

# Solid-State $^{31}\text{P}$ NMR and Structural Studies on Copper(I) Complexes of Tetradentate- $\text{N}_2\text{P}_2$ Ligands

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The new tetradentate- $\text{N}_2\text{P}_2$  ligands 1,10-bis(dimethylphosphino)-4,7-dimethyl-4,7-diazadecane (1,10-mm- $\text{N}_2\text{P}_2$ ), 1,10-bis(diphenylphosphino)-4,7-dimethyl-4,7-diazadecane (1,10-pp- $\text{N}_2\text{P}_2$ ), and 1,10-bis(dicyclohexylphosphino)-4,7-dimethyl-4,7-diazadecane (1,10-cycy- $\text{N}_2\text{P}_2$ ) have been synthesized and characterized in solution by  $^1\text{H}$  and  $^{31}\text{P}$  NMR spectroscopy. Copper(I) complexes of these ligands have been isolated and characterized by liquid-state  $^1\text{H}$  and  $^{31}\text{P}$  and solid-state CPMAS  $^{31}\text{P}$  NMR spectroscopy. The solid-state structures of  $[\text{Cu}(1,10\text{-pp-}\text{N}_2\text{P}_2)]\text{BF}_4$  and  $[\text{Cu}(1,10\text{-cycy-}\text{N}_2\text{P}_2)]\text{BF}_4$  have been determined by single-crystal X-ray analyses. For both complexes the coordination geometry around the copper atom can be described as tetrahedral with large distortions.  $[\text{Cu}(1,10\text{-pp-}\text{N}_2\text{P}_2)]\text{BF}_4$  crystallizes with a water of solvation in the triclinic space group  $P\bar{1}$  with unit cell parameters  $a = 9.956(1) \text{ \AA}$ ,  $b = 12.336(2) \text{ \AA}$ ,  $c = 14.269(2) \text{ \AA}$ ,  $\alpha = 93.995(10)^\circ$ ,  $\beta = 93.865(9)^\circ$ ,  $\gamma = 93.742(10)^\circ$ ,  $V = 1740.0(4) \text{ \AA}^3$ ,  $Z = 2$ , and  $R_w = 4.56\%$  for 2177 observed reflections ( $I > 3.0\sigma(I)$ ).  $[\text{Cu}(1,10\text{-cycy-}\text{N}_2\text{P}_2)]\text{BF}_4$  crystallizes with a water of solvation in the monoclinic space group  $C2/c$  with unit cell parameters  $a = 20.111(3) \text{ \AA}$ ,  $b = 25.740(3) \text{ \AA}$ ,  $c = 17.314(2) \text{ \AA}$ ,  $\beta = 117.441(8)^\circ$ ,  $V = 7954.5(1.6) \text{ \AA}^3$ ,  $Z = 8$ , and  $R_w = 6.8\%$  for 2932 observed reflections ( $I > 3.0\sigma(I)$ ). These new cationic Cu(I) complexes are sufficiently stable to warrant evaluation as  $^{62}\text{Cu}$  PET radiopharmaceuticals for myocardial perfusion imaging.

## Introduction

Recent interest in Cu(I) phosphine complexes is based on their potential significance as diagnostic and therapeutic agents. The cytotoxicity and antitumor activity of some diphosphine ligands are greatly enhanced when these ligands are complexed to copper(I).<sup>4-6</sup> Phosphine complexes of Cu(I) are also relevant to nuclear medicine, in part because of the recent development of a generator for the isotope  $^{62}\text{Cu}$ .<sup>7</sup> This isotope demonstrates very favorable nuclear properties for PET (positron emission tomography)<sup>8,9</sup> imaging ( $t_{1/2} = 9.7 \text{ min}$ ,  $\beta^+$ -emitter), and thus cationic Cu(I) phosphine complexes might find employment as PET radiopharmaceuticals analogous to  $^{99\text{m}}\text{Tc}$  radiopharmaceuticals used in SPECT (single photon emission computed tomography).<sup>10</sup> In addition, due to the air sensitivity of many phosphine ligands, Cu(I)-protected phosphines might be useful as starting materials for technetium radiopharmaceuticals.

In this light, we noted the synthesis of a class of tetradentate- $\text{N}_2\text{P}_2$  ligands which contain two nitrogen and two phosphorus atoms in an open chain (Figure 1). Ligands with a PNNP donor atom sequence are not yet common, and most of the ligands prepared to date bear pendant phenyl groups on the terminal phosphorus atoms<sup>11-20</sup> due to the extreme air sensitivity of aliphatic substituted phosphines. In an effort to further extend and

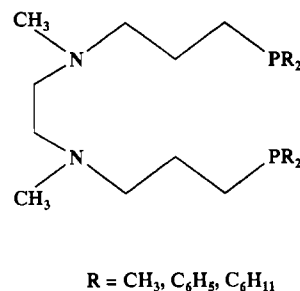


Figure 1. Structural formula of the  $\text{N}_2\text{P}_2$  ligands.

characterize the class of tetradentate- $\text{N}_2\text{P}_2$  phosphine ligands, we have prepared new examples with varying substituents on the phosphorus atoms and then used these ligands to prepare the corresponding Cu(I) complexes. After the completion of our work, the synthesis of one of the ligands prepared in our study (i.e., that with methyl groups on the pendant phosphorus atoms) was reported in the context of technetium radiopharmaceutical development.<sup>11</sup>

## Experimental Section

**Methods and Materials.** *Caution!* Many of the reagents used in this study are air sensitive and potentially flammable; appropriate precautions

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Table I. <sup>1</sup>H NMR Data<sup>a</sup>

