_4$  and 0.02 M  $\text{H}_2\text{O}_2$  in 0.05 M  $\text{H}_2\text{SO}_4$  into the flask at a constant feed rate (3.33 mL/min for each solution). This feed rate was selected in order to resemble the reaction conditions similar

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(2) Walling, C.; Johnson, R. A. *J. Am. Chem. Soc.* **1975**, *97*, 363.

(3) Walling, C. *Acc. Chem. Res.* **1975**, *8*, 125.

(4) Norman, R. O. C.; Pritchett, R. J. *J. Chem. Soc., B* **1967**, 926.

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**Table I.** <sup>18</sup>O Content (%) in the Reacting Gas and Products in the Fe<sup>2+</sup>/H<sub>2</sub>O<sub>2</sub> System

<i>p</i> O <sub>2</sub> <sup>b</sup>	reacting gas		phenol			benzoquinone <sup>8</sup>		
	before	after	<i>m/e</i>	obsd	incorp <sup>a</sup>	<i>m/e</i>	obsd	incorp <sup>a</sup>
0.19	24.3	24.7	94	93.7		108	78.3	
						110	21.7	92
			96	6.3	27	112	(0)	
0.40	22.1	22.2	94	95.9		108	77.4	
						110	22.6	102
			96	4.1	19	112	(0)	

<sup>a</sup> The percentage incorporation is expressed by the following: {(isotope content in product)/(isotope content in oxygen)}100. <sup>b</sup> *p*O<sub>2</sub> is the partial pressure of total oxygen in helium.

**Table II.** Material Balance of Benzene<sup>a</sup>

run	molar ratios		oxygen <i>n</i> <sub>O</sub>	benzene <i>n</i> <sub>B</sub>	Fe <sup>2+</sup> <i>n</i> <sub>Fe</sub>	phenol <i>n</i> <sub>P</sub>	benzoquinone	biphenyl (×2)	<i>n</i> <sub>P</sub> / <i>n</i> <sub>B</sub>	<i>n</i> <sub>O</sub> / <i>n</i> <sub>B</sub>	<i>n</i> <sub>Fe</sub> / <i>n</i> <sub>B</sub>
	C <sub>6</sub> H <sub>6</sub> /H <sub>2</sub> O <sub>2</sub>	Fe <sup>2+</sup> /H <sub>2</sub> O <sub>2</sub>									
1	2	1	0.91	0.839		0.399	0.008	0.007	0.48	1.1	
2	2	2	1.04	0.944	1.6	0.410	0.029	0.030	0.43	1.1	1.7
3	3	2	1.37	1.109	1.8	0.504	0.022	0.011	0.45	1.2	1.6

<sup>a</sup> All data are expressed in mmol. <sup>b</sup> Amount of H<sub>2</sub>O<sub>2</sub> was fixed at 1 mmol for each run.

to those in the Cu<sup>+</sup>/O<sub>2</sub> system, where Cu<sup>+</sup> ions were supplied by slow dissolution of solid CuCl.<sup>1</sup>

Two series of experiments differing in partial pressure and isotope content of oxygen were carried out.

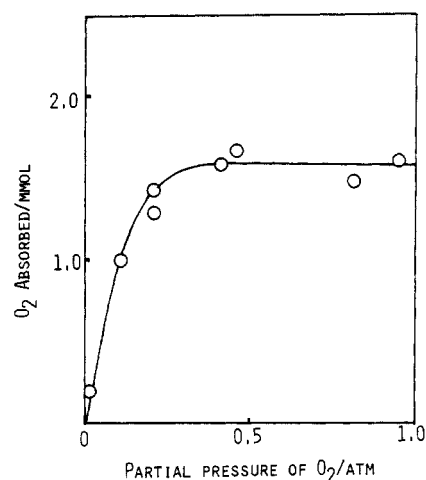
**2. Material Balance. a. O<sub>2</sub> absorption.** The reactant solutions (H<sub>2</sub>O<sub>2</sub> and FeSO<sub>4</sub>) were stocked in two separate containers, but the gas phases over the stock solutions and the reactor flask were linked by tubing to maintain the pressure constant everywhere. After the whole apparatus was held isothermal, reaction was started by feeding the reactant solutions into the reactor as before. The volume of oxygen absorbed was followed by a gas buret.

