APPLIED ORGANOMETALLIC CHEMISTRY
Appl. Organometal. Chem. 2004; **18**: 440–445
Materials, Nanoscience and Catalysis **AOC**

Catalytic oxidative reactions of organic compounds by nitrogen-containing copper complexes

Nilotpal Barooah, Sagar Sharma, Bipul Chandra Sarma and Jubaraj B. Baruah*

Department of Chemistry, Indian Institute of Technology, Guwahati, North Guwahati 781039, India

Received 2 February 2004; Revised 2 April 2004; Accepted 13 May 2004

The dimeric copper(II) complex di-μ-chloro-bis[chloro(di-3,5-dimethylpyrazole)copper(II)] (A) in the presence of co-oxidant hydrogen peroxide acts as a catalyst for the oxidation of benzylic alcohols to give the corresponding aldehydes. In the presence of hydrogen peroxide it also catalyses the oxidation reaction of 2,6-dimethylphenol to 4,4′-dihydroxy-3,5,3′,5′-tetramethylbiphenyl. The oxidative reactions by bis-pyridinium tetrachlorocopper(II) (B) in the presence of hydrogen peroxide were compared for similar catalytic reactions of A, and it is observed that B can catalyse the oxidation of aromatic diols, 2,6-dimethylphenol and thiophenol, but is not suitable for oxidation of benzylic alcohols. Bis-(*N*-phenyl-3,5-dimethylpyrazole)copper(II) nitrate monohydrate (C) has a suitable redox potential for one-electron oxidation. It can oxidize ferrocene to the ferricinium cation, and it can liberate bromine from tetra-alkylammonium bromides. The complex is catalytically effective for the oxidation of different aromatic and aliphatic aldehydes to the corresponding carboxylic acids. The compound is also effective in transforming benzylic amine to benzylalcohol and benzaldehyde. It can also oxidize diphenylmethane to give benzophenone and diphenylmethanol. It is observed that in each of these complexes a quasi-reversible Cu(I)–Cu(II) species is present and facilitates the single-electron oxidation process. Copyright © 2004 John Wiley & Sons, Ltd.

KEYWORDS: copper complexes; hydrogen peroxide; oxidation; benzylic alcohols; benzylamine; hydrocarbon oxidation

INTRODUCTION

Oxidative reactions of organic substrates by copper complexes[1–3] are common. Copper complexes can be involved in one-electron oxidations;[4] they can also act as catalysts for various oxidation reactions.[5] The course of copper-catalysed oxidation reactions can be modified by varying the ligand environment.[6–8] The radical stabilized by copper(II) centres carries out one-electron oxidations of organic substrates.[9–12] In many biological oxidative reactions the copper–pyrazole complexes play an important role.[5] In this study we discuss oxidative reactions of three copper(II) complexes towards oxidation of organic substrates in the presence of a co-oxidant to show the importance of a suitable redox couple of Cu(I)–Cu(II) for one-electron catalytic oxidative transformations.

EXPERIMENTAL

The bis-pyridinium tetrachlorocopper(II) was prepared by the procedure[13] reported earlier.

Preparation of di-μ-chloro-bis[chloro(di-3,5-dimethylpyrazole)copper(II)] (A)

A solution of cupric chloride dihydrate (0.17 g, 1 mmol), 1,3,5,7-tetramethylpyrazabole (0.215 g, 1 mmol) and 4-*tert*-butyl catechol (0.166 g, 2 mmol) in acetone (10 ml) was made up and allowed to stir at room temperature for 5 h. The solution changes from colourless to brown, and a green precipitate appeared. This precipitate was filtered and washed with acetone several times (4 × 5 ml) and dried in air to obtain 260 mg of **A**. IR (KBr): 3267 (s), 3200 (s), 1567 (s), 1470 (w), 1419 (m), 1275 (m), 1183 (m), 1050 (s), 819 (m), 615 cm^{-1} (w). Magnetic moment: 2.46 B.M. for dimer. Molar conductance (acetonitrile): 4.15 Ω^{-1} cm^2 mol^{-1}. Anal. Found C, 36.70; H, 3.11; N, 17.26. Calc. for $C_{10}H_{16}Cl_2CuN_4$: C, 36.73; H, 3.06; N, 17.14%.

