

Copper(II), Cobalt(II) and Nickel(II) Complexes of Alkyl-substituted Tris(2-benzimidazolymethyl)amines and Their Ternary Copper(II) Systems Containing Several Thiolates

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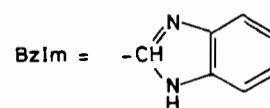
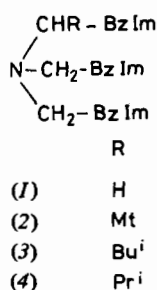
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Copper(II), cobalt(II) and nickel(II) complexes of tris(benzimidazolymethyl)amine(1) and of its methyl(2), isobutyl(3) or isopropyl(4)-substituted derivatives of one of the backbone methylene groups were prepared and characterized. The ligands (1)–(3) afforded trigonal bipyramidal copper(II) complexes, whereas ligand (4) gave a tetrahedrally distorted tetragonal one because of the steric hindrance arising from the isopropyl group. All the cobalt(II) complexes prepared were supposed to be tetrahedral or pseudo-tetragonal bipyramidal, and all the nickel(II) complexes to be slightly tetrahedrally distorted octahedral. Ternary copper(II) systems containing several thiolates as the third component exhibited intense blue, brown or green color under a reduced temperature by virtue of the charge transfer bands, $S^- \rightarrow Cu$.

Introduction

Tripod-like ligands with a variety of ligating groups have been highly estimated as a series of potent ligands to furnish the model compounds for the active sites of metalloproteins such as those of blue copper proteins [1]. On the other hand, many mono-nuclear and binuclear copper complexes coordinated by the benzimidazole group have been prepared and characterized as biological models [2], since the benzimidazole group satisfactorily takes the place of the imidazole group which participates in coordination around every type of copper binding site in proteins [3].

Here we report the syntheses and characterization of copper complexes with tripod-like ligands of structures (1)–(4), all of which differ from each other in the substituted group at the methylene group. With the introduction of these groups, a delicate stereochemical difference was observed in the coordination sphere of the copper(II) ion. It is known that coppers in proteins exist mostly at the active sites of a lower symmetry than the typical tetragonal or tetrahedral



geometry [4–6]. Cobalt(II) and nickel(II) complexes have also been prepared and their stereochemistries were comparatively estimated in order to shed light on the structural change of copper binding sites in proteins accompanied by cobalt(II)- or nickel(II)-substitution. Finally, ternary copper(II) systems containing a thiolate as the third component were investigated and it was found that some of the thiolates exhibit charge transfer absorptions arising from $S^- \rightarrow Cu$ transition characteristic of blue copper proteins.

Experimental

Preparation of Ligands

Ligand (1) was prepared according to the literature [1]. Ligand (2) was obtained by reaction of L-alanine and twice the amount of chloroacetic acid, and subsequent condensation of the resulting tricarboxylic acid and three times the amount of *o*-phenylenediamine. *Anal.* Found: C, 60.06; H, 5.94; N, 18.63. *Calc.* for $C_{25}H_{23}N_7 \cdot 3.5H_2O \cdot CH_3OH$: C, 60.45; H, 6.63; N, 18.93%. Ligands (3) and (4) were obtained by using L-leucine and L-valine, respectively as the starting material in place of L-alanine. *Anal.* Found: C, 65.79; H, 7.00; N, 18.32. *Calc.* for $C_{28}H_{29}N_7 \cdot 2H_2O \cdot CH_3OH$: C, 65.51; H, 7.01; N, 18.44%. (3). Found: C, 67.80; H, 6.26; N, 20.22. *Calc.* for $C_{27}H_{27}N_7 \cdot 1.5H_2O$: C, 68.04; H, 6.35; N, 20.57%. (4).

TABLE I. Analytical Data of the Isolated Complexes.

