Inorg. Chem. **1999,** *38,* 1239−1243 **1239**

Formation of Dinuclear Copper(II) Complexes from a Macrocycle with Built-in Pyrazole Groups

**Richard H. Bode,[†] Johan E. Bol,[†] Willem L. Driessen,*,[†] Frans B. Hulsbergen,[†]
Jan Reedijk,[†] and Anthony L. Spek[‡]**

Leiden Institute of Chemistry, Gorlaeus Laboratories, Leiden University, P.O. Box 9502,
2300 RA Leiden, The Netherlands, and Bijvoet Centre for Biomolecular Research, Crystal and
Structural Chemistry, Utrecht University, Padualaan 8, 3584 CH Utrecht, The Netherlands

Received October 2, 1998

The 22-membered macrocycle, containing four endocyclic pyrazole groups and two exocyclic pyridine groups, viz. (9,22-di(pyridin-2-ylmethyl)-1,4,9,14,17,22,27,28,29,30-decaaza-5,13,18,26-tetramethyl)pentacyclo-$[24.2.1.1^{4,7}.1^{11,14}.1^{17,20}]$triacontane-5,7(28),11(29),12,18,20(30),24(27),25-octaene (**MePy22Pz**), has been synthesized in an eleven-step procedure. Two dinuclear copper(II) compounds, viz. $[Cu_2(MePy22Pz)(NO_3)_4](MeOH)_2$ (**A**) and $[Cu_2(MePy22Pz)(CF_3SO_3)_2(H_2O)_2](CF_3SO_3)_2(MeOH)_2$ (**B**), were prepared with this macrocycle. In both compounds the copper(II) ions are in a square pyramidal N_3O_2 environment involving a pyrazole nitrogen, a pyridine nitrogen, and a tertiairy amine nitrogen and two oxygen atoms, which stem from two different nitrate anions in compound **A** and from a triflate anion and a water molecule in compound **B**. Two of the four pyrazole groups of the macrocycle do not participate in the coordination. The pendent pyridine groups protrude on opposite sides of the macrocycle. Consequently, the copper ions are on different sides of the macrocyclic ring and quite far apart with Cu−Cu distances of 8.668(4) Å in **A** and 6.814(1) Å in **B**.

Introduction

Type-3 site copper proteins, like hemocyanin and tyrosinase, are important dioxygen-processing enzymes.[1] Hemocyanin is an oxygen transporter in arthropods and molluscs, while tyrosinase selectively catalyses phenols to *o*-catechols.[2,3] Low-molecular-weight model compounds of the dinuclear copper sites of these metalloproteins may shed light on the relation between the structure of the site and the function of the enzyme, and, moreover, may very well be useful as selective catalysts in oxidation or hydroxylation reactions.[4,5]

Our strategy in developing ligand systems for this purpose is to approach, as close as possible, the chemical signature of the donor ligands, while at the same time maintaining the entropy of self-assembly to a minimum. This strategy has resulted in the design and synthesis of macrocyclic ligands, with built-in pyrazole-groups[6] as the imidazole analogues, able to hold two copper ions in close proximity.[7,8] The dicopper(I) complexes of one of these ligands, $[Cu_2(MePy22Pz)]X_2$, binds 1 equiv of dioxygen between the two copper ions as an O_2^{2-} anion in an end-on *trans*-μ-1,2-peroxo fashion inside the 22-membered cavity.[9] This appeared to be the first example of a dinuclear copper complex capable of binding dioxygen at room temperature in a protic solvent with a reasonable lifetime. The present paper deals with more detailed investigations on this outstanding macrocycle: A significant modification and improvement of the synthetic procedures[7,8,10] and the spectroscopic and X-ray structural characterization of two important copper(II) complexes of the macrocycle. The structural details of such compounds are needed to understand and interpret the rich oxidation chemistry of the Cu(I) complexes of the ligand MePy22Pz[7] and its analogues.[7]

Experimental Section

Materials and Methods. Most of the synthetic work was carried out by using standard Schlenk techniques. All chemicals used were commercially available and mostly used without further purification. Ethyldiethoxyacetate (**1**) and hydrazine monohydrate were purchased from Aldrich. 2-(Aminomethyl)pyridine and tosyl chloride (tosCl), were obtained from Acros. Tetrahydrofuran (thf) was dried by reflux over sodium.

Column chromatography was performed using the flash chromatography technique on silica gel 60 (230−400 mesh ASTM, Merck).

Melting points were measured on a Pleuger Büchi melting point apparatus.

^{1}H NMR spectra were recorded on a Bruker WM-300 MHz spectrometer.

EPR spectra were recorded on a JEOL Esprit RE2X electron spin resonance spectrometer equipped with a JEOL Esprit 330 data system at room temperature and 77 K with dpph as an internal reference.

[†] Leiden University.

[‡] Utrecht University.

(1) Kaim, W.; Rall, J. *Angew. Chem., Int. Ed. Engl.* **1996**, 35, 43

(2) Magnus, K. A.; Ton-That, H.; Carpenter, J. *Chem. Rev.* **1994**, *94*, 727.