**b. Benzene Consumed.** Benzene (1–2 mmol) was sealed in a breakable capillary tube, which was put into a 200-mL Erlenmeyer flask together with 100 mL of 0.05 M H<sub>2</sub>SO<sub>4</sub>. The flask was closed tightly with a Teflon stopper to which a micromanometer 0.5 mL in volume, a gas tight glass syringe, and two inlets of the reactant solutions were jointly connected. Before the reaction was started, the capillary was broken with a magnetic spin bar and the whole system was kept isothermal under atmospheric pressure. The reaction was then started by feeding the reactant solutions at the same rate as above. After the reaction was finished, benzene remaining in the system was extracted with hexane and analyzed as before.

### III. Results and Discussion

Under the present conditions of experiment, the main product was phenol invariably. In contrast to the Cu<sup>+</sup>/O<sub>2</sub> system,<sup>1</sup> hydroquinone was not detected in the present case. Instead, *p*-benzoquinone was detected at a very low yield (less than 10% of phenol produced). Only a trace amount of biphenyl and an unidentified product, which might be hydroxymuconialdehyde (see ref 1), were frequently observed. In this study, no attention was paid to the latter two products.

**1. Tracer Experiment.** The isotope distribution in the products, phenol and benzoquinone, is listed in Table I. At first glance, there are two points to be noticed. The first is that phenol does incorporate heavy oxygen though only partly. If the hydroxyl group of phenol were solely originated from hydrogen peroxide, no isotope incorporation would be expected. Since the isotope scrambling among the reactants, O<sub>2</sub>, H<sub>2</sub>O<sub>2</sub>, and H<sub>2</sub>O, was found negligible, the origin of heavy oxygen in phenol seems to be ascribed to radical II. A possible explanation is that Tezuka's mechanism is operating in our system, too. Note that, however, if Tezuka's mechanism were the only route to yield phenol, the isotope incorporation would be 50% while the experimental values were 27 and 19% for the two series of measurements. Accordingly, if Tezuka's mechanism is the reason of the isotope incorporation, there must be some other parallel routes such as the direct oxidation of radical I or the Dorfman's path for yielding phenol. The second point is that, in contrast to phenol, the isotope incorporation in benzoquinone is very high.<sup>8</sup> This tells us that benzoquinone

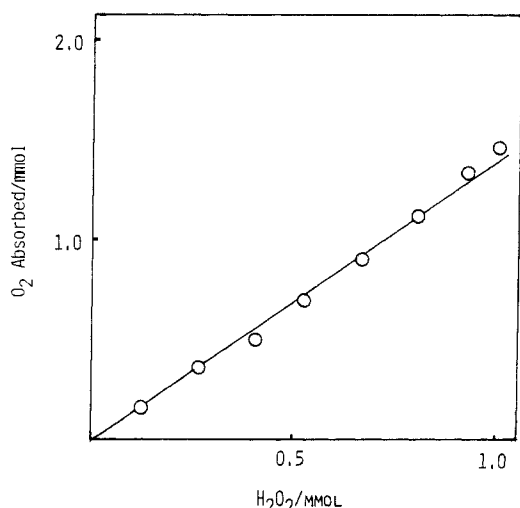


**Figure 1.** Variation of total amount of oxygen absorbed as a function of partial pressure of O<sub>2</sub> in the Fenton reaction. Molar ratio of Fe<sup>2+</sup>/H<sub>2</sub>O<sub>2</sub> was kept at 2.0.

is derived from radical II exclusively. One of the oxygen atoms in benzoquinone is introduced at the stage of radical I, and the other, the heavy oxygen, is taken in at the stage of radical II. It is also indicated that the further oxidation of phenol cannot be a main route for yielding benzoquinone. If this were occurring at an appreciable rate, the quantitative isotope incorporation in benzoquinone would be impossible.

