double bond equivalent. To support this hypothesis of "vicinal differentiation", we can note again[9] that with related complexes where the Schiff base is derived from ortho- or meta-substituted anilines, the dissymmetry introduced by the meta substituent is ineffective in differentiating the carbon atoms of the nearest double bond on the scale of ^{13}C NMR spectroscopy.

Acknowledgment. The authors wish to thank Professor R. Chevalier for providing the facility for X-ray measurements, Professor B. Ancian for communicating the DNMR3 program, and Professor Dr. G. Binsch for his useful advice.

Registry No. (Rh(cod))$_2$(salophen), 68858-45-7; (Rh(OMe)(cod))$_2$, 12148-72-0.

Supplementary Material Available: Listings of root-mean-square amplitudes of vibration, least-squares planes and atomic deviations therefrom, and structure factor amplitudes (11 pages). Ordering information is given on any current masthead page.

Contribution from the Department of Chemistry,
Boston College, Chestnut Hill, Massachusetts 02167

Synthesis and Structure of *trans*-[O$_2$(en)$_2$Tc^V]$^+$

M. E. KASTNER, M. J. LINDSAY, and M. J. CLARKE*

Received August 24, 1981

The octahedral complex ion *trans*-[O$_2$(en)$_2$Tc]$^+$ has been prepared by a facile and general synthetic technique and has been characterized by NMR and electronic absorption spectroscopy. Rapid hydrolysis of the ion occurs in acid media to yield free ethylenediamine. The iodide salt of the complex crystallizes in the triclinic space group $P\bar{1}$. Crystal data: a = 5.767 (4) Å, b = 8.759 (7) Å, c = 10.929 (7) Å, α = 84.13 (5)°, β = 92.18 (6)°, γ = 97.63 (5)°, Z = 2, V = 544.1 (6) Å^3, R = 9.4%. The chloride salt forms crystals belonging to the monoclinic space group $P2_1/c$. Crystal data: a = 5.637 (1) Å, b = 11.177 (2) Å, c = 16.112 (3) Å, β = 101.11 (1)°, Z = 4, V = 996.1 (3) Å^3, R = 4.1%. The average Tc=O distance is 1.75 Å, the average Tc—N distance is 2.15 Å, and the average N—Tc—N interior angle is 80°. The complex exhibits the δλ geometry with respect to the ethylenediamine conformation in the iodide salt, while in the chloride salt both the δδ and λλ configurations are observed.

The radiophysical properties of ^{99m}Tc are very nearly optimal for imaging various organs and locating anatomical or physiological abnormalities.[1-5] However, owing to the variability of reaction conditions employed in the clinical setting, mixtures of technetium complexes often result. A complicating factor is the short half-life (6 h) of the isotope, which limits the scope of purification procedures that are practical prior to injection. Consequently, there can be substantial variation in the quality of the diagnostic procedure. A major goal in the application of technetium chemistry is to develop a spectrum of synthetic methods that allows for the rapid and reproducible preparation of easily purified organ-specific complexes.

Of special interest are imaging agents that would show a high degree of selectivity for hypoxic or anoxic areas, which occur in tumors or infarcts.[6,7] Since such areas have lower ambient electrochemical potentials relative to the surrounding normal tissue, technetium complexes may be preferentially reduced and undergo substitution reactions which would cause them to localize in these environments. The lower pH of tumor tissue should favor pH-dependent metal ion reduction and may induce the hydrolysis of acid-labile complexes to also cause them to concentrate in the neoplasm.[8] Selective fixation by either method would provide a means for diagnosing and locating the diseased areas for treatment. One way of accomplishing this would be to utilize oxotechnetium complexes that substitute their oxygen ligands on reduction. Analogous chemistry is well-known for the adjacent element, molybdenum, which catalytically undergoes redox-induced substitution of coordinated oxygen in enzymatic systems.[9] The nitrogen ligands of these complexes are acid labile so that they might also selectively concentrate in tumors by the hydrolytic mechanism.