(3) Solomon, E. I.; Lowery, M. D. *Science* **1993**, *259*, 1575.

(4) (a) Karlin K. D.; Tyeklár, Z. *Bioinorganic Chemistry of Copper*; Chapman & Hall: New York, 1993. (b) Lippard, S. J. *Science* **1993**, *261*, 699.

(5) (a) Baesjou, P. J.; Driessen, W. L.; Challa, G.; Reedijk, J. *J. Mol. Catal. A* **1996**, *110*, 195. (b) Koolhaas, G. J. A. A.; Driessen, W. L.; Reedijk, J.; van der Plas, J. L.; de Graaff, R. A. G.; Gatteschi, D.; Kooijman, H.;. Spek, A. L *Inorg. Chem.* **1996**, *35*, 1509. (c) Tabbì, G.; Driessen, W. L.; Reedijk, J.; Bonomo, R. P.; Veldman, N.; Spek, A. L. *Inorg. Chem.* **1997**, *36*, 1168.

(6) Driessen, W. L.; de Graaff, R. A. G.; Parlevliet, F. J.; Reedijk, J.; de Vos, R. M. *Inorg. Chim. Acta* **1994**, *216*, 43.

(7) Bol, J. E. Synthetic models for dinuclear copper proteins. Ph.D. Thesis, Leiden University, 1997.

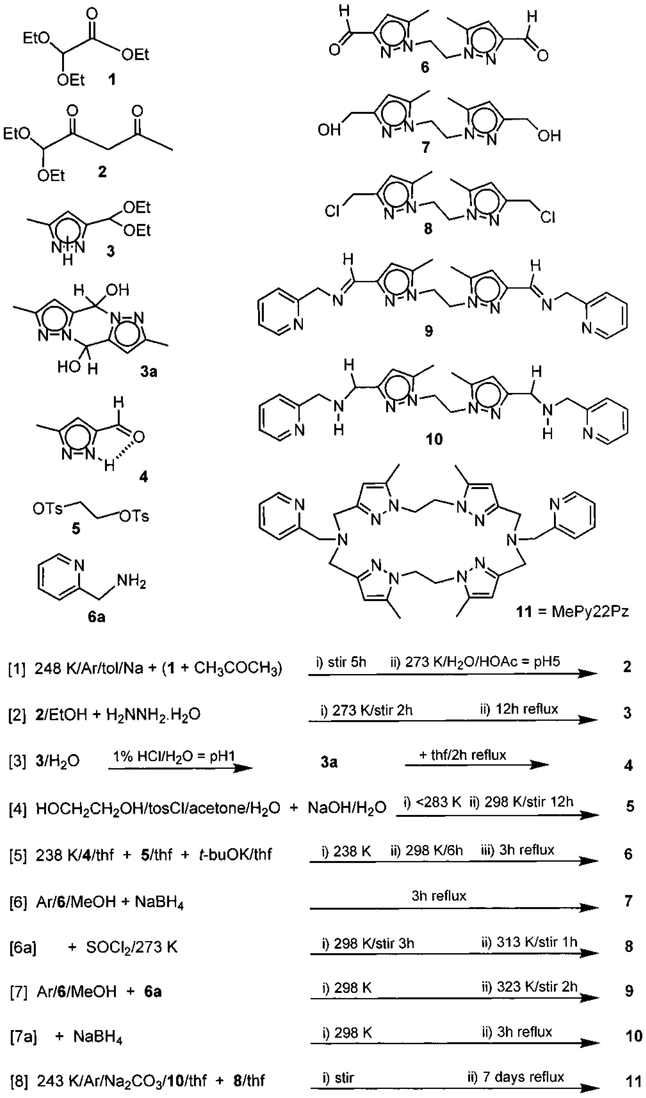
(8) Bol, J. E.; Maase, B.; Gonesh, G.; Driessen, W. L.; Goubitz, K.; Reedijk, J. *Heterocycles* **1997**, *45*, 1477.

(9) Bol, J. E.; Driessen, W. L.; Ho, R. Y. N.; Maase, B.; Que, L.; Reedijk, J. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 998.

(10) Tarrago, G.; Zidane, I.; Marzin, C.; Tep, A. *Tetrahedron* **1988**, *44*, 91

10.1021/ic9811704 CCC: $18.00

Scheme 1. Eleven-Step Synthesis of **MePy22Pz**



Mass spectra (MS) were recorded on a Finnigan MAT 900 double focusing mass spectrometer.

FT-IR spectra were recorded on a Perkin-Elmer paragon 1000 FT-IR spectrometer as KBr disks (4000−400 cm^{-1}).

Ligand field spectra were recorded on a Perkin-Elmer lambda 900 UV/vis/NIR spectrometer.

Synthesis of the Macrocycle MePy22Pz. The macrocyclic ligand (MePy22Pz) was synthezised by an improved modification of the method by Bol et al.,[6,7] resulting in higher yields. The numbers of the intermediate products refer to Scheme 1.