	1,10-mm-N <sub>2</sub> P <sub>2</sub>	[Cu(1,10-mm-N <sub>2</sub> P <sub>2</sub> )]BF <sub>4</sub>
NCH <sub>2</sub> CH <sub>2</sub> N	δ = 2.44 (s), 4H	δ = 2.55 (br), 4H
NCH <sub>3</sub>	δ = 2.20 (s), 6H	δ = 2.49 (s), 6H
NCH <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> P	δ = 2.40 (t), <sup>3</sup> J <sub>HH</sub> = 7.3 Hz, 4H	δ = 2.58 (br), 4H
NCH <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> P	δ = 1.54 (m), 4H	δ = 1.74 (m), 4H
NCH <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> P	δ = 1.36 (m), 4H	δ = 1.63 (m), 4H
PCH <sub>3</sub>	δ = 1.00 (d), <sup>2</sup> J <sub>HP</sub> = 2.1 Hz, 12H	δ = 1.22 (br s), 12H
	1,10-pp-N <sub>2</sub> P <sub>2</sub>	[Cu(1,10-pp-N <sub>2</sub> P <sub>2</sub> )]BF <sub>4</sub>
NCH <sub>2</sub> CH <sub>2</sub> N	δ = 2.32 (s), 4H	δ = 2.47 (br), 4H
NCH <sub>3</sub>	δ = 2.06 (s), 6H	δ = 2.41 (s), 6H
NCH <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> P	δ = 2.36 (t), <sup>3</sup> J <sub>HH</sub> = 7.2 Hz, 4H	δ = 3.00 (br), 4H
NCH <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> P	δ = 1.48 (m), 4H	δ = 1.94 (m), 4H
NCH <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> P	δ = 2.06 (dt), <sup>2</sup> J <sub>HP</sub> = 15.2 Hz, <sup>3</sup> J <sub>HH</sub> = 7.7 Hz, 4H	δ = 2.44 (m), 4H
P-aromatic	δ = 7.40–7.28 (m), 20H	δ = 7.45–7.28 (m), 20H
	1,10-cycy-N <sub>2</sub> P <sub>2</sub>	[Cu(1,10-cycy-N <sub>2</sub> P <sub>2</sub> )]BF <sub>4</sub>
NCH <sub>2</sub> CH <sub>2</sub> N	δ = 2.50 (s), 4H	δ = 2.61 (br), 4H
NCH <sub>3</sub>	δ = 2.22 (s), 6H	δ = 2.52 (s), 6H
NCH <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> P	δ = 2.44 (t), <sup>3</sup> J <sub>HH</sub> = 6.9 Hz, 4H	δ = 2.61 (br), 4H
NCH <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> P	δ = 1.55 (m), 4H	under cyclohexyl signal
NCH <sub>2</sub> CH <sub>2</sub> CH <sub>2</sub> P	δ = 1.37 (m), 4H	under cyclohexyl signal
P-cyclohexyl	δ = 1.84–1.10 (m), 44H	δ = 1.90–1.65, 1.35–1.25 (m)

<sup>a</sup> All spectra were recorded in acetonitrile-*d*<sub>3</sub>.

should be taken at all times. All manipulations involving phosphine compounds were conducted in a drybox under an argon atmosphere using Schlenk glassware. Solvents used in these reactions were dried and distilled under argon prior to use. Diphenylphosphine and dicyclohexylphosphine were obtained from Strem Chemical Inc. The tetrafluoroborate and hexafluorophosphate salts of tetrakis(acetonitrile)copper(I) were prepared according to a literature method.<sup>21</sup> <sup>1</sup>H NMR spectra were recorded on a Bruker AC-250 spectrometer at 250 MHz with CH<sub>3</sub>CN as solvent and tetramethylsilane (TMS) as internal standard. The fast atom bombardment mass spectra (FAB-MS) were recorded on a Masslab VG 30-250 instrument, operated in the positive-ion mode (Xe cations, 7 kV), with nitrobenzyl alcohol as matrix. Elemental analyses were conducted by Galbraith Laboratories, Inc., Knoxville, TN.

**Synthesis of 1,10-Bis(dimethylphosphino)-4,7-dimethyl-4,7-diazadecane (1,10-mm-N<sub>2</sub>P<sub>2</sub>).** A dry three-necked, 500-mL flask was fitted with a dry ice condenser which was connected to an argon inlet, a dropping funnel containing tetramethyldiphosphine<sup>22</sup> (3.8 g, 31.1 mmol), and an argon outlet. The apparatus was evacuated and refilled with argon five times. Then the flask was charged with sodium chips (1.44 g, 62.5 mmol) and 250 mL of liquid ammonia at -78 °C against a counterstream of argon. After 30 min of stirring, the tetramethyldiphosphine was added dropwise. The characteristic blue color of sodium in ammonia gradually changed to the red color of sodium dimethylphosphide during the 30-min addition period. The dry ice bath was removed, and 1,10-dichloro-4,7-dimethyl-4,7-diazadecane<sup>23,24</sup> (7.0 g, 29.0 mmol) was added slowly. After the addition was finished, stirring was continued for 1 h, during which time the red color of the suspension gradually disappeared. The ammonia was allowed to evaporate under a slow stream of argon; then 25 mL of water and 50 mL of ether (both degassed) were added. The ether layer was separated from the mixture, and the aqueous layer was extracted three times with 50 mL of ether. The organic layers were combined and then dried over magnesium sulfate. The pure ligand was obtained by vacuum distillation as a colorless, air-sensitive liquid (bp<sub>0.6mm</sub> 126 °C). Anal. Calcd for C<sub>14</sub>H<sub>34</sub>N<sub>2</sub>P<sub>2</sub>: C, 57.51; H, 11.72; N, 9.58. Found: C, 57.83; H, 11.83; N, 9.90. <sup>1</sup>H NMR data are compiled in Table I. FAB-MS, *m/z* (relative intensity): 293 (MH<sup>+</sup>, 10), 160 (18), 146 (100), 103 (88).

