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KINETICS OF THE AROMATIC HYDROXYLATION WITH PERMONOPHOSPHORIC ACID

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Abstract—Oxidation of phenol, anisole and toluene with permonophosphoric acid in acetonitrile or water gives the corresponding *ortho* and *para* hydroxylated aromatics ($HO{-}C_6H_4{-}X$, X = OH, OMe, Me). The observed *ortho* : *para* ratio in a solvent acetonitrile are as follows: 5·0 with phenol, 3·5 with anisole and 2·0 with toluene. The oxidation rates for phenol and anisole in acetonitrile are expressed as: $v = k''[ArH][H_3PO_5]^2 h_0$, where h_0 is the Hammett's acidity function and ArH is phenol or anisole. A mechanism involving a rate-determining attack of protonated dimeric perphosphoric acid **4** on aromatic carbon is presented and discussed.

The preparation of permonophosphoric acid was established by Schmidlin and Massini in 1910.[1] Since then various techniques for its preparation[2,3] and isolation[4] have been postulated and decomposition mechanisms[5] and dissociation constants[6,7] have been reported. But in the field of oxidation of organic compounds by this peracid, the only available data are the reaction of aromatic amines with permonophosphoric acid, yielding aminophenol, amine oxide and azo compounds etc.[8] Although hydroxylations of aromatic carbon by various peroxy reagents have been studied, e.g., the hydroxylation of phenol and alkylbenzenes with CH_3CO_3H,[9] CF_3CO_3H,[10] $CF_3CO_3H{-}BF_3$[11,12] $H_2O_2{-}BF_3$,[13] there seems to be no kinetic studies probably because the secondary oxidation accompanied by the formation of tarry material proceeds faster than the primary hydroxylation, hence the reaction is complicated.

The present paper describes principally the kinetics and mechanism for the oxidation of phenol with permonophosphoric acid in dry acetonitrile to give catechol and hydroquinone. The rates of oxidation were measured by means of GLC analysis of phenol and iodometry of peracid. In order to ensure the mechanism, the oxidation of anisole and toluene with permonophosphoric acid in acetonitrile yielding the corresponding *ortho* and *para* hydroxlated aromatics were studied.

RESULTS

Products and their o/p *ratio.* Phenol, anisole and toluene were oxidized with permonophosphoric acid (H_3PO_5) in acetonitrile, water or deuterium oxide as a solvent, yielding *ortho* and *para*-hydroxylated aromatics, but virtually no *meta* isomer. Further oxidation of products is suppressed by using a large excess of the aromatic to an equivalent amount of H_3PO_5. Permonophosphoric acid in water may be hydrolyzed to give H_2O_2, which, however, cannot attack the substrate under these conditions and thus exerts no effect on the *ortho* : *para* ratio of products.

The *o*/*p* ratio measured by GLC analysis are listed in Table 1.

When an equimolar mixture of catechol and hydroquinone is oxidized with an equivalent

Table 1. The *ortho* : *para* ratio (*o*/*p*) of products for oxidation of substituted benzenes (PhX) with H_3PO_5

X	Solvent	Temp. (°C)	Reaction time (h)	pH	(*o*/*p*)
OH	H_2O^a	50	9	−0·079	1·76
OH	H_2O^a	50	9	0·699	1·93
OH	H_2O^a	50	9	1·08	1·85
OH	H_2O^a	50	9	5·10	2·90
OH	H_2O^a	50	9	9·80	8·55
OH	H_2O^a	50	9	11·1	large
OH	D_2O^a	50	9	1·08	5·5
OH	CH_3CN^b	0	0·5	—	5·0
OH	CH_3CN^b	0	1	—	5·0
OH	CH_3CN^b	0	3	—	5·0
OH	CH_3CN^b	0	6	—	5·0
OMe	CH_3CN^b	0	0·5	—	3·5
OMe	CH_3CN^b	0	1	—	3·5
OMe	CH_3CN^b	0	3	—	3·5
OMe	CH_3CN^b	0	6	—	3·5
Me	CH_3CN^b	0	0·5	—	2·0
Me	CH_3CN^b	0	1	—	2·0
Me	CH_3CN^b	0	3	—	2·0
Me	CH_3CN^b	0	6	—	2·0

$^a[PhX]_0 = 0{\cdot}106$ M, $[H_3PO_5]_0 = 0{\cdot}106$ M, where $[\,]_0$ means initial concentration.