Synthesis of Diethoxyacetylacetone (2).[7,10] A 26.1 g (1.14 mol) amount of freshly cut sodium was added to 800 mL of dry toluene under an argon atmosphere at 298 K. After 100 g (0.57 mol) **1** was quickly added, the reaction mixture was cooled to 248 K. A mixture of 100 g (0.57 mol) **1** and 87.5 mL (1.19 mol; 1.05 equiv) dry acetone p.a. was added dropwise (2 h). After about 15 min the reaction mixture turned yellow. After stirring for 5 h, the reaction mixture was allowed to warm to 298 K. The resulting dark red brown solution was cooled to 273 K. Subsequently, 250 mL H_2O (slowly) and a mixture of 100 mL of acetic acid and 100 mL of H_2O was added until the pH was below 5. The resulting sand-brown H_2O suspension with a red-brown toluene layer was stirred for 1.5 h. The organic layer was washed with a saturated solution of NaCl (100 mL). The H_2O layers were combined and washed three times with 150 mL diethyl ether (Et_2O). The combined tol/Et_2O layer was slowly neutralized with a saturated solution of $NaHCO_3$. After drying with anhydrous Na_2SO_4 and filtration, the resulting clear orange brown solution was concentrated by evaporation. A clear light-yellow oil results after vacuum distillation (0.02 mmHg; 140 °C). Yield: 149.7 g of **3** (0.80 mol; 70%). ^1H NMR (300 MHz, dmso-d_6): δ 5.88 (s, 1H, $(EtO)_2CH$), 3.54 (m, 4H, CH_3CH_2O), 2.49 (s, 1H, COC*H*CO), 2.10 (s, 3H, $COCH_3$), 1.13 (t, 6H, CH_3CH_2O, $^3J_{H-H}$ = 7.2 Hz).

Synthesis of 3-Diethoxymethyl-5-methylpyrazole (3).[7,10] A 42 g (0.84 mol) amount of hydrazine monohydrate was added to a solution of 144.7 g (0.77 mol) **2** in 1.2 L absolute ethanol (EtOH) at 273 K. After stirring for 2 h and refluxing overnight, the reaction mixture was concentrated by evaporation of the solvent. A light-yellow oil resulted which was sufficiently pure to be used for further synthesis. Yield: 128 g of **3** (0.70 mol; 90%). ^1H NMR (300 MHz, $CDCl_3$): δ 6.10 (s, 1H, N*H*), 5.61 (s, 1H, Pz-*H*(4)), 3.62 (m, 4H, CH_3CH_2O), 2.30 (s, 3H, $PzCH_3$), 1.22 (t, 6H, CH_3CH_2O, $^3J_{H-H}$ = 7.1 Hz).

Synthesis of 3-Pyrazolylaldehyde (4).[7,10] A suspension of 128.9 g (0.70 mol) of **3** in 1 L of water was acidified with 215 mL of 1% HCl until the pH was below 1. The color of the reaction mixture changed from green to yellow, whereafter a white precipitate resulted. After standing overnight the white product was filtered off. After subsequent washing with 60 mL of saturated $NaHCO_3$ solution, five times 100 mL of H_2O, two times 100 mL of MeOH, and four times 100 mL of Et_2O a white powder was obtained. Yield: 54.9 g (0.50 mol; 71%). ^1H NMR (300 MHz, dmso-d_6): δ 9.82 (s, 1H, *H*C═O), 6.51 (s, 1H, Pz-*H*(4)), 2.28 (s, 3H, $PzCH_3$).

Synthesis of 1,2-Bis-tosylate-ethane (5).[7] A 62.1 g (1.0 mol) amount of ethylene glycol and 381.3 g (2.0 mol) tosCl was added to a mixture of 1 L of acetone and 1 L of H_2O. After cooling to <283 K (ice-bath), a solution of 80 g (2.0 mol) of NaOH in 300 mL of H_2O was added during 2 h. After 12 h mechanical stirring at 298 K, the product was filtered off and washed with petroleum ether (PE 40-60). After drying in air, 135 g of crude product was obtained, which was dissolved in 400 mL of hot thf. After cooling to 298 K, 50 mL of Et_2O was added. After addition of PE 60-80 till the beginning of crystallization, the solution was allowed to stand for one night at 258 K. A white solid resulted. Yield: 94.8 g (0.26 mol; 26%). Mp 122−124 °C; ^1H NMR (300 MHz, dmso-d_6): δ 7.71 (d, 4H, Ar−(*o*)-*H*, $^3J_{H-H}$ = 8.3 Hz), 7.45 (d, 4H, Ar−(*m*)-*H*, $^3J_{H-H}$ = 8.4 Hz), 4.16 (s, 4H, ethylene-*H*), 2.41 (s, 6H, Ar−CH_3).