**2. Material Balance. a. Amount of Oxygen Absorbed.** During the course of the present study, we found frequently that the amount of oxygen consumed exceeded that of H<sub>2</sub>O<sub>2</sub> fed to the reactor. In order to confirm this more precisely, we carried out a series of measurements for absorption of gaseous oxygen. Results obtained are shown in Figure 1. As the figure shows, the amount of oxygen absorbed increases with the increase of partial pressure of oxygen (*p*<sub>O</sub>) and reaches saturation when *p*<sub>O</sub> exceeds 0.4. The

(8) The values of isotope incorporation in benzoquinone are 92 and 102% for two series of measurements, respectively. If the regeneration of H<sub>2</sub>O<sub>2</sub>, which is estimated to be some 20% of the original amount of H<sub>2</sub>O<sub>2</sub>, is taken into consideration, the value is expected to be around 110%. The difference should be attributed to the ease of oxygen exchange between carbonyl oxygen and water. We have confirmed that a prolonged treatment of the reaction mixture causes a gradual loss of heavy oxygen from benzoquinone. If the regeneration path is working, there must be some doubly labeled benzoquinone (*m/e* 112) in the products. Although we have failed to detect it, a simple calculation indicates that the amount of the doubly labeled species should be less than 1%, which is close to the limit of detection, of the total benzoquinone produced.



**Figure 2.** Amounts of oxygen absorbed in the time course of the Fenton reaction. Partial pressure of  $O_2$  and molar ratio of  $Fe^{2+}/H_2O_2$  were kept at 0.2 and 2.0, respectively. The abscissa stands for the total amounts of  $H_2O_2$  added to the reactor system.

point to be stressed is that the amount of oxygen absorbed at higher  $p_{O_2}$ 's is 50 to 60% greater than the moles of  $H_2O_2$  fed to the reactor. If  $H_2O_2$  was converted quantitatively to radical I and all of radical I reacted with oxygen to form radical II, the molar ratio of  $O_2/H_2O_2$  should be unity. In an actual system, however, the ratio should be less since deactivation of OH radicals is thought to occur. There must be some reason to increase the oxygen consumption.

**b. Amount of Benzene Consumed.** The excess consumption of oxygen can be understood if the peroxy radical is transformed to phenol liberating  $O_2H$  radical (Dorfman mechanism), which will be reduced by  $Fe^{2+}$  ions to regenerate  $H_2O_2$ . If this is the case, the amount of benzene consumed should also exceed the initial amount of  $H_2O_2$ . Behind this statement, there is an implicit assumption that the amount of  $H_2O_2$  regenerated exceeds the amount of it wastefully deactivated. We thus tried to determine the material balance of benzene precisely. As far as we are aware, nobody has discussed the material balance with respect to aromatic reactants in the Fenton reaction, while the yield on the base of  $H_2O_2$  has been discussed frequently.

Results obtained are summarized in Table II. Although the amount of benzene consumed varies with the change in composition of reactants,  $H_2O_2$ ,  $Fe^{2+}$ , and benzene, it is not doubted that when sufficient amounts of benzene and  $Fe^{2+}$  are present (run 3), moles of benzene consumed exceed that of  $H_2O_2$  by an amount of 10%, which is beyond the limit of experimental uncertainty ( $\pm 2\%$ ). Furthermore, it should be noted that the ratios of oxygen absorbed ( $n_O/n_B$ ) and phenol produced ( $n_P/n_B$ ) against benzene consumed are constant in all cases (runs 1–3). This reflects that the reaction concerned is occurring at a steady rate, which makes it possible for us to proceed with our analysis in the following section and in the Appendix. Another support for the steadiness of the reaction is shown in Figure 2, in which the uptake of gaseous oxygen during the reaction is plotted against the amount of  $H_2O_2$  fed externally. Since the feeding of  $H_2O_2$  was made at a constant rate, the scale of the abscissa is equivalent to time and the slope of the line shows the rate of oxygen uptake.