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**Synthesis of 1,10-Bis(diphenylphosphino)-4,7-dimethyl-4,7-diazadecane (1,10-pp-N<sub>2</sub>P<sub>2</sub>).** A 500-mL, three-necked flask equipped with a dry ice condenser which was connected to an argon inlet, a dropping funnel, and an argon outlet was loaded with metallic potassium (0.78 g, 20.0 mmol) against a counterstream of argon. Addition of 250 mL of liquid ammonia at -78 °C yielded the characteristic dark-blue solution. To this stirred solution was added diphenylphosphine (3.72 g, 20.0 mmol) via syringe. After 1 h of stirring, the color of the suspension turned to the orange color of potassium diphenylphosphide. The cooling bath was removed, and 1,10-dichloro-4,7-dimethyl-4,7-diazadecane<sup>23,24</sup> (4.8 g, 19.0 mmol) was slowly added dropwise to the stirred reaction mixture. Stirring was continued for 1 h, resulting in a colorless suspension. The ammonia was evaporated at room temperature; then 30 mL of water and 50 mL of ether (both degassed) were added to the remaining white residue. The ether layer was separated from the mixture, and the aqueous layer was extracted three times with 50 mL of ether. The collected organic layers were dried over magnesium sulfate. After the solvent was removed under reduced pressure, the crude ligand appeared as a pale yellow oil. Silica gel column chromatography (1.5 × 25 cm column), performed under argon, was used for the final purification. Unreacted diphenylphosphine was removed with chloroform, and finally the desired ligand was eluted with methanol. Rotary evaporation of the solvent yielded a colorless oil. Anal. Calcd for C<sub>34</sub>H<sub>42</sub>N<sub>2</sub>P<sub>2</sub>: C, 75.53; H, 7.76; N, 5.18. Found: C, 75.56; H, 7.76; N, 5.06. <sup>1</sup>H NMR data are compiled in Table I. FAB-MS, *m/z* (relative intensity): 541 (MH<sup>+</sup>, 13), 284 (18), 270 (100), 227 (92).

**Synthesis of 1,10-Bis(dicyclohexylphosphino)-4,7-dimethyl-4,7-diazadecane (1,10-cycy-N<sub>2</sub>P<sub>2</sub>).** The preparation of lithium dicyclohexylphosphide was achieved according to a literature procedure.<sup>25</sup> To a solution of dicyclohexyldiphosphine (3.93 g, 19.8 mmol) in 30 mL of ether was added phenyllithium (1.8 M solution in cyclohexane/ether, 70/30 (v/v)) (11 mL, 1.67 g, 19.8 mmol) with stirring. The yellow precipitate which crystallized after a few minutes was isolated on a G3 frit filter, washed three times with 20 mL of ether, and dried under vacuum. Any extraneous oxygen which reacted with the yellow precipitate caused an intense yellow-greenish luminescence. The lithium dicyclohexylphosphide (3.64 g, 17.8 mmol) was suspended in 25 mL of ether, and the suspension was slowly added to 1,10-dichloro-4,7-dimethyl-4,7-diazadecane<sup>23,24</sup> (1.98 g, 8.25 mmol) dissolved in 15 mL of ether. Then 30 mL of deoxygenated water was added to yield a colorless organic layer and a yellow aqueous layer. The organic layer was separated from the mixture, and the aqueous layer was extracted three times with 10 mL of ether. The organic fractions were then combined and dried over magnesium sulfate. Evaporation of the solvent under reduced pressure yielded a colorless highly viscous oil. Final purification was achieved by chromatography on a 1.5 × 25 cm silica gel column (performed under argon). Dicyclohexylphosphine and other byproducts were removed from the column with chloroform, and then the pure ligand was eluted with methanol. After complete evaporation of the methanol under reduced pressure, the ligand remained as a highly viscous, colorless liquid. Anal. Calcd for C<sub>34</sub>H<sub>66</sub>N<sub>2</sub>P<sub>2</sub>: C, 72.28; H, 11.73; N, 4.98. Found: C, 72.43; H, 11.91; N, 4.79. <sup>1</sup>H NMR data are compiled in Table I. FAB-MS, *m/z* (relative intensity): 565 (MH<sup>+</sup>, 12), 296 (19), 270 (100), 239 (89).

**Synthesis of [Cu(1,10-mm-N<sub>2</sub>P<sub>2</sub>)]PF<sub>6</sub>.** Freshly prepared tetrakis(acetonitrile)copper(I) hexafluorophosphate (3.2 g, 10.2 mmol) was added in small portions to a stirred solution of 1,10-mm-N<sub>2</sub>P<sub>2</sub> ligand (3.1 g, 10.6 mmol) in 20 mL of methanol. The colorless reaction mixture was stirred for 24 h at room temperature and then heated at reflux for 2 h. After the mixture was cooled to room temperature, filtration of the slightly brown solution resulted in a colorless filtrate. The filtrate was evaporated to dryness, yielding an off-white powder. A suspension of this residue in ethyl acetate was applied to a 1.5 × 25 cm column of silica gel. Excess ligand was eluted with ethyl acetate, and then acetonitrile was used to elute the desired product. The retention of copper(II) species (formed by oxidation) on the column can be monitored by their blue color. Elution with chloroform is not advised since this yields a significant amount of a blue copper(II) species; a similar observation on chloroform oxidation of another Cu(I) complex has been reported by Anderson.<sup>26</sup> Complete solvent evaporation resulted in a white crystalline material which is very sensitive to air and moisture. Anal. Calcd for C<sub>14</sub>H<sub>34</sub>CuF<sub>6</sub>N<sub>2</sub>P<sub>2</sub>·H<sub>2</sub>O: C, 33.57; H, 6.84; N, 5.59; Cu, 12.69. Found: C, 33.43; H, 6.86; N, 5.58; Cu, 12.83. <sup>1</sup>H NMR data are compiled in Table I. FAB-MS, *m/z* (relative intensity): 355 (M<sup>+</sup>, 100), 251 (10), 222 (11), 194 (13); the