Synthesis of 1,2-Di(3′-formyl-5′-methyl-1′-pyrazolyl)ethane (6).[7,8] A 32.0 g (290 mmol) amount of **4** was dissolved in 2.4 L of dry thf until the solution became bright yellow (ca. 2 h reflux). After cooling to 238 K, 53.8 g (145 mmol) of **5**, dissolved in 200 mL of dry thf, and 32.65 g (290 mmol) potassium *tert*-butylate (KO^tBu) dissolved in 100 mL of dry thf were added. The obtained suspension was allowed to warm to 298 K in 6 h and additionally refluxed for 3 h. After cooling to 273 K, the white solid was filtered off on a glass filter, which was washed with CH_2Cl_2. The solvent of the thf/CH_2Cl_2 mixture was removed by evaporation. The resulting orange-yellow solid was recrystallized in thf/Et_2O/hexane (2:1:4 v/v). Off-white, hygroscopic crystals were obtained after 24 h at 258 K. Yield: 17.5 g (71 mmol; 49%). Mp 174−178 °C. ^1H NMR (300 MHz, $CDCl_3$): δ 9.90 (s, 2H, PzC*H*O), 6.44 (s, 2H, Pz*H*(4)), 4.61 (s, 4H, $PzCH_2a$), 1.83 (s, 6H, $PzCH_3$).

Synthesis of 1,2-Di(3′-hydroxymethyl-5′-methyl-1′-pyrazolyl)-ethane (7).[7,8] A 2.00 g (8.1 mmol) amount of **6** was dissolved under reflux in dry MeOH (ca 1 h), after which 0.92 g (24.4 mmol, 1.5 equiv/CH═O) $NaBH_4$ was added. After the evolution of hydrogen gas, the bright yellow solution was refluxed for 3 h, after which the solvent and residual water was removed in vacuo. The resulting yellow solid salt-residue was rinsed with 10 mL aliquots of CH_2Cl_2. The resulting yellow solid still contains some salt, which, however, does not effect the next step (halogenation with $SOCl_2$). Yield: 2.0 g (8.1 mmol; 99%). ^1H NMR (300 MHz, CD_3OD): δ 5.94 (s, 2H, Pz-*H*(4)), 4.48 (s, 4H, $PzCH2OH$), 4.35 (s, 4H, $PzCH_2a$), 1.68 (s, 6H, $PzCH_3$).

Synthesis of 1,2-Di(3′-chloromethyl-5′-methyl-1′-pyrazolyl)ethane (8).[7,8] A 3.60 g (14.4 mmol) amount of **7** was added to 40 mL (0.55 mol) of pure $SOCl_2$ at 273 K. After stirring at 298 K for 3 h and 1 h at 313 K, the excess $SOCl_2$ was removed by evaporation. The resulting brown oil was washed with Et_2O, dissolved in 100 mL of CH_2Cl_2, and neutralized with 50 mL of $NaHCO_3$ (sat), respectively. After drying with anhydrous Na_2SO_4 (20 min) and evaporation of the solvent, a viscous gold-brown oil remained, which solified upon standing at 258 K. The product was stored under a dinitrogen atmosphere. Yield: 2.75 g (9.64 mmol; 67%). ^{1}H NMR (300 MHz, $CDCl_3$): δ 5.94 (s, 2H, Pz-*H*(4)), 4.52 (s, 4H, C*H*$_2$Cl), 4.38 (s, 4H, PzC*H*$_2$a), 1.68 (s, 6H, PzC*H*$_3$).

Synthesis of 1,2-Di(3′-(2-pyridin-2-ylmethylimino)-5′-methyl-1′-pyrazolyl)ethane (9).[7,8] A 3.00 g (12.18 mmol) amount of **6** was dissolved in 150 mL dry of MeOH at reflux under a dry argon atmosphere. A solution of 2.51 mL (2.63 g; 24.4 mmol) of 2-AMP in 50 mL of MeOH was added dropwise at 298 K to the resulting solution. The subsequent clear, yellow brown solution was stirred for 2 h at 323 K. A sample was taken (for control by NMR), which rendered a clear yellow oil after evaporation of the solvent. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.53 (d, 2H, Py*H*(6), $^3J_{\mathrm{H-H}} = 4.5$ Hz), 8.38 (s, 2H, C*H*═N), 7.62 (dt, 2H, Py*H*(4), $^3J_{\mathrm{H-H}} = 8.5$ Hz), 7.35 (d, 2H, Py*H*(3), $^3J_{\mathrm{H-H}} = 7.8$ Hz), 7.13 (m, 2H, Py*H*(5)), 6.37 (s, 2H, Pz*H*(4)), 4.86 (s, 4H, PyC*H*$_2$a), 4.45 (s, 4H, PzCH$_2$a), 1.70 (s, 6H, PzC*H*$_3$).

