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Mechanistic Studies on the Oxidation of Naphthalenes and Methylbenzenes to Quinones with H_2O_2 in the Presence of Pd(II) Catalysts

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The oxidation of naphthalenes and methylbenzenes to quinones with aqueous 60% hydrogen peroxide in the presence of a 0.24% Pd(II)–sulfonated polystyrene-type resin catalyst was studied. The presence of electron-donating substituents on carbon-2 of naphthalenes accelerated the oxidation. A reaction path by way of hydroxylated intermediates to the quinones is proposed.

By using the MINDO/3 method, quantum chemical indices such as the superdelocalizability for electrophilic species (S_r^E) and for radical species (S_r^R), and the net charge (Q_r) of naphthalenes, methylbenzenes, and naphthols were calculated. The activity in the above reaction could be explained in terms of both Q_r and S_r^E. The decrease of the selectivity was correlated with side reactions by radical species attacking the sites of largest S_r^R.

Keywords——oxidation; hydrogen peroxide; naphthalene; methylbenzene; palladium catalyst; 1,4-naphthoquinone; sulfonated polystyrene-type resin

In recent years, much attention has been paid to quinone compounds, since some of them show antibiotic and antitumor activities, as well as being source materials for vitamin E and K group. Previously a novel type of palladium catalyst for the oxidation of 2-methylnaphthalene (I) to 2-methyl-1,4-naphthoquinone (IV) with H_2O_2 was reported from our laboratory.[1] Catalysts prepared from palladium acetate and sulfonated polystyrene-type resin (SP resin) gave quinone yields of 50—60% at reaction temperatures of 50—60 °C; the yields were higher than those with chromic acid.[2] The activity and the selectivity to IV increased with increasing amount of palladium acetate up to 0.24% relative to the support.[3] This catalyst system has also been applied for the oxidation of several methylnaphthalenes and methylbenzenes.[4] Methylnaphthalenes such as 2,3- and 2,6-dimethylnaphthalenes also gave corresponding quinones in 50—70% yields. However, the catalyst system was not effective for the oxidation of methylbenzenes; the rates were low and the selectivities were poor. These results led us to study the oxidation of methylbenzenes and methylnaphthalenes by means of molecular orbital (MO) calculations using the MINDO/3 method[5] in conjunction with theoretical rate analyses.

Experimental

Reagents and Preparation of the Catalysts——Methylbenzenes, naphthalenes, naphthoquinones, phenols, naphthols, and aqueous (30%) H_2O_2 were purchased commercially. Aqueous (60%) H_2O_2 was kindly provided by Mitsubishi Gas Chemical Co. Such quinones as 2,3-dimethyl-1,4-naphthoquinone, 2,6-dimethyl-1,4-naphthoquinone, and 2,3,5-trimethylbenzoquinone were prepared according to the reported methods.[4] Homogeneous $PdSO_4$ catalyst was prepared *in situ* from $Pd(AcO)_2$ and sulfuric acid in acetic acid. The SP resin (DOWEX 50w-x8, 1 g, H form, water content 50%) was conditioned by standing it for 1 h in 30 ml of acetic acid and washing it three times with acetic acid. A 0.24% Pd(II)–SP resin catalyst was prepared from 5 mg of $Pd(AcO)_2$ and the SP resin by stirring in 20 ml of

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acetic acid for 5 h at 50 °C.

General Procedures for Determining Initial Rate of Oxidation——a) Oxidation in a Homogeneous System: Substrate (2.5 mmol), acetic acid (5 ml), $Pd(AcO)_2$ (10 mg), and sulfuric acid (4.6 mg) were added to a 50 ml flask. Then 30% H_2O_2 (0.76 ml, 7.4 mmol) was added to start the reaction at 45 °C. At appropriate time intervals, 0.5 ml of the reaction mixture was pipetted out and diluted with 10 ml of methanol. The initial rate was determined from the decrease of the substrate at each time.

b) Oxidation in a Heterogeneous System: Substrate (5.0 mmol), acetic acid (20 ml), and the Pd(II)–SP resin catalyst (2 g) were added to a 50 ml flask. Then 60% H_2O_2 (0.7 ml, 15.6 mmol) was added to start the reaction at 50 °C. The substrates and the products were analyzed by high-performance liquid chromatography (HPLC) (M&S pack C-18, 4.6 × 150 mm column, Gilson Co. model 302) using MeOH or MeOH–H_2O (100 : 15) as the eluent (flow rate, 0.5 ml/min; detector, ultraviolet (UV) at 250 or 285 nm). 2,6-Dimethylnaphthalene was used as an internal standard.

