Pergamon

PII: S0277-5387(97)00147-2

Polyhedron Vol. 16, No. 21, pp. 3765–3774, 1997

0277–5387/97 $17.00+0.00

Oxidation of cyclohexane with hydrogen peroxide catalysed by copper(II) complexes containing N,N-bis(2-pyridylmethyl)-β-alanineamide ligands

Takashi Okuno,[a] Shigeru Ohba[b] and Yuzo Nishida[a]*

[a] Department of Chemistry, Faculty of Science, Yamagata University, Yamagata 990, Japan

[b] Department of Chemistry, Faculty of Science and Technology, Keio University, Yokohama 223, Japan

(Received 27 February 1997; accepted 11 April 1997)

Abstract—In the presence of hydrogen peroxide, a mononuclear copper(II) complex, [Cu(bdpg)Cl]Cl [where (bdpg) represents N,N-bis(2-pyridylmethyl)-β-alanine-amide] exhibits a much higher activity for the oxygenation of cyclohexane than other analogs. Crystal structure determinations and spectroscopic data indicate that the amide group in the (bdpg) ligand, which can interact with a hydroperoxide-ion η^1-bonded to copper(II) plays an important role in activation of hydrogen peroxide, leading to the facile oxygenation of cyclohexane. © 1997 Elsevier Science Ltd

Keywords: oxygenation by copper(II) complex; hydrogen peroxide; monomeric copper(II) complex; oxygenation of cyclohexane; tripodal-ligands.

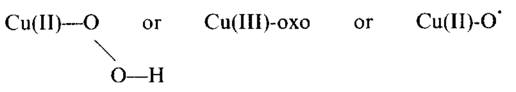
Dopamine-β-hydroxylase(DβH) catalyzes the hydroxylation of phenylethylamines and related substrates at the benzylic positions (see Scheme 1, below) [1]. The enzyme is a copper-containing monooxygenase and is responsible for the conversion of dopamine to noradorenalin. The catalytic mechanism of DβH is of a particular interest due to overwhelming evidence that dioxygen binding and subsequent monooxygenase chemistry is carried out at mononuclear copper centers [1], which seems to be quite different from reactions of dicopper proteins such as oxy-hemocyanin or oxytyrosinase, etc [2].

$$RCH_2CH_2NH_2+O_2 \rightarrow RCHOHCH_2NH_2+H_2O$$

Scheme 1.

A major challenge has been to elucidate the chemical steps involved in the combination of substrate and O_2 to yield a hydroxylated product at a single copper center, and there are few mononuclear copper(II) coordination compounds that catalyze the oxygenation of alkanes in the presence of hydrogen peroxide [3,4]. Early studies have implicated to the formation of a copper(II) hydroperoxide species as an intermediate in C—H bond cleavage [5], however little has been known regarding the nature of the oxygen species responsible for substrate activation, in particular whether this is copper(II) hydroperoxide itself or a copper-oxo species derived from copper(II) hydroperoxide (see Scheme 2) [6].

In our previous papers, we have pointed out that metal hydroperoxide adducts exhibit electrophilic properties which play a very important role in reactions with organic compounds [7–9]. In this paper, we show that a copper(II) complex with an amide-containing tripodal-ligand, N,N-bis(2-pyridylmethyl)-β-alanineamide, exhibits a much higher activity for the oxygenation of cyclohexane in the presence of hydrogen peroxide than any other hom-



Cu(II)—O(—H) or Cu(III)-oxo or Cu(II)-O$^{\bullet}$

Scheme 2.

---

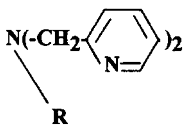
* Author to whom correspondence should be addressed.

ologues. This complex is, to our knowledge, the mononuclear copper(II) compound having the highest alkane functionalization ability in the presence of H_2O_2.

EXPERIMENTAL

Materials

The new copper(II) compounds used in this study were prepared by mixing methanolic solution of copper(II) chloride and the ligands (see Scheme 3), which were obtained according to the method by Toftlund *et al.* [10]. These are formulated as [Cu(dpgs)Cl]ClO_4 (**1**), [Cu(dpa)Cl]·$2H_2O$ (**3**), [Cu(dpal)]PF_6 (**4**), [Cu(bdpg)Cl]Cl (**2**), and [Cu(bdpg)Cl]ClO_4 (**5**). Analytical data of the new compounds are listed in Table 1.



R=-CH$_2$C(=O)OH, H(dpa)
=-CH$_2$C(=O)NH$_2$, (dpgs)
=-CH$_2$CH$_2$C(=O)NH$_2$ (bdpg)
=-CH$_2$CH$_2$COOH H(dpal)

Scheme 3.

Crystal structure determination

The compounds in the structure determination were recrystallized from a methanol/water mixture. The structures of four new compounds (**1–4**) were determined in this study, and the crystal data of the compounds are summarized in Table 2. X-ray diffraction intensities were measured up to $2\theta = 55°$ using Mo–Kα radiation on a Rigaku AFC-5 four-circle diffractometer, and absorption corrections were carried out by a numerical integration method. The structures were refined using CRYSTAN-GM software, and details have been deposited as supplementary data.

Oxygenation of cyclohexane in the presence of copper(II) complex and hydrogen peroxide

In a typical run, an acetonitrile solution (20 ml) containing the copper(II) complex (0.1 mmole) and cyclohexane (840 mg, 0.01 mole) was added to an acetonitrile solution (20 ml) containing hydrogen peroxide (1.13 g of commercial 30% aqueous solution), and the products were analyzed by GC at an appropriate time after mixing. Cyclopentanone was used as an internal standard. The turn-over numbers of the oxygenated products were also examined under nitrogen atmosphere (by bubbling nitrogen gas which had been passed through an acetonitrile/cyclohexane solution).