Several research groups have now shown that Tc(V) has a high affinity for O^{2-} and that the technetyl ion often adopts a square-pyramidal structure with chloride, sulfur, or sulfur and oxygen ligands occupying the basal plane.[2,10,11] Early work by Polish[12] and Russian[13] workers suggested that Tc(V), when coordinated with nitrogen ligands, tended to form octahedral complexes with the oxygens trans to each other. In this communication we report a facile synthetic method for the synthesis of *trans*-[O$_2$(en)$_2$Tc]$^+$ and the structure of this complex as both the chloride and iodide salts.

Experimental Section

Synthesis. Approximately 150 mg of the starting material, (n-Bu$_4$N)TcOCl$_4$ (n-Bu = n-butyl), which was prepared by the method of Trop,[11] was dissolved in a minimum of tetrahydrofuran. Ethylenediamine (5–7 drops) was then added until the green color of the technetium starting material disappeared. When the solution was allowed to stand, a brownish orange to pink aggregate formed, which was removed by filtration and washed with THF. The residue was dissolved in a minimum of water and charged onto a Sephadex CM C-25 chromatographic column. The column was eluted with water

---

(1) Clarke, M. J.; Fackler, P. H. *Struct. Bonding (Berlin)*, **1982**, *50*, in press.

(2) Deutsch, E. In "Radiopharmaceuticals II"; Sorenson, J. A., Ed.; Society of Nuclear Medicine: New York, 1979; pp 129–146.

(3) Marzilli, L. G.; Dannals, R. F.; Burns, H. D. In "Inorganic Chemistry in Biology and Medicine"; Martell, A. E., Ed.; American Chemical Society: Washington, D.C., 1980; ACS Symp. Ser. No. 140, pp 91–102.

(4) Deutsch, E.; Barnett, B. L. In "Inorganic Chemistry in Biology and Medicine"; Martell, A. E.; Ed.; American Chemical Society: Washington, D.C., 1980; ACS Symp Ser. No. 140, pp 103–120.

(5) Srivastava, S. C.; Richards, P. In "Radiotracers for Medical Applications"; Rayud, G. V. S., Ed.; CRC Press: Boca Raton, FL, 1981.

(6) Gullino, P. M. *Adv. Exp. Med. Biol.* **1975**, *75*, 521.

(7) Klieser-Muller, W.; Vaupel, P.; Manz, R.; Grunewals, W. *Eur. J. Cancer* **1980**, *16*, 195–207.

(8) Clarke, M. J. *Met. Ion Biol. Syst.* **1980**, *11*, 231–284.

(9) Coughlan, M. P. "Molybdenum and Molybdenum Containing Enzymes"; Pergamon Press: New York, 1980.

(10) Jones, A. G.; DePamphilis, B. V.; Davison, A. *Inorg. Chem.* **1981**, *20*, 1617–1618.

(11) Cotton, F. A.; Davison, A.; Day, V. W.; Gage, L. D.; Trop, H. S. *Inorg. Chem.* **1979**, *18*, 3024.

(12) Baluka, M.; Hanuza, J.; Jezowska-Trzebiatowska, B. *Bull. Acad. Pol. Sci., Ser. Sci. Chem.* **1972**, *20*, 271–278.

(13) Kuzina, A. F.; Oblova, A. A.; Spitsyn, V. I. *Zh. Neorg. Khim.* **1971**, *17*, 2630.

0020-1669/82/1321-2037$01.25/0

Table I. Crystal Data and Intensity Collection Data for TcO_2en_2Cl and TcO_2en_2I

	$TcO_2(en)_2Cl$	$TcO_2(en)_2I$
a, Å	5.637 (1)	5.767 (4)
b, Å	11.177 (2)	8.759 (7)
c, Å	16.112 (3)	10.929 (7)
α, deg		84.13 (5)
β, deg	101.11 (1)	92.18 (6)
γ, deg		97.63 (5)
V, Å^3	996.1 (3)	544.1 (6)
space group	$P2_1/c$	$P\bar{1}$
ρ(calcd), g cm^{-3}	1.135	1.375
formula	$TcO_2N_4C_4Cl$	$TcO_2N_4C_4I$
Z	4	2
crystal size, mm	1.00 × 0.15 × 0.05	0.40 × 0.25 × 0.05
2θ limits, deg	3-100	3-50
scan rate, deg/min	2-12	2-8
scan range, deg		
above Kα_1	0.7	0.8
below Kα_2	0.7	0.8
radiation source (λ, Å)	Cu Kα (1.5407)	Mo Kα (0.710 69)
no. of obsd data	984	1629
no. of parameters	109	62
R,[a] %	4.1	9.4
R_w,[b] %	6.3[c]	12.6[d]