---

*Correspondence to: Jubaraj B. Baruah, Department of Chemistry, Indian Institute of Technology, Guwahati, North Guwahati 781039, India.
E-mail: juba@iitg.ernet.in

Preparation of bis-(*N*-phenyl-3,5-dimethyl-pyrazole)copper(II) nitrate monohydrate (C)

To a solution of copper(II) nitrate trihydrate (482 mg, 2 mmol) in ethanol (10 ml) a solution of *N*-phenyl-3,5-dimethylpyrazole (1023 mg 6 mmol, in 10 ml ethanol) was added and stirred at room temperature. The solution became dark blue and precipitation of the complex was observed (yield 79%). IR (KBr): 3442 (bs), 3129 (s), 2925 (s) 1598 (s), 1562 (s), 1501 (s), 1378 (s), 1291 (s), 1168 (s), 1071 (s), 1025 (s), 922 (s), 805 (s), 769 cm^{-1} (s). Molar conductance (acetonitrile): 84 Ω^{-1} cm^2 mol^{-1}. Anal. Found C, 48.10; H, 4.67; N, 10.11. Calc. for $C_{22}H_{26}CuN_4O_7$: C, 48.04; H, 4.73; N, 10.19.

Oxidation of benzylic alcohols by A in the presence of H_2O_2

To a solution of the benzylic alcohol (2 mmol) and the copper complex **A** (0.02 mmol) in acetonitrile (5 ml), hydrogen peroxide (1 ml, 10%) was added. The reaction mixture was stirred at room temperature for 6–8 h and the formation of aldehydes in the reaction was monitored by gas chromatography from time to time. When all the alcohol was consumed, the reaction mixture was extracted by dichloromethane after treating the reaction mixture with hydrochloric acid (1 M, 1 ml). The crude product obtained from the dichloromethane extraction was purified by column chromatography.

Oxidation of benzenethiol by B

To a well stirred solution of benzenethiol (500 mg, 4.5 mmol) in acetonitrile (10 ml), bis-pyridinium tetrachlorocopper(II) (35 mg, 0.104 mmol) was added. The reaction mixture was stirred under aerial conditions at room temperature for 8 h. The solvent was removed under reduced pressure, the residue obtained was extracted with dichloromethane (2 × 25 ml), and the dichloromethane layer was washed with water (30 ml) to remove the catalyst. On removal of dichloromethane and subsequent purification by column chromatography, diphenyldisulfide was obtained (120 mg). The compound was characterized by NMR and IR spectroscopy and comparison with an authentic sample.

Reaction of 2,6-dimethylphenol with B in the presence of H_2O_2

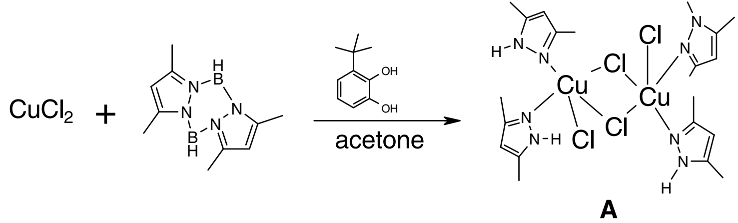
To a solution of 2,6-dimethylphenol (400 mg, 3.2 mmol) in methanol (7 ml) containing hydrogen peroxide (0.5 ml, 30 vol.%), bis-pyridinium tetrachlorocopper(II) (35 mg, 0.104 mmol) was added. The reaction mixture on stirring at room temperature resulted in the precipitation of a red solid. The red solid was filtered and the residue was washed with hexane. The residue was dried to obtain 4,4′-dihydroxy-3,5,3′,5′-tetramethylbiphenyl (80 mg). ^1H NMR (DMSO-d^6) 8.2 (s, 4H), 7.1 (s, 2H), 2.1 (12H). IR (KBr): 2950 (w), 2924 (w), 2858 (w), 1654 (m), 1597 (s), 1377 (w), 1218 (m), 1039 (m), 916 (w), 835 (w), 784 (w), 481 (w). FAB mass (*m/e*) 242, 237, 226, 213, 209, 202, 196, 189, 178, 165, 163, 154, 152, 138, 128, 124, 120, 115, 107, 105, 102.

