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MECHANISM OF OXIDATIVE COUPLING REACTION CATALYSED BY CUPROUS CHLORIDE-AMINE COMPLEX

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Abstract—A study has been made on the mechanism of catalysis of cuprous chloride–amine complexes in the oxidative coupling reaction of 2,6-di(t-butyl)phenol to form 3,3′,5,5′-tetra(t-butyl) diphenoquinone. It was concluded that copper acts through the cycle of oxidation and reduction and that O^{2-}, which is formed by the reduction of O_2 by Cu^+ or OH^- which is added as KOH, plays an important role, perhaps, as the acceptor of proton from the phenol.

INTRODUCTION

CUPROUS CHLORIDE is reported to catalyse oxidative coupling or polymerization of such substances as aniline,[1] *p*-nitrotoluene,[2] phenols[3] and acetylenes[4] in the presence of an amine such as pyridine, ethylamine or ethylenediamine. While cupric chloride in pyridine, $CuCl_2pyr_2$ complex, is not known to catalyse these reactions, many other cupric complexes, except for cupric acetate,[5] are also reported to be inactive for this type of reaction.

The following mechanism

$$\begin{cases} C_6H_5NH_2 + Cu(II){-}Cl_2 \rightleftharpoons (C_6H_5NH_2Cu(II)Cl)^+Cl^- \rightarrow C_6H_5NH{-}Cu(I), \\ 2C_6H_5NH{-}Cu(I) \rightarrow C6H_5NH{-}HNC_6H_5 \rightarrow C_6H_5N{=}NC_6H_5 \end{cases}$$

proposed by Kinoshita[1] does not explain the complete inactivity of $CuCl_2pyr_2$.

Copper is found in a variety of enzymes such as hemocyanine, tyrosinase etc.[6] Hemocyanine is known to add oxygen molecule in the cuprous state and tyrosinase is assumed to activate oxygen molecule or to form the cupryl ion CuO^+ in the cuprous state.[7] The known fact that cuprous chloride is active for the oxidative coupling while cupric chloride is not suggests the formation of an ion of this type CuO^+ in the reaction.

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[1] K. Kinoshita, *Bull. Chem. Soc. Japan* **32,** 777, 780 (1959).
[2] H. A. Stansbury and W. R. Proops, *J. Org. Chem.* **26,** 4162 (1961).
[3] A. S. Hay, G. F. Endres and J. W. Eustance, *J. Org. Chem.* **28,** 1300 (1963); *J. Polymer Sci.* **58,** 581 (1962); *J. Amer. Chem. Soc.* **81,** 6335 (1959); G. F. Endres and J. Kiwatek, *J. Polymer Sci.* **58,** 593 (1962).
[4] H. A. Stansbury and W. R. Proops, *J. Org. Chem.* **27,** 320 (1962); F. Bohlmann, P. Herbstand and H. Gleining, *Chem. Ber.* **94,** 948 (1961); A. S. Hay, *J. Org. Chem.* **25,** 1275 1960; F. Sondheimer, Y. Gaoni, *J. Amer. Chem. Soc.* **81,** 1313 (1959).
[5] G. Eglinton, A. R. Galbraith, O. M. Behr and R. A. Raphael, *J. Chem. Soc.* 889 (1959); 3614 (1960); F. Bohlmann and K. M. Kleine, *Chem. Ber.* **95,** 39 (1962), M. Nakagawa, F. Toda, S. Akiyama and S. Misumi, *Bull. Chem. Japan* **33,** 223, 230, 1291, 1293 (1960).
[6] *Oxygenases* (Edited by O. Hayaishi). Academic Press (1962).
[7] L. L. Ingraham, *Mechanism of Biochemical Reactions* Part II. J. Wiley (1962).

This study is concerned with the mechanism of catalysis of CuCl–amine complex and related complexes in the oxidative coupling reaction of 2,6-di(t-butyl)phenol (abbreviated as DBP or HϕOH), on which Hay[3] reported that a main product is 3,3′,5,5′-tetra(t-butyl)diphenoquinone.