Electrochemical measurements

The cyclic voltammongrams (CV) of the compounds were measured in the usual manner [11], under an Ar atmosphere in acetonitrile, using 0.1 M tetra(*n*-butyl)ammonium tetrafluoroborate as supporting electrolyte, and a concentration of 0.001 M of the copper(II) compound. The potential was referenced to a saturated sodium chloride calomel electrode (SSCE) at 25°C.

Molecular orbital calculations

MO calculations for Cu$(NH_3)_3$(formamide)$(OOH)^+$ were performed by the use of Extended Huckel method reported by Hoffmann [12], and the parameters used for copper(II) ion are the same as those used in the literature [13].

Measurements

Absorption spectra were obtained with a Shimadzu Spectrophotometer model UV-2200 at 298 K. ESR spectra were measured with a JEOL ESR apparatus model RE-2X (X-band, 77 K).

RESULTS

Crystal structure

The ORTEP drawings of two of copper(II) complexes, Cu(dpgs)Cl^+ (**1**) and Cu(bdpg)Cl^+ (**2**) are shown in Fig. 1. The structural features of the former complex are essentially the same as those of the latter, the geometry around the copper(II) ion is that of a tetragonal pyramid, with the oxygen atom of the amide-group at the apical position. Three nitrogen

Table 1. Analytical data of the new compounds

	C		H		N	
	Calcd	Found	Calcd	Found	Calcd	Found
[Cu(dpgs)Cl]ClO_4 (**1**)	36.98	37.47	3.55	3.70	12.32	12.53
[Cu(dpa)Cl]·$2H_2O$ (**3**)	42.92	42.92	4.24	4.64	10.55	10.74
[Cu(dpal)]PF_6 (**4**)	37.62	37.99	3.37	3.58	8.78	9.29
[Cu(bdpg)Cl]ClO_4 (**5**)	37.16	36.91	3.74	3.96	11.56	11.29

Table 2. Crystallographic data of the copper(II) compounds

	(1) [Cu(dpgs)Cl]ClO$_4$	(2) [Cu(bdpg)Cl]Cl · 2H$_2$O	(3) [Cu(dpa)Cl] · 3H$_2$O	(4) [Cu(dpal)]PF$_6$ · 2H$_2$O
Formula	$C_{14}H_{16}CuCl_2N_4O_5$	$C_{15}H_{22}CuCl_2N_4O_3$	$C_{14}H_{20}CuClN_3O_5$	$C_{15}H_{20}CuF_6N_3O_4P$
M	454.76	440.82	409.33	514.85
Crystal system	triclinic	triclinic	monoclinic	monoclinic
Space group	$P\bar{1}$	$P\bar{1}$	$C2/m$	$P2_1/n$
a (Å)	10.667(3)	10.439(2)	9.836(3)	14.451(2)
b (Å)	12.517(3)	11.398(2)	13.620(3)	9.744(3)
c (Å)	7.095(2)	8.489(2)	13.958(3)	14.730(2)
α (°)	101.27(2)	91.16(2)	90	90
β (°)	95.32(2)	112.81(1)	109.89(2)	109.58(1)
γ (°)	99.98(2)	89.83(2)	90	90
V (Å^3)	907.1(4)	930.9(3)	1758.4(8)	1954.2(7)
Z	2	2	4	4
Dc (g cm^{-3})	1.665	1.573	1.546	1.750
Observed reflections ($Fo > 3\sigma$)	3348	3796	1753	3246
R	0.0497	0.0402	0.0437	0.0619
wR	0.0491	0.0473	0.0526	0.0590

Table 3. Selected bond lengths (Å) and angles (°)

[Cu(dpgs)Cl]ClO$_4$ (**1**)			
Cu(1)—Cl(2)	2.240(1)	Cu(1)—O(3)	2.294(2)
Cu(1)—N(4)	1.981(2)	Cu(1)—N(5)	2.067(2)
Cu(1)—N(6)	1.977(2)		
Cl(2)—Cu(1)—O(3)	103.2(1)		
O(3)—Cu(1)—N(5)	80.4(1)		
Cu(1)—O(3)—C(20)	109.4(2)		
Cu(1)—N(5)—C(19)	110.6(2)		
[Cu(bdpg)Cl]Cl · 2H$_2$O (**2**)			
Cu(1)—Cl(2)	2.271(1)	Cu(1)—O(4)	2.287(2)
Cu(1)—N(8)	1.995(2)	Cu(1)—N(9)	2.065(2)
Cu(1)—N(10)	1.994(2)		
Cl(2)—Cu(1)—O(4)	91.1(1)		
O(4)—Cu(1)—N(9)	92.1(1)		
Cu(1)—O(4)—C(25)	123.9(1)		
Cu(1)—N(9)—C(23)	115.1(1)		
[Cu(dpa)Cl] · 3H$_2$O (**3**)			
Cu(1)—Cl(2)	2.281(2)	Cu(1)—O(3)	2.233(4)
Cu(1)—N(4)	1.994(3)	Cu(1)—N(4) i	1.994(3)
Cu(1)—N(5)	2.074(4)		
Cl(2)—Cu(1)—O(3)	99.0(1)		
O(3)—Cu(1)—N(5)	81.4(2)		
Cu(1)—O(3)—C(13)	110.9(3)		
Cu(1)—N(5)—C(12)	109.8(3)		
Cu(dpal) · PF$_6$ · 2H$_2$O (**4**)			
Cu(1)—O(9)	2.409(3)	Cu(1)—O(10) ii	1.936(3)
Cu(1)—N(13)	1.986(4)	Cu(1)—N(14)	2.039(4)
Cu(1)—N(15)	1.989(4)		
O(9)—Cu(1)—O(10) ii	87.9(2)		
O(9)—Cu(1)—N(14)	90.0(2)		
Cu(1)—O(9)—C(30)	120.7(3)		
Cu(1)—N(14)—C(28)	112.9(3)		

Symmetry codes: (i) x, −y, z; (ii) 3/2−x, 1/2+y, 3/2−z.

atoms (two pyridine nitrogens and the aliphatic amine) and the chloride ion are located in the basal plane of the complex. Selected bond distances and angles of the compounds are listed in Table 3. These are very similar to those of analogous complexes [14].