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**Table II.** Crystallographic Data

	[Cu(1,10-pp-N <sub>2</sub> P <sub>2</sub> )]- BF <sub>4</sub> ·H <sub>2</sub> O	[Cu(1,10-cycy-N <sub>2</sub> P <sub>2</sub> )]- BF <sub>4</sub> ·H <sub>2</sub> O
formula	C <sub>34</sub> H <sub>44</sub> BCuF <sub>4</sub> N <sub>2</sub> O <sub>2</sub>	C <sub>34</sub> H <sub>68</sub> BCuF <sub>4</sub> N <sub>2</sub> O <sub>2</sub>
fw	709.03	733.23
a, Å	9.956(1)	20.111(3)
b, Å	12.336(2)	25.740(3)
c, Å	14.269(2)	17.314(2)
α, deg	93.995(10)	
β, deg	93.865(9)	117.441(8)
γ, deg	93.74(1)	
V, Å <sup>3</sup>	1740.0(4)	7954.5(1.6)
Z	2	8
λ, Å	0.710 73	0.710 73
T, °C	21	21
space group	P $\bar{1}$ (No. 2)	C2/c (No. 15)
ρ(calc), g cm <sup>-3</sup>	1.35	1.224
μ, cm <sup>-1</sup>	7.34	6.73
transm coeff	0.449–0.386	0.858–0.909
R <sup>a</sup>	0.047	0.069
R <sub>w</sub> <sup>a</sup>	0.046	0.068

$$^a R = (\sum|\Delta F|)/\sum|F_o|; R_w = [(\sum w|\Delta F|^2)/\sum wF_o^2]^{1/2}.$$

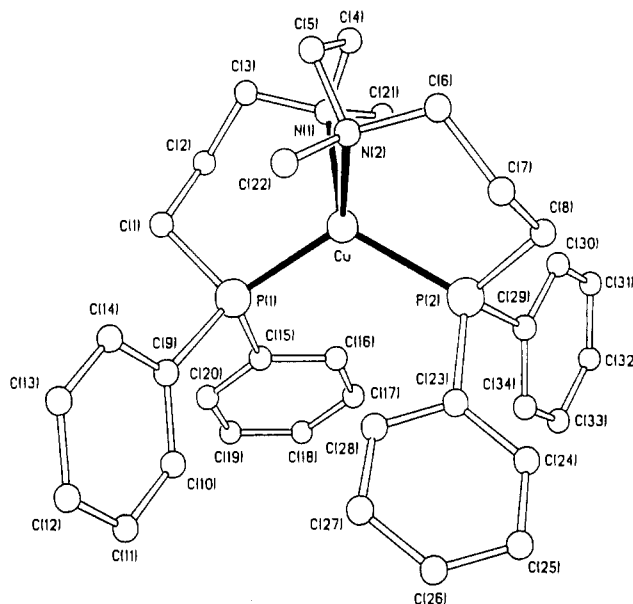
observed isotopic ratio for the molecular ion and all fragments is in good agreement with the natural abundance ratio of the two copper isotopes <sup>63</sup>Cu/<sup>65</sup>Cu = 69/31.

**Synthesis of [Cu(1,10-pp-N<sub>2</sub>P<sub>2</sub>)]BF<sub>4</sub>.** Tetrakis(acetonitrile)copper(I) tetrafluoroborate (1.1 g, 3.50 mmol) was added to 1,10-pp-N<sub>2</sub>P<sub>2</sub> (2.0 g, 3.70 mmol) in 20 mL of methanol, and the mixture was stirred for 2 h at room temperature. Following a 2-h reflux, the colorless solution was concentrated to 10 mL and stored in a refrigerator. The resulting white precipitate was removed by filtration, washed with ether, and then dried in vacuo. The colorless crystals thus obtained were recrystallized from acetonitrile, yielding colorless single crystals suitable for X-ray analysis. Anal. Calcd for C<sub>34</sub>H<sub>42</sub>BCuF<sub>4</sub>N<sub>2</sub>P<sub>2</sub>·H<sub>2</sub>O: C, 57.60; H, 6.25; N, 3.95; Cu, 8.96. Found: C, 58.52; H, 6.36; N, 3.96; Cu, 8.86. (A reviewer has noted that the relatively high % C may result from loss of the water of hydration during analysis.) <sup>1</sup>H NMR data are compiled in Table I. FAB-MS, *m/z* (relative intensity): 603 (M<sup>+</sup>, 100), 346 (10), 307 (14); the observed isotopic ratio for the molecular ion and all fragments is in good agreement with the natural abundance ratio of the two copper isotopes <sup>63</sup>Cu/<sup>65</sup>Cu = 69/31.

**Synthesis of [Cu(1,10-cycy-N<sub>2</sub>P<sub>2</sub>)]BF<sub>4</sub>.** Tetrakis(acetonitrile)copper(I) tetrafluoroborate (0.95 g, 3.02 mmol) was added in small portions to a stirred solution of 1,10-cycy-N<sub>2</sub>P<sub>2</sub> ligand (1.8 g, 3.19 mmol) in 20 mL of methanol. The reaction mixture was stirred for 2 h at ambient temperature and then heated to reflux for 2 h to yield a colorless solution. This solution was concentrated to 8 mL and chilled, yielding colorless crystals. The crystals were removed by filtration, washed with ether, and then dried at 50 °C in vacuo for 24 h. Recrystallization from acetonitrile yielded colorless single crystals suitable for X-ray analysis. Anal. Calcd for C<sub>34</sub>H<sub>66</sub>BCuF<sub>4</sub>N<sub>2</sub>P<sub>2</sub>·H<sub>2</sub>O: C, 55.70; H, 9.35; N, 3.82; Cu, 8.67. Found: C, 56.66; H, 9.39; N, 3.63; Cu, 8.47. (A reviewer has noted that the relatively high % C may result from loss of the water of hydration during analysis.) <sup>1</sup>H NMR data are compiled in Table I. FAB-MS, *m/z* (relative intensity): 627 (M<sup>+</sup>, 100), 358 (12), 330 (11); the observed isotopic ratio for the molecular ion and all fragments is in good agreement with the natural abundance ratio of the two copper isotopes <sup>63</sup>Cu/<sup>65</sup>Cu = 69/31.

