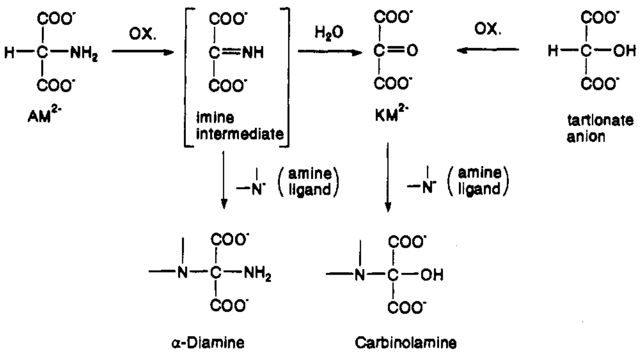
Scheme I



same reaction was not observed in water, EtOH, or acetone under both aerobic and basic conditions. This indicates that MeOH plays some important role in the reaction, especially in the oxidation of AM^{2-}.

In contrast, in the en system, the α-diamine formation was not influenced by the existence of O_2 and daylight. In addition, the carbinolamine formation was dominant in H_2O/NEt_3 in air in the en system,[11] whereas the reaction of AM^{2-} with **1** gave no complexes containing the new C-N bonds under similar conditions. It is obvious that the reaction mechanism is different in each amine system.

The existence of a ketomalonato intermediate was confirmed when $(KM)H_2$ reacted with **1** to afford **5**. As it is likely that the ketomalonato intermediate is formed via the hydrolysis of the imine intermediate, this observation would provide evidence for the formation of the imine intermediate. A schematic description of the conversion of AM^{2-} to the α-diamine and the carbinolamine linkages is shown in Scheme I. The conversion of AM^{2-} toward ketomalonate via iminomalonate can be compared to reactions performed by amino acid oxidases containing flavin adenine dinucleotide (FAD) as a cofactor.[27]

Summary

We have described the reaction of AM^{2-} with *trans*-$[CoCl_2(2,3,2\text{-tet})]^+$ to give α-diamine and carbinolamine complexes. Those reactions are essentially *thermal*, are enhanced photochemically, and need *MeOH* as a solvent. The oxidation of AM^{2-} to form the imine intermediate is conducted by Co(III) ion and *dioxygen*. Because of various discrepancies between the observations in the en and 2,3,2-tet systems, the oxidation mechanisms seem to depend on the polyamine systems employed.[28]

The remarkable properties of α-diamine and carbinolamine complexes are as follows: (1) New C-N bonds are formed between a coordinated amino group and a saturated sp^3 α-carbon of AM^{2-}. (2) The complexes have uncoordinated functional groups on the molecular surfaces and these functional groups show some properties similar to those attached to aromatics.

Acknowledgment. We are grateful to Dr. Y. Mizobe for his helpful comments on X-ray analyses. This work was partially supported by a Grant-in-Aid of the Ministry of Education, Science and Culture of Japan (Nos. 63612002, 63470035, 01612002, and 02245106) and grants from the Mitsubishi Foundation and the Asahi Grass Foundation and the Iwatani Naoji Foundation's research grant.

Registry No. **1**, 20631-56-5; **2**, 136847-03-5; **3**, 96760-21-3; **4**, 136847-06-8; **5**, 132879-49-3; 2,3,2-tet, 4741-99-5; ammonium α-aminomalonate, 25624-92-4; $[Co(AM)(en)_2]ClO_4$, 125108-72-7.

Supplementary Material Available: Tables of anisotropic thermal parameters and positional parameters of **2**–**5**, mean-square displacement, tensor values, and full details of X-ray crystallography (17 pages); tables of observed and calculated structure factors for **2**–**5** (50 pages). Ordering information is given on any current masthead page.

---

(27) Bentley, R. In *Applications of Biochemical Systems in Organic Chemistry*; Jones, J. B., Sih, C. J., Perlman, D., Eds.; John Wiley & Sons: New York, 1976; p 403.

(28) Kojima, T.; Kuroda, R.; Yano, S.; Hidai, M. *Inorg. Chem.* **1991**, *30*, 3580.

Contribution from the Biomedical Chemistry Research Center, Department of Chemistry, University of Cincinnati, Cincinnati, Ohio 45221, and Department of Chemistry, University of Missouri at St. Louis, St. Louis, Missouri 63121

X-ray Structural and NMR Characterization of the Copper(I) Dimer $[Cu(dmpe)_2]_2(BF_4)_2$, Where Dmpe is 1,2-Bis(dimethylphosphino)ethane

Bernhard Mohr,[1] Elwood E. Brooks,[1] Nigam Rath,[2] and Edward Deutsch*,[1]