There is another important fact in Table II. The values of  $n_B$ , moles of benzene reacted per unit mole of  $H_2O_2$ , are near unity in all cases. On the other hand, the selectivity of phenol ( $n_P/n_B$ ) is 48% at the highest. These data suggest that the conversion of  $H_2O_2$  into aromatic oxidation products is quite high although the yield of phenol is rather low. According to this view, at least under the present conditions of experiment, the dehydration of radical I followed by  $Fe^{2+}$  ion reduction to go back to benzene (the path denoted by a2 in Scheme I) cannot be the main reason of the low phenol yield.<sup>9</sup> Probably the presence of oxygen favors the for-

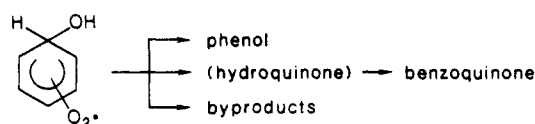
**Table III.** Acceptable Values of Rate Parameters<sup>a</sup>

parameters	range of Acceptable Values					
	I			II		
$\alpha$	1.00	~ 0.95	~ 0.90	~ 0.85	1.00	~ 0.78
$\beta$	0.33	0.37	0.41	0.45	0.26	0.48
$\gamma$	0.27	0.39	0.49	0.59	0.16	0.81
$\delta$	0.19	0.13	0.07	0	0.28	0
$x$	0.09	0.14	0.18	0.23	0.07	0.28
$y$	0.13	0.08	0.04	0	0.20	0
$Fe^{2+}(\text{calcd})$	1.63	1.52	1.44	1.37	1.87	1.28
$O_2(\text{calcd})$	0.84	0.85	0.87	0.90	0.75	1.03

<sup>a</sup> Input data. I:  $\eta_P = 0.23$ ,  $n_B = 1.10$ ,  $n_P = 0.50$ . II:  $0.18 \leq \eta_P \leq 0.28$ ,  $1.08 \leq n_B \leq 1.12$ , and  $0.48 \leq n_P \leq 0.52$ .

mation of radical II and lowers the rate of the dehydration reaction. There must be some byproducts, though they are not identified. We assume that a substantial part of benzene reacted is converted to polymeric products which are inactive to HPLC analysis. An appreciable coloring of the solution may be correlated with this.

A control experiment in which benzoquinone was reacted with Fenton's reagent indicated that benzoquinone certainly decomposes by the attack of OH radicals, but the extent of this reaction is insufficient to account for the high yield of unknown byproducts. In other words, it is unlike that benzoquinone is the precursor of the unknown byproduct. Accordingly, we assume that the branching point leading to benzoquinone and byproduct is located at radical II.



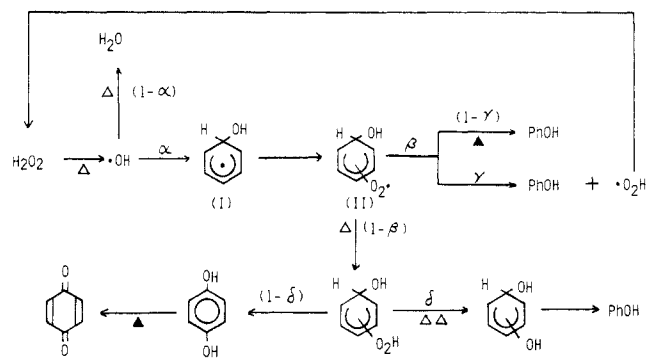
By a separate experiment, we have confirmed that the step from hydroquinone to benzoquinone proceeds only when  $Fe^{3+}$  ions are in the system, but not with  $Cu^{2+}$  ions.