Complex	Analysis (%)					
	observed			calculated		
	C	H	N	C	H	N
Cu(2)(ClO ₄) ₂ ·2H ₂ O	41.99	3.87	13.40	41.70	3.77	13.61
Cu(2)Cl ₂ ·3.5H ₂ O	48.59	4.56	15.77	48.51	4.88	15.84
Cu(3)(ClO ₄) ₂ ·3H ₂ O	42.99	4.44	12.75	43.11	4.52	12.57
Cu(3)Cl ₂ ·3H ₂ O	51.91	5.55	14.52	51.57	5.40	15.03
Cu(4)(ClO ₄) ₂ ·4H ₂ O	41.38	4.23	12.21	41.28	4.49	12.48
Cu(4)Cl ₂ ·3H ₂ O·0.5CH ₃ OH	49.96	5.03	14.54	50.49	5.39	14.99
Co(2)Cl ₂ ·4H ₂ O	48.19	4.86	15.84	48.17	5.01	15.73
Co(3)Cl ₂ ·5H ₂ O	49.12	5.23	14.26	49.20	5.75	14.34
Co(4)Cl ₂ ·3.5H ₂ O	50.71	5.09	15.37	50.47	5.33	15.26
Ni(2)Cl ₂ ·2H ₂ O	51.19	4.56	16.50	51.14	4.63	16.70
Ni(3)Cl ₂ ·2H ₂ O	53.46	5.25	15.45	53.45	5.29	15.58
Ni(4)Cl ₂ ·4H ₂ O	49.88	4.83	14.96	49.80	5.42	15.06

Preparation of Metal Complexes

Copper(II), cobalt(II) and nickel(II) complexes were obtained by mixing equal amounts of each metal ion and ligand (1)–(4) in methanol, and allowing the solution to stand at room temperature or at 4 °C in a refrigerator. Cobalt(II) complexes were synthesized under nitrogen atmosphere to avoid the oxidation of cobalt(II) by air. Analytical data of complexes isolated are tabulated in Table I.

Measurements

Infrared spectra were measured by the KBr disk method with a Hitachi 260-10 grating infrared spectrometer, and PMR spectra with a Varian EM-390 spectrometer. Absorption spectra were obtained on a Hitachi 323 spectrophotometer at room temperature using a 1 cm path length quartz cell. For measurements of visible spectra at –78 °C, a specially designed Dewar vessel was attached to the spectrophotometer. ESR spectra of copper(II) complexes at X-band frequencies were measured on a JEOL JES-FE1X spectrometer for methanol glass samples at 77 K. Cyclic voltammetry was carried out on a Yanagimoto P-1000 voltammetric analyzer using a glassy carbon electrode as a working electrode for methanol solutions containing 0.1 mol dm⁻³ tetra n-butylammonium perchlorate as supporting electrolyte at 25 °C.

Results and Discussion

Copper Complexes

Absorption spectra of copper(II) complexes with ligands (1)–(3) exhibit two maxima at around 760–

TABLE II. Absorption Spectral Data of Complexes in Methanol.

Complex	λ_{\max} (ε)		
Cu(1)(ClO ₄) ₂	778(71)	935(72)	
Cu(2)(ClO ₄) ₂	800(76)	990(88)	
Cu(3)(ClO ₄) ₂	760(71)	970(66)	
Cu(4)(ClO ₄) ₂	701(151)		
Co(1)Cl ₂	549(231)	588(215)	920(41)
Co(2)Cl ₂	551(260)	580(232)	930(52)
Co(3)Cl ₂	556(313)	580(286)	940(48)
Co(4)Cl ₂	561(294)	578(290)	950(70)
Ni(1)Cl ₂	395(37)	637(24)	1081(11)
Ni(2)Cl ₂	395(33)	645(24)	1075(21)
Ni(3)Cl ₂	398(34)	645(26)	1018(11)
Ni(4)Cl ₂	388(43)	634(30)	1080(10)

800 and 940–990 nm, suggesting that these complexes have a trigonal bipyramidal structure. However, the copper(II) complex with (4) affords a single maximum which is indicative of a tetragonal structure at about 700 nm (Table II). The former three complexes also gave ESR signals characteristic of trigonal bipyramidal copper(II)'s ($g_{\perp} > g_{\parallel} \sim 2$) (Table III). On the other hand, ESR signals for the last complex exhibited the relation $g_{\parallel} > g_{\perp} > 2$, hence the structure was considered to be tetragonal. In addition to that, seven lines of superhyperfine splitting due to the three coordinated nitrogens were clearly recorded (Fig. 1). The value of the ESR parameter of g_{\parallel} (2.33) seems to be rather greater

TABLE III. ESR Spectral Data of Copper(II) Complexes.