RESULTS AND DISCUSSION

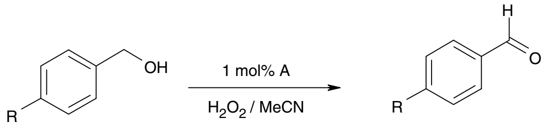
The di-μ-chloro-bis[chloro(di-3,5-dimethylpyrazole)copper (II)] complex (**A**) was prepared by the reaction of cupric chloride dihydrate with 1,3,5,7-tetramethylpyrazabole and 4-*tert*-butyl catecohol. In this reaction, the role of catecohol is to produce *in situ* generation of 1,3-dimethylpyrazole. The reaction is shown in Scheme 1.

The structure of the compound was determined by X-ray crystallography and matches well with the compound reported by a different method of preparation.[14] The dimeric nature of the complex gives the copper a penta-coordinated environment with a distorted trigonal bipyramid structure.[14]

Complex **A** is non-ionic in aprotic media, as determined by molar conductance measurement. The compound has a quasi-reversible Cu(II)–Cu(I) couple at 452 mV in acetonitrile versus Ag/AgCl electrode (positive scan; scan speed 10 mV s^{-1}). The ΔE between anodic and cathodic peaks is 160 mV ($i_{pa}/i_{pc} = 1.4$). It acts as a catalyst for oxidation of benzylic alcohols to the corresponding aldehydes. The reactions work at room temperature with 1 mol% of the catalyst. Various benzylic alcohols that were converted to the corresponding aldehydes are shown in Scheme 2. The one-electron oxidant as catalyst is a process in galactose oxidase.[12] Galactose oxidase has two nitrogen donor atoms attached to the copper in the form of histidine



Scheme 1.



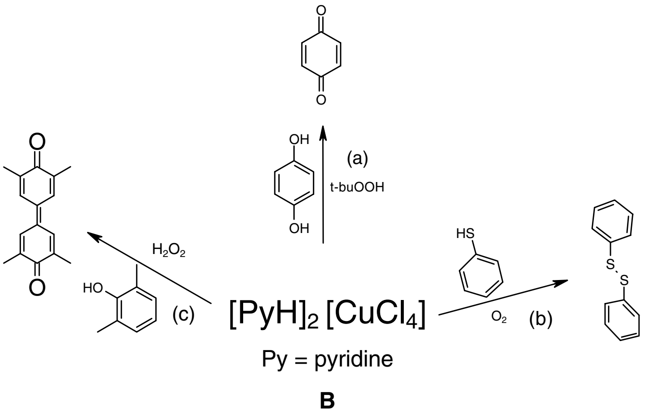
R	Reaction condition	Yield
H	RT/ 6hrs	78%
CH_3	RT/ 6hrs	84%
NO_2	RT/6hrs	90%
Cl	RT/8hrs	80%
OMe	RT/6hrs	76%

Scheme 2.

residues; complex **A** also has a similar nitrogen ligand environment.

Complex **A**, along with hydrogen peroxide, is also effective for conversion of 2,6-dimethylphenol to 4,4′-dihydroxy-3,5,3′,5′-tetramethylbiphenyl with a side product 4-(3′,5′-dimethylcyclohexa-2′,5′-dinenone)-methylidene-2,6-dimethyl-cyclohexadienone. This reaction led to conversion of 50 mol% of 2,6-dimethylphenol with 1 mol% of catalyst in hydrogen peroxide within 15 min at room temperature. In a recent study, several copper(II) dimeric complexes were found to be suitable oxidation catalysts in the presence of oxygen.[15] We studied this further to check the reactivity of the analogous chloro-complex of copper having a polymeric structure. For this purpose, bis-pyridinium tetrachlorocopper(II) (**B**) was chosen, because of its well-characterized structural data in the literature.[16] Bis-pyridinium tetrachlorocopper(II) (**B**) reacts with various organic substrates in the presence of different co-oxidants under mild reaction conditions. However, this complex is used at a concentration of 10 mol% of the substrates, and thus the efficiency is lower.