$^b[PhX]_0 = 0{\cdot}700$ M, $[H_3PO_5]_0 = 0{\cdot}0500$ M.

amount of H_3PO_5 in water, the molar ratio of remaining catechol to hydroquinone is held almost constant (*ca* 1), which is independent of pH of the solution (Table 2).

Table 2. Competitive reaction of catechol (Cat) and hydroquinone (Hyd) with the equivalent amount of H_3PO_5 in water at 50° for 7 h

pH	Remaining Cat (%)	Remaining Hyd (%)	Cat/Hyd
0·00	81	63	1·3
1·08	97	81	1·2
9·00	57	47	1·2

Initial concns. $[\mathrm{Cat}]_0 = 0{\cdot}106$ M, $[\mathrm{Hyd}]_0 = 0{\cdot}106$ M.

Hence, the observed high *o*/*p* ratio would not be a result of the faster consumption of hydroquinone.

Kinetics for phenol. The rate of oxidation of phenol with an excess of H_3PO_5 was measured in acetonitrile at 0° by following a decrease of phenol concentration by GLC. The effect of decreasing the H_3PO_5 concentration by the further oxidation of products was minimized by the use of a large excess of H_3PO_5; further, since dry acetonitrile was used as a solvent, the influence of H_2O_2 which may be formed by an equilibrium with water ($H_3PO_5 + H_2O \rightleftharpoons H_3PO_4 + H_2O_2$) needs no consideration. Furhter, the rate of H_2O_2 oxidation of phenol is negligible, because the yield of expected oxidation product is below 0·08%.[14] The second-order plot ($[\mathrm{PhOH}]^{-1}$ *vs* time) gives a straight line, and hence the rate equation is expressed as:

$$v = k_{\mathrm{obs}}[\mathrm{PhOH}]^2. \qquad (1)$$

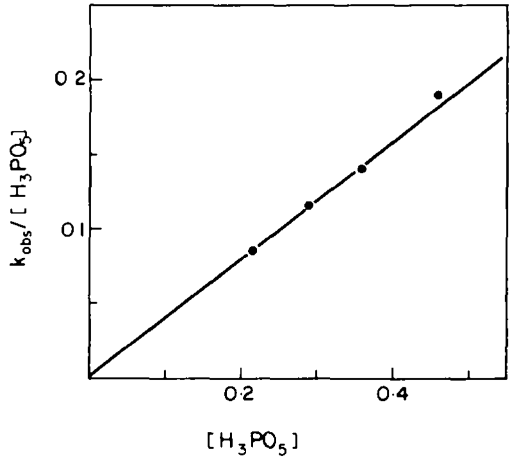


Fig 1. The plot of $k_{\mathrm{obs}}/[H_3PO_5]$ *vs* $[H_3PO_5]$. (GLC analysis method).

Table 3. Second-order rate constants for the reaction of phenol with permonophosphoric acid in acetonitrile at 0°

$[H_3PO_5]_0$ M	k_{obs} M^{-1} sec^{-1}	$k_{\mathrm{obs}}/[H_3PO_5]_0$ M^{-2} sec^{-1}
0·213	0·0177	0·0830
0·286	0·0330	0·115
0·360	0·0501	0·139
0·460	0·0874	0·190

Initial concn. $[\mathrm{PhOH}]_0 = 0{\cdot}0053$ M.

Since a plot of $k_{\mathrm{obs}}/[H_3PO_5]$ *vs* $[H_3PO_5]$ affords a straight line (Fig 1 and Table 3), the more accurate kinetic equation is as follows:

$$v = -\frac{\mathrm{d}[\mathrm{PhOH}]}{\mathrm{d}t} = [\mathrm{PhOH}]^2(k'_p[H_3PO_5] + k''_p[H_3PO_5]^2). \qquad (2)$$

Here, k'_p and k''_p can be calculated from the intercept and the slope of the line in Fig 1 to be less than 0·005 sec^{-1} M^{-2} for k'_p and 0·40 sec^{-1} M^{-3} for k''_p, i.e., the rate is almost second-order in H_3PO_5.