Molecular Orbital Calculations——MO calculations were carried out using one of the semiempirical MINDO/3 methods according to the literature.[5] In order to compare the activity and the selectivity of methylbenzenes and naphthalenes, the atomic reactivity indices for the electrophilic species, S_r^E, and radical species, S_r^R, were calculated from eigenvectors and eigenvalues as approximate superdelocalizabilities[6] according to the following equations

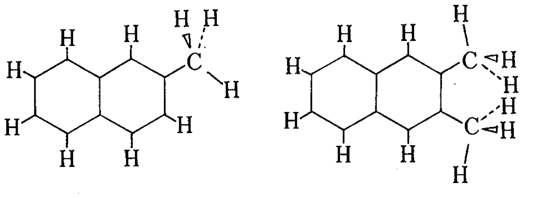
$$S_r^E = 2\sum_v^r [C_v(\mathrm{HOMO})]^2 / -E(\mathrm{HOMO})$$

$$S_r^R = \sum_v^r [C_v(\mathrm{HOMO})]^2 / -E(\mathrm{HOMO}) + \sum_v^r [C_v(\mathrm{LUMO})]^2 / E(\mathrm{LUMO})$$

where C_v(HOMO) and C_v(LUMO) are the atomic orbital coefficients of X_v, in the highest occupied and the lowest unoccupied molecular orbitals with the energy of E(HOMO) and E(LUMO), respectively. The summation was done over the atomic orbitals which belong to the r-th atom. The net charge, Q_r, for carbon atoms is given as follows

$$Q_r = 4 - 2\sum_i^{\mathrm{occ}} \sum_v^r (C_{iv})^2$$

where C_{iv} is the atomic orbital coefficient of X_v, in the i-th molecular orbital. The second summation was done over the atomic orbitals which belong to the r-th atom. The atomic coordinates of the substrates such as naphthalenes, methylbenzenes, and phenols were obtained using the standard bond lengths and valence angles.[7] Optimization with respect to the rotation of methyl groups was carried out for 2-methylnaphthalene (A) and 2,3-dimethylnaphthalene (B). The results are shown in Chart 1, and the orientations of methyl groups in other naphthalenes and methylbenzenes were taken to be similar.



A B

Chart 1

TABLE I. Oxidation Rates of 2-Substituted Naphthalenes

Substrate	Initial rate[a) $\times 10^{-4}\,\mathrm{mol \cdot l^{-1} \cdot min^{-1}}$
2-Methoxynaphthalene	92.6
2-Methylnaphthalene	18.7
Naphthalene	8.3
2-Chloronaphthalene	4.8
2-Nitronaphthalene	0.6

Substrate (5 mmol), 60% H_2O_2 (0.7 ml, 15.6 mmol), 0.24% Pd(II)–SP resin (DOWEX 50w-x8, 200—400 mesh) (2 g), and AcOH (20 ml) were used. The oxidation was carried out at 50 °C. *a*) Rate of decrease of the substrate.

The orientation of the OH group in each hydroxylated compound was determined by selecting the most stable one among several in-plane and perpendicular-to-the-plane structures of the naphthalene or benzene skeletons. In 2,3-dimethyl-1-naphthol, 2,3,5,6-tetramethylphenol, and 2,3,6-trimethylphenol, the perpendicular orientation was the most stable, and in other compounds, the in-plane orientation was favorable.