The reactions were carried out with different organic substrates with bis-pyridinium tetrachlorocopper(II) as a catalyst, as shown in Scheme 3. Bis-pyridinium tetrachlorocopper(II) in the presence of *tert*-butyl hydroperoxide catalyses oxidation of 1,4-benzenediol as well as 1,4-naphthalenediol. These reactions led to the corresponding quinone. In the reaction of 1,4-dihydroxy-aromatic compounds, the use of other co-oxidants, such as hydrogen peroxide and oxygen at room temperature in the presence of the catalyst **B** did not give the desired oxidized product. Complex **B** also reacts with 2,6-dimethylphenol under ambient conditions in the presence of hydrogen peroxide to give 4,4′-dihydroxy-3,5,3′,5′-tetramethylbiphenyl in good yield (Scheme 3, c). However, a fraction of this product is oxidized to 4-(3′,5′-dimethylcyclohexa-2′,5′-dinenone)-methylidene-2,6-dimethyl-cyclohexadienone, which can be monitored by UV–visible spectroscopy (Fig. 1).



Scheme 3.

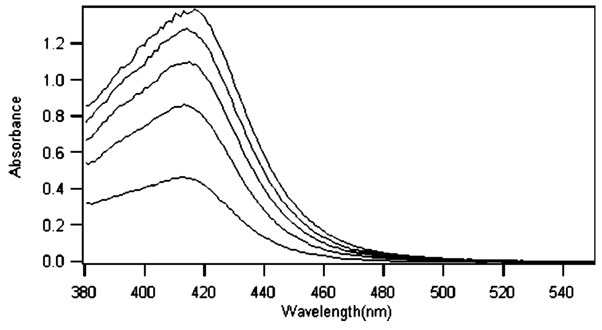


Figure 1. The increase in absorbance at 414 nm during formation of 4-(3′,5′-dimethylcyclohexa-2′,5′-dinenone)-methylidene-2,6-dimethyl-cyclohexadienone (10 min intervals) in the reaction between 2,6-dimethylphenol (12.8 mg, 0.105 mmol) and complex **B** (3 mg, 0.01 mmol) and hydrogen peroxide (30 µl, 30%) in methanol (3 ml).

4-(3′,5′-Dimethylcyclohexa-2′,5′-dinenone)-methylidene-2,6-dimethyl-cyclohexadienone has a absorption at 414 nm with high extinction coefficient ($\varepsilon = 9.05 \times 10^4$ mol^{-1} cm^{-1}). The methanolic solution of the bis-pyridinium tetrachlorocopper does not have an absorption in this region. Advantage of this was taken and the reaction was monitored with different catalyst concentrations. The growth of the absorption maximum at 414 nm is shown in Fig. 2. From the time versus product-formation plot it was found that the amount of quinone formed was of the order 1/1500 mole ratio with copper, suggesting it to be a side product. This is further confirmed by monitoring this absorption at 414 nm in a different reaction mixture versus time with an increase in concentration of the catalyst **B**. The effect of concentration of copper(II) complex **B** on the yield of 4-(3′,5′-dimethylcyclohexa-2′,5′-dinenone)-methylidene-2,6-dimethyl-cyclohexadienone is shown for three different ratios of copper to substrate in Fig. 2. From Fig. 2 it is apparent that the side product 4-(3′,5′-dimethylcyclohexa-2′,5′-dinenone)-methylidene-2,6-dimethyl-cyclohexadienone does not increase significantly with increase in catalyst concentration. The control experiment with hydrogen peroxide alone with 2,6-dimethylphenol (without the catalyst) under similar reaction conditions did not show formation

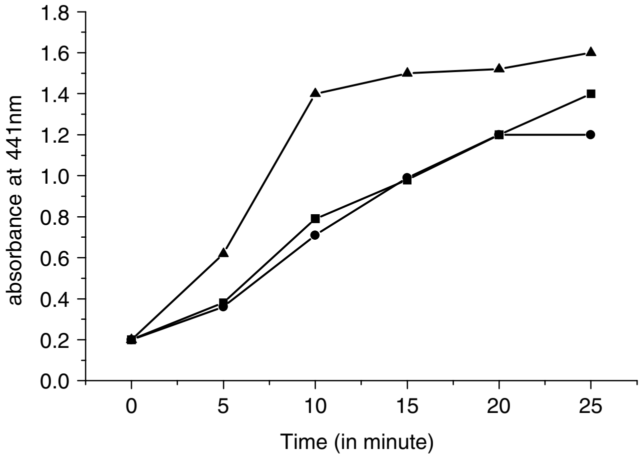


Figure 2. The effect of concentration of bis-pyridinium tetrachlorocopper(II) during oxidative reaction of 2,6-dimethylphenol with H_2O_2 (30 µl, 30%, methanol 3 ml) on the formation of 4-(3′,5′-dimethylcyclohexa-2′,5′-dinenone)-methylidene-2,6-dimethyl-cyclohexadienone at 30 °C measured at 414 nm (▲, phenol : **B** = 30 : 1; ■, phenol : **B** = 10 : 1; ●, phenol : **B** = 6 : 1).