[a] $R = \Sigma||F_o| - |F_c||/\Sigma|F_o|$. [b] $R_w = [\Sigma w(|F_o| - |F_c|)^2/\Sigma w|F_o|^2]^{1/2}$. [c] $1/\sigma^2(F_o)$ weights applied. [d] Unit weights applied.

followed by 0.05 M ammonium formate, which removed the desired complex as an orangish pink band. The iodide salt precipitated in fairly large yellow crystalline plates, upon standing overnight, following the addition of a saturated aqueous solution of NaI. Yields were typically 80–90%. (A reviewer checking the method obtained a 65% yield.) So that the chloride salt could be obtained, the chromatographic fraction was repeatedly rotary evaporated (with occasional addition of water) until the buffer was entirely removed. The residue was dissolved in a minimum of water and filtered and a few drops of a saturated (n-Bu_4N)Cl solution added. A 65% yield of crystalline orange needles formed upon overnight diffusion of ethanol into a quiescent solution of the complex. Magnetic susceptibility measurements of the compound revealed it to be diamagnetic. Anal. Calcd for $TcC_4H_{16}N_4O_2Cl$: C, 16.76; H, 5.63; N, 19.55; Cl, 12.37. Found: C, 16.53; H, 5.38; N, 19.29; Cl, 11.95.

Caution! The ^{99}Tc isotope is a weak β emitter with a long half-life (2.12 × 10^5 years). Quantities less than 50–100 mg are easily handled with suitable caution since the β radiation is eliminated by the glassware or solvent. However, quantities larger than 250 mg should be handled with tongs in order to maintain a safe working distance from the soft X-rays generated by the impact of the emitted electrons on the glassware.

Crystallography. Data was collected on a Syntex P2$_1$ automated four-circle diffractometer. The XRAY76[14] package of computer programs was employed for the solution and refinement of the structure. Crystal data and the data collection parameters are given in Table I for both the iodide and chloride salts of *trans*-$[O_2(en)_2Tc]^+$.

The Patterson function for the iodide salt indicated the iodide at a general position and technetium atoms at centers of symmetry at 0, 0, 0 and 0, 0, $^1/_2$. Thus, there are two independent half-cations in the asymmetric unit. The final model of the iodide salt includes anisotropic refinement of the thermal parameters of the iodide anion and the technetium cation, isotropic refinement of all other nonhydrogen atoms, and calculated, but unrefined, positions for the hydrogen parameters (C–H of 0.95 Å, N–H of 0.85 Å, and U = 0.038 Å^2). Calculated hydrogen positions are given in Table IX of the supplementary material. The fractional crystal coordinates, thermal parameters, bond distances and angles as well as the structure factor tables are given in the supplementary materials.

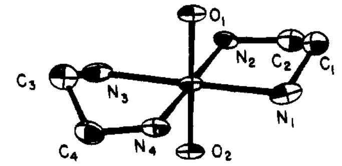

Figure 1. ORTEP drawing of *trans*-$[O_2(en)_2Tc]^+$.

Table II. Atomic Coordinates in $TcO_2(en)_2Cl$[a]

atom	x	y	z
Tc	0.7459 (1)	0.1084 (1)	0.2374 (1)
C_1	0.3462 (1)	0.2790 (1)	0.4423 (1)
O_1	0.9826 (2)	0.0043 (1)	0.2572 (1)
O_2	0.5057 (2)	0.2089 (1)	0.2170 (1)
N_1	0.8049 (3)	0.1505 (2)	0.3697 (1)
N_2	0.5123 (3)	−0.0254 (1)	0.2789 (1)
N_3	0.6969 (3)	0.0649 (2)	0.1058 (1)
N_4	0.9852 (3)	0.2385 (1)	0.1973 (1)
C_1	0.7555 (3)	0.0381 (2)	0.4147 (1)
C_2	0.5246 (4)	−0.0148 (2)	0.3717 (1)
C_3	0.9124 (4)	0.1113 (2)	0.0728 (1)
C_4	0.9572 (4)	0.2371 (2)	0.1057 (1)

[a] The numbers in parentheses are the esd's in the last significant figure.