RESULTS

Some results of kinetic measurements are presented in Fig. 1 and summarized in Table 1. $CuCl_2pyr_2$ was found to be completely inactive for this reaction. Log 1/(1 — x) was found to be linear against reaction time, where x was the conversion; this shows the 1st power dependence of the oxygen absorption rate on [HϕOH]. The activation energies were 14–15 kcal/mole in all the cases. The catalytic activity of oxidized CuCl–pyr complex was slightly less than CuCl–pyr complex prepared under nitrogen and was found to become less active during storage under air. The addition of ethylenediamine changed the oxygen absorption rate in pyridine solution as shown in Fig. 2. The effect of diethylenetriamine is shown in Fig. 3. Both ethylenediamine and diethylenetriamine did not inhibit the reaction even if added in excess, but triethylenetetramine inhibited the reaction completely when added in excess, [triethylenetetramine]/[Cu] $\geq$ 1.

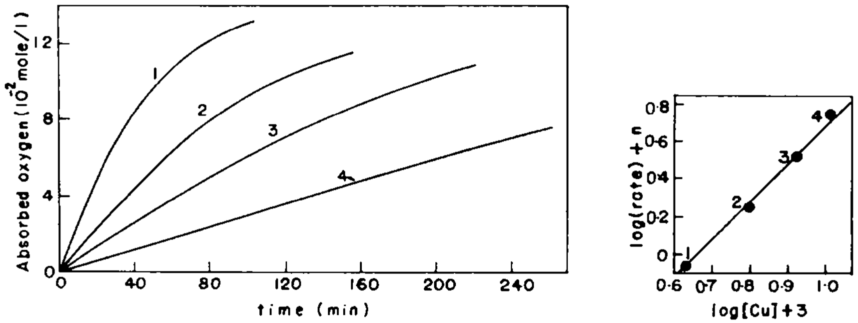

FIG. 1. Dependence of oxygen uptake rate upon the concentration of catalyst in the reaction catalysed by CuCl–pyr complex, at 39·4°, [HϕOH] = 0·2 mole/1; (1) [Cu] = $1{\cdot}0 \,.\, 10^{-2}$ mole/1, P_{O_2} = 844 mmHg, (2) $8{\cdot}5 \,.\, 10^{-3}$, 785, (3) $6{\cdot}3 \,.\, 10^{-3}$, 800, (4) $4{\cdot}3 \,.\, 10^{-3}$, 791.

The product of the reaction was 3,3′,5,5′-tetra(t-butyl)diphenoquinone (red crystal, m.p. 225°C), the IR spectrum of which is presented in Fig. 4.

TABLE 1. RESULTS OF KINETIC MEASUREMENTS

Apparent rate equation: $-d[O_2]/dt = k[Cu]^m P_{O_2}^n [H\phi OH]$, $[H\phi OH]_0 = 0{\cdot}2$ mole/l

Catalyst	CuCl-pyr	$CuCl_2pyr_2$-OH^-
Concentration of catalyst (mole/l)	$1{\cdot}0 \,.\, 10^{-2} - 4{\cdot}3 \,.\, 10^{-3}$	$1{\cdot}0 \,.\, 10^{-2} - 5{\cdot}0 \,.\, 10^{-3}$
Oxygen press (mmHg)	1133 – 621	1163 – 510
m	2·0	ca. 2
n	1·3	1·2
k*(l^2mole^{-2} atm^{-1} min^{-1})	76·5	33·5

* rate Eq. $d[\phi_2O_2]/dt = -d[O_2]/dt = k[Cu]^2[H\phi OH]P_{O_2}^1$ is assumed

Absorption spectra of some complexes are shown in Fig. 5. The oxidized CuCl–pyr complex has a spectrum similar to that of $CuCl_2pyr_2$—OH^- complex and an absorption maximum about 320 mμ. This absorption maximum at 320 mμ was reported[8] to be common to hydroxy amine complexes of copper (2+); and would be due to a charge transfer between Cu^{2+} and O^{2-} or OH^-.