of 4-(3′,5′-dimethylcyclohexa-2′,5′-dinenone)-methylidene-2,6-dimethyl-cyclohexadienone. It was also found that the yield of the quinone in this reaction could be enhanced by bubbling oxygen. All these results suggest that a one-electron oxidation of 2,6-dimethylphenol is the prime process in this oxidation.

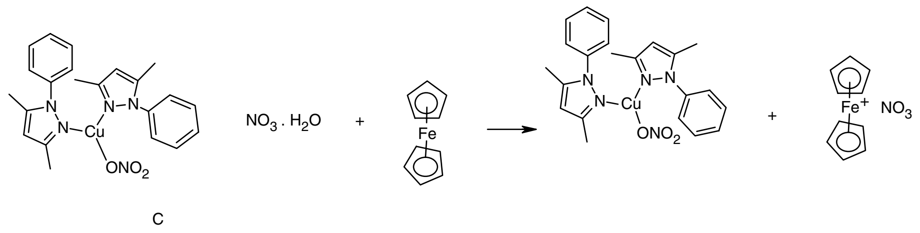
Benzenethiol reacted with a catalytic amount of **B** in aerobic conditions resulted in disulfide formation. The reaction of thiophenol proceeds under aerobic conditions with a catalytic amount of the complex **B**. The catalytic role of the copper(II) complex can be understood with the formation of copper(I) followed by its oxidation with oxygen to copper(II) to complete the cycle. The initial reduction of copper(II) to copper(I) is observed from the decolorization of the starting solution.

The crystal structure of bis-pyridinium tetrachlorocopper(II) shows a tetrahedral geometry around the copper centre.[16] We have found that bis-pyridinium tetrachlorocopper(II) has a quasi-reversible Cu(I)–Cu(II) couple with $E_{1/2}$ at 520 mV in acetonitrile (versus Ag/AgCl in acetonitrile and tetrabutylammonium perchlorate as supporting electrolyte). The cathodic and anodic peak separation of the complex is 207 mV in the voltammogram, with $i_{pa}/i_{pc} = 1.33$. The complex also shows a similar quasi-reversible redox couple in methanol, but in this case the oxidation occurs at 394 mV and reduction occurs at 493 mV, with $i_{pa}/i_{pc} = 1.16$. On the basis of the result on the solvent-induced shift in the peak separation and the shift in the redox potential, as well as from visual observations, a dissociative mechanism would explain the quasi-reversible nature of the peaks. Deviation of the couple from the reversible nature is reflected in the peak separation; this is 207 mV in the case of bis-pyridinium tetrachlorocopper(II) in acetonitrile, and it is 99 mV in methanol. This observation suggests that the copper(I)–copper(II) cycle could be the key factor involved in this reaction. The role of the co-oxidant, such as hydrogen peroxide or *tert*-butylhydroperoxide, is to bring back the copper(I) state to the copper(II) state.

In order to understand further the effect of the redox couple of Cu(I)–Cu(II), another copper(II) complex, namely bis-(*N*-phenyl-3,5-dimethylpyrazole)copper(II) nitrate monohydrate, was prepared from the reaction of *N*-phenyl-3,5-dimethylpyrazole with copper(II) nitrate trihydrate. The complex was characterized from its elemental analysis, molar conductance and IR spectra. The thermal properties of the complex suggest that it loses a water molecule on heating at 160 °C (theoretical weight loss 3.2%; found 3.8%); loses two molecules of *N*-phenyl-3,5-dimethylpyrazole at 180–300 °C (theoretical 65.8%; found 64.6%) and it finally forms cupric oxide at 300–550 °C (theoretical 86.6%; found 87%) by losing N_2O_5.