**3. Regeneration of Hydrogen Peroxide.** In the above discussion, there are several things to be reconsidered. For instance, the excess uptake of oxygen shown in Figure 1 was left unanswered. Although a part of the excess uptake is thought to have been consumed to form unidentified byproducts, it is doubtful whether this is the only reason. That the molar ratio of benzene to  $H_2O_2$  exceeds unity is more difficult to explain. If the consumption of benzene is only caused by OH radicals which are derived from  $H_2O_2$  externally added, the relative consumption of benzene to  $H_2O_2$  should be less than unity. The isotope content in phenol was found within 1/4 to 1/5 of the isotope level in the reacting gas (Table I). Although this can be explained if both the Dorfman and diol paths are taking place simultaneously at a nearly equal rate, it seems too arbitrary as an assumption. In order to be consistent with all of these findings, it seems more realistic to take into account the regeneration of  $H_2O_2$  resulting from the Dorfman mechanism. If the regeneration takes place at an appreciable rate, heavy oxygen will be incorporated in phenol even by this mechanism alone, and the contribution of the diol path becomes unnecessary. It is worth noting that the regeneration of  $H_2O_2$  was originally postulated by Kolthoff and Medalia.<sup>10</sup> Balakrishnan and Reddy<sup>11</sup> also employed this hypothesis to account for the enhancing effect of  $Fe^{2+}$  ions observed in  $\gamma$ -radiolysis of aqueous benzene solutions.

(9) This may be thought to correspond with the observation that no isotope exchange between radical I and water molecules was detected in the  $Cu^+/O_2$  system,<sup>1</sup> where we explained the absence of isotope exchange by assuming a rapid reduction of benzene cation radical to neutral benzene. It is obvious, however, that if radical I is converted to radical II almost exclusively, there is no need of such an assumption. In addition, Walling<sup>2,3</sup> reported that  $Cu^{2+}$  ions are more powerful oxidants in oxidizing radical I than  $Fe^{3+}$  ions. This may also inhibit the acid-catalyzed dehydration of radical I. Unfortunately, data are insufficient to determine either mechanism.

(10) Kolthoff, I. M.; Medalia, A. I. *J. Am. Chem. Soc.* **1949**, *71*, 3784.

(11) Balakrishnan, I.; Reddy, M. P. *J. Phys. Chem.* **1970**, *74*, 850.

Scheme II<sup>a</sup>

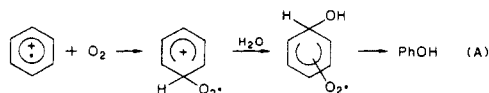
<sup>a</sup>Triangular symbols stand for those as described in Scheme I. Greek symbols are fractional rates of branching processes.

A strong support for the regeneration mechanism was obtained by a computer simulation, and part of the results obtained are shown in Table III. The basic assumptions we made to obtain this table were (1) the reaction proceeds as expressed by Scheme I and (2) the reaction is always under a steady state. Further details of the treatment are given in the Appendix.<sup>12</sup>

Table III should be read as  $\alpha$ , the fraction of OH radicals which are incorporated in radical I (see Scheme II), lies in the range  $1 \leq \alpha \leq 0.85$  and once  $\alpha$  is determined other parameters are uniquely determined. Accordingly, if  $\alpha$  takes its maximum value ( $\alpha = 1$ ) then  $x$ , the fractional contribution of the regeneration path, takes the minimum (0.09), but if  $\alpha$  takes the minimum (0.85)  $x$  takes the maximum (0.23). The most important conclusion is that  $x$  lies between 0.09 and 0.23 but never becomes 0. This means that without consideration of the regeneration mechanism, any consistent explanation of the observed result is impossible. The table also shows that the larger the value of  $x$  is the smaller are the values of  $y$  and  $\delta$ , where  $y$  defined by  $y = \delta(1 - \beta)$  stands for the fractional contribution of the diol path (see Scheme II). In other words, the increasing contribution of the regenerative mechanism reflects in the decreasing contribution of the diol path. In actual reactions, it seems unlikely that  $\alpha = 1$ , i.e., all OH radicals produced are quantitatively transformed to products without any deactivation. This implies that the contribution of the diol path is unimportant.