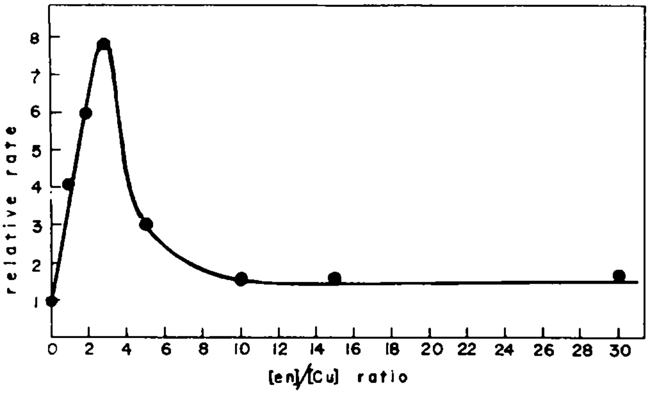

FIG. 2. Effect of addition of ethylenediamine upon the oxygen uptake rate; [Cu] = 8·0 . 10^{-3} mole/1, [HϕOH] = 0·2 mole, P_{O_2} = 788 mmHg, 39·7°.

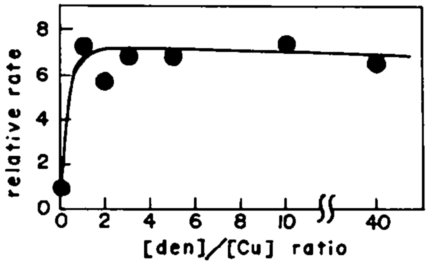

FIG. 3. Effect of addition of diethylenetriamine upon the oxygen uptake rate; the data are the same as in Fig. 2.

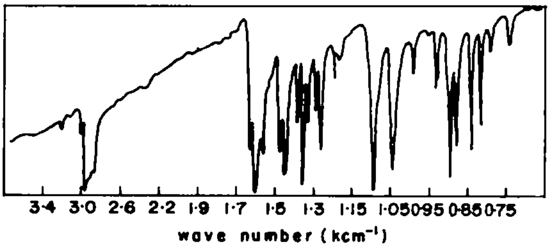

FIG. 4. IR spectrum of the reaction product, 3,3′,5,5′,-tetra(t-butyl)diphenoquinone (KBr tablet method).

ESR spectra of some complexes in solution are shown in Fig. 6. The ESR spectra of $CuCl_2pyr_2$, $CuCl_2pyr_2$—OH^- and oxidized CuCl–pyr complexes are similar to each

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[8] D. L. Leussing and R. C. Hansen, *J. Amer. Chem. Soc.* **79**, 4270 (1957).

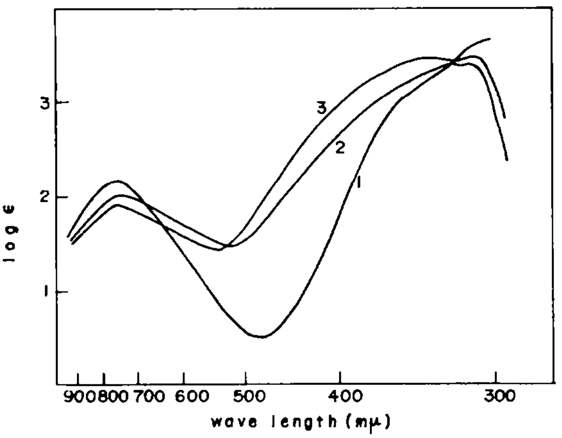

FIG. 5. Absorption spectra in pyridine of (1) CuCl$_2$pyr$_2$, (2) CuCl$_2$pyr$_2$-OH$^-$([Cu]/[OH$^-$] = 1), and (3) oxidized CuCl-pyr.

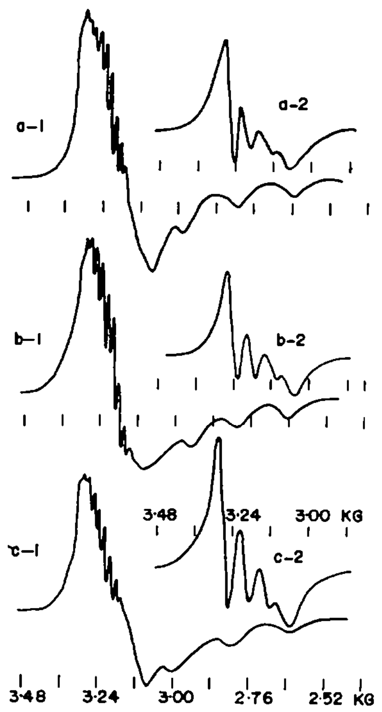

FIG. 6. ESR spectra ([Cu] = 2·10^{-2} mole/l) of (a) CuCl$_2$pyr$_2$ in 10% methanol-pyridine, (b) oxidized CuCl-pyr in pyridine, (c) CuCl$_2$pyr$_2$-OH$^-$ in 10% methanol-pyridine, at (1) liquid nitrogen temp, and (2) room temp.