Results and Discussion

Rates of Oxidation of I

In the oxidation of I with H_2O_2, strong coordination of anions to Pd(II) ion increased the activity.[3] These results suggested that the oxidation occurred catalytically on the Pd complexes. Therefore, at first, the order of the substrate in the rate equation was estimated. The logarithm of initial oxidation rate was plotted against the logarithm of the concentration of I. The slope afforded the order, 0.45. The effects of the concentrations of other components such as H_2O_2, H_2SO_4, and Pd(II) ion on the oxidation rate were also estimated by fixing the concentration of other components. The rate equation at 45 °C was obtained as follows (I was denoted as 2-MN).

$$v=k[\text{2-MN}]^{0.45}[H_2O_2]^{0.86}[H_2SO_4]^{1.1}[\text{Pd(II)}]^{1.0}$$

Lineweaver–Burk plots of the oxidation rates of I at various concentrations gave the K_m value of 0.16. This value indicates a rather weak interaction between the Pd(II) ions and I, since most enzymes take small K_m values of 10^{-2}—10^{-5}.[8] In fact, the UV and visible spectra of a mixture of $Pd(II)SO_4$ and I in acetic acid were the same as the sum of those of the components. No shift of the spectra was observed on the addition of H_2O_2. A smaller order than unity for H_2O_2 suggested that the mechanism is complicated, since peracetic acid was formed from H_2O_2 and acetic acid. Almost 96% of H_2O_2 had been changed into peracetic acid after 20 min at 50 °C; H_2O_2 in acetic acid was titrated separately with potassium permanganate solution followed by iodimetric titration for peracetic acid in the same sample.[9] The concentration of sulfuric acid also affected the oxidation rate; mineral acids or fluoroacetic acid themselves accelerate the oxidation.[10]

Effect of Substituents

The activity depended markedly on the nature of the substituent on naphthalene.

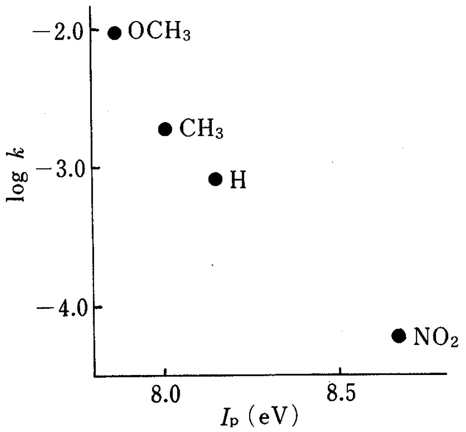


Fig. 1. Relationship between the Initial Oxidation Rates of 2-Substituted Naphthalenes and I_p

Substrate (5.0 mmol), 60% H_2O_2 (0.7 ml, 15.6 mmol), 0.24% Pd(II)-SP resin (DOWEX 50w-x8, 200—400 mesh) (2 g), and AcOH (20 ml) were used. The oxidation was carried out at 50 °C.

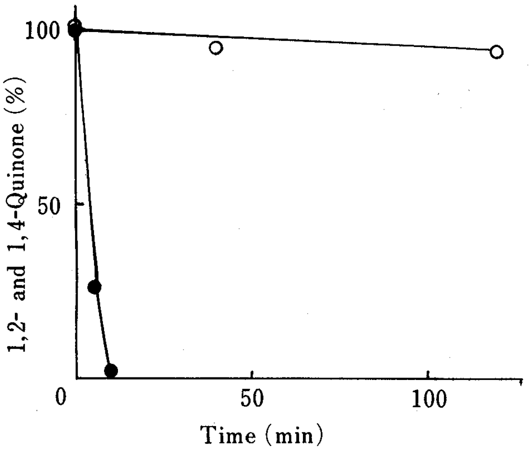


Fig. 2. Decomposition of 1,2- and 1,4-Naphthoquinone with 60% H_2O_2

Quinone (200 mg), 60% H_2O_2 (0.7 ml, 15.6 mmol), 0.24% Pd(II)-SP resin (DOWEX 50w-x8, 200—400 mesh) (2 g), and AcOH (20 ml) were used. The oxidation was carried out at 50 °C. ○, 1,4-naphthoquinone; ●, 1,2-naphthoquinone.