**Structure Determinations.** The single-crystal X-ray diffraction experiments were performed on Nicolet R3-series diffractometers with Mo Kα radiation and a graphite monochromator at ambient temperature. The structures were solved by Patterson techniques and refined with the programs SHELX-76 and SHELXTL. Absorption corrections were based on empirical methods. A summary of crystallographic parameters is presented in Table II. For [Cu(1,10-pp-N<sub>2</sub>P<sub>2</sub>)]BF<sub>4</sub>·H<sub>2</sub>O all atoms occupy general positions in the unit cell. [Cu(1,10-cycy-N<sub>2</sub>P<sub>2</sub>)]BF<sub>4</sub>·H<sub>2</sub>O consists of two independent half-cations, each with Cu occupying a crystallographic 2-fold axis, a BF<sub>4</sub><sup>-</sup> anion with disordered fluorine atoms, and a water of hydration disordered between two sites.

**<sup>31</sup>P NMR Spectroscopy.** Liquid-state <sup>31</sup>P NMR spectra were recorded on a Bruker AC-250 spectrometer at 101.256 MHz in acetonitrile-*d*<sub>3</sub>. Chemical shifts for <sup>31</sup>P NMR spectra were referenced to 85% H<sub>3</sub>PO<sub>4</sub> in H<sub>2</sub>O by means of a coaxial tube. Solid-state <sup>31</sup>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.

**Figure 2.** Molecular representation of the crystal structure of [Cu(1,10-pp-N<sub>2</sub>P<sub>2</sub>)]<sup>+</sup>. Hydrogen atoms are omitted.**Table III.** Selected Bond Parameters for [Cu(1,10-pp-N<sub>2</sub>P<sub>2</sub>)]BF<sub>4</sub>·H<sub>2</sub>O

Bond Lengths (Å)			
Cu-P(1)	2.255(2)	N(1)-C(4)	1.460(11)
Cu-P(2)	2.251(2)	N(1)-C(21)	1.483(11)
Cu-N(1)	2.185(7)	N(2)-C(5)	1.477(11)
Cu-N(2)	2.173(7)	N(2)-C(6)	1.484(9)
P(1)-C(1)	1.833(8)	N(2)-C(22)	1.481(10)
P(1)-C(9)	1.842(8)	P(2)-C(23)	1.826(8)
P(1)-C(15)	1.824(9)	P(2)-C(29)	1.817(8)
P(2)-C(8)	1.828(8)	N(1)-C(3)	1.497(9)
Bond Angles (deg)			
P(2)-Cu-P(1)	120.4(1)	N(1)-Cu-P(1)	97.7(2)
N(1)-Cu-P(2)	126.0(2)	N(2)-Cu-P(1)	126.6(2)
N(2)-Cu-P(2)	97.7(2)	N(2)-Cu-N(1)	86.0(3)
C(1)-P(1)-Cu	110.8(3)	C(9)-P(1)-Cu	120.9(3)
C(9)-P(1)-C(1)	104.4(4)	C(15)-P(1)-Cu	112.5(3)
C(15)-P(1)-C(1)	100.8(4)	C(15)-P(1)-C(9)	105.2(4)
C(8)-P(2)-Cu	111.3(3)	C(23)-P(2)-Cu	112.0(3)
C(23)-P(2)-C(8)	100.0(4)	C(29)-P(2)-Cu	121.8(3)
C(29)-P(2)-C(8)	103.9(4)	C(29)-P(2)-C(23)	105.4(4)
C(3)-N(1)-Cu	118.8(5)	C(4)-N(1)-Cu	101.5(6)
C(6)-N(2)-Cu	118.6(5)	C(21)-N(1)-Cu	110.7(5)
C(5)-N(2)-Cu	100.6(6)	C(22)-N(2)-Cu	110.9(5)
C(6)-N(2)-C(5)	108.0(7)		

## Results and Discussion

**Crystal Structures.** (1,10-Bis(diphenylphosphino)-4,7-dimethyl-4,7-diazadecane)copper(I) Tetrafluoroborate Hydrate. The structure of the cation is shown in Figure 2 together with the atomic numbering system. Selected bond angles and distances are presented in Table III. The structure of [Cu(1,10-pp-N<sub>2</sub>P<sub>2</sub>)]<sup>+</sup> consists of discrete monomer cations; each copper atom in the cation is bonded to two phosphorus atoms and two nitrogen atoms of the tetradentate-N<sub>2</sub>P<sub>2</sub> ligand. The coordination environment around the copper atom is tetrahedral with large distortions. These angular distortions are primarily due to the small N-Cu-N angle of 86.0(3)° imposed by the five-membered CuN<sub>2</sub>C<sub>2</sub> ring. The P-Cu-P and P-Cu-N angles range from 97.7(2) to 126.6(2)°. The two phosphorus atoms are connected to the two nitrogen atoms through a propylene bridge, resulting in two six-membered CuNC<sub>3</sub>P rings. The Cu-P bond distances amount to 2.255(2) and 2.251(2) Å, while the Cu-N bond lengths are 2.185(7) and 2.173(7) Å; these lengths are commonly observed for Cu(I)-P and Cu(I)-N bonds.