Table III. Bond Lengths (Å) and Angles (Deg) in *trans*-$[O_2(en)_2Tc]Cl$[a]

Tc–O_1	1.752 (1)	N_1–C_1	1.506 (3)
Tc–O_2	1.741 (1)	N_2–C_2	1.487 (3)
Tc–N_1	2.146 (2)	N_3–C_3	1.509 (3)
Tc–N_2	2.181 (2)	N_4–C_4	1.454 (3)
Tc–N_3	2.140 (2)	C_1–C_2	1.476 (3)
Tc–N_4	2.165 (2)	C_3–C_4	1.507 (3)
O_1–Tc–O_2	178.6 (3)	N_2–Tc–N_3	100.25 (6)
O_1–Tc–N_1	89.86 (6)	N_2–Tc–N_4	178.6 (7)
O_1–Tc–N_2	88.41 (7)	N_3–Tc–N_4	79.97 (6)
O_1–Tc–N_3	88.76 (7)	Tc–N_1–C_1	106.7 (1)
O_1–Tc–N_4	90.23 (7)	Tc–N_2–C_2	109.9 (1)
O_2–Tc–N_1	90.66 (6)	Tc–N_3–C_3	108.2 (1)
O_2–Tc–N_2	90.37 (6)	Tc–N_4–C_4	110.1 (1)
O_2–Tc–N_3	90.73 (6)	N_1–C_1–C_2	109.7 (2)
O_2–Tc–N_4	90.99 (6)	N_2–C_2–C_1	111.7 (2)
N_1–Tc–N_2	80.37 (6)	N_3–C_3–C_4	106.7 (2)
N_1–Tc–N_3	178.5 (4)	N_4–C_4–C_3	110.1 (2)
N_1–Tc–N_4	99.38 (7)		

[a] The numbers in parentheses are the esd's in the last significant figure.

As a result of the thin platelike quality of the iodide crystals, ψ scans of the crystal selected showed absorption of up to 70% (μ = 18.8 cm^{-1}). When a semiempirical correction of the intensity data failed to improve the model, data were collected on the needlelike crystals of the chloride salt, where ψ scans showed absorption of less than 35% (μ = 74.9 cm^{-1}).

The Patterson function of the chloride salt indicates that the Tc atom is located in a general position. The final model for the chloride salt includes anisotropic refinement of all nonhydrogen atoms and experimental positions of the hydrogens determied by difference Fourier maps; hydrogen positions were held constant and each was assigned an isotropic thermal parameter of U = 0.038 Å^2. The thermal parameters and structure factors for the chloride salt are given in the supplementary material.

Spectra. Electronic spectra were recorded in 0.1 M LiCl solution adusted to pH 7 at 23 °C on a Perkin-Elmer Model 575 spectrophotometer. Infrared spectra of solid samples dispersed in CsI were taken on a Perkin-Elmer Model 599B. ^1H NMR spectra were acquired in a Fourier transform mode on a Varian FT-80 spectrometer. Magnetic susceptibility measurements were made on a Cahn Model 7600 Faraday balance at a field strength of 14 502 G.

Results

Molecular Structures. Figure 1 illustrates the labeling scheme and the structure of the ion as the chloride salt. Table II lists the fractional crystal coordinates for this compound, and Table III summarizes the bond distance and angle information. The coordination sphere around the Tc(V) ion is

---

(14) Stewart, J. M. Technical Report TR-446; Computer Science Center, University of Maryland: College Park, MD.