The structural characteristics of the other two complexes with H(dpa), (**3**) and H(dpal) (**4**) (see Fig. 2), are essentially the same as those of the (dpgs)- and (bdpg)-complexes. The (dpa) complex (**3**) has crystallographic mirror symmetry. In contrast to the other three structures reported in this paper, the second oxygen atom of the (dpal) complex (**4**) coordinate to different copper atoms to make a polymer chain.

Oxygenation of cyclohexane

Figure 3 shows a plot of turn-over numbers as a function of time referring to the products produced when cyclohexane was reacted with a copper(II) complex and hydrogen peroxide are shown, these results are also summarized in Table 4. It should be noted here that the formation of oxygenated products is greatly dependent on the complex used; the yields of the oxygenated products are very high for the (bdpg)-complex (**2**), but are negligible in the cases of the (dpa) complex (**3**) and the (tpa) complex, [Cu(tpa)Cl]ClO_4, which has a trigonal bipyramidal coordination (tpa = tris(2-pyridylmethyl) amine).

Spectral features of the compound

We have measured the ESR spectra of the compounds, as illustrated in Fig. 4. The ESR spectra of the copper(II) compounds used in this study exhibit one isotropic signal in frozen acetonitrile (77 K) (for example, see Fig. 4(A)). These are frequently observed for the copper(II) complexes with tripodal-like ligands: for example, broad isotropic signal was observed in acetonitrile for $Cu(bbt)Cl^+$ (see Fig. 5(A)) whose structure was determined to be square-pyramidal ((bbt) = 2-[bis(benzimidazol-2-ylmethyl) amino]ethanol) [15]. It is also well known that addition of a ligand, which coordinates to copper(II) stronger than halide, leads to a spectral change from one broad absorption to one characteristic for the tetragonal symmetry, as shown in Fig. 5(B). We have observed in this study that the addition of hydrogen peroxide to an acetonitrile solution of $Cu(bdpg)Cl^+$ (**2**) causes the ESR spectrum to change to that characteristic for a square pyramidal structure [16], as shown in Figs 4(B)–(D). The addition of imidazole to a $Cu(bdpg)Cl^+$ solution (**2**) also induced the formation of an imidazole-complex of tetragonal structure, $Cu(bdpg)(imidazole)^{2+}$ (see Fig. 4(E)): the presence of nine superhyperfine structures in the g-region indicates the coordination of imidazole in the basal plane of the square pyramid. These observations suggest that peroxide addition occurs at the basal-plane, leading to the formation of a peroxide adduct, $Cu(bdpg)(O_2H)^+$ (see Scheme 4) upon addition of hydrogen peroxide. The ESR spectral changes observed for the complex (**2**) by the addition of hydrogen peroxide were observed for all the complexes (**1**), (**3**), and (**4**), studied in this study.

The absorption spectra of the copper(II) compounds (**1**–**4**) are similar to each other, and also similar to those of the corresponding benzimidazole derivatives with a square pyramidal structure [14]. A small change was observed when hydrogen peroxide was added to the solution (see Fig. 6). This could be consistent with the suggestion that a peroxide adduct may be formed by the addition of hydrogen peroxide, and that this should occur by the replacement of chloride ion, as described above.

Active species for oxygenation reaction of cyclohexane

As shown in Table 4, it should be noted here that the activity of the (bdpg)-complex (**2**) is much higher than that of any other analogous compound. If we assume that a peroxide adduct is formed in the course of the reaction (see Scheme 4), the life-time of the adduct should be very important for the oxygenation of cyclohexane. It seems quite likely that the facile formation of an intramolecular hydrogen bond, in which the oxygen atom of the tripodal-ligand is interacting with the hydrogen atom of the hydroperoxide ligand, may considerably affect the life-time of the peroxide adduct in solution (see Scheme 5); this was pointed out earlier in an analogous iron(III) compound with the (dpgs) ligand [17].

In the case of $Cu(dpgs)Cl^+$ (**1**), the angle (θ, see Scheme 5) of Cl–Cu–O (amide oxygen), is 103.2(1), which is much larger than that in complex (**2**) with (bdpg), 91.1(1). Moreover, the Cu–O–C angle at the amide oxygen, ϕ, is smaller [109.4(2)°] in the (dpgs)-complex (**1**) than that in the (bdpg)-complex (**2**), the value being 123.9(1)° in the latter case. Assuming sp^2-hybridization of the amide oxygen atom, the (bdpg)-complex (**2**) has the oxygen lone-pair orbital oriented in a more preferable direction to accept the hydrogen bond (see Scheme 5). Thus, it seems quite reasonable to assume that peroxide adduct formation may be more favorable in the (bdpg)-complex (**2**) than that in the (dpgs)-complex (**1**), and this may explain the higher turn-over numbers of the oxygenated products by the (bdpg)-complex (**2**).

We also measured the cyclicvoltammograms of the $Cu(dpgs)Cl^+$ (**1**) and $Cu(bdpg)Cl^+$ (**2**) complexes (data not shown). The reduction potentials, $Cu^{II} \rightarrow Cu^I$, are -0.12 and -0.146 V (*vs* SSCE), respectively, indicating that the reduction reaction of the copper(II) ion to copper(I) is not related with the high activity of the $Cu(bdpg)Cl^+$ complex (**2**) in the oxygenation reaction.