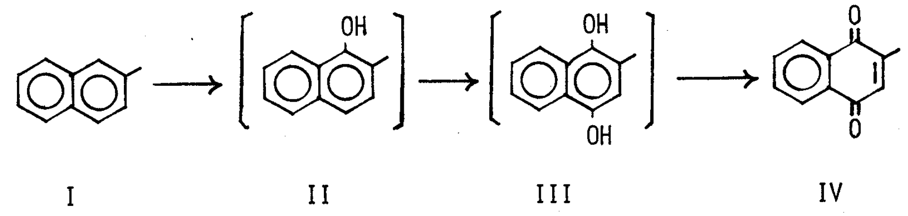
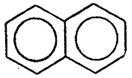
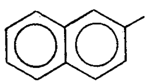
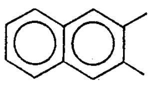
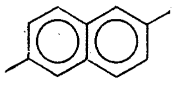
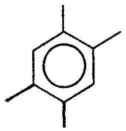
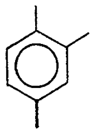
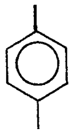


Chart 2

TABLE II. Atomic Reactivity Indices and Initial Rates of Methylbenzenes and Naphthalenes

Substrate	Ind.[a]	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	Initial rate[b] $\times 10^{-5}$ mol·l^{-1}·min^{-1}
	Q_r	−0.017	0.005	0.005	−0.017	−0.017	0.005	0.005	−0.017	0.039	0.039	82.5
	S_r^E	0.044	0.017	0.017	0.044	0.044	0.017	0.017	0.044	0.000	0.000	
	S_r^R	0.573	0.233	0.233	0.573	0.573	0.233	0.233	0.573	0.000	0.000	
	Q_r	−0.032	0.018	−0.008	−0.012	−0.015	0.002	0.006	−0.019	0.043	0.035	186.6
	S_r^E	0.048	0.021	0.013	0.042	0.042	0.020	0.014	0.044	0.000	0.000	
	S_r^R	0.618	0.272	0.212	0.603	0.580	0.254	0.226	0.586	0.000	0.000	
	Q_r	−0.026	0.005	0.005	−0.026	−0.017	0.004	0.004	−0.017	0.038	0.038	167.0
	S_r^E	0.046	0.016	0.016	0.046	0.043	0.017	0.017	0.043	0.000	0.000	
	S_r^R	0.624	0.243	0.243	0.624	0.580	0.239	0.239	0.580	0.000	0.000	
	Q_r	−0.030	0.017	−0.006	−0.014	−0.030	0.017	−0.006	−0.014	0.038	0.038	300.0
	S_r^E	0.045	0.023	0.010	0.042	0.045	0.023	0.010	0.042	0.000	0.000	
	S_r^R	0.630	0.296	0.206	0.620	0.630	0.296	0.206	0.620	0.001	0.001	
	Q_r	0.004	0.004	−0.014	0.004	0.004	−0.014					68.8
	S_r^E	0.049	0.049	0.000	0.049	0.049	0.000					
	S_r^R	0.238	0.238	0.000	0.238	0.238	0.000					
	Q_r	0.000	0.008	−0.018	0.017	−0.009	0.000					36.7
	S_r^E	0.064	0.034	0.004	0.057	0.034	0.005					
	S_r^R	0.289	0.171	0.013	0.272	0.165	0.019					
	Q_r	0.013	−0.004	−0.004	0.013	−0.004	−0.004					19.2
	S_r^E	0.064	0.016	0.019	0.064	0.016	0.019					
	S_r^R	0.300	0.065	0.093	0.300	0.065	0.093					

Substrate (5.0 mmol), 60% H_2O_2 (0.7 ml, 15.6 mmol), 0.24% Pd(II)-SP resin (DOWEX 50w-x8, 200—400 mesh) (2 g), and AcOH (20 ml) were used. The oxidation was carried out at 50 °C. *a*) Atomic reactivity indices; Q_r, net charge, S_r^E, approximate superdelocalizability for the electrophilic species; S_r^R, approximate superdelocalizability for the radical species. *b*) Rate of decrease of the substrate.

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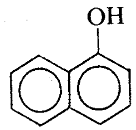
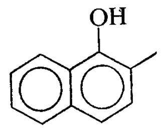
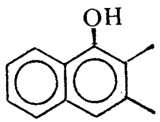
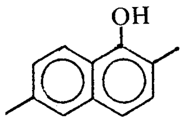
TABLE III. Atomic Reactivity Indices for the Monohydroxylated Naphthalenes and the Selectivities from Monohydroxylated Naphthalenes and Naphthalenes to 1,4-Quinones