Synthesis of 1,2-Di(3′-(2-pyridin-2-ylmethylamino)-5′-methyl-1′-pyrazolyl)ethane (10).[7,8] A 2.76 g (73.1 mmol, 3 equiv/CH═N) of $NaBH_4$ was added in situ at 298 K to the MeOH solution containing 12.2 mmol of **9**. The clear, colorless solution was refluxed for 3 h. After stirring overnight at 298 K, the solvent was evaporated, 150 mL of H_2O was added, and the solution was acidified with 30 mL of 2 M HCl. The acidic layer was washed with CH_2Cl_2 and made basic again with concentrated ammonia to pH 9. The obtained white suspension was extracted 3 times with 100 mL of CH_2Cl_2 and dried during 20 min with anhydrous Na_2SO_4. A hygroscopic, viscous residue was obtained after evaporation of the solvent. The clear yellow brown oil was stored under an argon atmosphere. Yield: 4.81 g (11.2 mmol; 92%). ^{1}H NMR (300 MHz, $CDCl_3$): 8.54 (d, 2H, Py*H*(6), $^3J_{\mathrm{H-H}} = 4.7$ Hz), 7.63 (dt, 2H, Py*H*(4), $^3J_{\mathrm{H-H}} = 5.8$ Hz), 7.32 (d, 2H, Py*H*(3), $^3J_{\mathrm{H-H}} = 7.8$ Hz), 7.14 (m, 2H, Py*H*(5)), 5.87 (s, 2H, Pz*H*(4)), 4.34 (s, 4H, PzC*H*$_2$a), 3.94 (s, 4H, PyC*H*$_2$a), 3.79 (s, 4H, PzC*H*$_2$N), 1.65 (s, 6H, Pz-C*H*$_3$).

Synthesis of (9,22-Di(pyridin-2-ylmethyl)-1,4,9,14,17,22,27,28,29,30-decaaza-5,13,18,26-tetramethyl)pentacyclo[24.2.1.1^{4,7}.1^{11,14}.1^{17,20}]-triacontane-5,7(28),11(29),12,18,20(30),24(27),25-octaene (11 = MePy22Pz).[7,8] Under an argon atmosphere, 1.12 g (10.52 mmol) of anhydrous Na_2CO_3 and 2.26 g (5.25 mmol) of **10** were suspended in 300 mL of dry thf. A solution of 1.50 g (5.26 mmol) of **8** in 100 mL of dry thf was added dropwise at 243 K under vigorous stirring. A 100 mL amount of dry acetonitrile was added to obtain a clear solution. The suspension was refluxed for 7 days and gradually turned from white to brown orange. During this period samples were frequently taken to control (by NMR) the progression of the reaction. A saturated NaCl solution (75 mL) was added, and the mixture was acidified with concentrated HCl to pH 1 and washed with Et_2O. The H_2O layer was made basic with concentrated ammonia and extracted (three times, 100 mL of CH_2Cl_2). After drying with anhydrous Na_2SO_4, filtration, and evaporation of the solvent, a red-brown solid with a small amount of oil remained. Column purification of 3.37 g of the crude product on Silicagel (18 cm × XXX 9.5 cm) using CH_2Cl_2/MeOH (85:15 vv) as eluent, gave a pale yellow solid (920 mg) after evaporation of the solvent. The obtained solid was recrystallized from MeOH/Et_2O. Yield: 665 mg (20%) of crystalline product (**11**). ^{1}H NMR (300 MHz, MeOD-*d*$_3$): δ 8.41 (d, 2H, Py*H*(6), $^3J_{\mathrm{H-H}} = 4.1$ Hz), 7.80 (dt, 2H, Py*H*(4), $^3J_{\mathrm{H-H}} = 7.6$ Hz), 7.57 (d, 2H, Py*H*(3), $^3J_{\mathrm{H-H}} = 7.8$ Hz), 7.27 (m, 2H, Py*H*(5)), 5.92 (s, 4H, Pz*H*(4)), 4.41 (s, 8H, PzC*H*$_2$a), 3.56 (s, 4H, PyC*H*$_2$a), 3.34 (d, 8H, PzC*H*$_2$N, $^3J_{\mathrm{H-H}} = 2.0$ Hz), 2.14 (s, 12H, PzC*H*$_3$). MS (ESI, positive ion): *m/z* 645 [M$^+$ + H and parent peak, expected 644.38], 677.4 [M + Na$^+$], 683.6 [M + K$^+$], 323 [M + 2H]$^{2+}$.

Synthesis of the Coordination Compounds. $[Cu_2(MePy22Pz)(NO_3)_4](MeOH)_2$ (A). To a solution of 25.9 mg of MePy22Pz (40.2 mmol) in 5 mL of MeOH and 1 mL of H_2O was added 2 equiv (19.4 mg; 80.4 mmol) of $Cu(NO_3)_2 \cdot 3H_2O$. A clear green solution was obtained after gentle warming and subsequent filtration. Vapor diffusion with Et_2O at 298 K resulted after 2 weeks in light-blue crystals of **A**, suitable for X-ray diffraction.

$[Cu_2(MePy22Pz)(F_3CSO_3)_2(H_2O)_2](F_3CSO_3)_2(MeOH)_2$ (B). To a solution of 46.5 mg MePy22Pz (72.2 mmol) in 10 mL MeOH was added 2 equiv (2.3 mL) of a solution of $Cu(F_3CSO_3)_2$ in MeOH (63 mmol). A clear green solution was obtained after gentle warming and subsequent filtration. Vapor diffusion with Et_2O at 298 K resulted after 3 weeks in dark-blue crystals of **B**, suitable for X-ray diffraction.