The negligible activities of the other compounds, such as compounds with (tpa) and (dpa) (**3**), may be reasonably explained in terms of the discussion as

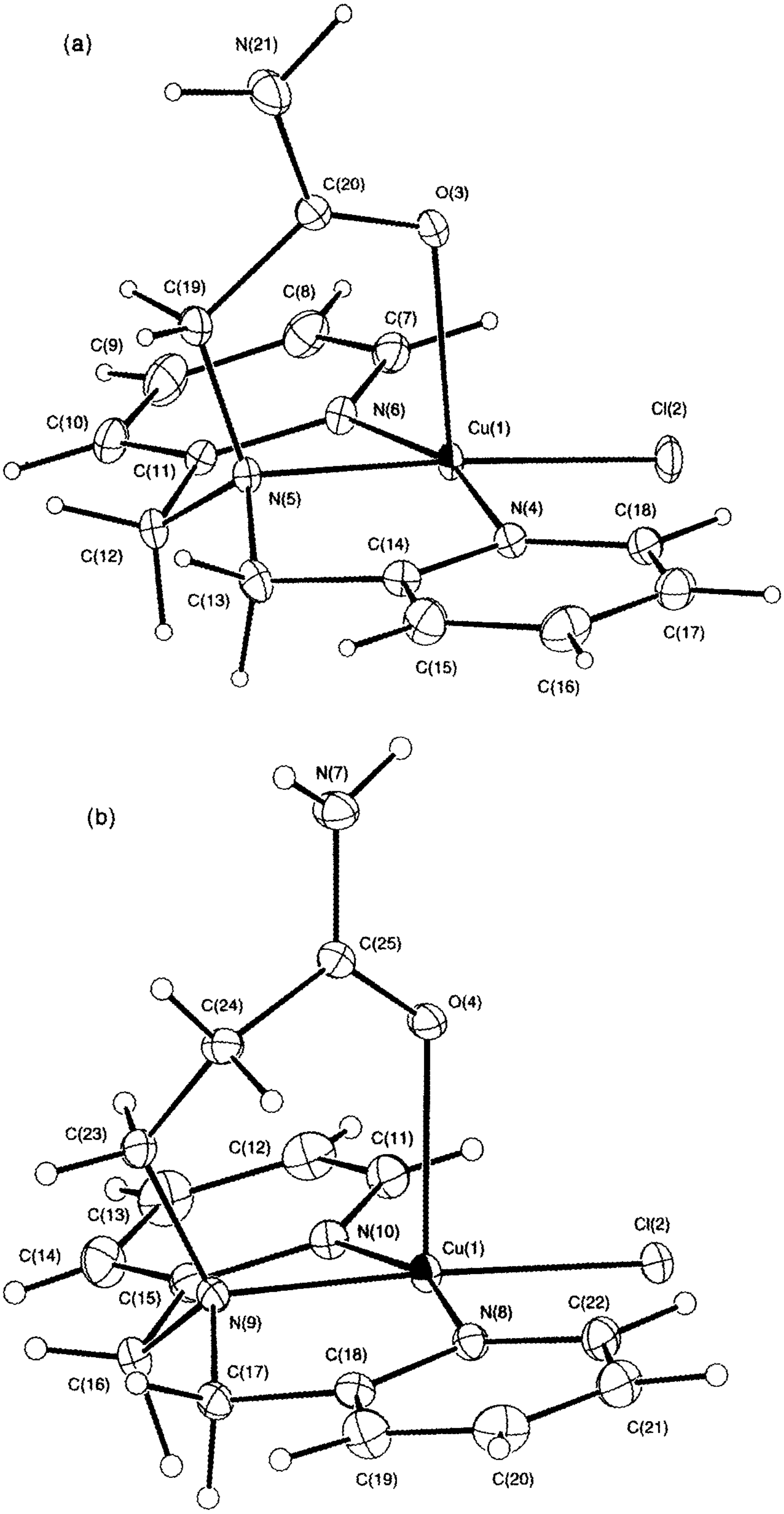


Fig. 1. Molecular structures of (A) Cu(dpgs)Cl$^+$ (**1**) and (B) Cu(bdpg)Cl$^+$ (**2**)

described above: the higher activity of the (dpal)-complex (**4**) as compared to that of the (dpa)-complex (**3**) should be due to the larger Cl–Cu–O(carboxylic acid) in (**3**) [99.0(1)°] as compared to that in the (dpal)-complex (**4**) (in this case, O–Cu–O = 87.9(2)°, see Fig. 2(B)).