(1,10-Bis(dicyclohexylphosphino)-4,7-dimethyl-4,7-diazadecane)-copper(I) Tetrafluoroborate Hydrate. The asymmetric unit

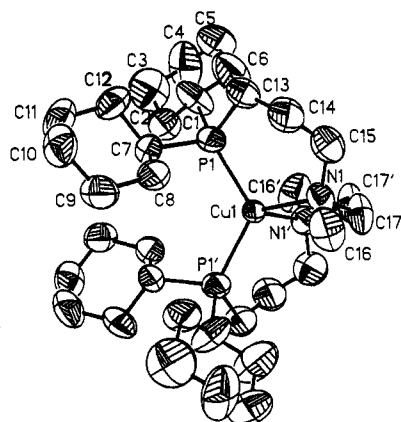


Figure 3. Molecular representation of the crystal structure of [Cu(1,10-cycy-N<sub>2</sub>P<sub>2</sub>)]<sup>+</sup> half-cation 1. The atoms are shown with 50% probability. Hydrogen atoms are omitted.

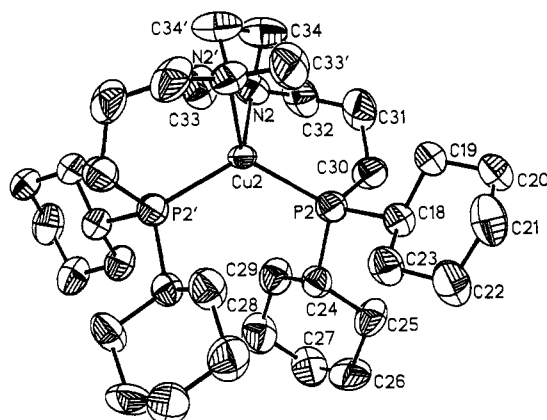


Figure 4. Molecular representation of the crystal structure of [Cu(1,10-cycy-N<sub>2</sub>P<sub>2</sub>)]<sup>+</sup> half-cation 2. The atoms are shown with 50% probability. Hydrogen atoms are omitted.

Table IV. Selected Bond Parameters for [Cu(1,10-cycy-N<sub>2</sub>P<sub>2</sub>)]BF<sub>4</sub>·H<sub>2</sub>O

Bond Lengths (Å)			
Cu(1)–P(1)	2.299(2)	Cu(2)–P(2)	2.299(2)
Cu(1)–N(1)	2.207(7)	Cu(2)–N(2)	2.201(7)
P(1)–C(1)	1.877(6)	P(2)–C(18)	1.849(5)
P(1)–C(7)	1.855(8)	P(2)–C(24)	1.868(8)
P(1)–C(13)	1.839(9)	P(2)–C(30)	1.840(8)
N(1)–C(15)	1.47(1)	N(2)–C(32)	1.51(1)
N(1)–C(16)	1.464(7)	N(2)–C(33)	1.484(8)
N(1)–C(17)	1.50(1)	N(2)–C(34)	1.49(1)
Bond Angles (deg)			
Cu(1)–P(1)–C(1)	128.6(3)	Cu(2)–P(2)–C(18)	127.8(3)
Cu(1)–P(1)–C(7)	109.9(2)	Cu(2)–P(2)–C(24)	111.4(2)
Cu(1)–P(1)–C(13)	111.4(3)	Cu(2)–P(2)–C(30)	111.3(3)
Cu(1)–N(1)–C(15)	112.8(5)	Cu(2)–N(2)–C(32)	117.4(5)
Cu(1)–N(1)–C(16)	115.2(6)	Cu(2)–N(2)–C(33)	110.0(6)
Cu(1)–N(1)–C(17)	101.4(5)	Cu(2)–N(2)–C(34)	104.2(4)
P(1)–Cu(1)–N(1)	101.4(2)	P(2)–Cu(2)–N(2)	99.9(2)
P(1)–Cu(1)–P(1')	123.5(1)	P(2)–Cu(2)–P(2')	120.3(1)
P(1)–Cu(1)–N(1')	119.9(2)	P(2)–Cu(2)–N(2')	124.5(2)
N(1)–Cu(1)–N(1')	85.3(3)	N(2)–Cu(2)–N(2')	84.3(2)
C(1)–P(1)–C(7)	100.2(4)	C(18)–P(2)–C(24)	102.2(3)
C(1)–P(1)–C(13)	100.0(4)	C(18)–P(2)–C(30)	98.8(3)
C(7)–P(1)–C(13)	103.9(4)	C(24)–P(2)–C(30)	102.0(3)

contains two [Cu(1,10-cycy-N<sub>2</sub>P<sub>2</sub>)]<sup>+</sup> half-cations, each on a 2-fold crystallographic axis, a BF<sub>4</sub><sup>-</sup> anion with disordered fluorine atoms, and a water molecule disordered between two sites. The structures of the two half-cations are displayed in Figures 3 and 4 with their atomic labeling schemes. Selected bond distances and angles are listed in Table IV. The copper coordination approaches that of a tetrahedron. Distortions arise from the acute N–Cu–N angles (average 85°) of the five-membered chelate rings and the larger

Table V

Liquid-State <sup>31</sup> P NMR Data (ppm) <sup>a</sup>		
complex	calcd <sup>b</sup>	found
1,10-mm-N <sub>2</sub> P <sub>2</sub>	-51.0	-51.3
[Cu(1,10-mm-N <sub>2</sub> P <sub>2</sub> )]PF <sub>6</sub>		-39.5
1,10-cycy-N <sub>2</sub> P <sub>2</sub>	-5.0	-4.4
[Cu(1,10-cycy-N <sub>2</sub> P <sub>2</sub> )]BF <sub>4</sub>		-9.4
1,10-pp-N <sub>2</sub> P <sub>2</sub>	-15.0	-15.6
[Cu(1,10-pp-N <sub>2</sub> P <sub>2</sub> )]BF <sub>4</sub>		-14.8

$$\text{Grim's Equation for PR}_1\text{R}_2\text{R}_3: \delta(^{31}\text{P})_{\text{calcd}} = \sum \text{GC}_i f$$