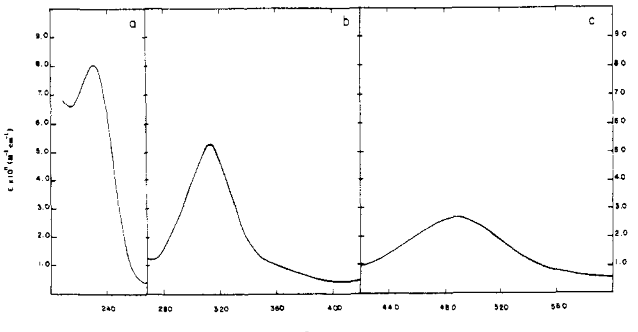

Figure 2. Electronic spectra of *trans*-$[O_2(en)_2Tc]^+$ in 0.1 M LiCl at pH 6.8. Scale exponent: (a) $n = 3$, (b) $n = 2$, (c) $n = 1$.

essentially identical in both the iodide and chloride salts. The only significant difference between the two compounds relates to the configuration of the nitrogen ligands. In the iodide salt the Tc is located at a center of symmetry, which imposes the requirement that the conformation of the ethylenediamines be $\delta\lambda$. However, in the chloride salt, no crystallographic symmetry is demanded of the complex ion since it resides at a general position. In this case, the complex adopts equal populations of the enantiomeric geometries $\delta\delta$ (shown in Figure 1) and $\lambda\lambda$, which are related either through the center of symmetry or the *c* glide of the $P2_1/c$ space group.

The ethylenediamine does not exhibit the typical C_{2v} symmetry often found in transition-metal complexes of this ligand. The displacement of the carbon atoms from the mean plane of the four nitrogens in the chloride salt are C_1 0.64 Å, C_2 0.03 Å, C_3 0.54 Å, and C_4 −0.17 Å. The four nitrogen atoms are coplanar in both structures and the technetium atom is displaced by only 0.026 Å toward O_2 in the chloride salt. The O=Tc=O moiety is nearly linear and perpendicular to the plane of the nitrogens. The average interior angle of the ethylenediamines is 80.2°.

Spectra. The UV–visible spectrum for the complex is shown in Figure 2. The infrared spectrum (200–4000 cm^{-1}) is given in Figure 4 in the supplementary material and exhibits an intense absorption at 833 cm^{-1}, which has been assigned to a Tc=O stretching mode. Proton NMR spectra taken on fresh samples dissolved in D_2O exhibited a single peak at 3.07 ppm downfield from trimethylsilypropionate (TSP). Solutions allowed to stand for periods over 1 h exhibited an additional peak at δ 2.23, which was attributed to free ethylenediamine. While solutions above pH 7 were stable for hours, solutions in the pH range 2–6 showed an apparent biphasic decomposition. At pH 5 the first step of this decomposition exhibited apparent first-order kinetics and proceeded with a half-life of 2.9 min.

Discussion

Structure. The synthetic method employed here has proven applicable for the formation of *trans*-dioxotechnetium(V) complexes with both chelating and nonchelating nitrogen ligands including 1,2-diaminocyclohexane, 1,2-diaminopropane, imidazole, and several pyridine derivatives. While the method used in this study employed THF as the solvent, Packard has indicated that *trans*-dioxotechnetium(V) complexes with chelating nitrogen ligands can be formed directly from pertechnetate in aqueous solution.[15] Analogous complexes with monodentate imidazole and pyridine derivatives are possible by dithionite reduction of pertechnetate in ethanol.[16] A preliminary crystal structure of *trans*-$[O_2(Im)_4Tc]^+$ shows the imidazole ligands to be at essentially right angles from one another and from the oxygens;[16] however, in the present structures the ethylenediamine constrains the interior N–Tc–N angle to be approximately 80.2°.