Table 1. Crystallographic Data for $[Cu_2(MePy22Pz)(NO_3)_4](MeOH)_2$ (**A**) and $[Cu_2(MePy22Pz)(CF_3SO_3)_2(H_2O)_2](CF_3SO_3)_2(MeOH)_2$ (**B**)

	A	**B**
empirical formula	$C_{38}H_{52}Cu_2N_{16}O_{14}$	$C_{42}H_{56}Cu_2F_{12}N_{12}O_{16}S_4$
fw	1084.02	1468.31
cryst syst	monoclinic	triclinic
cryst size [mm]	0.10 × 0.25 × 0.35	0.15 × 0.50 × 0.82
cryst habit	prismatic	prismatic
cryst color	light blue	dark blue
space group	$P2_1/c$	$P\bar{1}$
a [Å]	9.5662(5)	10.9305(8)
b [Å]	20.5522(16)	12.3260(11)
c [Å]	13.9733(13)	12.5830(7)
α [deg]	90.0	114.528(6)
β [deg]	121.290(6)	93.872(5)
γ [deg]	90.0	103.208(6)
V [Å^3]	2347.7(3)	1476.1(2)
Z	2	1
T [K]	150	150
D(calc) [g/cm^3]	1.533	1.652
F(000)	1124	750
λ(Mo Kα) [Å]	0.710 73	0.710 73
μ [cm^{-1}]	9.9	9.7
θ max [deg]	27.5	27.5
h range	−12/12	−14/14
k range	−26/0	−16/14
l range	−18/18	−10/16
Rfl total	11 257	9525
Rfl unique	5386	6759
R(int)	0.12	0.039
Rfl obs [$I > 2\sigma(I)$]	2943	5867
R	0.066	0.046
wR	0.15	0.13
S	0.92	1.00
$\Delta\rho$ min/max [e/Å^3]	−0.55/0.68	−0.68/1.11

X-ray Data Collection and Structure Refinement. X-ray data were collected on an Enraf-Nonius CAD4T diffractometer with rotating anode. Correction for absorption was found not necessary. Pertinent data for the two structures are assembled in Table 1. The structures were solved with automated Patterson techniques using DIRDIF/PATT[11] and refined on F^2 using full-matrix least-squares techniques with SHELXL-97.[12,13] All non-hydrogen atoms were refined with anisotropic displacement parameters. Hydrogen atoms were introduced on calculated positions and refined riding on their carrier atoms. Geometric calculations and molecular graphics were performed with PLATON.[14] Table 2 contains selected bond lengths and angles for the two compounds.

Results and Discussion

Synthetic Aspects. In Scheme 1 an overview is presented of the synthesis of the 22-membered macrocyclic ligand, containing four endocyclic pyrazole groups and two exocyclic pyridine groups, viz. (9,22-di(pyridin-2-ylmethyl)-1,4,9,14,17,22,27,28,29,30-decaaza-5,13,18,26-tetramethyl)pentacyclo-[24.2.1.1^{4,7}.1^{11,14}.1^{17,20}]triacontane-5,7(28),11(29),12,18,20(30),24(27),25-octaene (**MePy22Pz**). The multistep synthetical procedure, reported in a previous communication,[8] has been

---

(11) Beurskens, P. T.; Admiraal, G.; Beurskens, G.; Bosman, W. P.; Garcia-Granda, S.; Gould, R. O.; Smits, J. M. M.; Smykalla, C. *The DIRDIF program system*; Technical Report of the Crystallography Laboratory: University of Nijmegen, The Netherlands, 1992.

(12) Sheldrick, *G. M. SHELXL97: Program for the Refinement of Crystal Structures*; University of Göttingen: Germany, 1997.

(13) Wilson, A. J. C. (Ed.) *International Tables for Crystallography*; Kluwer Academic Publishers: Dordrecht, The Netherlands, 1992; Vol. C.

(14) Spek, A. L. *Acta Crystallogr.* **1990**, *A46*, C34.

Table 2. Selected Bond Distances (Å) and Angles (deg)

