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Reactivity of Nickel(II) and Copper(II) Complexes of a β-Aminohydrazone Ligand with Pyridine-2-aldehyde: Macrocyclization vs Unprecedented Pyrazole Ring Synthesis via C−C Bond-Forming Reaction

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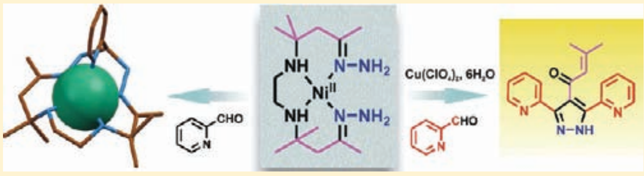
Supporting Information

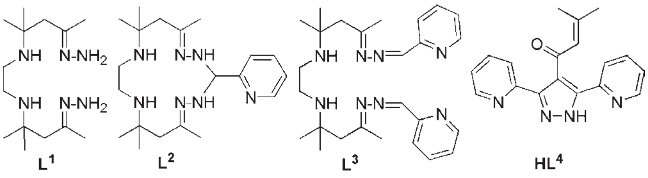


ABSTRACT: The synthesis and characterization of a mononuclear nickel(II) complex $[Ni(L^2)](ClO_4)_2$ (**1**) and an analogous mononuclear copper(II) complex $[Cu(L^2)](ClO_4)_2$ (**2**) of a 15-membered azamacrocycle (L^2 = 3-(2-pyridyl)-6,8,8,13,13,15-hexamethyl-1,2,4,5,9,12-hexaazacyclopentadeca-5,15-diene) are reported. The macrocyclic ligand is formed during the reaction of 4,4,9,9-tetramethyl-5,8-diazadodecane-2,11-dione dihydrazone (L^1) with pyridine-2-aldehyde (PyCHO) templated by metal ions. The X-ray crystal structure of **1** exhibits a distorted square-pyramidal coordination geometry, where the metal ion sits in the macrocyclic cavity and the pendant pyridine group of L^2 occupies the axial position. While **1** is stable in the presence of an excess of PyCHO, **2** reacts further with copper(II) salt and PyCHO to form a mononuclear copper(I) complex, $[Cu(H_2L^3)](ClO_4)_3$ (**3**). The structure of the complex cation of **3** reveals a distorted tetrahedral coordination geometry at the copper center with a pseudo 2-fold screw axis. A two-dimensional (2D) polymeric copper(II) complex, $\{[Cu_2(L^4)_2](ClO_4)_2\}_n$ (**4**) is obtained by reacting complex **2** (or $[Ni(L^1)](ClO_4)_2$) with copper(II) perchlorate and pyridine-2-aldehyde in a methanol−water solvent mixture. Complex **4** is also obtained by treating **3** with copper(II) perchlorate and pyridine-2-aldehyde in the presence of a base. The X-ray structural analysis of **4** confirms the formation of a pyrazolate bridged dimeric copper(II) complex. The extended structure in the solid state of **4** revealed the formation of a 2D coordination polymer with the dimeric core as the repeating unit. The ligand (HL^4) in **4** is a 3,4,5-trisubstituted pyrazole ring formed in situ via C−C bond formation and represents an unprecedented transformation reaction.

■ INTRODUCTION

Aminoketones are important precursors for the synthesis of various functional derivatives exhibiting versatile reactivity with transition metal ions. The β-aminoketone, 4,4,9,9-tetramethyl-5,8-diazadodecane-2,11-dione reported by Love et al. in 1968,[1,2] is one of the well-studied ligands in this category from which metal complexes of β-iminoamines, β-aminoketoximes, and β-aminohydrazones have been synthesized.[3−15] The copper(II), cobalt(II), and nickel(II) complexes of dihydrazone derivatives of the β-aminoketone ligand have been reported by Curtis et al.[2] The nickel(II)-dihydrazone complex shows versatile reactivity with 1,2-diketones.[2,16−22] The copper(II)- and nickel(II)-hydrazone complexes have been shown to react with monofunctional aldehydes and ketones to form the corresponding complexes of azamacrocylic ligand.[17] However, there is no report on the reaction of heterocyclic carbonyls with metal complexes of 4,4,9,9-tetramethyl-5,8-diazadodecane-2,11-dione dihydrazone (L^1) (Chart 1). In this work, we have explored the reactivity of copper(II) and nickel(II) complexes of dihydrazone derivatives of β-aminoketone with pyridine-2-aldehyde (PyCHO). The nitrogen donor of PyCHO is expected to direct the reactivity of copper(II)- and nickel(II)-dihydrazone complexes.