Unlike the structures of several previously reported Tc(V) complexes with oxygen, the ethylenediamine complex exhibits an octahedral geometry with the two oxygens trans to one another rather than a square-pyramidal, monooxygen arrangement. The geometry described here is in agreement with the interpretation of the infrared spectrum of the ethylenediamine complex offered by Baluka and co-workers[12] and is also in harmony with the recently reported structure of *trans*-$[O_2(cyclam)Tc^V]$[17] as well as the suggested structure of $[O_2(py)_4Tc]^+$.[13] The trans-dioxo octahedral geometry is common for isoelectronic metal complexes from the same region of the periodic table when coordinated by nitrogen ligands such as *trans*-$[O_2(py)_4Re]^+$ [18] and *trans*-$[O_2(en)_2Re]^+$ [19] and various ruthenyl complexes.[20] In fact, the structural parameters of the technetium complex are quite similar to those of *trans*-$[O_2(en)_2Os]^{2+}$.[21]

The average Tc=O bond distance of 1.746 Å is substantially longer than the corresponding bond distances of 1.62–1.65 Å typically found in a number of square-pyramidal monooxotechnetium(V) complexes[11,22,23] and in the six-coordinate dichloro[hydrotris(1-pyrazolyl)borato]oxotechnetium(V).[24] The mutual lengthening of the Tc=O bonds is consistent with the pronounced trans effect exerted by the oxo ligand, which has been observed in monooxotechnetium(V) complexes.[24]

Spectra. Since several twist geometries around the ethylenediamines are evident between the two crystals, it is likely that there is only a small energy of interconversion between the various forms. This is substantiated by the NMR spectrum of the complex in D_2O at room temperature which exhibits only a single proton peak.

The rapid spectral changes of the complex below pH 6 and the appearance of free ethylenediamine in the NMR spectra suggest an acid-catalyzed dissociation of the ethylenediamine. Since *trans*-$[O_2(en)_2Re]^+$ exhibits a pK_a of 3.26 for the addition of a proton to the oxygen,[25] it is possible that a similar protonation equilibria is responsible for the hydrolysis of the technetium complex. Further studies of the hydrolysis of this complex and its potential as a synthetic intermediate are now under way.

The intense infrared absorption at 833 cm^{-1}, which has been attributed to the O=Tc=O group,[12] differs appreciably from the Tc=O stretching frequencies observed in the monooxotechnetium(V) complexes, which typically occur in the range 930–1020 cm^{-1}.[10-12,22,23] Stretching frequencies in the range 820–880 cm^{-1} have now been observed for a number of technetium(V) compounds containing the *trans*-$[O_2Tc]^+$

---

(15) Packard, A. B.; Srivastava, S. C.; Richards, P.; Hung, Y., abstracts of paper presented at the Second International Symposium on Radiopharmacology, Chicago, IL, Sept 9–11, 1981.

(16) Kastner, M. E.; Fackler, P.; Clarke, M. J.; Pan, Y. K.; Zhu, L., to be submitted for publication.

(17) Zuckman, S.; Freeman, G. M.; Troutner, D. E.; Volkert, W. A.; Holmes, R. A.; Van Derveer, D. G.; Barefield, E. K. *Inorg. Chem.* **1981**, *20*, 2386–2389.

(18) Lock, C. J. L.; Turner, G. *Can. J. Chem.* **1978**, *56*, 179; **1977**, *55*, 333.

(19) Khodashova, T. S.; Paraj-Koshits, M. A.; Babeshkin, G. K.; Gannulina, R. S.; Sergienko, V. S.; Smepanovich, V. M. *Zh. Strukt. Khim.* **1970**, *11*, 783.

(20) Griffith, W. P. "The Chemistry of the Rarer Platinum Metals"; Interscience: New York, 1967; p 152.

(21) Malin, J. M.; Schlemper, E. O.; Murmann, R. K. *Inorg. Chem.* **1977**, *16*, 615–619.

(22) Jones, A. G.; DePamphilis, B. V.; Davison, A. *Inorg. Chem.* **1981**, *20*, 1617–1618.

(23) Smith, J. E.; Byrne, E. F.; Cotton, F. A. *J. Am. Chem. Soc.* **1978**, *100*, 5571.

(24) Thomas, R. W.; Estes, G. W.; Elder, R. C.; Deutsch, E. *J. Am. Chem. Soc.* **1979**, *101*, 4581–4585.