other at room temperature. In the spectra at 77°K the peak at highest magnetic field corresponds to $g\perp$ (g value in the direction perpendicular to a molecular axis) and the four peaks with equal spacing, which are due to nuclear magnetic moment of copper I = 3/2, correspond to the resonance at $g\|$. The spacing of the four peaks corresponding to g‖ resonance is nearly equal both in $CuCl_2pyr_2$ and $CuCl_2pyr_2$—OH^- complexes, but is slightly less in oxidized CuCl–pyr complex than in the former two complexes. At higher field peak 9 hyperfine lines are discernible in the spectra of $CuCl_2pyr_2$ and oxidized CuCl–pyr at 77°K, while the spectrum of $CuCl_2pyr_2$—OH^- has less hyperfine lines, perhaps, 7 lines. These lines would be due to hyperfine coupling with nitrogen atoms of the ligands, pyridine. These ESR spectra do not afford any definite information on the structures of the complexes, but they at least suggest that these complexes have approximately square planar structures.

TABLE 2. REDOX POTENTIAL AND pH OF SOME COMPLEX SOLUTIONS
$[Cu^{2+}] = 2{\cdot}5 \,.\, 10^{-2}$ mole/l

Solution	pH	Redox potential
Pyridine	8·6	—
$CuCl_2pyr_2$ in pyridine	8·9	−44 mV
$CuCl_2pyr_2$-OH^- in 5% methanol-pyridine	11·8	−55 mV
Oxidized CuCl-pyr	12·4	−138 mV

The pH values and the redox potentials of some solutions are listed in Table 2. The redox potential E listed is the potential at the equivalent point of titration and is related to that of copper complex E_{Cu} and that of ascorbic acid E_{asc} by the following Eq.

$$E = \tfrac{1}{3}(E_{Cu} + 2E_{asc})$$

Therefore the value of E is parallel to E_{Cu}. The pH value measured by glass electrode is not readily interpreted but may to some extent be parallel to the actual proton activity in those solutions.

The copper–pyridine complexes in pyridine described can be precipitated by the addition of large amounts of a non-polar solvent such as benzene or ether. The content of copper in oxidized CuCl–pyr complex and $CuCl_2pyr_2$—OH^- complex thus precipitated was analysed by iodometry, and their IR spectra were recorded (Fig. 7). The iodometry showed that the content of copper was 30 wt% in the precipitate of oxidized CuCl–pyr complex and 24 wt% in that of $CuCl_2pyr_2$—OH^- complex, and the IR spectra clearly demonstrated the existence of an OH group; that is, oxygen which was used to oxidize Cu^+ to Cu^{2+} exists as OH^-, presumably being bound to copper in the precipitate.

The absorption spectra were also recorded for the reaction mixture: catalyst + DBP in pyridine; they are shown in Fig. 8. This figure distinctly demonstrates the reaction $Cu^{2+} + DBP \rightarrow Cu^+$. This reaction is also supported by the ESR data on the mixture: Cu^{2+} + DBP in pyridine (Fig. 9). By the addition of DBP the resonance due to Cu^{2+} in a catalyst is diminished as shown in Fig. a, or the resonance peaks vanish rapidly as shown in Figs. b and c. The shape of the resonance spectrum of oxidized CuCl–pyr complex was not appreciably changed by the addition of DBP as shown in Fig. a. The Fig. also shows that a weak resonance peak appeared at $g = 2{\cdot}00$ when DBP was added. This peak is probably due to a free radical, presumably of an intermediate $(t\text{-butyl})_2C_6H_3O\cdot$ or of a reaction by-product.