Chart 1. Ligands



We report herein the synthesis and characterization of a mononuclear nickel(II) complex, $[Ni(L^2)](ClO_4)_2$ (**1**), and its copper(II) analogue, $[Cu(L^2)](ClO_4)_2$ (**2**), of a new 15-membered azamacrocyclic ligand containing a pendant pyridine arm, 3-(2-pyridyl)-6,8,8,13,13,15-hexamethyl-1,2,4,5,9,12-hexaazacyclopentadeca-5,15-diene (L^2), derived from the dihydrazone

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ligand (L^1). Complex **2**, upon reaction with copper(II) perchlorate and pyridine-2-aldehyde, transforms to a mononuclear copper(I) complex, $[Cu(H_2L^3)](ClO_4)_3$ (**3**), or to a copper(II) coordination polymer, $\{[Cu_2(L^4)_2](ClO_4)_2\}_n$ (**4**), depending upon the reaction conditions. The ligand (HL^4) in **4** is a pyrazole derivative formed in situ during the reaction of ligand L^1 with pyridine-2-aldehyde mediated by copper(II) ion. To the best of our knowledge, this is the first example of a novel transformation where 3,4,5-trisubstituted pyrazole ring is synthesized from pyridine-2-aldehye through a C−C bond forming reaction. The isolation of a 3,4,5-trisubstituted pyrazole has relevance to the pharmaceutical industry and in the coordination chemistry of pyrazole-derived ligands.[23−26]

■ EXPERIMENTAL SECTION

General Methods. Commercial grade chemicals and distilled solvents were used for the synthetic purposes. ***Caution!*** *Although no problem was encountered during the synthesis of the ligand and the complexes, perchlorate salts are potentially explosive and should be handled with care!*[27] The nickel(II) complex, $[Ni(L^1)](ClO_4)_2$, was synthesized according to the procedure reported by Curtis et al.[2] Fourier transform infrared spectra were recorded on a Shimadzu FT-IR 8400S instrument. Elemental analyses were performed on a Perkin-Elmer 2400 series II CHN analyzer. Solution electronic spectra were measured at room temperature on an Agilent 8453 diode array spectrophotometer. Electrospray ionization mass spectra were recorded with Waters QTOF Micro YA263. Room temperature magnetic data were collected on a Gouy balance (Sherwood Scientific, Cambridge, UK). Diamagnetic contributions were estimated for each compound by using Pascal's constants. Solution conductivity measurements were carried out in acetonitrile solution at room temperature on a Systronics Conductivity Meter 306.

Synthesis of Complexes. *$[Ni(L^2)](ClO_4)_2$ (**1**).* To a suspension of $[Ni(L^1)](ClO_4)_2$ (0.54 g, 1 mmol) in 20 mL of methanol was added pyridine-2-aldehyde (0.095 mL, 1 mmol). The mixture was allowed to stir for 24 h at room temperature to precipitate a small amount of pink solid from the solution. The solid was isolated by filtration, and the filtrate was kept for slow evaporation of solvent to yield pink crystals suitable for X-ray single crystal diffraction. Yield: 0.34 g (54%). Anal. Calcd for $C_{20}H_{35}Cl_2N_7NiO_8$ (631.16 g/mol): C, 38.06; H, 5.59; N, 15.54. Found: C, 38.28; H, 5.77; N, 15.73%. FTIR (KBr): 3431(br), 3309(s), 3280(s), 2972−2943(m), 1630(m), 1605(m), 1477(m), 1445(m), 1371(m), 1248(w), 1120−1090(vs), 927, 777−764, 625 cm^{-1}. UV−vis (in MeCN) [λ_{max}, nm (ε, M^{-1} cm^{-1})]: 385 (sh), 503 (20). Λ (mho cm^2 mol^{-1} in MeCN): 270. ESI-MS (positive ion in MeCN): m/z = 530.07 (30%, $[\mathbf{1} - ClO_4]^+$), 430.13 (100%, $[(\mathbf{1} - H) - 2ClO_4]^+$).