Secondly, a decrease of H_3PO_5 in acetonitrile at 0° was measured iodometrically with an excess of phenol to minimize the secondry oxidation. The second order plot for H_3PO_5 ($[H_3PO_5]^{-1}$ *vs* time) gave a straight line, whose slope afforded the second-order rate constant, k'_{obs}, and further the following equation.

$$v = -\frac{\mathrm{d}[H_3PO_5]}{\mathrm{d}t} = k'_{\mathrm{obs}}[H_3PO_5]^2 = k''_p[\mathrm{PhOH}]^2[H_3PO_5]^2. \qquad (3)$$

The kinetic data are listed in Table 3. Apparently, the value of k''_p (0·42 sec^{-1} M^{-3}) obtained by following the decrease of H_3PO_5 is close to the value of k''_p (0·40 sec^{-1} M^{-3}) obtained by following the decrease of phenol (Eq 2).

On the other hand, the rate in the presence of H_2SO_4 as a catalyst, which was measured by the same method (iodometry), was found to be first-order with respect to phenol. The acidity function H_0 of this acetonitrile solution of H_2SO_4 was determined by Braude's method,[15] and a plot of log (k'_{obs}) *vs* H_0 gave a straight line with a slope of −1 (Fig 2). Therefore, the rate in this case is expressed:

$$v = k''_p[\mathrm{PhOH}][H_3PO_5]^2h_0 \qquad (4)$$

where $\log h_0 = H_0$.

Kinetics for anisole.[16] The rate of oxidation of anisole with H_3PO_5 in acetonitrile at 0° was measured by means of iodometry of H_3PO_5 (Table 4 and Fig 3), where the secondry oxidation is also suppressed by the use of much excess anisole. As apparent from Fig 3, the rate expression is:

$$v = k''_A[\mathrm{PhOMe}][H_3PO_5]^2h_0. \qquad (5)$$

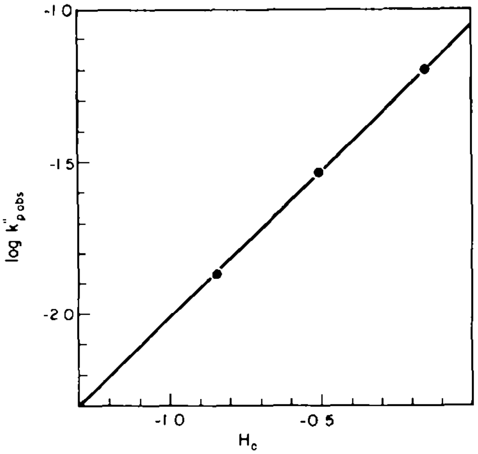


Fig 2. The plot of $k''_{P,obs}$ vs H_0. (Iodometry method).

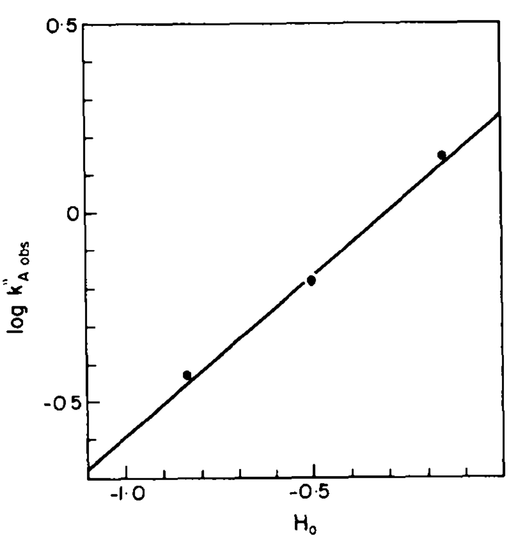


Fig 3. The plot of $k''_{A,obs}$ vs H_0. (Iodometry method).