Complex	g_{\parallel}	g_{\perp}	$10^4 A_{\parallel}$ (cm^{-1})	$10^4 A_{\perp}$ (cm^{-1})
Cu(1)(ClO ₄) ₂	2.00	2.23	6.0	8.4
Cu(2)(ClO ₄) ₂	2.01	2.24	9.2	10.8
Cu(3)(ClO ₄) ₂	2.01	2.23	6.8	9.9
Cu(4)(ClO ₄) ₂	2.33	2.07	15.6	

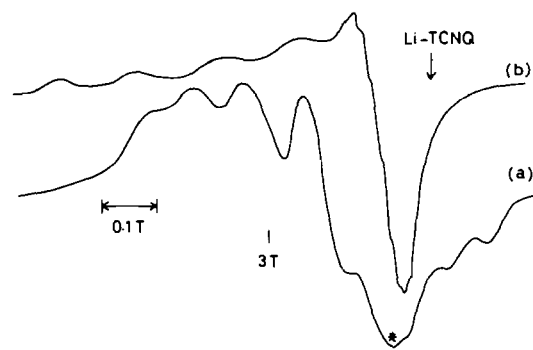


Fig. 1. X-band ESR spectra of (a), Cu(2) and (b), Cu(4). Asterisk indicates contaminating binuclear species.

and that of A_{\parallel} (15.6 mK)* rather smaller for the usual tetragonal copper(II) complexes, in which three nitrogens are coordinated on the equatorial binding sites. This may suggest that there exists some tetrahedral distortion in the structure of the complex. A comparatively greater molar extinction coefficient ($\epsilon = 151 \text{ M}^{-1} \text{ cm}^{-1}$) of the complex is also reasonably elucidated by the same tetrahedral distortion.

The structural difference in copper(II) complexes with ligands (1)–(4) is attributed to different steric effects caused by the substituted alkyl groups. Although methyl and isobutyl groups do not seem to afford appreciable steric hindrance for the complexes, the existence of cascade of isopropyl group at the α -position would make the steric hindrance so serious that the formation of the similar highly symmetrical C_{3v} complex would become difficult. This situation was confirmed by the use of a CPK-model.

The oxidation and reduction processes of the complexes were reversible and their half wave potentials determined by cyclic voltammetry are summarized in Table IV. That the complex with (4) exhibited *ca.* 0.05 ~ 0.1 V greater $E_{1/2}$ value than those with ligands (1)–(3) indicates that a tetrahedrally distorted structure is more suitable for both the oxidized

TABLE IV. Half Wave Potentials of Copper(II) Complexes.

Complex	$E_{1/2}$ (V) vs. SCE
Cu(1)(ClO ₄) ₂	-0.10
Cu(2)(ClO ₄) ₂	-0.13
Cu(3)(ClO ₄) ₂	-0.04
Cu(4)(ClO ₄) ₂	0.01

and reduced forms of the complex. The appropriate steric arrangement of donor groups around a central copper ion may facilitate the central ion to alter its oxidation state in proteins.

Cobalt(II) Complexes

A series of cobalt(II) complexes with ligands (1)–(4) isolated as violet crystals exhibit absorption maxima at around 550 and 940 nm. The observed bands were considered to be due to the transitions ${}^4E(P) \leftarrow {}^4A_2$ and ${}^4E \leftarrow {}^4A_2$, respectively. The transition due to ${}^4A_2(P) \leftarrow {}^4A_2$ was supposed to be enveloped in an absorption band associated with ${}^4E(P) \leftarrow {}^4A_2$. Unlike the copper(II) complexes, all cobalt(II) complexes including that with (4) showed very similar absorption spectra because of the same pseudo-trigonal bipyramidal structure which was found by Thompson *et al.* [7] for the complex with (1). The isopropyl group in (4) might not be so bulky as to distort the cobalt(II) ion effectively, probably because the Co(II) ion is slightly larger than the Cu(II) ion in size. The steric hindrance arising from the isopropyl group could also be decreased by opening the angle of the legs. Furthermore the less flexible character of Co(II) compared with the Cu(II) ion would not allow the formation of such an intermediate structure as observed in the Cu(II) complex of (4).