The complex bis-(*N*-phenyl-3,5-dimethylpyrazole)copper (II) nitrate monohydrate has a quasi-reversible redox cycle at 870 mV versus Ag/AgCl electrode (positive scan; scan speed 10 mV s^{-1}). The ΔE between anodic and cathodic peaks is 200 mV ($i_{pa}/i_{pc} = 1.5$). This is attributed to a Cu(II)–Cu(I) quasi-reversible redox cycle. The high redox potential of **C** makes it suitable as a good oxidizing agent. For this purpose, the complex was reacted with ferrocene and was found to oxidize it in a stoichiometric manner (Scheme 4). The visible spectra observed by titrating a solution of complex **C** with ferrocene is shown in Fig. 3. The original absorption of the complex at 775 nm changes to give a new peak at 625 nm due to formation of the ferricinium cationic species. Similarly, complex **C** is suitable for generation of bromine from reaction with different tetra-alkylammonium bromides. For example, reaction of an equimolar amount of the complex **C** with tetrabutylammonium bromide, tetraethylammonium bromide, or tetramethylammonium bromide yielded bromine. These reactions could be monitored by UV–visible spectroscopy and one such representative absorption spectroscopic study is shown in Fig. 4. The complex has a d–d transition at 775 nm, and this absorption peak decreases due to anion exchange. Initially, this peak at 775 nm decreases and there is an increase in absorption at 486 nm. This absorption at 486 nm is attributed to formation of bromine. There is also a growth of absorption after the liberation of bromine at 637 nm with an isosbestic point at 710 nm, suggesting the transformation of the complex to bis-(*N*-phenyl-3,5-dimethylpyrazole)copper(II) bromide. However, when the peak grows at 637 nm, the absorption at 486 nm decreases. This suggests that the copper(I) complex formed in this reaction during liberation of bromine becomes oxidized by the liberated bromine to give the new copper(II) complex.

Various of organic substrates can be oxidized by catalytic amounts of **C** at ambient temperature in the presence of



Scheme 4.

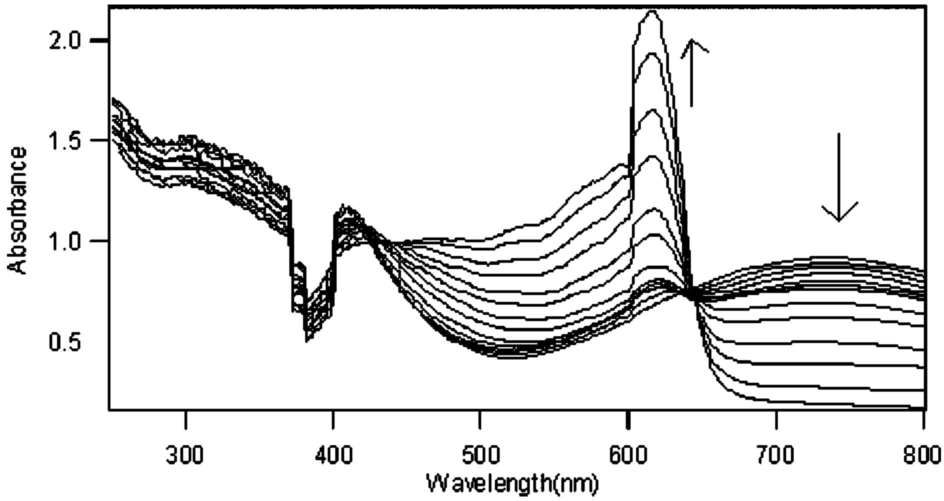


Figure 3. Change of absorbance of complex **C** (0.01 M 3 ml in acetonitrile) on addition of aliquots of ferrocene solution (20 μl aliquots from 0.01 M solution in acetonitrile).