Received May 29, 1991

The reaction of $[Cu(CH_3CN)_4]BF_4$ with dmpe (where dmpe is 1,2-bis(dimethylphosphino)ethane) in methanol yields the air-stable, white solid $[Cu(dmpe)_2]_2(BF_4)_2$. This dimeric Cu(I) complex has been characterized by single-crystal X-ray crystallography, variable-temperature ^{31}P and ^{63}Cu NMR spectroscopy in solution, and solid-state CPMAS ^{31}P NMR spectroscopy. The complex crystallizes in the triclinic space group $P\bar{1}$ with unit cell parameters $a = 8.8390$ (10) Å, $b = 10.0080$ (10) Å, $c = 12.479$ (2) Å, $\alpha = 99.300$ (10)°, $\beta = 95.640$ (10)°, $\gamma = 93.940$ (10)°, $V = 1080.1$ (2) Å^3, and $Z = 2$; $R_w = 4.20\%$ for 5126 observed reflections [$F > 6.0\sigma(F)$]. The structure consists of a centrosymmetric $[Cu(dmpe)_2]_2^{2+}$ dimer and two disordered BF_4^- anions. The two copper atoms in the cation are bridged by two dmpe ligands to form a ten-membered $Cu_2P_4C_4$ ring. Tetrahedral coordination around each copper atom is completed by a bidentate dmpe ligand. Cu-P bond lengths range from 2.263 (1) to 2.293 (1) Å. The P-Cu-P bond angle for the chelating dmpe ligand is 89.2 (1)°, while the P-Cu-P angles linking different dmpe ligands range from 110.3 (1) to 116.9 (1)°. The solution ^{31}P NMR spectrum at ambient temperature shows a well-resolved quartet centered at −14.6 ppm (relative to 85% H_3PO_4), while the ^{63}Cu NMR spectrum at room temperature consists of a quintet centered at 186.7 ppm (relative to $[Cu(CH_3CN)_4]BF_4$ in CH_3CN). The line spacings due to Cu-P coupling amount to 800 Hz in both spectra. Lowering the temperature causes line broadening; both the ^{31}P and the ^{63}Cu spectra start to collapse at −33 °C due to quadrupolar relaxation of the copper atoms. The CPMAS ^{31}P solid-state spectrum shows a quartet centered at −22 ppm relative to solid ammonium phosphate; the asymmetry of the line spacings within this quartet is consistent with the distorted tetrahedral coordination observed in the crystal structure.

Introduction

Detailed investigations of Cu(I) diphosphine complexes have been reported for only a few diphosphine ligands. The best defined systems involve dppe (1,2-bis(diphenylphosphino)ethane) and dppm (1,2-bis(diphenylphosphino)methane) for which Cu(I) complexes with P:Cu ratios of 4:1, 3:1, 2:1, 1:1, 3:2, and 4:3 have been isolated.[3-8] These complexes are mostly polynuclear species

---

(1) University of Cincinnati.

(2) University of Missouri at St. Louis.

(3) Camus, A.; Marsich, N.; Randaccio, L.; Nardin, G. *Transition Met. Chem.* (*London*) **1976**, *1*, 205.

0020-1669/91/1330-4541$02.50/0

Table I. Crystal Data Summary for $[[Cu(dmpe)_2]BF_4]_2$

empirical formula	$C_{12}H_{32}BCuF_4P_4$
color; habit	colorless; rectangular
cryst size, mm	0.4 × 0.3 × 0.3
cryst syst	triclinic
space group	$P\bar{1}$
unit cell dimens	a = 8.8390 (10) Å b = 10.0080 (10) Å c = 12.479 (2) Å α = 99.300 (10)° β = 95.640 (10)° γ = 93.940 (10)°
vol	1080.1 (2) $Å^3$
Z	2
fw	450.6
density (calcd)	1.386 Mg/m^3
abs coeff	1.329 mm^{-1}
$F(000)$	468
no. of reflcns collected	10068
no. of indep reflcns	9586 (R_{int} = 0.95%)
no. of obsd reflcns	5126 ($F > 6.0\sigma(F)$)
final R indices	R = 3.79%, R_w = 4.20%

Table II. Atomic Coordinates ($\times 10^4$) and Equivalent Isotropic Displacement Coefficients ($Å^2 \times 10^3$)

	x	y	z	U(eq)[a]
Cu	1303 (1)	1419 (1)	2219 (1)	32 (1)
P(1)	1734 (1)	2487 (1)	795 (1)	35 (1)
P(2)	1951 (1)	−747 (1)	1900 (1)	36 (1)
P(3)	−1024 (1)	1601 (1)	2862 (1)	37 (1)
P(4)	2425 (1)	2702 (1)	3827 (1)	39 (1)
C(1)	734 (3)	1790 (3)	−560 (2)	40 (1)
C(2)	1406 (5)	4271 (3)	936 (3)	58 (1)
C(3)	3702 (4)	2535 (5)	481 (3)	61 (1)
C(4)	996 (3)	−1746 (3)	616 (2)	40 (1)
C(5)	1588 (5)	−1844 (3)	2897 (3)	65 (1)
C(6)	3938 (4)	−971 (4)	1735 (4)	71 (2)
C(7)	−1780 (5)	247 (4)	3523 (3)	65 (1)
C(8)	−2740 (3)	2021 (4)	2106 (3)	57 (1)
C(9)	−631 (3)	3001 (3)	4023 (2)	48 (1)
C(10)	866 (3)	2843 (3)	4692 (2)	50 (1)
C(11)	3959 (4)	2141 (5)	4688 (3)	69 (1)
C(12)	3051 (5)	4479 (3)	3883 (3)	65 (1)
B	−3063 (5)	5801 (4)	2360 (3)	67 (1)
F(1)	−3313 (3)	5138 (2)	3201 (2)	88 (1)
F(21)	−4671 (7)	5796 (9)	1941 (7)	146 (4)
F(22)	−3496 (15)	5141 (9)	1413 (6)	154 (5)
F(31)	−2436 (15)	5198 (10)	1556 (8)	145 (5)
F(32)	−1392 (7)	5734 (9)	2487 (7)	125 (3)
F(41)	−3130 (10)	7115 (6)	2537 (8)	131 (3)
F(42)	−2491 (24)	7030 (13)	2680 (14)	128 (8)

[a] Equivalent isotropic U defined as one-third of the trace of the orthogonalized U_{ij} tensor.