A preliminary ESR study on the system: oxidized CuCl + aniline in pyridine showed that the resonance spectrum of the complex is appreciably changed by the

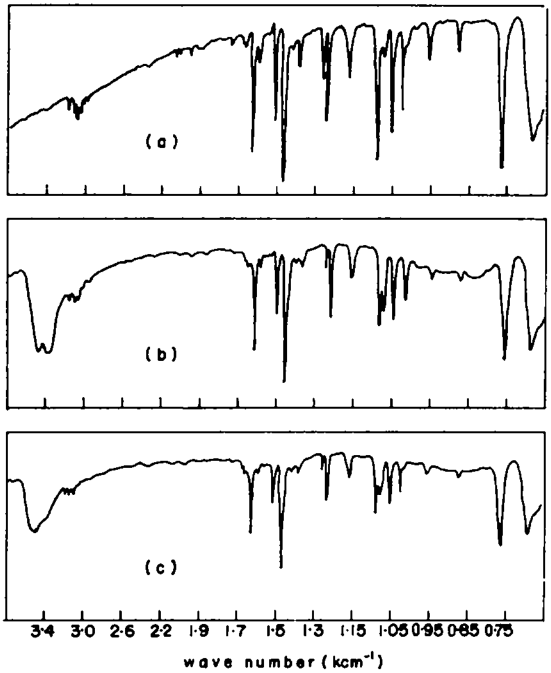

FIG. 7. IR spectra (KBr tablet) of (a) CuCl$_2$pyr$_2$, (b) the precipitate from pyridine solution of oxidized CuCl–pyr, and (c) the precipitate from pyridine solution of CuCl$_2$pyr$_2$-OH$^-$.

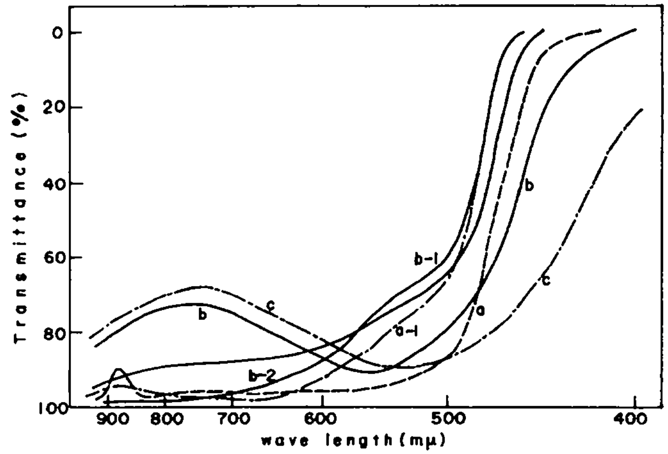

FIG. 8. Absorption spectra of pyridine solutions of (a) CuCl–pyr (measured under N$_2$), (b) oxidized CuCl–pyr, b-1,-2 oxidized CuCl–pyr + HϕOH, (c) CuCl$_2$pyr$_2$-OH$^-$, c-1 CuCl$_2$pyr$_2$-OH$^-$ + HϕOH.

addition of aniline (Fig. 10). This fact suggests the coordination of aniline to Cu^{2+}.

$CuCl_2pyr_2$ was never found to change upon addition of DBP, both in absorption spectroscopy and ESR spectroscopy.

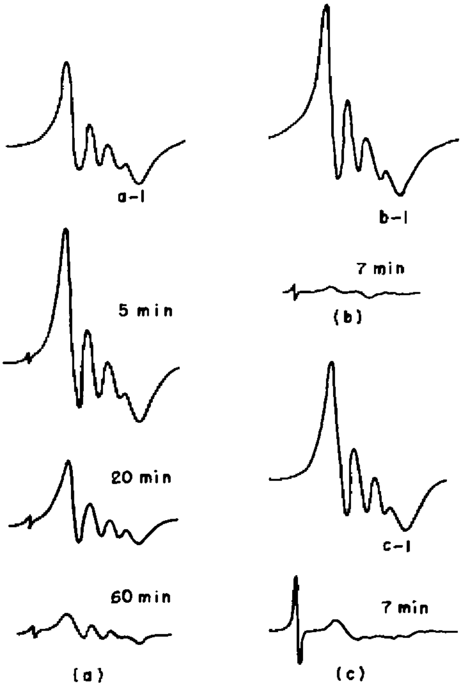

FIG. 9. ESR spectra at room temp of pyridine solution of the reaction mixtures, (a) oxidized CuCl-pyr + HφOH (a-1, catalyst only), (b) $CuCl_2pyr_2$-OH^- + HφOH (b-1, catalyst only), and (c) HφOH + oxidized CuCl-pyr (prepared immediately before measurement) (c-1, catalyst only).