*$[Cu(L^2)](ClO_4)_2$ (**2**).* To a solution of $[Ni(L^1)](ClO_4)_2$ (0.54 g, 1 mmol) in methanol (20 mL) was added $Cu(ClO_4)_2 \cdot 6H_2O$ (0.44 g, 1.2 mmol) with stirring to obtain a clear blue solution. The blue solution was then treated with pyridine-2-aldehyde (0.095 mL, 1 mmol), whereupon the solution turned to deep green immediately. The green solution was stirred further for 12 h at room temperature. The solution was then filtered, and the filtrate was kept at room temperature for slow evaporation of solvent to obtain a green crystalline solid. Yield: 0.52 g (82%). Anal. Calcd for $C_{20}H_{35}Cl_2CuN_7O_8$ (635.99 g/mol): C, 37.77; H, 5.55; N, 15.42. Found: C, 37.65; H, 5.58; N, 14.95%. FTIR (KBr): 3433(br), 3278(s), 3242(s), 2978(s), 1623(m), 1603(m), 1479(m), 1443(s), 1373(s), 1144−1090(vs), 983, 777(m), 625 cm^{-1}. UV−vis (in MeCN) [λ_{max}, nm (ε, M^{-1} cm^{-1})]: 385(sh), 620 (150). Λ (mho cm^2 mol^{-1} in MeCN): 310. ESI-MS (positive ion in MeCN): m/z = 534.84 (100%, $[\mathbf{2} - ClO_4]^+$), 434.94 (40%, $[(\mathbf{2} - H) - 2ClO_4]^+$).

*$[Cu(H_2L^3)](ClO_4)_3$ (**3**).* To a methanolic solution (25 mL) of **2** (0.2 g, 0.315 mmol), $Cu(ClO_4)_2 \cdot 6H_2O$ (0.23 g, 0.63 mmol) was added with stirring. To that solution pyridine-2-aldehyde (0.22 mL, 2.31 mmol) was added, and the reaction mixture was allowed to stir for 36 h at room temperature. The deep brown solution was filtered, and the filtrate was kept for slow evaporation of solvent to isolate a red crystalline solid. Yield: 0.18 g (91%). Anal. Calcd for $C_{26}H_{40}Cl_3CuN_8O_{12} \cdot H_2O$ (844.56 g/mol): C, 36.88; H, 5.01; N, 13.27. Found: C, 36.93; H, 5.07; N, 13.04%. FTIR (KBr): 3460(br), 3087(br), 2976(m), 2879(m), 1643(s), 1589(m), 1475(s), 1443(m), 1380(m), 1113−1088(vs), 777(s), 625(s) cm^{-1}. UV−vis (in MeOH) [λ_{max}, nm (ε, M^{-1} cm^{-1})]: 340(sh), 435 (3300), 535(sh). Λ (mho cm^2 mol^{-1} in MeOH): 102. ESI-MS (positive ion in MeOH): m/z = 725.20 (40%, $[\mathbf{3} - ClO_4]^+$), 625.23 (70%, $[\mathbf{3} - H(ClO_4)_2]^+$), 525.26 (85%, $[\mathbf{3} - H_2(ClO_4)_3]^+$), 364.16 (100%, $[(\mathbf{3} - C_9H_{11}N_3) - H_2(ClO_4)_3]^+$).