Substrate	Ind.	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	Select.[a] OH (%)	Select.[b] HC (%)
	S_r^R	0.424	0.134	0.145	0.334	0.428	0.238	0.129	0.486	0.013	0.001		32
	Q_r	0.362	−0.173	0.074	−0.096	−0.043	0.030	−0.025	0.026	−0.060	0.090		
	S_r^E	0.037	0.030	0.016	0.058	0.038	0.010	0.020	0.031	0.002	0.000		
	S_r^R	0.467	0.159	0.130	0.353	0.439	0.265	0.122	0.506	0.017	0.004	64	32
	Q_r	0.350	−0.151	0.059	−0.091	−0.041	0.029	−0.023	0.025	−0.057	0.087		(55)[c]
	S_r^E	0.039	0.034	0.013	0.056	0.036	0.011	0.018	0.031	0.001	0.000		
	S_r^R	0.629	0.204	0.222	0.531	0.541	0.262	0.198	0.585	0.003	0.002		53
	Q_r	0.321	−0.110	0.047	−0.079	−0.034	0.023	−0.015	0.016	−0.059	0.074		
	S_r^E	0.042	0.024	0.015	0.053	0.039	0.013	0.018	0.035	0.000	0.000		
	S_r^R	0.464	0.177	0.115	0.355	0.469	0.312	0.099	0.523	0.027	0.007		50
	Q_r	0.352	−0.153	0.061	−0.093	−0.056	0.042	−0.036	0.030	−0.061	0.090		
	S_r^E	0.038	0.035	0.012	0.056	0.039	0.013	0.015	0.030	0.000	0.000		

a) The selectivity was obtained from the ratio of the initial rate of the 1,4-quinone formation to that of the overall oxidation of monohydroxylated naphthalenes. *b*) The selectivity was obtained from the ratio of the initial rate of the 1,4-quinone formation to that of the overall oxidation of naphthalenes. *c*) The selectivity after 8 h.

Electron-donating substituents accelerated the oxidation. The oxidation rates for the 2-substituted naphthalenes were in the order of MeO > Me > H > Cl > NO_2 (Table I).

In the oxidation of naphthalene, the yield of 1,4-naphthoquinone (VI) was as low as 13%. On the other hand, I and 2,3-dimethyl- and 2,6-dimethylnaphthalene were easily oxidized to give the corresponding 1,4-quinones with selectivity of 50—70%. However, methylbenzenes such as 1,4-dimethyl-, 1,2,4-trimethyl-, and 1,2,4,5-tetramethylbenzene (VIII) gave only 3—8% yields with 37—78% conversions.[4)]

Usually a lower reaction temperature increases the selectivity. However, in this case, the selectivities from I to IV were 37% at 20 °C and 68% at 70 °C.[4)] These results suggest the involvement of two different types of active species, *e.g.*, the ionic species working dominantly at higher temperatures to give IV effectively and the radical species working at lower temperatures to give by-products. This hypothesis was supported by the results of MINDO/3 calculations. As was described in the previous section, the weak coordination of 2-methylnaphthalene to Pd(II) ion allowed us to calculate the electronic state of each naphthalene as an isolated system. Q_r, S_r^E, and S_r^R were each calculated, and the results are summarized in Table II.

Both Q_r and S_r^E on carbon-1 of naphthalene and methylnaphthalenes were the highest among all the substrates examined. Furthermore, the rates increased with increasing Q_r and S_r^E. In fact, the ionization potentials, I_p, , experimentally obtained[11)] showed a good correlation with the oxidation rates (Fig. 1), since S_r^E implies I_p, from Koopman's theorem.

Therefore, it was considered that the first step of the oxidation occurred by the attack of electron-deficient species such as OH^+ [12)] or weakly dissociated $OH^{\delta+}$ [13)] bound to Pd(II) ion on carbon-1 of naphthalenes, followed by hydroxylation at carbon-4 at higher temperatures (Chart 2). The oxidation rates from I to IV, from II to IV, and from III to IV were 5.9×10^{-4}, 7.2×10^{-3}, and 1.5×10^{-1} $mol \cdot l^{-1} \cdot min^{-1}$, respectively, under the same reaction conditions as those in Table I. These results show that the oxidation of I to II is the rate-determining step.

Selectivity to 1,4-Naphthoquinones

The selectivity of oxidation of 2-methylnaphthol or naphthalenes to 1,4-quinones is shown in Table III. The selectivity from I to IV mainly relied upon the pathway from II to III, since the selectivity from II to IV was almost the same as that from I to IV and the oxidation of III to IV was fast and quantitative. Since the coordination of II to Pd(II) ion was weak as evaluated from Lineweaver–Burk plots ($K_m = 2.7 \times 10^{-2}$), the MOs for several naphthols were calculated.