**4. General Trend of Oxygen Incorporation.** It is interesting to note that different results have been reported for the isotope incorporation in phenol during the reaction of benzene with hydroxyl radicals. Recently, Cohen<sup>13</sup> reported that no incorporation of heavy oxygen was observed during the pulse radiolysis of aqueous benzene solution, while a partial incorporation was observed during a Fenton-type reaction. On the other hand, Narita and Tezuka<sup>7</sup> observed a high-level incorporation during the photodecomposition of azohydroperoxide in benzene. They proposed the formation of dihydrodiol intermediate, which is finally dehydrated to give phenol. These two observations together with ours, which are seemingly contradictory, provide a general trend

(12) A referee suggested the possibility of a reaction between benzene cation radical and oxygen, which is not considered in Scheme I. In fact, several recent papers<sup>16</sup> reported such reactions involving radical cations of some olefins and dienes in nonaqueous media. At the present stage of our knowledge, we cannot judge whether such a reaction is occurring in our system and whether it leads to phenolic products or not. However, even if the reaction is occurring, it presumably does not affect the argument developed here, since in aqueous solutions the hydration to the intermediate oxygen adduct will follow as below.



Reaction A is one of the parallel routes connecting radical I to radical II which cannot be discriminated from the route in Scheme I by overall stoichiometry alone.

(13) Cohen, G.; Ofodile, S. E. *Proc. Int. Conf. Superoxide Superoxide Dismutase*, 3rd 1982, 1, 74-83; *Chem. Abstr.* 1984, 100, 5595r.

of the isotope incorporation. The trend can be summarized as follows: (1) a high-level incorporation is observed in benzene solution when reducing ions are absent, (2) a partial incorporation is observed when the reaction is conducted in an aqueous solution containing certain reducing ions, and finally, (3) no incorporation is observed in aqueous phase reaction when reducing ions are absent.

It is likely that two factors, medium effect and the presence of reducing agent, affect the isotope incorporation in these systems. It is known that  $HO_2$  radicals disproportionate to give  $O_2$  and  $H_2O_2$  and the rate of disproportionation decreases drastically as the polarity of the medium increases.<sup>14</sup> A similar solvent effect was also reported<sup>15</sup> with some alkyl peroxy radicals though the effect is less enhanced. In aqueous phase reactions under an atmosphere of oxygen, the Dorfman path may operate predominantly and  $O_2H$  radicals liberated from radical II may be further reduced to  $H_2O_2$  when reducing ions are present. This should be the main reason for the partial incorporation as has been observed by Cohen and also by us. In contrast to this, when no reducing agent is present, as in the case of Cohen, no incorporation is expected. This implies that, in aqueous solutions, the paths via diol intermediate are hardly used. In this case, the regeneration of  $H_2O_2$  seems unfavorable or, more probably, even were  $H_2O_2$  produced in the reaction system, the reductive decomposition of it to produce OH radicals would not take place when there is no particular reactant.

Tezuka's observation may be understood in view of the medium effect. In some nonpolar medium such as benzene, bimolecular disproportionation of the organic peroxy radicals yielding dihydrodiol will become so fast as to compete with unimolecular detachment of  $HO_2$  (Dorfman mechanism). On the other hand, in aqueous solutions, protonation or hydrogen bonding will act to facilitate the Dorfman mechanism.