(25) Kriege, L. B.; Murmann, R. K. *J. Am. Chem. Soc.* **1972**, *94*, 4557–4564.

group[16] and can now be considered as useful evidence of the presence of this moiety. Preliminary Xα molecular orbital calculations indicate the absorptions in the visible and ultraviolet regions of the spectrum to be due to ligand to metal charge-transfer transitions.[16]

Acknowledgment. This work was supported by PHS Grant CA24344. An allotment of computer time from the Boston University Computing Center is gratefully acknowledged by M.E.K. We are grateful to Drs. S. Srivastava and A. Packard of Brookhaven National Laboratory for making available preprints of several papers and to Dr. E. Deutsch and collaborators (University of Cincinnati), who verified the synthetic method and indicated the presence of a previously unnoticed absorption band.

Registry No. *trans*-[$O_2(en)_2Tc$]I, 80720-95-2; *trans*-[$O_2(en)_2Tc$]Cl, 37473-42-0; (n-Bu_4N)$TcOCl_4$, 71341-65-6.

Supplementary Material Available: Tabulations of structure factor amplitudes for *trans*-[$O_2(en)_2Tc$]Cl, thermal parameters and atomic coordinates for hydrogen atoms in the chloride salt, calculated hydrogen positions, atomic coordinates and thermal parameters, bond lengths and angles for the iodide salt, and absorption maxima and molar absorptivities for electronic transitions, an ORTEP drawing of the complex in the iodide salt, and the infrared spectrum of the chloride salt (16 pages). Ordering information is given on any current masthead page.

Contribution from the Department of Hydrocarbon Chemistry,
Faculty of Engineering, Kyoto University, Sakyo-ku, Kyoto, Japan 606

Electronic Structures of Copper(II) Complexes with N_4 and S_4 Ligand Fields

TOKIO YAMABE,* KENZI HORI,* TSUTOMU MINATO,* KENICHI FUKUI,* and YUKIO SUGIURA[1]

Received September 9, 1980

The relation between unique natures of some copper complexes and the Cu–S bonding nature in conjunction with the geometry of the ligand field is studied by use of molecular orbital calculations. It is ascertained that unique spectral features of blue-copper proteins (BCP's) as well as several copper complexes can be understood in terms of the two potentials V_{as} and V_{sp}. V_{as} equally ascends all energy levels of d electrons, and V_{sp} splits them. The Cu–S bonding nature is compared with that of Cu–N. Analysis of E_{AB} shows that the former has more covalent nature than the latter.

Introduction

It has been known that blue-copper proteins (BCP's) have unique spectral features in comparison with those of other copper complexes,[2] i.e., (a) an unusually large extinction coefficient of the absorption near 600 nm (ϵ 1000–5000), (b) an abnormally small copper hyperfine coupling constant ($A_{\parallel} = (30–100) \times 10^{-4}$ cm^{-1}), and (c) a remarkably positive redox potential ($E_{1/2} = +0.2–0.8$ V).

Recent investigations of BCP's by resonance Raman spectra,[3] CD,[4] MCD,[5] and XPS[6] suggested the coordination of a cysteine thiol sulfur and two histidine imidazole nitrogens to the central Cu in the distorted ligand field. The X-ray crystallographic analysis of poplar plastocyanin and *Pseudomonas aeruginosa* azurin confirmed the coordination of the methionine thioether sulfur as the fourth ligand.[7] Brill et al. used the ligand field theory (LFT) for azurin and calculated 12.5° for the angle of the distortion from square-planar symmetry.[8] Solomon et al. also discussed the three features by use of LFT.[9] Roberts et al. investigated the relation between the coordination geometry and the natures of (a) and (b) according to the results of ENDOR.[10]