In the oxidation of naphthalene (V), VI and tar compounds were obtained. From the MO for V (Table II), oxidation at carbon-1, -4, -5, and -8 seems most probable. However, in the successive oxidation of 1-naphthol to VI, the values of Q_r and S_r^E in Table III showed that carbon-2 and -4 were reactive. Therefore, the formation of both VI and 1,2-naphthoquinone (VII) is possible. The stability of VI and VII in our reaction system was next examined, and the results are shown in Fig. 2.

The rate of decomposition of VII was 300 times faster than that of VI. Therefore, it might be difficult to confirm that VII had been produced during the reaction.

Although the selectivity from II to IV (64%) differed from that from I to IV (32%) at the initial oxidation period, the selectivity from I to IV increased gradually to reach 55% after 8 h; a higher initial concentration of H_2O_2 might have decreased the selectivity.

However, the reasons for the slow oxidation rates and the poor selectivity from methylbenzenes to 1,4-quinones are still ambiguous, since a substrate such as VIII, which has no vacant sites except carbon-3 and -6 also gave a low yield. As shown in Table IV, the oxidation rate from supposed intermediates of 2,3,5,6-tetramethylphenol or 2,3,5,6-tetramethylhydroquinone to 2,3,5,6-tetramethyl-*p*-benzoquinone (IX) was fast and the selectivi-

TABLE IV. Oxidation Rates of 1,2,4,5-Tetramethylbenzene, 2,3,5,6-Tetramethylphenol, and 2,3,5,6-Tetramethylhydroquinone to 2,3,5,6-Tetramethyl-*p*-benzoquinone

Substrate	Initial rate[a] $\times 10^{-5}\,\mathrm{mol \cdot l^{-1} \cdot min^{-1}}$	Selectivity[b] (%)
1,2,4,5-Tetramethylbenzene	4.9	7
2,3,5,6-Tetramethylphenol	885.6	47
2,3,5,6-Tetramethylhydroquinone	too fast to measure	100

Substrate (5.0 mmol), 60% H_2O_2 (one equivalent with respect to the substrate), 0.24% Pd(II)–SP resin (DOWEX 50w-x8, 200—400 mesh) (2 g), and AcOH (20 ml) were used. The oxidation was carried out at 50 °C. *a*) Rate of formation of 2,3,5,6-tetramethyl-*p*-benzoquinone. *b*) The selectivity to 2,3,5,6-tetramethyl-*p*-benzoquinone.

ties were high.

These results indicate that the low selectivity from VIII to IX is due to the poor hydroxylatability of VIII. Therefore, Q_r, S_r^E, and S_r^R of methylbenzenes were calculated and the values were compared with those of naphthalenes (Table II).

In the oxidation of I, Q_r and S_r^E at carbon-1 were the largest. On the other hand, in VIII the largest Q_r was at carbon-3 while S_r^E at carbon-3 was zero. Though the I_p values of I (8.01 eV) and VIII (8.05 eV) were almost the same, the oxidation to the latter was considerably slower; the former reaction was 2.7 times faster under the same reaction conditions. These results suggest that both large Coulomb interaction (Q_r) and charge transfer (S_r^E) are required for the hydroxylation.

As regards side reactions, a large interaction with radical species was apparent at carbon-8 of 1-naphthols, at carbon-1, -2, -4, and -5 of VIII, at carbon-1 and -4 of 1,2,4-trimethylbenzene, and at carbon-1 and -4 of 1,4-dimethylbenzene. Liquid chromatography showed that the by-products of methylbenzenes were more polar than the quinones. The hydrogen atoms of methyl or phenoxyl groups are known to be oxidized easily by radical species to give carboxylic acids or polymerized quinone compounds. In fact, polymerized red-colored products were separated from the reaction products of I after the extraction of IV with hexane followed by ethyl acetate. Tar products were also obtained with both 2,3- and 2,6-dimethylnaphthalene. Thus, it is considered that the selectivity to the quinones is decreased as a result of many kinds of side reactions caused by radical species.

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