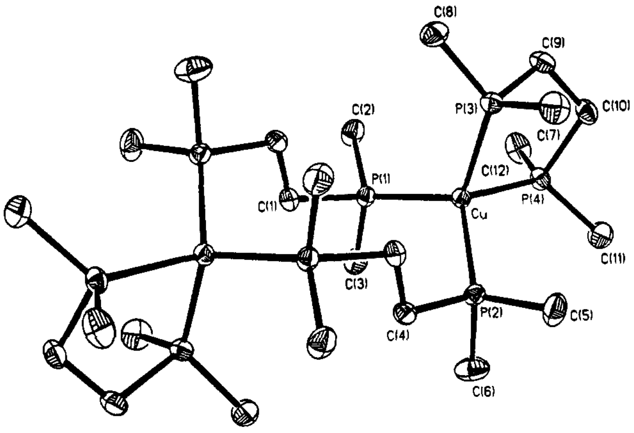


Figure 1. Molecular representation of the crystal structure of $[Cu(dmpe)_2]_2^{2+}$. The atoms are shown with 50% probability. Hydrogen atoms are omitted.

which contain bridging diphosphines and halides. More recently, the structure of the monomeric complex $[Cu(dmpe)_2]^+$ was reported.[9]

Recent interest in Cu(I) diphosphine complexes stems from their potential biological significance. The cytotoxicity and antitumor activity of dppe and related diphosphines are greatly enhanced when these ligands are complexed with copper(I).[10-12] However, the mechanism and structural dependence of cytotoxic action are still unknown.

Diphosphine complexes of Cu(I) are also relevant to nuclear medicine, in part because of the recent development of a generator for the isotope ^{62}Cu.[13] This isotope demonstrates very favorable nuclear properties for PET (positron emission tomography) imaging ($t_{1/2}$ = 9.7 min, β^+-emitter), and thus cationic Cu(I) phosphine complexes might find employment as PET radiopharmaceuticals analogous to ^{99m}Tc radiopharmaceuticals used in SPECT (single photon emission computed tomography).[14,15] In addition, due to the air sensitivity of most phosphine ligands, Cu(I)-protected phosphines might find employment as starting materials for technetium-99m radiopharmaceuticals.

Experimental Section

Methods and Materials. All manipulations were conducted in a drybox under an argon atmosphere using Schlenk glassware. Reagent grade methanol was dried over molecular sieves and then distilled under argon prior to use. Tetrakis(acetonitrile)copper(I) tetrafluoroborate was purchased from Alfa Chemical Co., and dmpe was obtained from Strem Chemicals Inc.; both were used without further purification.

Synthesis of $[Cu(dmpe)_2]_2(BF_4)_2$. Dmpe (1.1 g; 7.33 mmol) was added to a stirred solution of tetrakis(acetonitrile)copper(I) tetrafluoroborate (1.0 g; 3.18 mmol) in 15 mL of methanol. The reaction mixture was stirred for 6 h at room temperature and then heated to reflux for 10 min and filtered upon cooling. The colorless filtrate was evaporated to incipient precipitation and then stored for 2 h at 0 °C to complete the precipitation. The resulting white crystalline product was filtered off, washed with ether, and then dried under vacuum. Crystallization from methanol at −10 °C yielded single crystals suitable for X-ray analysis. Anal. Calcd for $C_{24}H_{64}B_2Cu_2F_8P_8$: C, 31.98; H, 7.16; Cu, 14.10. Found: C, 32.16; H, 7.28; Cu, 14.27.

Structure Determination. A colorless crystal of the appropriate dimensions was mounted on a glass fiber in a random orientation and was coated with Super Glue to protect it from air and moisture. Preliminary examination and data collection were carried out with molybdenum K(α) radiation on a Siemens R3 four-circle automated diffractometer. Final cell constants and an orientation matrix for data collection were obtained by least-squares analysis of 25 automatically centered reflections (20° $< 2\theta <$ 25°). Data were collected by the θ–2θ scan technique, and the intensities of three reflections were monitored every 50 reflections. There was no significant change in intensity of the standard reflections during data collection. Empirical absorption corrections were applied to the data using seven reflections (82° $< \psi <$ 90°). Crystal data and intensity collection parameters are summarized in Table I, while final atomic coordinates are given in Table II.

Data collection and structure solution and refinement were carried out using the SHELXTL-PLUS structure solution package (G. M. Sheldrick, Siemens Analytical X-Ray Division, Madison, WI, 1989). The structure was solved by the Patterson method for heavy atoms. The rest of the atoms were located from subsequent difference Fourier syntheses. Full-matrix least-squares refinement was carried out by minimizing $\sum w(F_o - F_c)^2$. Hydrogen atoms were located from the difference Fourier

---

(4) Leoni, P.; Pasquali, M.; Ghilardi, C. A. *J. Chem. Soc., Chem. Commun.* **1983**, 240.

(5) Gaughan, A. P.; Ziolo, R. F.; Dori, Z. *Inorg. Chem.* **1971**, *10*, 2776.

(6) Churchill, M. R.; Rotella, F. J. *Inorg. Chem.* **1979**, *18*, 166.

(7) Diez, J.; Gamasca, M. P.; Gimeno, J.; Tiripichicchio, A.; Camellini, M. T. *J. Chem. Soc., Dalton Trans.* **1987**, 1257.

(8) Camus, A.; Nardin, G.; Randaccio, L. *Inorg. Chim. Acta* **1975**, *12*, 23.

(9) Darensbourg, D.; Chao, C.-S.; Reibenspies, J.; Bischoff, C. J. *Inorg. Chem.* **1990**, *29*, 2153.