Here log $h_0 = H_0$. Thence the $[H_3PO_5]^2$ term is much more important than the $[H_3PO_5]$ term as stated with the reaction of phenol (Eqs 2 and 4).

DISCUSSION

ortho : para *Ratio.* The oxidation of phenol with peroxycarboxylic acid gives usually a higher yield of catechol than hydroquinone.[9] The same is true with this H_3PO_5 oxidation. It is of interest to note that the *ortho* position suffering the steric hindrance is hydroxylated in a higher yield than the *para* position. McClure *et al.* postulated for the explanation of this high *o*/*p* ratio that produced hydroquinone was consumed faster than catechol in the CF_3CO_3H oxidation.[10] However, the analogous rates of oxidation of hydroquinone and catechol with H_3PO_5 were observed in acetonitrile (k''_C = 17 sec^{-1} M^{-3} for catechol and k''_H = 6·3 sec^{-1} M^{-3} for hydroquinone at 0°), and similar results were observed in water solution as shown in Table 2.

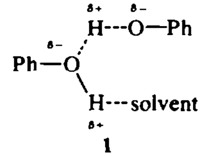
Table 4. The rate constant from Eq: $v = k''_{A,obs}[H_3PO_5]^2[PhOMe]$ for the reaction of anisole with H_3PO_5 in acetonitrile at 0°

$[PhOMe]_0$ M	$10^4 k''_{A,obs}$ sec^{-1} M^{-2}
0·376	1·83
0·526	1·85
0·677	1·65

Therefore, the high *o*/*p* ratio is not caused by the further oxidation of products, but probably by the acceleration of reaction with the H-bonding at *ortho* position. Table 1 shows that the *o*/*p* ratio in the oxidation of phenol decreases with increasing solvation ability which is $H_2O > CH_3CN$. In other words, the higher ability for the H-bonding between OH groups of phenol and peracid tends to increase the *o*/*p* ratio. Increasing solvation towards a solvent decreases the H-bonding ability of phenol and hence *o*/*p* ratio. The decrease of *o*/*p* ratio in the order of phenol > anisole > toluene (Table 1) supports this assumption.

Kinetics and mechanism. As stated above, the kinetics of oxidation of phenol was studied under the exclusion of water, i.e., H_2O_2. In view of Eqs 2 and 3, the rate is each second-order in phenol and H_3PO_5 in the absence of H_2SO_4. Here, the value of k'_p is so small compared with the value of k''_p that it is negligible at rather high concentration of H_3PO_5.

The presence of the $[PhOH]^2$ term in the rate Eq (3) can be explained by assuming that H-bound dimeric phenol is more active than monomeric form because of the increased nucleophilicity of phenol.[17,18] Our following observations support this assumption. (i) The rate becomes first-order with phenol in the presence of H_2SO_4. (ii) First-order kinetics with acidity function h_0. (iii) The rate of H_2SO_4-catalyzed oxidation of anisole having no dissociating proton is first-order in anisole (Table 4).

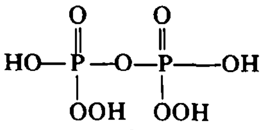


1

Goh *et al.* suggested that peroxydiphosphoric acid **2** hydrolyzed to give H_3PO_5 and H_3PO_4 (Eq 6).[6] Since the hydrolysis was reported to be reversible,[19] H_3PO_5 may give **2** by the following equilibrium.[19]

$$H_3PO_5 + H_3PO_4 \rightleftharpoons \underset{\mathbf{2}}{H_4P_2O_8} + H_2O \qquad (6)$$

This fact suggests the presence of dimeric form of perphosphoric acid (**3**) in an aprotic solvent, acetonitrile. Dimeric form **3** should be an acid stronger than monomeric H_3PO_5 because of the presence of an electron-withdrawing –OP=O group as in the case of H_3PO_4 (pK_a = 2·12) and dimeric