DISCUSSION

A probable mechanism according to the following equations is proposed:

$$2Cu^+ + 2nX + O_2 \xrightarrow{k_1} (X_nCu^{2+}O^{2-}Cu^{2+}X_n) \xrightarrow{k_1'} 2(X_nCu^{2+}O^-) \quad (1)$$

$$(X_nCu^{2+}O^-) + Cu^+ + nX \xrightarrow{k_2} 2(X_nCu^{2+}) + O^{2-} \quad (2)$$

$$(X_nCu^{2+}) + O^{2-} + H\phi OH \underset{k_{-3}}{\overset{k_3}{\rightleftharpoons}} (X_{n-2}Cu^{2+}(O^{2-})(H\phi OH)) + 2X \quad (3)$$

$$(X_{n-2}Cu^{2+}(O^{2-})(H\phi OH)) \xrightarrow{k_4} (n-2)X + OH^- + Cu^+ + H\phi O. \quad (4)$$

$$2H\phi O\cdot + \tfrac{1}{2}O_2 \xrightarrow{k_5} H_2O + \phi_2O_2 \quad (5)$$

Where X is pyridine, ethylenediamine, diethylenetriamine or triethylenetetramine. The rate constants k_1, k_1', k_2, k_3, k_{-3}, k_4 would depend on the nature of X. k_1, k_1' and k_2, and thus the total oxygen uptake rate were observed to be much larger for X = ethylenediamine or diethylenetriamine than for X = pyridine. This is understood

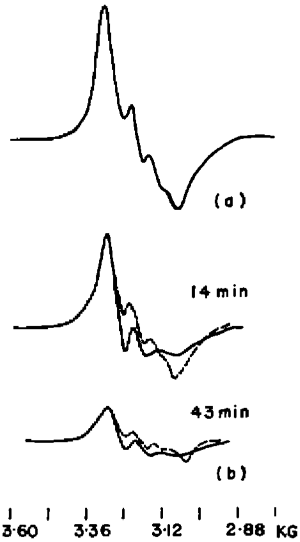

FIG. 10. ESR spectra at room temp of pyridine solution of (a) oxidized CuCl–pyr, and (b) aniline + oxidized CuCl–pyr; in (b) the solid line is the observed one and the dotted line is the one corresponding to that of the catalyst (a).

on the basis that the stability of $Cu^{2+}X_n$ compared with that of $Cu^{+}X_m$ is greater for X = the former two than for X = the latter; that is, the larger the stability of $Cu^{2+}X_n$ compared to that of $Cu^{+}X_m$, the larger the rate of the reaction $Cu^{+} + O_2 \rightarrow Cu^{2+}$ may be. Although steps (1) and (2) may be accelerated, the stationary concentration of the intermediate catalyst–reactant complex may be decreased by an increase in the concentration of X. Thus the addition of X to the reaction solution may to some extent accelerate the oxygen uptake rate but decrease it when in excess; this is shown by Fig. 2 in this paper and Fig. 3 in the report by Hay[3] (effect of the concentration of pyridine). If [X] is large enough as in the case where solvent and X are pyridine, the reduction process of Cu^{2+} by HϕOH, steps (3) and (4) would be rate-determining, and $[X_nCu^{2+}] = [Cu]_{total}$. On this assumption one obtains the following rate equation from the above mechanism.

$$\begin{aligned}-d[H\phi OH]/dt &= -2d[O_2]/dt\\ &= k_3[Cu]_{total}[H\phi OH][O^{2-}]/(k_3[Cu]_{total}[H\phi OH][O^{2-}]\\ &\quad + K_{-3}[X]^2 + K_4)\end{aligned} \tag{6}$$

As the stationary state concentration of O^{2-} under these conditions would be nearly equal to $\frac{1}{2}(Cu)_{total}$, Eq. (6) becomes

$$\begin{aligned}-d[H\phi OH]/dt &= -2d[O_2]/dt\\ &= \tfrac{1}{2}k_3[Cu]^2_{total}[H\phi OH]/(\tfrac{1}{2}k_3[Cu]^2_{total}[H\phi OH] + k_{-3}[X]^2 + k_4)\end{aligned} \qquad (6)'$$