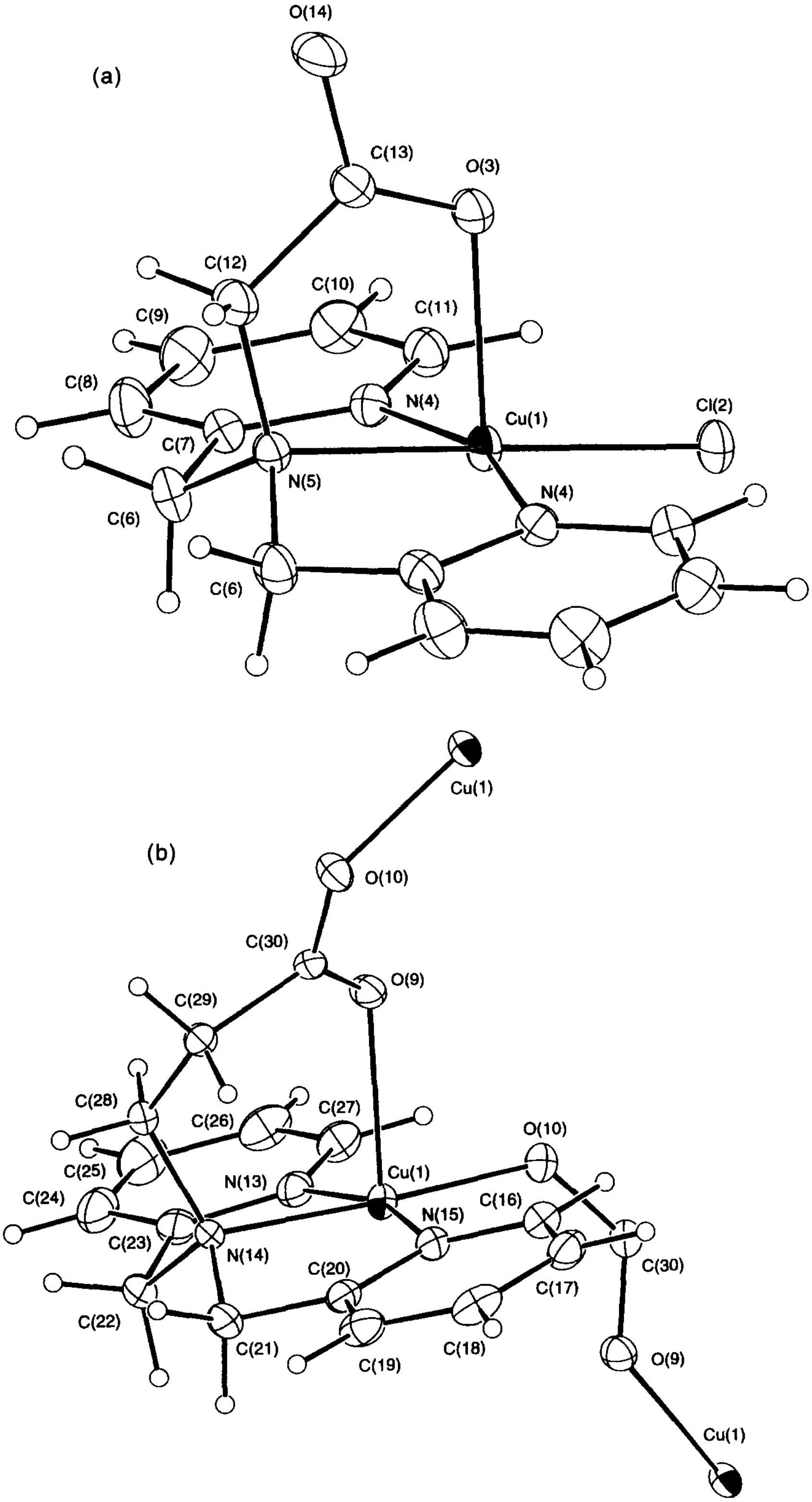


Fig. 2. Molecular structures of (A) Cu(dpa)Cl (**3**) and (B) Cu(dpal)$^+$ (**4**) showing a part of the polymer chain.

DISCUSSION

It seems very likely that a mononuclear copper(II)-hydroperoxide adduct, as shown in Scheme 4 or Scheme 5, may form in all of the copper(II) complex solutions (**1–4**). This is because of the following facts: (1) the ESR spectral features (77 K) of solutions containing a copper(II) complex (**1–4**) and hydrogen per-

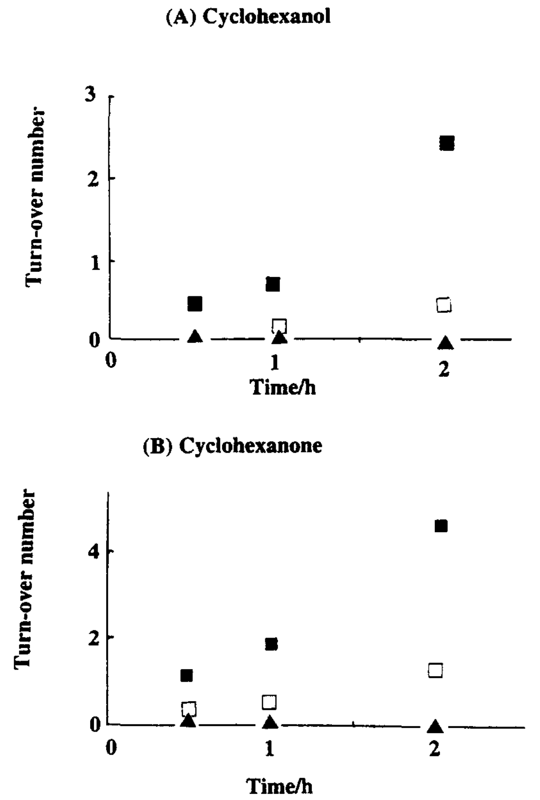


Fig. 3. A plot of time versus turn-over numbers of products catalyzed by copper(II) compounds (turn-over number = [mole of oxygenated product]/[mole of copper(II) complex])

(A) cyclohexanol (B) cyclohexanone

■ (bdpg) (2) □ (dpal) (4) ▲ (dpa) (3)

oxide are quite similar to those of mononuclear copper(II) compounds with tetragonal symmetry, (2) large excess of hydrogen peroxide ($[H_2O_2]/[Cu^{2+}] = 100$) was added, and (3) a coloration characteristic for a (μ-η^2: η^2-peroxo)dicopper(II) complex [18] was not observed for the solutions in the temperature range 290–77 K. The results shown in Table 4 clearly suggest that the formation and reactivity of a mononuclear copper(II)–hydroperoxide complex are greatly dependent on the chemical group surrounding the copper atom. Since the catalytic activities of the (bdpg) (**2**) and H(dpal) (**4**) complexes, which have a six-membered chelate ring, are higher than those of the corresponding (dpgs) (**1**) and H(dpa) (**3**) complexes with a five-membered chelate ring, it seems reasonable to conclude that the smaller angle (91.1°) of Cl(2)–Cu(1)–O(4) and the neutral charge of the ligand in the (bdpg)-complex (**2**) are highly suitable for the formation of Scheme 5, and the Cu(1)–O(3)–C(20) angle of 109.4° in the (dpgs)-complex (**1**) indicates an unsuitable direction of the lone-pair orbital for participating in the intramolecular hydrogen bond. All this discussion shows that the formation of the peroxide adduct in Scheme 5 is a critical step for the oxygenation reaction of cyclohexane. The lower activity of the H(dpal)-complex (**4**) compared to the (bdpg) complex (**4**) suggests that the neutral charge