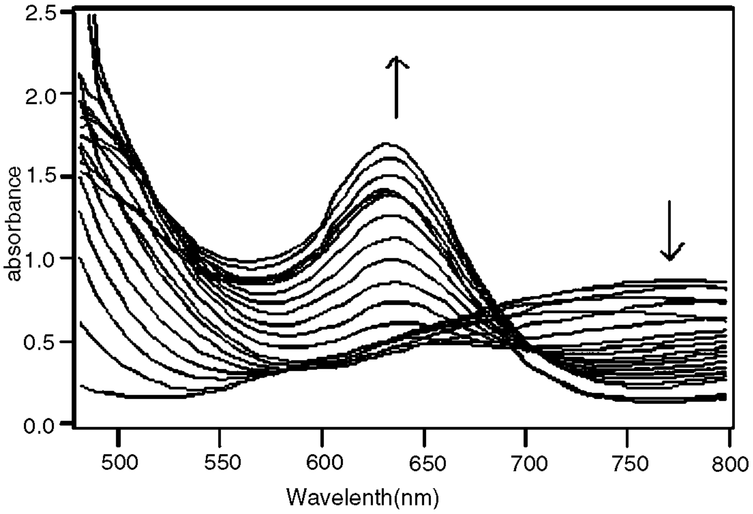


Figure 4. Absorption changes during the addition of **C** (2 ml, 0.01 M in methanol) on addition of tetraethylammonium bromide (aliquot of 20 μl of 0.01 M solution).

hydrogen peroxide. Aromatic aldehydes, such as benzaldehyde, *p*-methoxy-benzaldehyde, *p*-methyl-benzaldehyde, *p*-nitrobenzaldehydes, oxidize to benzoic acids in the presence of 1 mol% catalyst within 2 h in the presence of hydrogen peroxide. The 1 mol% of the complex **C** can also cause transformation of benzylamine to benzylalcohol (35%) and benzaldehyde (48%) at room temperature within 2 h in the presence of hydrogen peroxide (30 vol.%). Complex **C** with hydrogen peroxide is also an effective catalyst in causing oxidation of diphenylmethane at room temperature to give a mixture of diphenylmethanol (32%) and benzophenone (10%) in 6 h.

These results suggests that copper(II) complexes having suitable redox properties are useful for one-electron oxidation reactions. The use of peroxide as a co-oxidant helps in the catalytic cycle by regenerating the copper(II) species formed during the oxidation reaction.

Acknowledgements

We thank the Department of Science and Technology, New Delhi, India, for financial assistance.

REFERENCES

1. Sheldon RA, Kochi JK. *Metal Catalysed Oxidation of Organic Compounds*. Academic Press: New York, 1991.
2. Que Jr L, Tolman WB. *Angew. Chem. Int. Ed. Engl.* 2002; **41**: 1114.
3. Puzari A, Baruah JB. *J. Mol. Catal. A* 2002; **187**: 147.
4. Pierre JL. *Chem. Soc. Rev.* 2000; **29**: 251.
5. Tyklar Z, Karlin KD. *Acc. Chem. Res.* 1989; **22**: 241.
6. Halfen JA, Mahapatra S, Wilkinson EC, Kaderli S, Young Jr VG, Que Jr L, Zuberbuhler AD, Tolman WB. *Science* 1996; **271**: 1397.
7. Holland PL, Rodgers KR, Tolman WB. *Angew. Chem. Int. Ed. Engl.* 1999; **38**: 1139.
8. Capdevivielle P, Sparfel D, Lafont JB, Cuong NK, Maumy M. *J. Chem. Soc. Chem. Commun.* 1990; 565.
9. Whittaker JW. In *Metal Ions in Biological Systems*, vol. 30, Sigel H, Sigel A (eds). Mercel Dekker: New York, 1994; 315.
10. Chaudhuri P, Hess M, Weyhermuller T, Wieghardt K. *Angew. Chem. Int. Ed. Engl.* 1999; **38**: 1095.
11. Pratt RC, Stack TDP. *J. Am. Chem. Soc.* 2003; **125**: 8716.
12. Ling K-Q, Lee Y, Macikenas D, Protasiewicz JD, Sayre LM. *J. Org. Chem.* 2003; **68**: 1358.
13. Purkayshtha A, Baruah JB. *Thermochim Acta* 2002; **390**: 187.
14. Chandrasekhar V, Kingley S, Viz A, Lam KC, Rheingold A. *Inorg. Chem.* 2000; **39**: 3238.
15. Alves WA, de Almeida SA, de Almeida MV, Paduan A, Beccerra CC, Ferierra AMD. *J. Mol. Catal.* 2003; **198**: 63.
16. Czugler M, Kotai L, Sreedhar B, Rockenbauer A, Gacs I, Holly S. *Eur. J. Inorg. Chem.* 2002; 3298.