On the other hand, low-molecular-weight Cu(II) complexes that can mimic the characteristic properties in these proteins have been investigated. Rorabacher et al. synthesized some polythioether–Cu(II) complexes with properties (a) and (c).[11] They insisted that the two properties did not primarily depend on the distortion of the coordination geometry. On the contrary, the relation between the distorted environment around Cu and the small $A_{\parallel}$ value was pointed out by Betes et al.[12] The study of complexes Cu(P2A-H)$_2$ and Cu(P2A$_2$-B) (A and B = H, CH_3, C_2H_5, etc.) proved the importance of this condition for properties (b) and (c).[13] By ^{60}Co γ irradiation of the crystal of the Cu(I) analogue,[14] Sakaguchi and Addison obtained the complex $Cu(S{=}C(CH_3)NH_2)_4^{2+}$, which has the distorted ligand field and small $A_{\parallel}$ value. Recently, the complex Cu(pea)$^{2+}$ with two thioether sulfur donors and distorted geometry was synthesized.[15] The complex shows properties similar to those of BCP's except for the $A_{\parallel}$ value. Sugiura et al. also obtained several copper–sulfur complexes with properties similar to those of BCP's, though their detailed structures are unknown.[16] Miskowski et al. observed the absorption near 450 nm in some Cu(II) complexes with sulfur

---

(1) Faculty of Pharmaceutical Science.

(2) (a) Peisach, J.; Aisen, P.; Blumberg, W. E. "Biochemistry of Copper"; Academic Press: New York, 1966. (b) Malkin, R.; Malmstrong, B. G. *Adv. Enzymol. Relat. Areas Mol. Biol.* **1970**, *33*, 177.

(3) (a) Siiman, O.; Young, N. M.; Carey, P. R. *J. Am. Chem. Soc.* **1974**, *96*, 5583.

(4) Solomon, E. I.; Hare, J. W.; Gray, H. B. *Proc. Natl. Acad. Sci. U.S.A.* **1976**, *73*, 1389.

(5) Solomon, E. I.; Rawlings, J.; McMillin, D. R.; Stephen, P. J.; Gray, H. B. *J. Am. Chem. Soc.* **1976**, *98*, 8040.

(6) Solomon, E. I.; Clendening, P. J.; Gray, H. B. *J. Am. Chem. Soc.* **1975**, *97*, 3987.

(7) (a) Coleman, P. M.; Freeman, H. C.; Murata, M.; Norris, V. A.; Ramshaw, J. A. M.; Venkatappa, M. P. *Nature* (*London*) **1978**, *273*, 319. (b) Adman, E. T.; Stenkap, R. E.; Seker, L. C.; Jensen, L. H. *J. Mol. Biol.* **1978**, *128*, 35.

(8) Brill, A. S.; Bryce, G. F. *J. Chem. Phys.* **1968**, *48*, 4398.

(9) Solomon, E. I.; Hare, J. W.; Doley, D. M.; Dawson, J. H.; Stephen, P. J.; Gray, H. B. *J. Am. Chem. Soc.* **1980**, *102*, 168.

(10) Roberts, J. E.; Brown, T. G.; Hoffman, M. B.; Peisach, J. *J. Am. Chem. Soc.* **1980**, *102*, 825.

(11) (a) Jones, T. E.; Rorabacher, D. B.; Ochrymocyz, L. A. *J. Am. Chem. Soc.* **1975**, *97*, 7485. (b) Dockel, R. R.; Jones, T. E.; Sokol, W. F.; Engerer, R. J.; Rorabacher, D. B.; Ochrymocyz, L. A. *Ibid.* **1976**, *98*, 4322.

(12) Betes, C. A.; Moore, W. S.; Standley, K. J.; Steven, K. W. H. *Proc. Phys. Soc., London* **1962**, *72*, 73.

(13) Yokoi, H.; Addison, A. W. *Inorg. Chem.* **1977**, *16*, 1341.

(14) Sakaguchi, U. U.; Addison, A. W. *J. Am. Chem. Soc.* **1977**, *99*, 5190.

(15) Karlin, K. D.; Dahlstrom, P. L.; Standord, M. L.; Zubieta, J. *J. Chem. Soc., Chem. Commun.* **1974**, 465.

(16) (a) Sugiura, Y.; Hirayama, Y.; Tanaka, H.; Ishizu, K. *J. Am. Chem. Soc.* **1975**, *97*, 5777. (b) Sugiura, Y.; Hirayama, Y. *Inorg. Chem.* **1967**, *15*, 697. (c) Sugiura, Y.; Hirayama, Y. *J. Am. Chem. Soc.* **1977**, *99*, 1581.

0020-1669/82/1321-2040$01.25/0