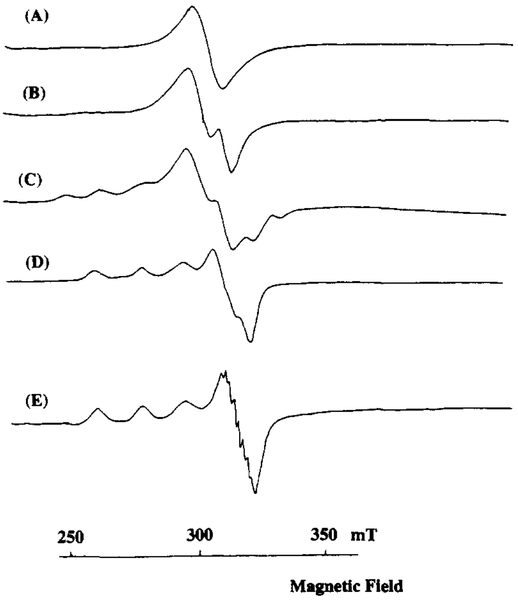


Fig. 4. ESR spectra of the [Cu(bdpg)Cl]Cl (**2**) (in acetonitrile, 1/500 M, 77 K, X-band)

A : [Cu(bdpg)Cl]Cl

B : [Cu(bdpg)Cl]Cl containing H_2O_2 ($[H_2O_2]/[Cu^{2+}] = 1$)

C : [Cu(bdpg)Cl]Cl containing H_2O_2 ($[H_2O_2]/[Cu^{2+}] = 5$)

D : [Cu(bdpg)Cl]Cl containing H_2O_2 ($[H_2O_2]/[Cu^{2+}] = 25$)

E: [Cu(bdpg)Cl]Cl containing imidazole ($[\text{imidazole}]/[Cu^{2+}] = 10$)

Table 4. Turn-over numbers of the oxygenated products catalyzed by copper(II) complex (turn-over number = [mole of product]/[mole of copper(II) complex])

	cyclohexanol		cyclohexanone	
	30 min	2 h	30 min	2 h
(**2**) [Cu(bdpg)Cl]Cl	0.42	2.45	1.2	4.7
(**1**) [Cu(dpgs)Cl]ClO_4	0.0	0.2	0.0	0.4
(**3**) [Cu(dpa)Cl]	0	0	0	0
(**4**) [Cu(dpal)]PF_6	0.1	0.4	0.2	1.4

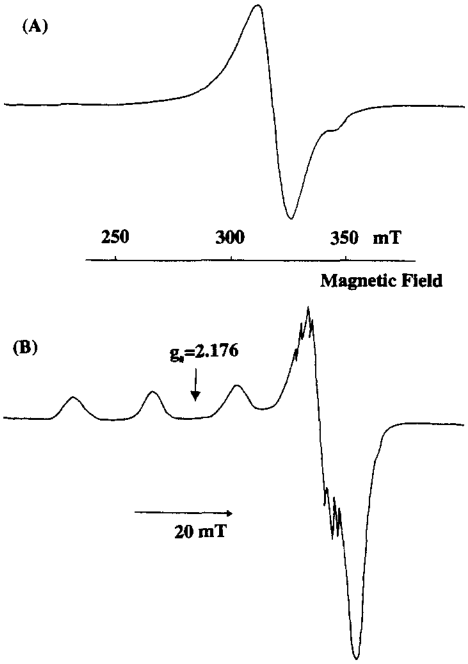
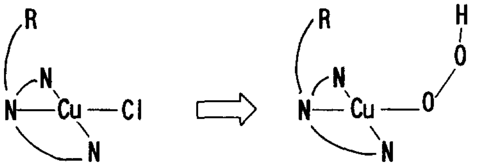


Fig. 5. ESR spectra of [Cu(bbt)Cl]ClO$_4$ (in acetonitrile, 77 K, 1/500 M, X-band)
A: [Cu(bbt)Cl]ClO$_4$
B: Copper(II) complex in the presence of imidazole ([imidazole]/[Cu^{2+}] = 10).



Scheme 4.

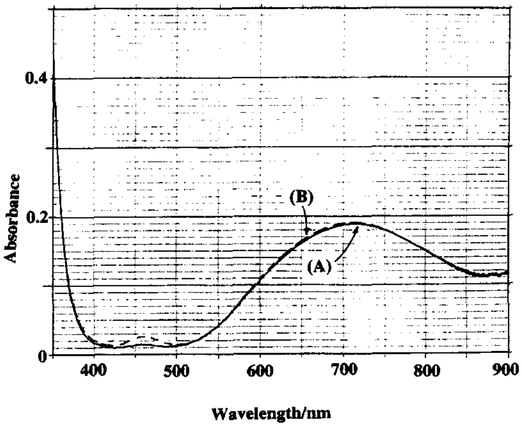
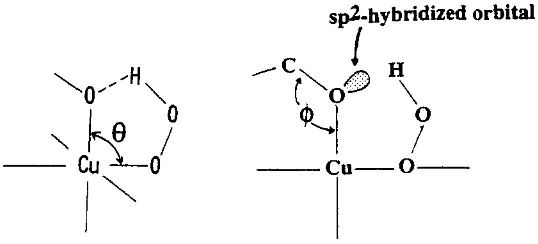


Fig. 6. Absorption spectra of the copper(II) compound
A(——): [Cu(bdpg)Cl]Cl (2) (in acetonitrile, 1/500 M, 298 K)
B(– – –): [Cu(bdpg)Cl]Cl (2) (in acetonitrile, 1/500 M 298 K) containing hydrogen peroxide ([H$_2$O$_2$]/[Cu^{2+}] = 10).