*$\{[Cu_2(L^4)_2](ClO_4)_2\}_n$ (**4**).* To a hot solution of $[Ni(L^1)](ClO_4)_2$ (0.54 g, 1 mmol) in a methanol−water mixture (1:1) (25 mL) was added $Cu(ClO_4)_2 \cdot 6H_2O$ (1.85 g, 5.0 mmol) with stirring. To the resulting blue solution pyridine-2-aldehyde (0.475 mL, 5 mmol) was added, and the solution was stirred for 3 h at warm conditions. The greenish-brown solution was allowed to stir at room temperature for 12 h. The solution was then filtered, and the filtrate was kept for slow evaporation of solvent to isolate a brown residue. The crude solid was then recrystallized from methanol to afford a brown crystalline solid. Yield: 0.23 g (23%). Anal. Calcd for $C_{36}H_{30}Cl_2Cu_2N_8O_{10} \cdot 3H_2O$ (986.71 g/mol): C, 43.82; H, 3.68; N, 11.36. Found: C, 43.71; H, 3.74; N, 11.39%. FTIR (KBr): 3433(br), 2922(s), 2852(m), 1635(m), 1607(s), 1461(m), 1445(m), 1375, 1089(vs), 783, 760, 625 cm^{-1}. UV−vis (in MeCN) [λ_{max}, nm (ε, M^{-1} cm^{-1})]: 385 (sh), 600 (450). Λ (mho cm^2 mol^{-1} in MeCN): 270. ESI-MS (positive ion in MeCN): m/z = 366.25 (100%, $[\mathbf{4} - 2ClO_4]^{2+}$).

X-ray Crystallographic Data Collection and Refinement of the Structures. Crystallographic data for the complexes are summarized in Table 1. Diffraction data for **1** were collected at 293 K on a Nonius DIP-1030H system. Intensity data for **2**, **3** (293 K), and **4** (150 K) were collected on a Bruker Smart APEX II. All the experiments were carried out with Mo Kα radiation (λ = 0.71073 Å). Cell refinement, indexing, and scaling of the data sets were carried out using Denzo and Scalepack packages[28] and the APEX2 v2.1-0 software.[29] The structures were solved by direct methods[30] and subsequent Fourier analyses and refined by the full-matrix least-squares method based on F^2 with all observed reflections. The ΔF map of **3** indicated the presence of a methanol molecule in the lattice. A perchlorate ion of **4** was found disordered over two positions (0.50 occupancy each); of these, one is close to a 2-fold axis and the other has the chlorine sitting on the binary axis. All the calculations were performed using the WinGX System, Ver 1.80.05.[31]