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## Appendix

The fate of OH radicals in the presence of benzene and oxygen can be expressed as in Scheme I<sup>12</sup> by summarizing the reaction paths reported in the literature together with our regeneration mechanism. For the convenience of mathematical analysis, Scheme I was modified as in Scheme II. Note that, in changing Scheme I to II, steps which are essentially indistinguishable by stoichiometry reason are put together in one step. For instance, the deactivation process of OH radicals indicated by a1 is indistinguishable from that indicated by a2 since these two steps are stoichiometrically equivalent. Similarly, the direct oxidation of radical I to phenol (step b1) is equivalent to the step from radical II to phenol (step b2). The Dorfman path c1 also has an equivalent path (c2) being indistinguishable from the former. In addition, the process to yield biphenyl was deleted from the scheme since the yield of biphenyl was negligibly small. Although the yield of unidentified byproducts is relatively high (ca. 50%), this is not a serious defect for the following treatment in so far as the reaction occurs steadily as mentioned in the text.

In Scheme II, steps with Greek symbols over each arrow stand for the fractional rate of two branching reaction, and steps shown without any Greek symbols are assumed to occur quantitatively. In this scheme, we assume that 1 mol of starting  $H_2O_2$  degrades to form 1 mol of OH radicals of which  $\alpha$  moles react with benzene leading to radical I and the remaining  $(1 - \alpha)$  moles are deactivated to produce  $H_2O$ .

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If 1 mol of  $\text{H}_2\text{O}_2$  regenerates  $x$  mol of  $\text{H}_2\text{O}_2$  which is incorporated additionally in the reaction cycle to produce  $x^2$  mol of  $\text{H}_2\text{O}_2$ , total mol of  $\text{H}_2\text{O}_2$  regenerated during the whole reaction should be expressed as

$$n_{\text{re}} = \sum_{s=1}^{\infty} x^s = x/(1-x)$$

where  $x = \alpha\beta\gamma$ . The overall number of moles of  $\text{H}_2\text{O}_2$  contributed to the whole reaction is

$$n(\text{H}_2\text{O}_2) = 1 + n_{\text{re}} = 1/(1-x)$$

The regeneration of  $\text{H}_2\text{O}_2$  will result in the apparent increase of oxygen uptake as well as the increasing consumption of benzene. At the same time, this will also cause the tracer content in phenol to have a smaller value than the gaseous content. The isotope content in phenol ( $\eta_p$ ), when the regenerative cycle is taking place, should be

$$\eta_p = (y + 2xy + 2x\beta)/2(y + \beta)$$

where  $y = \delta(1 - \beta)$ . The parameter  $y$  stands for the fractional contribution of the diol path to the total phenol yield. It is obvious

that if the diol path is ignored ( $y = 0$ ),  $\eta_p$  becomes simply  $x$ .

In a similar manner, moles of benzene consumed ( $n_B$ ) and the moles of phenol produced ( $n_p$ ) are expressed in terms of above symbols as

$$n_B = \alpha/(1-x)$$

$$n_p = \alpha(\beta + y)/(1-x)$$

Since the last three variables,  $\eta_p$ ,  $n_B$ , and  $n_p$ , were all determined experimentally to be  $0.23 \pm 0.05$ ,  $1.1 \pm 0.02$ , and  $0.5 \pm 0.02$ , respectively, we tried to determine values of four unknown parameters of  $\alpha$  to  $\delta$  by computer simulation. Part of the result obtained is shown in Table III where the input data were fixed at  $\eta_p = 0.23$ ,  $n_B = 1.1$ , and  $n_p = 0.5$ . Experimental values of  $\eta_p$  were, however, somewhat scattered and were 0.19 and 0.27 (see Table II). Even when a finite variation was allowed for the value of  $\eta_p$ , the acceptable range of each parameter was enlarged only slightly, as shown in column 2 of Table III.