(a) For $[Cu_2(MePy22Pz)(NO_3)_4](MeOH)_2$ (**A**)[a]			
Cu(1)−O(40)	2.185(4)	Cu(1)−N(31)	1.971(5)
Cu(1)−O(44)	2.083(4)	Cu(1)...O(42)	2.801(5)
Cu(1)−N(21)	1.966(5)	Cu(1)...O(47)	2.775(4)
Cu(1)−N(27)	2.056(4)	Cu(1)...Cu(1)a	8.668(4)
O(40)−Cu(1)−O(44)	75.53(15)	O(44)−Cu(1)−N(21)	102.73(16)
O(40)−Cu(1)−N(31)	98.25(17)	N(21)−Cu(1)−N(27)	80.26(18)
O(44)−Cu(1)−N(31)	93.12(16)	O(40)−Cu(1)−N(27)	133.68(16)
N(27)−Cu(1)−N(31)	82.84(17)	O(44)−Cu(1)−N(27)	150.78(16)
O(40)−Cu(1)−N(21)	91.82(18)	N(21)−Cu(1)−N(31)	162.96(16)
(b) For $[Cu_2(MePy22Pz)(CF_3SO_3)_2(H_2O)_2](CF_3SO_3)_2(MeOH)_2$ (**B**)			
Cu(1)−O(2)	1.956(2)	Cu(1)−N(27)	2.033(2)
Cu(1)−N(31)	1.984(2)	Cu(1)−O(41)	2.455(2)
Cu(1)−N(22)	1.985(2)	Cu(1)...Cu(1)b	6.814(1)
O(2)−Cu(1)−N(31)	96.88(9)	O(2)−Cu(1)−N(27)	179.14(10)
O(2)−Cu(1)−N(21)	99.15(9)	O(2)−Cu(1)−O(41)	93.45(8)
O(41)−Cu(1)−N(27)	87.41(9)	O(41)−Cu(1)−N(31)	87.66(9)
O(41)−Cu(1)−N(22)	88.91(9)	N(31)−Cu(1)−N(27)	83.09(9)
N(31)−Cu(1)−N(22)	163.78(10)	N(22)−Cu(1)−N(27)	80.91(10)

[a] Symmetry operations are denoted by the lower case roman letters: a, $-x, -y, -z$; b, $2 - x, -y, 1 - z$.

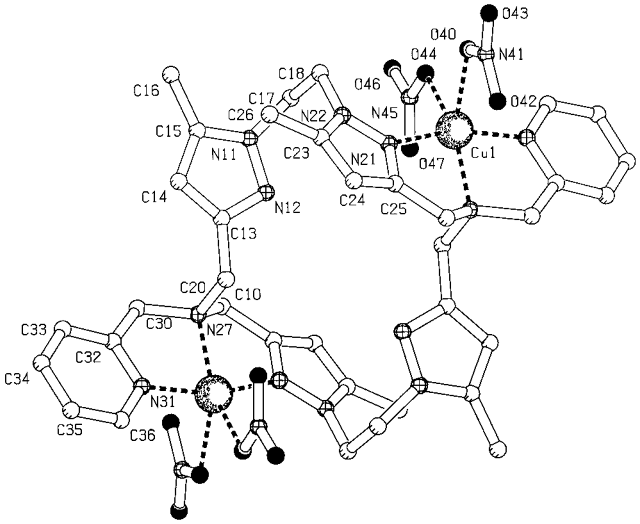


Figure 1. Pluton[14] projection of the cationic part of $[Cu_2(MePy22Pz)(NO_3)_4](MeOH)_2$ (**A**). Hydrogen atoms are omitted for clarity.

improved significantly (see the Experimental Section for details), now allowing the synthesis of the title ligand and its derivatives in gram scale.

Copper(II) coordination compounds were easily obtained by treating a solution of MePy22Pz in methanol or methanol/water with a solution of the appropriate salt in methanol. Vapor diffusion using diethyl ether resulted in the growth of single crystals suitable for X-ray diffraction.

Description of the Structures. A PLUTON[14] plot of **A** is given in Figure 1. The asymmetric unit comprises half a molecule $[Cu_2(MePy22Pz)(NO_3)_4](MeOH)_2$, the other half of the molecule is generated through a center of symmetry. The copper(II) ion is in an N_3O_2 environment which can best be described as distorted square pyramidal with a τ value of 0.2, indicating a geometry closer to a regular square pyramid ($\tau = 0.0$) than to a regular trigonal bipyramid ($\tau = 1.0$).[15] The axial position is occupied by the nitrate O(40) atom at a distance of 2.185(4) Å and the equatorial positions are occupied by the pyridine N(31) atom at a distance of 1.971(5) Å, the pyrazole N(21) atom at a distance of 1.966(5) Å, the tertiary amine N(27) atom at a distance of 2.056(4) Å, and the nitrate O(44) atom at a distance of 2.083(4) Å. Both nitrate ions coordinate monodentately to the copper(II) ion: the Cu(1)−O(47) and Cu(1)−O(42) distances of respectively 2.775(4) and 2.801(5) Å are quite long and these bond distances can at most be regarded as *semi*-coordinated. The small N(27)−Cu(1)−N(31) and N(27)−Cu(1)−N(21) angles of respectively 82.8° and 80.3° are imposed by the three-bond ligand bites. It is remarkable that the conformation of the ligand is such that the pyridine groups point outward with regard to the macrocycle and in opposite directions. Consequently, two of the four pyrazole groups of the macrocycle are unable to participate in the coordination of the copper ions and, moreover, the copper ions are separated at the largest possible distance, viz. at 8.668(4) Å. This situation is of course not favorable for the binding of a small molecule like dioxygen in a bridging fashion between the two copper ions. On the other hand, one has to realize that the present situation is a static one in crystallized material. In solution the macrocycle is sufficiently flexible to adopt another, more appropriate conformation.[7,9]