(10) Berners-Price, S. J.; Mirabelli, C. K.; Johnson, R. K.; Faucette, L. F.; McCabe, F. L.; Sadler, P. J. *Inorg. Chem.* **1987**, *26*, 3383.

(11) Snyder, R. M.; Mirabelli, C. K.; Johnson, R. K.; Sung, C.-M.; Faucette, L. F.; McCabe, F. L.; Zimmerman, J. P.; Whitman, M.; Hempel, J. C.; Crooke, S. T. *Cancer Res.* **1986**, *46*, 5054.

(12) Berners-Price, S. J.; Sadler, P. J. *Chem. Br.* **1987**, 541.

(13) Green, M. A.; Mathias, C. J.; Margenau, W. H.; Brodack, J. W.; Welch, M. J. Poster presented at the 8th International Symposium on Radiopharmaceutical Chemistry, Princeton, NJ, 1990.

(14) Deutsch, E.; Bushong, W.; Klavan, K. A.; Elder, R. C.; Sodd, V. J.; Fortman, D. L.; Lukes, S. J. *Science* **1981**, *214*, 85.

(15) Deutsch, E.; Libson, K.; Jurison, S. *Prog. Inorg. Chem.* **1983**, *30*, 75.

Table III. Selected Bond Parameters for $[[Cu(dmpe)_2]BF_4]_2$

Bond Lengths (Å)			
Cu-P(1)	2.267 (1)	Cu-P(2)	2.263 (1)
Cu-P(3)	2.289 (1)	Cu-P(4)	2.293 (1)
P(1)-C(1)	1.835 (2)	P(1)-C(2)	1.812 (3)
P(1)-C(3)	1.819 (3)	P(2)-C(4)	1.839 (2)
P(2)-C(5)	1.824 (4)	P(2)-C(6)	1.813 (4)
P(3)-C(7)	1.819 (4)	P(3)-C(8)	1.817 (3)
P(3)-C(9)	1.833 (3)	P(4)-C(10)	1.831 (3)
P(4)-C(11)	1.822 (4)	P(4)-C(12)	1.815 (4)
C(1)-C(4A)	1.521 (4)	C(4)-C(1A)	1.521 (4)
C(9)-C(10)	1.525 (4)		
Bond Angles (deg)			
P(1)-Cu-P(2)	110.7 (1)	P(1)-Cu-P(3)	116.9 (1)
P(2)-Cu-P(3)	113.2 (1)	P(1)-Cu-P(4)	110.3 (1)
P(2)-Cu-P(4)	115.1 (1)	P(3)-Cu-P(4)	89.2 (1)

map and were refined isotropically. The non-hydrogen atoms were refined anisotropically to convergence. The anion BF_4^- was found to be disordered, but this disorder could be resolved. The final residual factors were $R = 3.8\%$ and $R_w = 4.2\%$. The final difference Fourier map had electron densities of +0.41 and −0.33 e Å^{-3}. All calculations were performed on a VAX Station II GPX computer.

NMR Spectroscopy. Liquid-state ^{31}P and ^{63}Cu NMR spectra were recorded on a Bruker AC-250 spectrometer at 101.256 and 63.453 MHz, respectively. A Bruker VT 100 unit was used for the variable-temperature studies. The ^{31}P and ^{63}Cu variable-temperature NMR experiments were performed in methanol-d_4/dichloromethane-d_2 (50:50). Chemical shifts for ^{31}P NMR spectra were referenced to 85% H_3PO_4 by means of a coaxial tube. Chemical shifts for the ^{63}Cu NMR spectra were referenced to a 0.1 *m* solution of $[Cu(CH_3CN)_4]BF_4$ in acetonitrile[16,17] as external standard. Solid-state ^{31}P NMR spectra were recorded at room temperature on a Bruker AMX-400 instrument at 161.98 MHz. Chemical shifts were referenced to solid ammonium phosphate.

Results and Discussion

Crystal Structure. The structure of $[Cu(dmpe)_2]_2^{2+}$, together with the atomic numbering system, is depicted in Figure 1. Table I summarizes pertinent crystallographic data, while Table III provides selected bond distances and angles for the complex. The crystal structure consists of a dimeric $[Cu(dmpe)_2]_2^{2+}$ cation which contains a crystallographically imposed center of inversion and two independent BF_4^- anions which are disordered. The coordination sphere of the tetracoordinated copper is best described as a distorted tetrahedron in which each copper atom is bonded to four phosphorus atoms. The four dmpe ligands of the dimeric cation are in two different environments: each of two dmpe ligands chelates a copper atom to form a five-membered CuP_2C_2 ring whereas the other two dmpe ligands form bridges between the Cu(dmpe) units to create a ten-membered $Cu_2P_4C_4$ ring. All P–Cu–P angles exhibit deviations from the ideal tetrahedral value of 109.5°. The P(3)–Cu–P(4) angle for the chelating dmpe ligand is 89.2 (1)°, a value largely imposed by the geometry of the five-membered ring. The P–Cu–P angles for phosphorus atoms of different dmpe ligands range from 110.3 (1) to 116.9 (1)°. The P–Cu bond distances lie between 2.263 (1) and 2.293 (1) Å, with the values for the chelating dmpe (2.289 (1) and 2.293 (1) Å) being slightly larger than those observed for the bridging ligands (2.263 (1) and 2.267 (1) Å). The twelve P–C bond distances (average 1.824 (4) Å) are substantially equivalent and are comparable to corresponding values found in a number of phosphine complexes.