**Registry No.**  $\text{O}_2$ , 7782-44-7;  $\text{C}_6\text{H}_6$ , 71-43-2;  $\text{C}_6\text{H}_5\text{OH}$ , 108-95-2;  $\text{FeSO}_4$ , 7720-78-7;  $\text{H}_2\text{O}_2$ , 7722-84-1; hydroxyl radical, 3352-57-6; benzoquinone, 106-51-4.

## The Geometry of Displacements at Nonstereogenic Atoms: The Formal Displacement of Alkoxide from Alkoxyamines by Organolithium Reagents

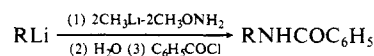
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**Abstract:** Amination of organolithium reagents can be achieved by reaction with methyllithium-alkoxyamines. Details of the methodology and analysis of the reaction mechanism are presented. Reactions of methyl-, ethyl-, *n*-butyl-, *sec*-butyl-, *tert*-butyl-, phenyl-, and (*o*-methoxyphenyl)lithium with methyllithium-methoxyamine give the corresponding amines, isolated as the benzamides, in yields of 71–97%. Lower yields are obtained with *o*-lithio-*N,N*-diisopropylbenzamide, 4-lithiodibenzothiophene, *n*-butylmagnesium bromide, and phenylmagnesium bromide. Reactions of *n*-butyl-, *sec*-butyl-, *tert*-butyl-, and phenyllithium with methyllithium-*N*-methylmethoxyamine provide the corresponding *N*-methyl amines, isolated as the benzamides, in yields of 30–77%. Retention of the *N*-methyl group in these reactions is considered to rule out a nitrene intermediate. Involvement of a lithium alkoxyamide is suggested by the formation and substitution of that species by two different routes. Dilithiation of *N*-methoxy-*N*-[2-(*o*-bromophenyl)ethyl]amine (17) gives, after an intramolecular reaction and addition of acetyl chloride, *N*-acetylindoline, in 78% yield. Dilithiation of *N*-methyl-*N*-[2-(*o*-bromophenyl)ethoxy]amine (19) gives *N*-methyl-*N*-[2-(*o*-acetoxyethyl)phenyl]acetamide (20), after reaction with acetyl chloride. The nitrogen transfer in this conversion is shown by a double labeling experiment to be intermolecular. This result is taken to suggest that the bond angles required for displacement cannot be achieved in a six-membered ring, and the mechanism of the reaction involves a complex in which displacement occurs via an  $\text{S}_{\text{N}}2$ -like transition state. The exocyclic-endocyclic intramolecular-intermolecular test is noted to provide a general approach for determination of the geometry of reactions at nonstereogenic centers.

We have contributed to methodology for the amination of organolithium compounds by development of methyllithium-methoxyamine as a useful reagent.<sup>1-3</sup> The original reaction, discovered by Sheverdina and Kocheshkov for the conversion of

### Scheme 1<sup>a</sup>



<sup>a</sup>  $\text{R} = \text{C}_2\text{H}_5$  (78%), *n*- $\text{C}_4\text{H}_9$  (71%, 77%<sup>b</sup>), *sec*- $\text{C}_4\text{H}_9$  (71%), *t*- $\text{C}_4\text{H}_9$  (80%<sup>b</sup>),  $\text{C}_6\text{H}_5\text{CH}_2$  (97%),  $\text{CH}_2=\text{CHCH}_2$  (78%),  $\text{C}_6\text{H}_5\text{Li}$  (90%),  $\text{CH}_3$  (80%), *o*- $\text{CH}_3\text{C}_6\text{H}_4\text{Li}$  (96%), *o*- $\text{CON}(\text{i-Pr})_2\text{C}_6\text{H}_4\text{Li}$  (14%<sup>c</sup>), 4-dibenzothiophenyl (55%<sup>c</sup>). <sup>b</sup> The solution was heated at reflux for 1 h. <sup>c</sup> The product is isolated as the amine.

one-half an equivalent of an organolithium or Grignard reagent with methoxyamine to the corresponding amine, has been used in a number of laboratories.<sup>4,5</sup> The overall process is a formal

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