Scheme 5.

of the ligand in (2) may induce a stronger coordination of hydroperoxide anion to a copper(II) ion.

The results by EHMO calculations performed for Cu(NH$_3$)$_3$(formamide) (HO$_2^-$), a model complex for species in Scheme 5, seem to be consistent with the above consideration (see Fig. 7). It should be noted here that the molecular orbital level labelled as $d_{x^2-y^2}$ is composed of the copper d-orbital and p-orbitals of the oxygen atoms of the peroxide ion. The coefficients of the p_x-atomic orbitals of atom O(1) and O(2) in the $d_{x^2-y^2}$ molecular orbital are quite different from each other; this means that the peroxide ion in the peroxide adduct could act as an oxo–oxygen atom [8]. The appearance of the molecular orbitals A and B in Fig. 7 indicates that the energetic stabilization of the amide group occurs through an interaction with the p_x-orbitals of the O(1) and O(2) atoms (peroxide ion) *via* the copper $d_{x^2-y^2}$ orbital; this should contribute to the facile formation of a peroxide adduct. For a peroxide adduct in the η^1-coordination mode, the σ^*-orbital of peroxide ion can interact with the $d_{x^2-y^2}$ atomic orbital, as is shown by the appearance of the p_z-orbitals of O(1) and O(2) atoms with the same phase in the molecular $d_{x^2-y^2}$ orbital (see Fig. 7). The above discussion indicates that electron transfer from the amide group to the σ^*-orbital occurs through the copper(II) d-orbital in the peroxide adduct shown in Scheme 5; this electron transfer may lead to a heterolytic cleavage of the O—O bond in the peroxide adduct more easily and the heterolytic cleavage of the peroxide ion may alternatively be considered to result in a water-oxide derivative [19,20]. Thus, we can predict that the copper(II)–hydroperoxide adduct assumed in Scheme 5 acts as a species like copper(II)–O (atomic oxygen)···OH$^-$, which may be formally written as a copper(IV)–oxo complex. We have already pointed out that the alkane can approach the O(1) atom of the peroxide adduct (see Scheme 6) through a HOMO–LUMO interaction in which the alkane is behaving as an electron-donor and the peroxide adduct acts as an electrophile [8,9,17] (in Scheme 6, the HOMO [21] of methane is approaching to the peroxide adduct, yielding a pentacoordinate carbon transition state). Since the approach of the substrate also leads to a more facile heterolytic O—O cleavage of the peroxide adduct (because the electron transfer from the substrate to σ^*-orbital of the peroxide ion proceeds in this step), the oxygenation reaction may

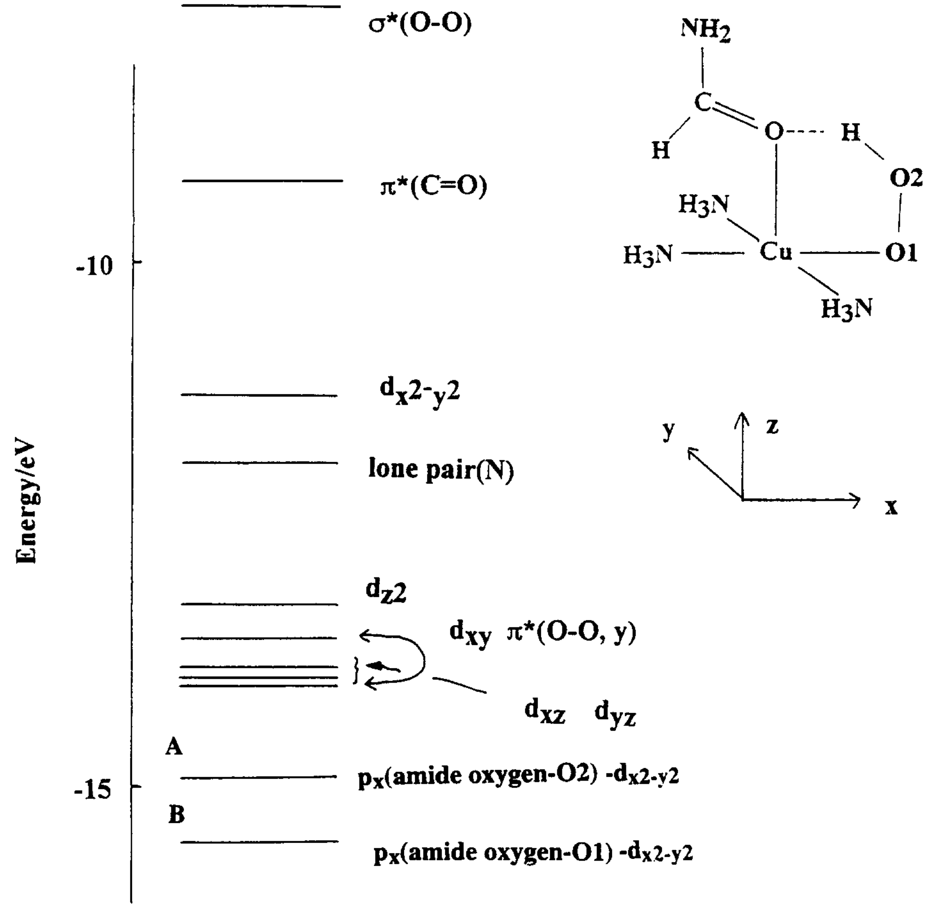
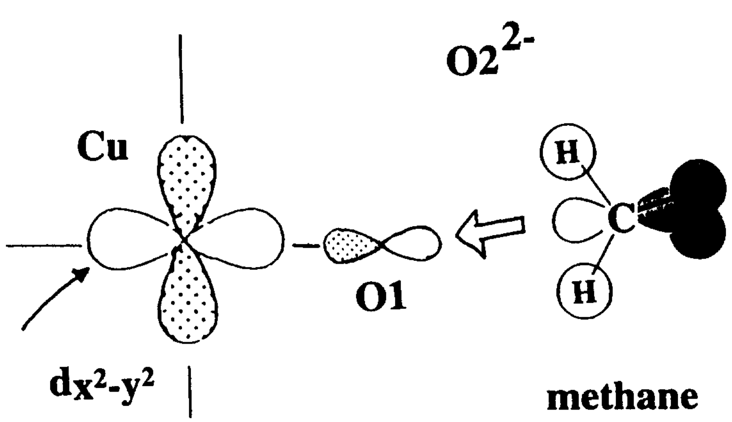