R <sub>i</sub>	Me	Et	Pr	<i>n</i> -Bu	<i>i</i> -Bu
GC <sub>i</sub>	-21	-7	-11	-11	-15
R <sub>i</sub>	<i>t</i> -Bu	Ph	Bz	cy	<i>c</i> -C <sub>5</sub> H <sub>11</sub>
GC <sub>i</sub>	23	-3	-4	2	0

<sup>a</sup> Chemical shifts for <sup>31</sup>P NMR spectra were referenced to 85% H<sub>3</sub>PO<sub>4</sub> in D<sub>2</sub>O. <sup>b</sup> Calculated according to Grim's group contribution.<sup>28</sup> <sup>c</sup> For R<sub>3</sub> (–CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>NR'R'') in the 1,10-N<sub>2</sub>P<sub>2</sub> ligands a value of –9 was estimated.

N–Cu–P and P–Cu–P angles which range from 99.2 to 124.5°. The Cu–P bond distance is 2.299(2) Å in both independent determinations; the Cu–N bond lengths are 2.207(7) and 2.201(7) Å.

The overall molecular structure and numerical values for bond angles and distances within the two [Cu(1,10-cycy-N<sub>2</sub>P<sub>2</sub>)]<sup>+</sup> half-cations are very close to those observed for [Cu(1,10-pp-N<sub>2</sub>P<sub>2</sub>)]<sup>+</sup>. Significant for both complexes is the highly distorted coordination environment around the copper atom mainly imposed by the small angle of the five-membered CuN<sub>2</sub>C<sub>2</sub> ring. The steric requirement of the bulky phenyl and cyclohexyl groups results in an additional enlargement of the P–Cu–P angles, ranging from 120.3(1) to 123.5(1)°, respectively, as also evidenced by the decreased N–Cu–P angles in the six-membered rings. This observation is consistent for [Cu(1,10-cycy-N<sub>2</sub>P<sub>2</sub>)]<sup>+</sup> and [Cu(1,10-pp-N<sub>2</sub>P<sub>2</sub>)]<sup>+</sup>. The Cu–P bonds for the cyclohexyl-substituted complex are 0.044 Å longer than the ones observed for the phenyl-substituted analogue. This observation is in good agreement with other literature results; going from PPh<sub>3</sub> to P(cy)<sub>3</sub> in the complexes Cu(NO<sub>3</sub>)(PR<sub>3</sub>)<sub>2</sub> causes the Cu–P distance to increase by 0.04 Å.<sup>27</sup>

**Liquid-State <sup>31</sup>P NMR Spectroscopy.** The <sup>31</sup>P NMR chemical shift data for the free ligands, as well as for the corresponding complexes, are compiled in Table V. <sup>31</sup>P NMR chemical shifts of tertiary phosphines are mainly determined by the electronegativity of the substituents bound to phosphorus and the angles between these substituents. Grim's group contributions (GC<sub>i</sub>) to <sup>31</sup>P chemical shifts of tertiary phosphines can be similarly understood, though he first explained them in terms of hyperconjugation.<sup>28</sup> Application of GC<sub>i</sub> generates chemical shifts which are almost identical to those experimentally obtained (Table V).

The <sup>31</sup>P NMR spectrum at 300 K of each of the Cu(I) complexes consists of a sharp singlet without any evidence for unresolved fine structure. Lowering the temperature to 210 K (in methanol-*d*<sub>4</sub>) has no influence on the spectra. The absence of <sup>63/65</sup>Cu–<sup>31</sup>P spin–spin coupling implies operation of a chemical exchange process which occurs on the NMR time scale. <sup>63/65</sup>Cu–<sup>31</sup>P spin–spin coupling has been observed only for highly symmetrical [Cu(PR<sub>3</sub>)<sub>4</sub>]<sup>+</sup> complexes.<sup>29–31</sup> In these, there is a spherical charge distribution at <sup>63/65</sup>Cu which results in an equally-spaced quartet.

The <sup>31</sup>P resonances of the [Cu(1,10-N<sub>2</sub>P<sub>2</sub>)]BF<sub>4</sub>/PF<sub>6</sub> complexes with methyl- and phenyl-substituted phosphorus atoms are shifted

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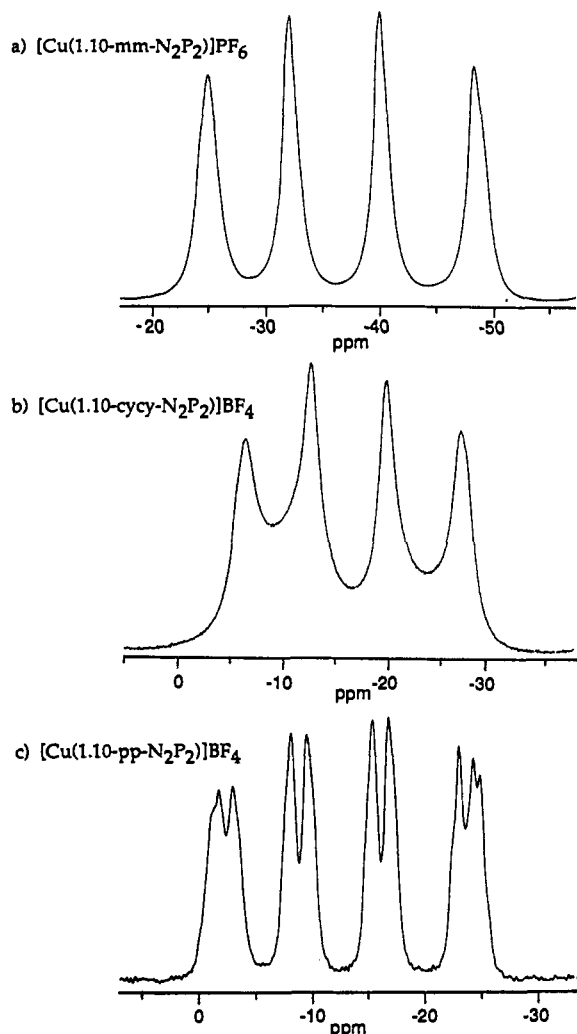


Figure 5. Solid-state CPMAS  $^{31}\text{P}$  spectra.