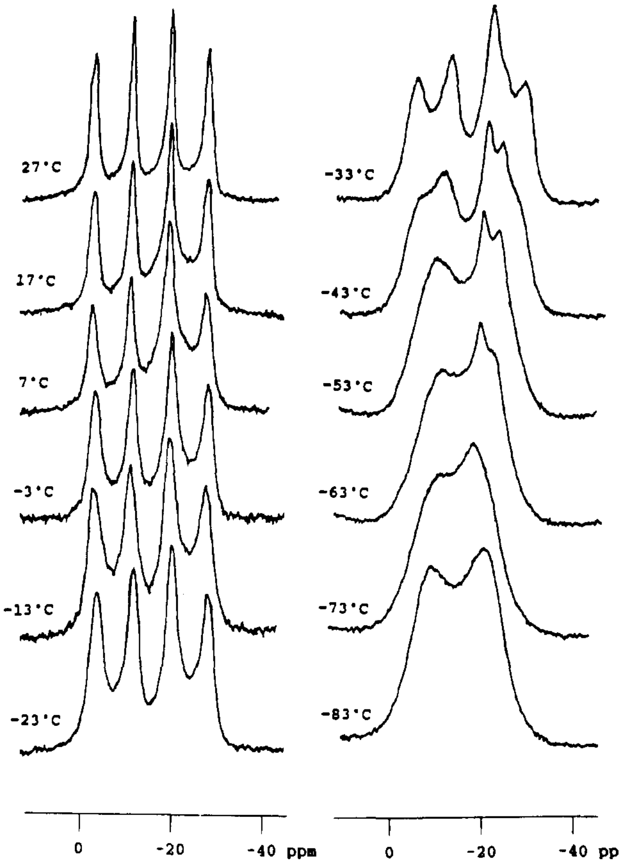


Figure 2. Variable-temperature ^{31}P NMR spectra for $[Cu(dmpe)_2]_2(BF_4)_2$.

Darensbourg et al.[9] recently reported the synthesis and crystal structure of $[Cu(dmpe)_2][Cu(Co(CO)_4)_2]$, which contains a monomeric $[Cu(dmpe)_2]^+$ cation. The coordination environment of this monomeric cation is that of a highly distorted tetrahedron with two perpendicular P–Cu–P planes. The P–Cu–P angles of 90.9 (1)° within the chelating dmpe ligand in the monomer are consistent with the 89.2 (1)° intraligand angles observed for the dimeric species. The values for the corresponding monomeric Cu(I) dppe complexes range from 89.2 (1) to 90.0 (2)°.[3,4] The P–Cu distances in the Cu–dmpe monomer (2.248 (3)–2.254 (3) Å) are somewhat shorter than the corresponding distances within the Cu–dmpe dimer (2.289 (1)–2.293 (1) Å), probably due to the enhanced steric requirements of the bridging dmpe ligands within the dimer. Other bond angles and distances for the monomeric and dimeric Cu–dmpe complexes are in good agreement. Apparently, cationic Cu(I)–dmpe complexes crystallize in monomeric or dimeric forms as a function of crystallization conditions and the properties of the anion.

Bridging diphosphine ligands are frequently observed in Cu(I) phosphine complexes. Well-known examples are the dimers $[(CuX)_2(dppe)_3]$ ($X = Cl^-, N_3^-, CF_3CO_4^-$),[5,18,19] which contain one bridging and two chelating diphosphine ligands. The anions in these complexes are coordinated to the copper atom. The dimers are centrosymmetric, with the center of symmetry located between the methylene groups of the bridging ligands; this markedly different symmetry makes meaningful comparison with $[Cu(dmpe)_2]_2^{2+}$ impossible. However, bond angles and distances observed for these complexes are generally similar to those found for $[Cu(dmpe)_2]_2^{2+}$.

Variable-Temperature ^{31}P and ^{63}Cu NMR Studies. Spectra resulting from the ^{31}P and ^{63}Cu variable-temperature NMR studies are presented in Figures 2 and 3, respectively. The ^{31}P NMR spectrum at room temperature consists of an equally spaced quartet centered at −14.6 ppm. The quartet structure is due to spin–spin coupling of the copper nucleus (^{63}Cu, ^{65}Cu; $I = {}^3/_2$) with phosphorus. The $^{63/65}Cu$–^{31}P coupling constant is 800 ± 10 Hz. Despite the crystallographic inequivalence of the four phosphorus atoms, only one quartet pattern is resolved. Therefore, within the resolution of the measurement, these four phosphorus atoms appear equivalent in the liquid state at room temperature. Lowering the temperature causes line broadening within the quartet; the quartet

---

(16) Lutz, O.; Oehler, H.; Kroneck, P. *Z. Naturforsch.* **1978**, *33A*, 1021.

(17) Kroneck, P.; Lutz, O.; Nolle, A.; Oehler, H. *Z. Naturforsch.* **1980**, *35A*, 221.

(18) Gaughan, A. P.; Bowman, K. S.; Dori, Z. *Inorg. Chem.* **1972**, *11*, 601.

(19) Albano, V. G.; Bellon, P. L.; Ciani, C. J. *J. Chem. Soc., Dalton Trans.* **1972**, 1938.