The first term of the denominator of the Eq. (6)′ is so small compared with the term $k_{-3}[X]^2$ or k_4 that it can be neglected. Thus,

$$v = -d[H\phi OH]/dt = \tfrac{1}{2}k_3[Cu]^2[H\phi OH]/(k_{-3}[X]^2 + k_4) \qquad (6)''$$

Except for P_{O_2} dependence, this Eq. is identical with the rate Eq. shown in Table 1.

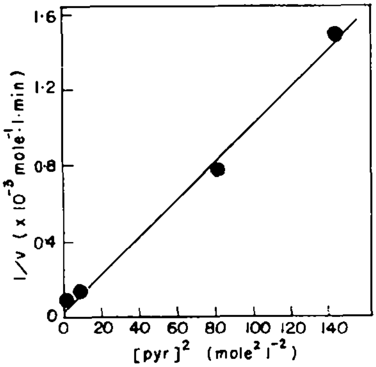

FIG. 11. A plot of 1/v vs. [pyr]² (the data were taken from Table 1 in A. S. Hay, G. F. Endres and J. W. Eustance, *J. Org. Chem.* **28**, 1300 (1963)).

The Eq. (6)″ leads to $1/v = k[X]^2 + c$; confirmed by Fig. 11, the data of which was taken from Table 1 in the report by Hay.[3]

The step (4) has been confirmed by the results mentioned in Figs. 8 and 9.

The inactivity of $CuCl_2pyr_2$ was first considered due to its low redox potential; i.e., an inability to oxidize HϕOH. The redox potential measured (Table 2), however, shows that inactive $CuCl_2pyr_2$ complex has a redox potential higher than the active two complexes, and it should, therefore, be able to oxidize HϕOH. The difference in catalytic activity between $CuCl_2pyr_2$ and CuCl–pyr or $CuCl_2pyr_2$—OH^- is not due to a difference in redox potential, but due to a difference in basicity. The O^{2-}, formed by the reduction of O_2 by Cu^+ or OH^- added, may play an important part as a proton acceptor. Any complex without O^{2-} or OH^- may not be catalytically active for this reaction although the solvent, pyridine, is a proton acceptor. The cupryl ion, CuO^+, which is often postulated in biochemical studies[7] is identical with $(X_nCuO)^+$ in the Eqs. (1) and (2) but any definite decision as to whether the active form of catalyst in this oxidative coupling is $(X_nCuO)^+$ or (X_nCu^{2+}) cannot be made. This model also explains that substances catalysed by these catalysts—aniline, phenols, acetylenes and *p*-nitrotoluene—all have labile hydrogen which may be removed as a proton.

The reactant–catalyst complex such as $(X_nCu^{2+}(O^{2-})(H\phi OH))$ could not be detected in the case of DBP as reactant (Fig. 9) but may be detected in the case of aniline as reactant as seen in Fig. 10. The rate constant k_3 may be rather small compared with k_{-3} and k_4 in the case of DBP, so that the complex

$$(X_nCu^{2+}(O^{2-})(H\phi OH))$$

would not be detected. In the case of aniline, k_3 may be large as aniline is more basic than pyridine.

The stability constants K_n of some cupric complexes are presented in Table 3. In the experiments mentioned, pyridine is the solvent and so [pyr] = 12·1 mole/l, and [added amine] = $10^{-2} - 4{\cdot}10^{-1}$ mole/l, so that under these conditions thermodynamically the most probable compositions of the cupric complexes without taking account of Cl^- may be $Cu^{2+}pyr_4$ in the case of pyridine only, $Cu^{2+}(en)pyr_2$ or $Cu^{2+}(en)_2$ depending on [en] in the case of en, $Cu^{2+}(den)pyr$ in the case of den, and