Table VI. Solid-State CPMAS  $^{31}\text{P}$  NMR Data<sup>a</sup>

complex	$\delta$	$\Delta\nu_1$	$\Delta\nu_2$	$\Delta\nu_3$	$\langle\Delta\nu_i\rangle$	$\Delta\nu_3/\Delta\nu_1$
1,10-mm	-36.1	1.14	1.28	1.37	1.27	1.20
1,10-cycy	-16.5	1.03	1.21	1.18	1.11	1.18
1,12-pp <sup>b</sup>	-11.6	1.04	1.16	1.24	1.15	1.20
1,12-pp <sup>b</sup>	-12.0	1.04	1.16	1.24	1.15	1.20

<sup>a</sup>  $\delta$  is the chemical shift relative to  $\text{NH}_4\text{H}_2\text{PO}_4$ ;  $\Delta\nu_i$  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. <sup>b</sup> The spectrum consists of two equally-spaced quartets.

downfield from the free-ligand resonances by 11.8 and 0.8 ppm, respectively, whereas that for the cyclohexyl-substituted analogue is shifted upfield by 5.0 ppm. The upfield shift of the complex with the bulky cyclohexyl substituents is rather unexpected, but there are related examples in transition metal chemistry.<sup>28</sup>

**Solid-State CPMAS  $^{31}\text{P}$  NMR Spectroscopy.** The solid-state CPMAS  $^{31}\text{P}$  NMR spectra of the  $[\text{Cu}(1,10\text{-N}_2\text{P}_2)]\text{BF}_4/\text{PF}_6$  complexes are presented in Figure 5. The resulting spectral parameters are listed in Table VI. The solid-state CPMAS  $^{31}\text{P}$  NMR spectra for the complexes  $[\text{Cu}(1,10\text{-mm-N}_2\text{P}_2)]\text{PF}_6$  and  $[\text{Cu}(1,10\text{-cycy-N}_2\text{P}_2)]\text{BF}_4$  consist of unequally spaced quartets. The spectrum of  $[\text{Cu}(1,10\text{-pp-N}_2\text{P}_2)]\text{BF}_4$  shows two overlapping quartets which arise from magnetic inequivalence of the two phosphorus atoms in this molecule, despite the fact that these atoms appear chemically equivalent in the crystal structure.

The quartet structure is due to spin-spin coupling of the copper nuclei ( $^{63}\text{Cu}, ^{65}\text{Cu}$ ;  $I = 3/2$ ) with phosphorus. The line spacings in the quartet are unequal, due to the presence of a nuclear quadrupole coupling interaction between the copper nucleus and its surroundings.<sup>29,32-35</sup> For a spherically symmetrical charge distribution, with a perfect tetrahedral coordination sphere around the copper nucleus, the nuclear quadrupole coupling constant would be 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 in the quartet.<sup>34</sup> The splitting ratios for the  $\text{Cu}(1,10\text{-N}_2\text{P}_2)$  complexes,  $\Delta\nu_3/\Delta\nu_1$ , range from 1.18 to 1.20, significantly higher than those observed for other copper-phosphine complexes; this reflects a less spherical charge distribution around the copper atoms in the  $\text{Cu}(1,10\text{-N}_2\text{P}_2)$  complexes. This is consistent with the distorted coordination environments of  $[\text{Cu}(1,10\text{-cycy-N}_2\text{P}_2)]^+$  and  $[\text{Cu}(1,10\text{-pp-N}_2\text{P}_2)]^+$  established by crystallographic analyses.

Bowmaker et al.<sup>35</sup> found that the scalar  $^{31}\text{P}\text{-}^{63/65}\text{Cu}$  coupling constant (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. The values reported by Bowmaker are about 1.6 kHz for one coordinated phosphine, 1.2 kHz for two coordinated phosphines, and 0.9 kHz for three coordinated phosphines. A recent investigation of a complex with four phosphorus atoms coordinated to one copper atom resulted in an average line spacing of 0.75 kHz.<sup>31</sup> Therefore, the average line spacings  $\langle\Delta\nu_i\rangle$  for these complexes (1.11–1.27 kHz), which contain two coordinated phosphines, follow this established trend.

**Conclusions.** The studies reported herein demonstrate that the stability of the  $\text{N}_2\text{P}_2$  ligands and their corresponding  $\text{Cu}(\text{I})$  complexes is highly dependent on the nature of the pendant groups bound to the terminal phosphorus atoms. Complexes with the bulky cyclohexyl and phenyl groups are air stable, whereas the methyl-substituted analogue is oxidized within a few minutes when exposed to air; thus, the nature of the pendant groups dramatically affects the potential of the  $\text{Cu}(\text{II}/\text{I})$  couple. This ability to vary the  $\text{Cu}(\text{II}/\text{I})$  redox potential could be useful in developing this class of complexes for  $^{62}\text{Cu}$  PET imaging, since it is well-known that the redox character of  $\text{Cu}(\text{II}/\text{I})$  complexes is relevant to their biodistribution.<sup>36</sup> The stability of the phenyl- and cyclohexyl-substituted complexes indicates that copper complexes of these ligands might be useful starting materials for the preparation of corresponding technetium-99m radiopharmaceuticals.

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**Supplementary Material Available:** Textual summaries of the structure solutions, tables of atomic positional parameters, bond lengths and angles, anisotropic thermal parameters, and crystal data, and additional structural diagrams (28 pages). Ordering information is given on any current masthead page.

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