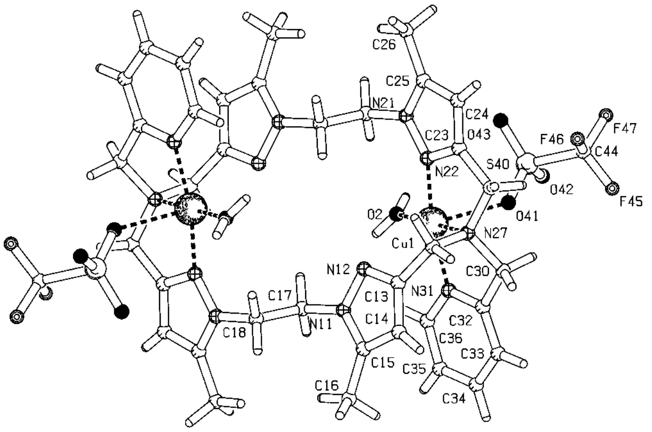


Figure 2. Pluton[14] projection of the cationic part of $[Cu_2(MePy22Pz)(CF_3SO_3)_2(H_2O)_2](CF_3SO_3)_2(MeOH)_2$ (**B**).

A PLUTON[14] plot of the cationic part of **B** is presented in Figure 2. The asymmetric unit comprises half a molecule $[Cu_2(MePy22Pz)(F_3CSO_3)_2(H_2O)_2](F_3CSO_3)_2(MeOH)_2$, the other half of the molecule is generated through a center of symmetry. The copper(II) ion is in an N_3O_2 environment which can best be described as distorted square pyramidal with a τ value of 0.25, indicating a geometry closer to a regular square pyramid ($\tau = 0.0$) than to a regular trigonal bipyramid ($\tau = 1.0$).[15] The axial position is occupied by the triflate O(41) atom at a distance of 2.455(2) Å and the equatorial positions are occupied by the pyridine N(31) atom at a distance of 1.984(2) Å, the pyrazole N(22) atom at a distance of 1.985(2) Å, the tertiary amine N(27) atom at a distance of 2.033(2) Å, and the water O(2) atom at a distance of 1.956(2) Å. The triflate anion coordinates monodentately. The small N(27)−Cu(1)−N(31) and N(27)−Cu(1)−N(22) angles of respectively 82.8° and 80.3° are imposed by the three-bond ligand bites. The conformation of the macrocycle is different from that in compound **A**. Again, two of the four pyrazole groups do not participate in the coordination of the copper ions, but the pyridine groups, which are also on different sides of the macrocyclic ring, now point toward the macrocyclic ring. Consequently, the copper ions are less far apart, viz. at 6.814(1) Å, although still on opposite sides of the macrocycle, and the noncoordinating pyrazole groups are now quite close to the copper ions. In fact the Cu(1) to N(12) distance is 2.75 Å, which could have been an indication for a *semi*-coordinate

---

(15) Addison, A. W.; Rao, N. T.; Reedijk, J.; van Rijn, J.; Verschoor, G. C. *J. C. S Dalton Trans.* **1984**, 1349.

interaction. However, the pyrazole electron lone pair is almost orthogonal to the Cu(1) to N(12) line.

Spectroscopic Results. The ligand field spectra of both compounds, taken as reflectance spectra of solid samples in the visible and near-infrared regions, show only one asymmetric band at 13 800 cm^{-1} for **A** and at 14 800 cm^{-1} for **B** consistent with their N_3O_2 chromophores (vide infra).

The EPR spectra taken as solid samples at room temperature show one slightly broadened signal at $g_{iso} = 2.09$ for **A** and at $g_{iso} = 2.06$ for **B**, while the spectra taken as frozen solutions in methanol at 77 K show an axial signal with $g_{||} = 2.27$, $A_{||} = 156$ G, and $g_{\perp} = 2.06$ for **A** and $g_{||} = 2.28$, $A_{||} = 160$ G, and $g_{\perp} = 2.06$ for **B**. These spectral parameters are typical for mononuclear copper(II) compounds, indicating that the copper(II) ions are too far apart to experience magnetic coupling, in agreement with the crystallographic data (vide infra).

Concluding Remarks

The results presented above have shown that macrocyclic ligands with *endocyclic* azole groups can now be prepared in high yields. This prototype macrocycle renders interesting copper(II) complexes in addition to the already reported copper(I) complexes. Finally, the two structures presented have illustrated that this ligand has a certain conformational flexibility for metal binding.

Ongoing work is dealing with further elucidating the coordination chemistry of this and related macrocyclic ligands and with reactivity studies toward dioxygen.

Acknowledgment. The authors are indebted to the EU for a grant as Host Institute in the EU Programme Human Capital and Mobility (1994-1997).

Supporting Information Available: Listings of crystallographic data, fractional coordinates, anisotropic thermal parameters, bond distances and bond angles and thermal motion ORTEP ellipsoid plots of the compounds $[Cu_2(MePy22Pz)(NO_3)_4](MeOH)_2$ (**A**) and $[Cu_2(MePy22Pz)(F_3CSO_3)_2(H_2O)_2](F_3CSO_3)_2(MeOH)_2$ (**B**). This material is available free of charge via the Internet at http://pubs.acs.org.

IC9811704