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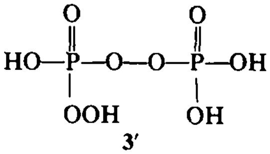
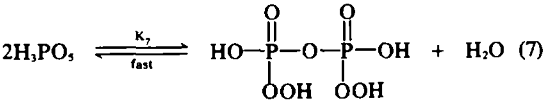


3′

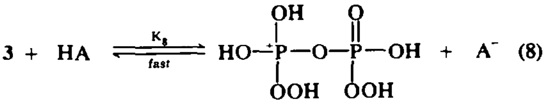
one, $H_4P_2O_7$ ($pK_a = 0{\cdot}854$) at 25°. This stronger acidity should endow the peracid 3 with a higher reactivity of oxidation,[16] and 3 should be a stronger attacking reagent than H_3PO_5, since the oxidation seems to involve an electrophilic attack of HO^+.[20] Another dimeric peracid 3′, which may be also formed from permonophosphoric acid, should have a less acidity and a less reactivity than 3 because of the poorer electron-withdrawing ability of -O-O-P=O than -O-P=O. Further, 3 have two active groups of -OOH, whereas 3′ have one. Hence, 3 should be the most probable reagent in this reaction.

The rate Eq (4) for the acid-catalyzed oxidation of phenol implies the participation of two molecules of H_3PO_5, one molecule of phenol and one proton in the rate-determining step. This rate behaviour can be explained by the following scheme, where HA is a catalyst acid.



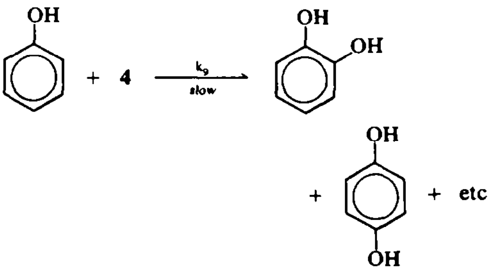
$$2H_3PO_5 \underset{fast}{\overset{K_7}{\rightleftharpoons}} HO-\overset{O}{\underset{OOH}{P}}-O-\overset{O}{\underset{OOH}{P}}-OH + H_2O \quad (7)$$

3



$$3 + HA \underset{fast}{\overset{K_8}{\rightleftharpoons}} HO-\overset{OH}{\underset{OOH}{\overset{+}{P}}}-O-\overset{O}{\underset{OOH}{P}}-OH + A^- \quad (8)$$

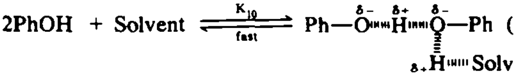
4



(9)

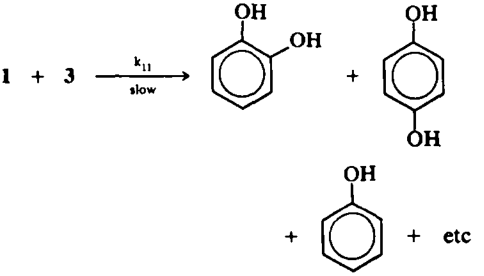
Dimeric acid 3, produced by a mobile equilibrium 7, gives on protonation 4, which reacts with phenol to produce catechol and hydroquinone.

The mechanism in the absence of catalyst acid may be as follows.



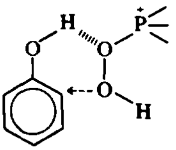
$$2PhOH + Solvent \underset{fast}{\overset{K_{10}}{\rightleftharpoons}} Ph-\overset{\delta-}{O}\cdots\overset{\delta+}{H}\cdots\underset{\overset{\vdots}{\delta+H\cdots Solvent}}{\overset{\delta-}{O}}-Ph \quad (10)$$

1

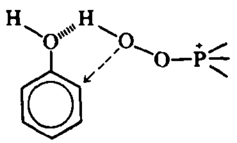


(11)

The observed higher o/p ratio for phenol than for anisole and toluene suggested the acceleration of reaction through the H-bonding such as **5** and/or **6**.



5



6

When step (11) and step (9) determines the rate, these mechanisms lead to rate expressions, respectively

$$v = k_{11}K_7K_{10}[H_3PO_5]^2[PhOH]^2 \quad (12a)$$

$$v = k_9K_7K_8[H_3PO_5]^2[PhOH][H^+]. \quad (12b)$$

This is consistent with the observed Eqs 3 and 4, respectively.