Fig. 7. EHMO calculation of $Cu(NH_3)_3(formamide)(OOH)^+$ Cu—NH_3, 2.00; Cu—O(1), 2.00; Cu—O(amide), 2.287; O(1)—O(2), 1.422; O(amide)—O(2), 2.415; O(amide)—H, 1.369 Å. Molecular orbital $d_{x^2-y^2}$ is roughly represented by: 0.763 $d_{x^2-y^2}$(copper)-0.386$p_y(NH_3)+0.386p_y(NH_3)-0.471p_x(NH_3)+0.286p_x(O1)-0.051p_x(O2)+0.063pz(O1)+0.026pz(02)$ orbital A: $0.422d_{x^2-y^2}+0.273px$ (amide oxygen)$+0.440px(O(2))$ orbital B: $0.507d_{x^2-y^2}-0.314p_x$ (amide oxygen) $-0.327p_x(O(1))-0.148p_x(O(2))$.



Scheme 6.

occur through the interaction between HOMO of methane and copper(II)–oxygen (atomic) species in a concerted manner as shown in Scheme 6.

The fact that the yields of the oxygenated products under nitrogen atmosphere are essentially the same as those under air for the (dpgs)- and (bdpg)-compounds (**1** and **2**, respectively) indicates that oxygenation of cyclohexane is independent of the presence of molecular oxygen; that is, radical reaction does not play an important role in this system [22]. The present results may give valuable information on elucidating the reaction mechanism of DβH and also of the enzyme pMMO, copper-containing methane monooxygenase in particulate form [23].

REFERENCES

1. Stewart, L. C. and Klinman, J. P., *Ann. Rev. Biochem.*, 1988, **57,** 164.
2. Karlin, K. D. and Tyeklar, T., *Bioinorganic Chemistry of Copper*, Chapman and Hall, New York (1993).
3. Barton, D. H. R. and Doller, D., *Acc. Chem. Res.*, 1992, **25,** 504.
4. Barton, D. H. R., Beviere, S. D., Chavasiri, W., Csuhai, E., Doller, D., *Tetrahedron*, 1992, **48,** 2895.
5. Ahn, N. G. and Klinman, J. P., *Biochemistry*, 1983, **22,** 3096.
6. Tian, G., Berry, J. A. and Klinman, J. P., *Biochemistry*, 1994, **33,** 226.
7. Nishida, Y. and Takeuchi, M., *Z. Naturforsch.*, 1987, **42B,** 52.
8. Nishida, Y., Itoh, H. and Yamazaki, A., *Polyhedron*, 1994, **13,** 2743.
9. (a) Nishida, Y. and Ito, S., *Z. Naturforsch.*, 1995, **50C,** 571; (b) Kobayashi, T., Tsuchiya, K. and Nishida, Y., *J. Chem. Soc., Dalton Trans.*, 1996, 2391; (c) Ito, S., Suzuki, M., Kobayashi, T., Itoh, H., Harada, A., Ohba, S. and Nishida, Y., *J. Chem. Soc., Dalton Trans.*, 1996, 2579.
10. Toftlund, H. and -Andersen, S. Y., *Acta Chem. Scand.*, 1981, **35A,** 575.
11. Nishida, Y., Watanabe, I. and Unoura, K., *Z. Naturforsch.*, 1992, **47B,** 119.
12. Hoffmann, R., *J. Chem. Phys.*, 1963, **39,** 1397.
13. Summerville, R. H. and Hoffmann, R., *J. Am. Chem. Soc.*, 1980, **102,** 4555.
14. (a) Young, M. J., Wahnon, D., Hynes, R. C. and Chin, J., *J. Am. Chem. Soc.*, 1995, **117,** 9441; (b) Nishida, Y. and Takahashi, K., *Inorg. Chem.*, 1988, **27,** 1406.
15. Nishida, Y., Takahashi, K. and Kida, S., *Momoirs Fac. Sc. Kyushu Univ.*, 1981, **13C,** 27.
16. Nishida, Y. and Takahashi, K., *J. Chem. Soc., Dalton Trans.*, 1988, 691.
17. Ito, S., Okuno, T., Matsushima, H., Tokii, T. and Nishida, Y., *J. Chem. Soc., Dalton Trans.*, 1996, 4469.
18. Kitajima, N. and Moro-oka, Y., *Chem. Rev.*, 1994, **94,** 737.
19. Bach, R. D., Owensby, A. L., Gonzales, C. and Schlegel, H. B., *J. Am. Chem. Soc.*, 1991, **113,** 6001.
20. Schroder, D., Schalley, C. A., Hrusak, J. and Schwarz, H., *Chem. Eur. J.*, 1996, **2,** 1235.
21. Fleming, I., *Frontier Orbitals and Organic Chemical Reactions*, Chpt. 2, John Wiley & Sons, London (1976).
22. Newcomb, M., -Biadatti, M.-L. T., Chestney, D. L., Roberts, E. S. and Hollenberg, P. F., *J. Am. Chem. Soc.*, 1995, **117,** 12085.
23. Wilkinson, B., Zhu, M., Priestley, N. D., Nguyen, H.-H. T., Morimoto, H., Williams, P. J., Chan, S. I. and Floss, H. G., *J. Am. Chem. Soc.*, 1996, **118,** 921.