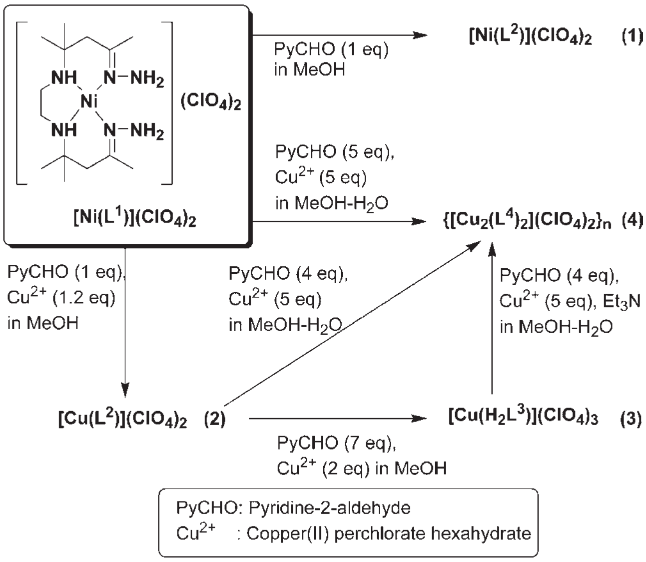
■ RESULTS AND DISCUSSION

Complex **1** is synthesized by treating $[Ni(L^1)](ClO_4)_2$ with 1 equiv of pyridine-2-aldehyde in methanol at ambient conditions. Complex **2** is obtained by reacting $[Ni(L^1)](ClO_4)_2$ with a small excess of copper(II) salt (1.2 equiv) and pyridine-2-aldehyde (1 equiv) in methanol. It is important to mention here that the copper(II)-dihydrazone complex, formed in situ in the reaction, was not isolated for further characterization. Interestingly, **2** reacts further with copper(II)-perchlorate and pyridine-2-aldehyde in methanol to give the monomeric copper(I) complex, $[Cu(H_2L^3)](ClO_4)_3$ (**3**). Complex **3** is stable in solid state and is unreactive toward dioxygen in solution. When **3** is treated further with copper(II)-perchlorate and pyridine-2-aldehye in the presence of triethylamine, $\{[Cu_2(L^4)_2](ClO_4)_2\}_n$ (**4**) is obtained (Scheme 1). Complex **4** can also be synthesized by

Table 1. Crystallographic Data for Complexes 1−4

crystal parameters	1	2	3	4
empirical formula	$C_{20}H_{35}Cl_2N_7NiO_8$	$C_{20}H_{35}Cl_2CuN_7O_8$	$C_{27}H_{44}Cl_3CuN_8O_{13}$	$C_{36}H_{30}Cl_2Cu_2N_8O_{10}$
formula weight	631.16	635.99	858.59	932.66
crystal system	monoclinic	triclinic	monoclinic	monoclinic
space group	$P2_1/n$	$P\bar{1}$	$P2_1$	$C2/c$
a/Å	8.433(3)	9.720(3)	9.4427(8)	23.147(3)
b/Å	15.889(4)	16.343(6)	20.7633(17)	24.849(4)
c/Å	20.827(5)	18.657(6)	10.9105(9)	13.631(3)
α/°	90.00	71.354(8)	90.00	90.00
β/°	94.58(2)	79.046(9)	115.444(2)	91.521(15)
γ/°	90.00	79.586(9)	90.00	90.00
V/Å^3	2781.7(14)	2733.8(16)	1931.6(3)	7838(2)
Z	4	4	2	8
D_{calc} /g cm^{-3}	1.507	1.545	1.476	1.581
F(000)	1320	1324	892	3792
μ Mo Kα /mm^{-1}	0.945	1.051	0.842	1.289
T/K	293(2)	293(2)	293(2)	150(2)
θ min/max/°	1.96−26.34	1.16−17.17	1.96−25.81	1.20−26.03
reflections collected	32862	10530	24162	49625
reflections unique	5027	3201	7435	7713
R_{int}	0.0853	0.0830	0.0327	0.0469
observed reflections [$I > 2\sigma(I)$]	2154	2223	5950	5977
parameters	349	495	477	524
goodness of fit on F^2	0.791	1.027	1.042	1.120
final R indices [$I > 2\sigma(I)$], R_1/wR_2	0.0490/0.1120	0.0777/0.2027	0.0481/0.1303	0.0449/0.1277
R indices (all data), R_1/wR_2	0.1232/0.1287	0.1131/0.2400	0.0626/0.1400	0.0588/0.1343

Scheme 1. Syntheses of Complexes 1−4



reacting **2** (or $[Ni(L^1)](ClO_4)_2$) with copper(II) salt and pyridine-2-aldehye in a methanol−water solvent mixture. The ratio of copper(II) and pyridine-2-aldehyde plays a big role in the formation of different copper complexes. It is also important to note that complex **4** is obtained only when the reactions are carried out in a solvent mixture of methanol and water at slightly warm conditions.