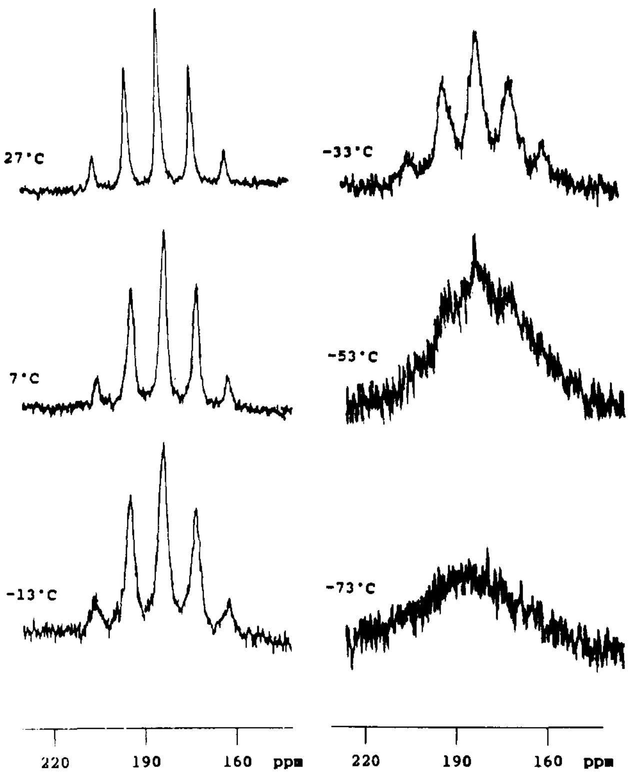


Figure 3. Variable-temperature ^{63}Cu NMR spectra for $[Cu(dmpe)_2]_2(BF_4)_2$.

begins to collapse at −33 °C, with the outer peaks moving inward while the inner peaks move outward. This collapse results in a broad, doubletlike pattern at −83 K (Figure 2). The observed line shapes are in good agreement with those calculated for the spectra of nuclei of spin $^1/_2$ coupled to a nucleus of spin $^3/_2$.[20]

An analogous situation occurs in the variable-temperature ^{63}Cu NMR spectra. The spectrum at ambient temperature consists of a symmetrical 1:4:6:4:1 quintet, due to spin–spin coupling of the four equivalent phosphorus nuclei (^{31}P; $I = {}^1/_2$) with the copper nucleus. The ^{31}P–$^{63/65}$Cu coupling constant at 27 °C is 800 ± 10 Hz. As the temperature is decreased, the peaks start to broaden and finally collapse to a very broad resonance ($\Delta\nu_{1/2}$ = 3500 Hz) at −73 °C.

The temperature dependence of the NMR line shapes observed in these ^{31}P and ^{63}Cu NMR studies can be interpreted in terms of quadrupolar relaxation arising from the ^{63}Cu and ^{65}Cu nuclei. The effects of quadrupolar relaxation on NMR line shapes have been treated in detail by several authors.[20,21] Marker and Gunther[22] have calculated ^{31}P NMR line shapes for CuP_4 complexes with varying copper quadrupolar relaxation rates. Both copper isotopes ^{63}Cu and ^{65}Cu have relatively large quadrupolar moments. Therefore they couple strongly, by means of molecular reorientation, to local electric fields; this coupling generates collapse of the multiplet structure as temperature is decreased. There is an approximate spherical charge distribution on $^{63/65}$Cu at ambient temperature; the electric field gradients are therefore very small at ambient temperature, and relaxation via a quadrupolar mechanism is relatively ineffective. Decreasing the temperature provides a lower symmetry and a greater quadrupolar contribution of the copper center to the spin relaxation process. As a result, both the ^{31}P quartet and the ^{63}Cu quintet begin to collapse at −33 °C.

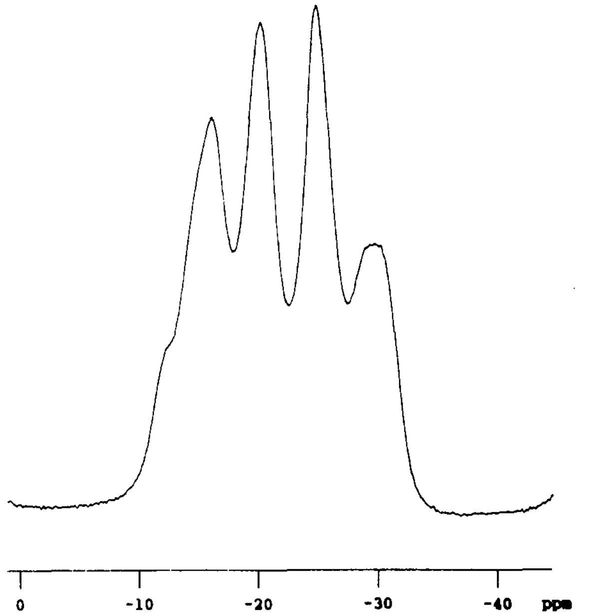


Figure 4. Solid-state CPMAS ^{31}P spectrum for $[Cu(dmpe)_2]_2(BF_4)_2$.

Table IV. Solid-State CPMAS Parameters[a]

δ	$\Delta\nu_1$	$\Delta\nu_2$	$\Delta\nu_3$	$\langle\Delta\nu_i\rangle$	$\Delta\nu_3/\Delta\nu_1$
−22.7	0.69	0.80	0.76	0.75	1.10

[a] δ is the chemical shift relative to $NH_4H_2PO_4$; $\Delta\nu_i$ is the splitting in kHz between each of the four peaks of the quartet; $\langle\Delta\nu_i\rangle$ is the average of the $\Delta\nu_i$ values for each quartet.