Nickel(II) Complexes

Nickel(II) complexes were obtained as pale blue-green crystals and their absorption bands were noticeable at *ca.* 390 (${}^3T_{1g}(P) \leftarrow {}^3A_{2g}$), 640 (${}^3T_{1g}(F) \leftarrow {}^3A_{2g}$) and 1020 ~ 1080 nm (${}^3T_{2g} \leftarrow {}^3A_{2g}$). Relatively small molar extinction coefficients of these bands suggest that the structure of these complexes is octahedral with a slight distortion. Water or the chloride ion would occupy the two residual sites other than those ligated by four nitrogenous groups. The nickel(II) ion is known to be octahedral in nickel substituted phosphoglucomutase [8], carboxypeptidase A [9], and stellacyanin [10] and to be tetrahedrally distorted octahedral in nickel substituted L-aspartate transcarbamylase [11], bovine serum amine oxidase [12] and azurin [13].

*mk = 10^4 cm^{-1} .

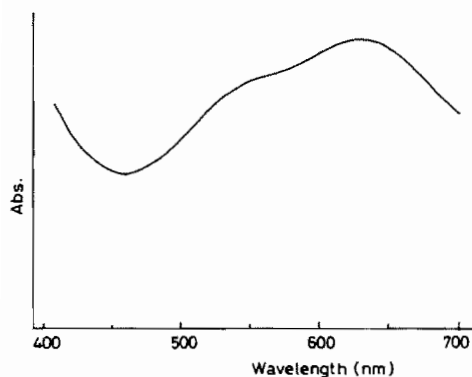


Fig. 2. Absorption spectrum of equimolar mixture of Cu(II) and *p*-thiocresol (-78°C , MeOH).

Ternary Copper(II) Systems Containing Thiolates

It is now widely accepted that the so called blue band at around 600 nm characteristic of blue copper proteins comes from the $\text{S}^{-} \rightarrow \text{Cu}$ charge transfer [14]. However, because of the highly reducing property of thiolates, few copper(II) complexes containing a coordinated thiolate group are known. In the present study several thiolates from thiophenol, *m*- and *o*-thiocresols, *p*-nitrothiophenol, benzylmercaptan, *p*-aminothiophenol, and other alkylthiols were added to the copper(II) complexes with (1)–(4) to form the respective ternary complexes. Immediately after the addition of thiolates, the solution of the complexes with (1)–(3) turned to intense blue, brown or green at low temperature. It may be considered that these thiolates are coordinated to the copper(II) ion in the ternary complexes to give the charge transfer band due to the $\text{S}^{-} \rightarrow \text{Cu}$ transition. The absorption spectrum of Fig. 2 obtained at -78°C for the methanol solution of an equimolar mixture of *p*-thiocresol and the copper(II) complex with ligand (1) clearly exhibits intense bands at ca. 630 and 540 nm attributable to $\text{S}^{-}(\pi) \rightarrow \text{Cu}$ and $\text{S}^{-}(\sigma) \rightarrow \text{Cu}$, respectively, although the magnitude of molar extinction coefficient which is probably greater than 1000 could not be exactly estimated because of the reduction of the Cu(II) ion by the thiolate. The relevant ternary species exhibited an ESR signal characteristic of tetragonal copper(II) ($g_{\parallel} 2.30$, $A_{\parallel} 13.7$ mK). Perhaps the ligation of the S^{-} group would have altered the electronic state of copper(II) from the d_{z^2} to the $d_{x^2-y^2}$ ground state. In consequence, the soft S^{-} group does not affect the ESR signal profoundly, although in all cases reported hitherto the extent has also been quite disappointing [15]. The S^{-} group is supposed to occupy the equatorial position, if all four nitrogenous groups coordinate to the copper(II) ion. A successful preparation of very small A_{\parallel} value was

only realized in copper substituted alcohol dehydrogenase [16].

Tris(2-aminoethyl)amine gives a copper(II) complex identical with that of (1) on its stereochemistry. However, the ternary system was immediately reduced upon addition of thiolates even under a reduced temperature. In a similar fashion, the complex with ligand (4) was also readily reduced without forming ternary species in an even shorter period. In order to realize the peculiar properties of blue copper proteins it may be important that (i) thiolate and aromatic nitrogens must be involved in coordination and (ii) their arrangement around a central metal ion must be adaptable both to its oxidized and reduced states.

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