Cu^{2+}(trien) in the case of trien. Although $Cu^{2+}(den)_2$ is possible in the case of den, it is not likely as K_2 is so small compared with K_1 and [den] is so small compared to [pyr] ([den]/[pyr] $\approx 10^{-3} - 10^{-2}$) that under these conditions, the concentration of $Cu^{2+}(den)_2$ should be very small in comparison with that of Cu^{2+}(den)pyr. This difference between en and den may explain the difference in the effect of addition of X as shown in Figs 2 and 3. In the case of den, as only one complex Cu^{2+}(den)pyr is possible even when den is added in excess under the experimental conditions, den may not change the oxygen uptake rate appreciably when [den]/[Cu] ≥ 1. Postulating that if more than four coordinative sites of Cu^{2+} in a cupric complex were tightly occupied by amines, it would be catalytically inactive for the oxidative coupling, the inhibiting action of trien when [trien]/[Cu] ≥ 1 and of en when [en] is large would be explained.

TABLE 3. STABILITY CONSTANTS K_n OF SOME CUPRIC COMPLEXES
$Cu^{2+}X_{n-1} \rightleftharpoons Cu^{2+}X_n$: K_n

X	log K_n	Ref
Pyridine (monodentate)	K_1: 2·52, K_2: 1·86, K_3: 1·31, K_4: 0·85	*a*
En* (bidentate)	K_1: 10·72, K_2: 9·31	*b*
Den† (tridentate)	K_1: 16·0, K_2: 5·3	*c*
Trien‡ (tetradentate)	K_1: 20·4	*d*

* Ethylenediamine, † Diethylenetriamine, ‡ Triethylenetetramine, [a] R. J. Bruehlman and F. H. Verhoek, *J. Amer. Chem. Soc.* **70**, 1401 (1948), [b] J. Bjerrum and E. J. Niesen, *Acta Chem. Scand.* **2**, 297 (1948), [c] J. E. Prue and G. Schwarzenbach, *Helv. Chim. Acta* **33**, 985 (1950), [d] G. Schwarzenbach, *Ibid.* **33**, 947 (1950).

EXPERIMENTAL

Materials. Cuprous chloride was prepared[9] from cupric chloride. Pyridine was commercially of purest grade and purified by the usual methods. The 2,6-di(t-butyl)phenol, ethylenediamine, diethylenetriamine, and triethylenetetramine were commercially of purest grade and used without further purification.

Measurement of oxygen uptake rate. This was done using a constant pressure reaction apparatus equipped with a reactor (120 ml) and a gas burette. Mercury in the gas burette was driven by a synchronous motor, which was switched on and off by means of a manometer and microrelay circuit so as to maintain a constant press. The level of Hg was recorded automatically as the change of resistance of a Pt wire stretched in the burette. The usual procedure was as follows: the reaction system was first evacuated then filled with oxygen and then a pyridine solution of reactant poured into the reaction vessel with a syringe through a silicone rubber cap, followed by a catalyst solution.

Catalyst solution. Catalyst solution of CuCl-pyr was prepared by dissolving weighed cuprous chloride into pyridine, which was beforehand air-freed by evacuation under freezing, under nitrogen. Catalyst solution of $CuCl_2pyr_2$-OH^- was prepared by adding methanolic KOH solution to a pyridine solution of $CuCl_2pyr_2$ ($[OH^-]/[Cu] = 1$, methanol 10 vol%).

Measurement of absorption spectra and ESR spectra. Absorption spectra of some catalyst solutions and reaction mixtures were recorded on a Hitachi Spectrophotometer Model EPS-2. ESR spectra of some solutions (catalyst only or catalyst with reactants) were recorded on a Japan Electron Optics Lab. ESR Spectrometer Model JES-3B (X-band, field modulation 100 kc/s), at room temp and at the temp of liquid nitrogen.

Measurement of pH and redox poential. The pH values of catalyst solutions were measured by glass electrode with Toadenpa pH meter Model HM-5A, but the correction for liquid junction potential was not made. Catalyst solutions were titrated with pyridine solution of ascorbic acid,

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[9] *Inorganic Synthesis* (Edited by W. C. Fernelius) vol. 1, p. 1. McGraw-Hill (1946).

and the potentials read with a Toadenpa pH meter Model HM-5A, with Pt wire as metal electrode and Ag plated Pt wire–pyridine solution of $AgNO_3$ (0·048 mole/l)[10] as reference electrode.

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[10] A. K. Gupta, *J. Chem. Soc.* 3473 (1952).