Solid-State ^{31}P NMR Spectrum. The solid-state CPMAS ^{31}P NMR spectrum of $[Cu(dmpe)_2]_2(BF_4)_2$ is shown in Figure 4. Here again, despite the crystallographic inequivalence of the four phosphorus atoms, only one quartet pattern is resolved, indicating the near chemical equivalence of the phosphorus atoms of the bridging and the chelating ligands. However, the line widths observed in this spectrum are significantly broader than those observed for other Cu(I) phosphine complexes with methyl-substituted phosphorus atoms.[23] The line spacings within the quartet are unequal (Table IV), due to the presence of a nuclear quadrupole coupling interaction of the copper nucleus with its surroundings.[20–22,24,25] For a spherical charge distribution induced by a perfect tetrahedral coordination sphere around the copper nucleus, the nuclear quadrupole coupling constant should approach zero, resulting in an equally spaced quartet. The asymmetry of the line spacings can be represented by the ratio $\Delta\nu_3/\Delta\nu_1$, where $\Delta\nu_1$ and $\Delta\nu_3$ are the low- and high-field line spacings within the quartet.[24] Bowmaker et al.[25] indicate that the scalar coupling constant for the ^{31}P–$^{63/65}$Cu bond (which is measured by the average line spacing of the quartet) appears only to depend on the number of phosphine ligands coordinated to the copper(I) atom. The reported values are about 1.6 (one coordinated phosphine), 1.2 (two coordinated phosphines), and 0.9 kHz (three coordinated phosphines). The value for $[Cu(dmpe)_2]_2(BF_4)_2$ with four coordinated phosphines is 0.75 kHz, consistent with the observed trend. The divergence of the $\Delta\nu_3/\Delta\nu_1$ ratio from unity is approximately proportional to the copper nuclear quadrupole coupling constant.[24] The ratio of 1.10 found for $[Cu(dmpe)_2]_2(BF_4)_2$ indicates significant deviation from perfect tetrahedral symmetry. However, most other Cu(I) phosphine complexes exhibit higher $\Delta\nu_3/\Delta\nu_1$ ratios.[25]

Conclusions. Dmpe can form both monomeric and dimeric Cu(I) complexes. When the solid dimeric complex is dissolved in 50:50 d_4-methanol-d_4/dichloromethane-d_2, the resulting ^{31}P and ^{63}Cu NMR spectra are consistent with either the monomeric or the dimeric form. However, observation of P–Cu coupling in both the solution ^{31}P and ^{63}Cu NMR spectra implies that the Cu–P

---

(20) Bacon, J.; Gillespie, R. J.; Quail, J. W. *Can. J. Chem.* **1963**, *41*, 3063.
(21) Menger, E. M.; Veeman, W. S. *J. Magn. Reson.* **1982**, *46*, 257.
(22) Marker, A.; Gunther, M. J. *J. Magn. Reson.* **1982**, *47*, 118.
(23) Mohr, B.; Brooks, E. E.; Deutsch, E. Unpublished results.
(24) Bowmaker, G. A.; Cotton, J. D.; Healy, P. C.; Kildea, J. D.; Silong, S. B.; Skelton, B. W.; White, A. H. *Inorg. Chem.* **1989**, *28*, 1462.
(25) Bowmaker, G. A.; Camus, A.; Healy, P. C.; Skelton, B. W.; White, A. H. *Inorg. Chem.* **1989**, *28*, 3883.

bond does not dissociate on the NMR time scale. Thus, the monomeric and dimeric forms are not in rapid equilibrium and the 50:50 methanol-d_4/dichloromethane-d_2 solution contains either the dimeric or the monomeric form. Isolation of one form or the other from various solutions presumably depends upon the nature of the anion used in the crystallization procedure. The stability of $[\mathrm{Cu(dmpe)_2}]_2(\mathrm{BF_4})_2$ indicates that Cu(I)-protected phosphines might be useful starting materials for the preparation of phosphine-based technetium-99m radiopharmaceuticals.

Acknowledgments. Support of this work by the National Institutes of Health (Grant No. HL-21276) is gratefully acknowledged. We wish to thank Dr. Martine Ziliox and Dr. George Kreishman for their discussions and assistance in obtaining the solid-state spectra and Mr. Johannes Schmidt for his early work on the $[\mathrm{Cu(dmpe)_2}]_2^{2+}$ system.

Registry No. $[\mathrm{Cu(CH_3CN)_4}]\mathrm{BF_4}$, 15418-29-8; $[\mathrm{Cu(dmpe)_2}]_2(\mathrm{BF_4})_2$, 136736-94-2; ^{63}Cu, 14191-84-5.

Supplementary Material Available: Tables of hydrogen atom positional parameters, bond lengths and angles, anisotropic thermal parameters, and crystal data and data collection and refinement parameters (7 pages); a listing of calculated and observed structure factors (35 pages). Ordering information is given on any current masthead page.

Contribution from the Biomedical Chemistry Research Center, Department of Chemistry, University of Cincinnati, Cincinnati, Ohio 45221, and Chemistry Division, Argonne National Laboratory, Argonne, Illinois 60439

Electron-Transfer Reactions of Technetium and Rhenium Complexes. 3.[1] Pulse Radiolysis Studies on *trans*-$[\mathrm{M^{III}X_2(DMPE)_2}]^+$ and $[\mathrm{M^{I}(DMPE)_3}]^+$ Complexes in Aqueous and Aqueous Surfactant Media, Where M = Tc or Re, X = Cl or Br, and DMPE = 1,2-Bis(dimethylphosphino)ethane

Andreas Roodt,[2,3] James C. Sullivan,[4] Dan Meisel,[4] and Edward Deutsch*[,3]