An attack of monomeric H_3PO_5 may be so slow that it can be neglected in the absence of mineral acid catalyst in view of the k'_p value which is much lower than the k''_p value in Eq 2.

EXPERIMENTAL

Materials. Acetonitrile was distilled from P_2O_5 in an all-glass apparatus under a high reflux ratio, b.p. 81–82°. Phenol (b.p. 181–182°), anisol (b.p. 155–156°) and toluene (b.p. 110–111°) were purified by distillation before use. All organic reagents were protected carefully from the atmospheric moisture. Hydroquinone (m.p. 169°) and catechol (m.p. 104°) were of guaranteed grade and used without further purification. Other o- and p-hydroxy aromatics are of commercial source.

Preparation of permonophosphoric acid. To a suspension of P_2O_5 (14·2 g) in MeCN (30 ml) was added an MeCN (10 ml) soln of 90% H_2O_2 (7·5 g) with stirring at − 5 to − 10° for 1 h. The mixture was stirred at *ca* 20° for additional 6 h. The soln contains 2·0–2·5 M H_3PO_5 at completion of the reaction. The yield of peracid was

10·8 g (48%) and virtually no H_2O_2 remained. The content of peracid was analysed iodometrically before use. The content of H_2O_2 was estimated by the $KMnO_4$ titration. The prepared H_3PO_5 can be stored as an MeCN soln in a refrigerator for a month with below 70% decrease of the content.

Oxidation

(A). *Oxidation in aqueous solution.* Phenol was oxidised by H_3PO_5 in H_2O at 50° in a thermostat, and analysed by GLC in the following way. The produced dihydroxybenzenes were converted to their dimethyl ethers by the treatment with alkaline dimethyl sulfate. The produced dimethoxybenzenes were added with acetophenone as an internal standard for GLC, extracted with ether and analysed by GLC using a Yanagimoto gas chromatograph Model 550F with a hydrogen ionization detector with a 3 mm × 1·5 m column of 3% Apiezon grease L on Chromosorb W with N_2 as a carrier gas in a flow rate of 15 ml/min.

(B). *Oxidation in acetonitrile.* Phenol was oxidized by H_3PO_5 in dry MeCN. The product soln was added with *p*-cresol as an internal standard for GLC, extracted with ether, washed with KI aq and then $Na_2S_2O_3$ aq and dried (Na_2SO_4). Identification and estimation of products were carried out by means of GLC using a Yanagimoto gas chromatograph Model 550F with a 3 mm × 1·2 m column of 13% polydiethylene glycol succinate on Chromosorb W with N_2 as a carrier gas in a flow rate of 15 ml/min.

Acidity function. All solns were prepared before use. The indicator ratio (I) for *p*-nitroaniline in an MeCN soln of H_2SO_4 was determined by means of UV spectrophotometry and the acidity function (H_0) was calculated from the indicator ratio by means of following equation as shown in Table 5.

Table 5. Acidity functions (H_0) for acetonitrile(H_2SO_4 derived from indicator ratios (I) of *p*-nitroaniline at 25°

c_A	λ_A	ϵ_A	ϵ_S	I	H_0
0·00720	365	6024	78·8	1·296	−0·841
0·0288	363	2880	92·0	3·892	−0·500
0·1152	362	1928	85·0	6·404	−0·148

$\lambda_N = 366$, $\epsilon_N = 13730$.

c_A; Concentration (N) of H_2SO_4.

λ; Wave-length at the maximum absorption (mμ).

ϵ; Molecular extinction coefficient.

Subscripts, A, N and S, refer to acidic solution, neutral solution and nitrobenzene solution, respectively.

$$I = \frac{\epsilon_N - \epsilon_A}{\epsilon_A - \epsilon_S}$$

$$H_0 = \log I - 0{\cdot}954$$

Products. All *o*- and *p*-hydroxy aromatics were identified by comparison with authentic samples by means of GLC using the conditions stated above.

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