Received April 3, 1991

Pulse radiolytic techniques have been employed to study the rate of reactions of the strong reductant e_{aq}^- and the strong oxidant $\mathrm{Cl_2^-}$ with lipophilic, cationic Tc and Re complexes in aqueous and aqueous surfactant media. In aqueous media the reactions of the M(III) complexes *trans*-$[\mathrm{Re^{III}Cl_2(DMPE)_2}]^+$, *trans*-$[\mathrm{Re^{III}Br_2(DMPE)_2}]^+$, and *trans*-$[\mathrm{Tc^{III}Cl_2(DMPE)_2}]^+$ have been studied with both reagents, while the reaction of the M(I) complexes $[\mathrm{Re^{I}(DMPE)_3}]^+$ and $[\mathrm{Tc^{I}(DMPE)_3}]^+$ have been studied with $\mathrm{Cl_2^-}$. Oxidation of the M(I) complexes cleanly yields the corresponding $[\mathrm{M^{II}(DMPE)_3}]^+$ species by an outer-sphere mechanism, whereas oxidation of the M(III) complexes appears to proceed by more complicated pathways, which could involve both outer-sphere electron transfer as well as oxidative addition. All reactions proceed at, or near, the diffusion-controlled limit. The positively charged surfactant CTAB (hexadecyltrimethylammonium bromide) and the uncharged surfactant Triton X-100 (α-[p-(1,1,3,3-tetramethylbutyl)phenyl]-ω-hydroxypolyoxyethylene(9.5)) have little or no effect on the rates of any of the reactions studied. However, micelles formed from the negatively charged surfactant SDS (sodium dodecyl sulfate) exert a dramatic effect on reaction rates by effectively sequestering the cationic complexes and rendering them relatively unavailable for reaction with the anionic reagents e_{aq}^- and $\mathrm{Cl_2^-}$. While the anionic reagents can penetrate the SDS micelles, the cationic complexes do not appear to be released from the micelle during the lifetime of the anionic radicals (ca. 10^2 μs). These results have implications for the use of surfactants in electrochemical studies, as well as for the pharmacokinetics of cationic complexes of interest to nuclear medicine.

Introduction

During the past 5 years detailed biological studies have demonstrated that in vivo redox reactions can dramatically affect the biodistributions of technetium-99m and rhenium-186 radiopharmaceuticals.[3-11] While in some cases the in vivo oxidation or reduction of a radiopharmaceutical adversely affects its biodistribution,[5,6,8,10] in other situations in vivo redox reactivity can be advantageous.[7,11] In either case the rational design of radiopharmaceuticals requires fundamental knowledge of the thermodynamic and kinetic factors which underlie the in vivo redox reactivity of technetium and rhenium complexes. Such knowledge is often difficult to obtain because the complexes of interest to nuclear medicine are generally very lipophilic and thus have very low water solubilities.[12,13] Studies in organic solvents can provide some useful, comparative data, but in general the results of such nonaqueous studies are not directly relevant to the biological milieu. To circumvent this difficulty aqueous surfactant solutions have been utilized to investigate the electrochemistry of lipophilic technetium and rhenium complexes of relevance to nuclear medicine.[14,15] These studies demonstrated that the observed redox potentials, i.e., the *thermodynamic* factors underlying redox reactivity, are sensitive to various properties of both the complexes and the surfactants. In this paper these initial studies are extended with the aim of determining whether or not these properties of

---

(1) Part 2: Libson, K.; Woods, M.; Sullivan, J. C.; Watkins, J. W., II; Elder, R. C.; Deutsch, E. *Inorg. Chem.* **1988**, *27*, 999.

(2) On leave from The University of the Orange Free State, Bloemfontein 9300, Republic of South Africa.

(3) University of Cincinnati.

(4) Argonne National Laboratory.

(5) Vanderheyden, J.-L.; Heeg, M. J.; Deutsch, E. *Inorg. Chem.* **1985**, *24*, 1666.

(6) Deutsch, E.; Libson, K.; Vanderheyden, J.-L.; Ketring, A. R.; Maxon, H. R. *Nucl. Med. Biol.* **1986**, *13*, 465.

(7) Neves, M.; Libson, K.; Deutsch, E. *Nucl. Med. Biol.* **1987**, *14*, 503.

(8) Hirth, W.; Deutsch, E. *J. Nucl. Med.* **1987**, *28*, 1491.

(9) Deutsch, E.; Vanderheyden, J.-L.; Gerundini, P.; Libson, K.; Hirth, W.; Colombo, F.; Savi, A.; Fazio, F. *J. Nucl. Med.* **1987**, *28*, 1870.

(10) Dilworth, J. A.; Archer, C. M.; Latham, I. A.; Bishop, P. T.; Kelly, J. D.; Highly, B. *J. Nucl. Med.* **1989**, *30*, 773.

(11) Roodt, A.; Libson, K.; Cutler, C.; Deutsch, E.; Thomas, S. R.; Maxon, H. R. *J. Nucl. Med.* **1989**, *30*, 732.

(12) Deutsch, E.; Libson, K.; Jurisson, S.; Lindoy, L. F. *Prog. Inorg. Chem.* **1983**, *30*, 75.

(13) Clarke, M. J.; Podbielski, L. *Coord. Chem. Rev.* **1987**, *78*, 253.

(14) Kirchhoff, J. R.; Heineman, W. R.; Deutsch, E. *Inorg. Chem.* **1988**, *27*, 3608.

(15) Kirchhoff, J. R.; Deutsch, E.; Heineman, W. R. *Anal. Lett.* **1989**, *22*, 1323.

0020-1669/91/1330-4545$02.50/0