The IR spectra of all the complexes show strong bands in the region 1150−1085 cm^{-1}, attributable to perchlorate counterions. Complexes **1** and **2** show sharp NH stretching bands from the ligand backbone at 3309 and 3280 cm^{-1} and at 3278 and 3242 cm^{-1}, respectively. The NH stretching bands of **3** are shifted to lower energy, indicating the presence of a strong hydrogen bonding interaction. Interestingly, the NH peaks are not observed in **4**, suggesting that the ligand backbone does not contain any NH unit. Electrospray ionization mass spectrometry (ESI-MS) in positive ion mode shows molecular ion peaks at m/z = 530.07 and 534.84 for **1** and **2** with the expected isotope distribution pattern calculated for $[\mathbf{1} - ClO_4]^+$ and $[\mathbf{2} - ClO_4]^+$, respectively. Complex **3** exhibits mass peaks at m/z = 725.20, 625.23, and 525.26, attributable to $[\mathbf{3} - ClO_4]^+$, $[\mathbf{3} - H(ClO_4)_2]^+$, and $[\mathbf{3} - H_2(ClO_4)_3]^+$ ions, respectively. Complex **4** shows a peak in the ESI-MS at m/z = 366.25, with the isotope distribution pattern calculated for $[\mathbf{4} - 2ClO_4]^{2+}$, suggesting a dinuclear copper complex. The nickel(II) complex, **1**, shows effective magnetic moment of 2.95 μ_B at room temperature. The mononuclear copper(II) complex **2** shows a room temperature magnetic moment value of 1.78 μ_B, expected for a system with one unpaired electron. While complex **3** is diamagnetic, complex **4** is paramagnetic, showing a room temperature magnetic moment value of 1.95 μ_B, which is higher than for a mononuclear copper(II) complex but lower than that expected for two noninteracting copper(II) centers. This indicates that the two copper(II) centers are exchange coupled.

Crystal Structures. The X-ray structure determination of $[Ni(L^2)](ClO_4)_2$ (**1**) reveals a five-coordinate nickel(II) center

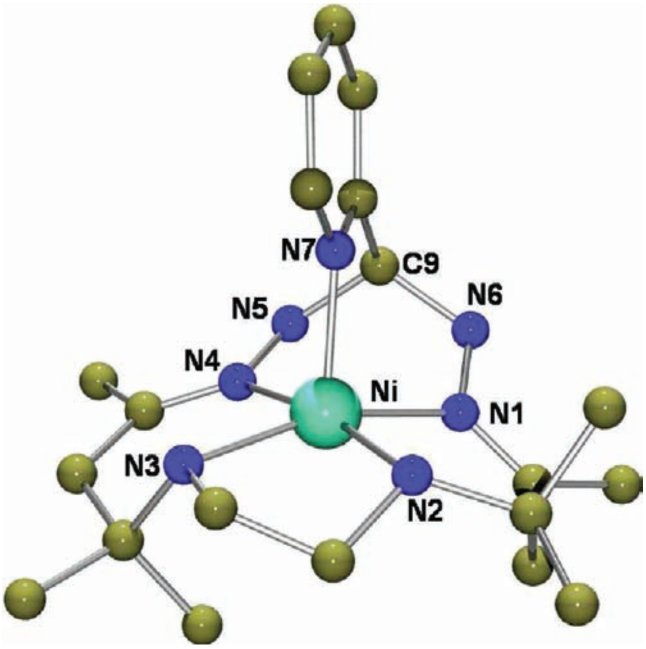


Figure 1. Molecular structure of the complex cation of **1** with atom labeling scheme.

Table 2. Selected Bond Distances (Å) and Angles (deg) for 1

Ni−N(1)	2.036(4)	Ni−N(2)	2.108(4)
Ni−N(3)	2.063(4)	Ni−N(4)	2.091(4)
Ni−N(7)	2.009(4)	N(1)−N(6)	1.402(5)
N(4)−N(5)	1.399(5)		
N(1)−Ni−N(2)	92.49(16)	N(2)−Ni−N(4)	170.21(15)
N(1)−Ni−N(3)	162.07(16)	N(2)−Ni−N(7)	103.18(15)
N(1)−Ni−N(4)	89.64(16)	N(3)−Ni−N(4)	89.83(15)
N(1)−Ni−N(7)	90.76(16)	N(3)−Ni−N(7)	107.09(15)
N(2)−Ni−N(3)	85.20(15)	N(4)−Ni−N(7)	86.33(15)

in the complex cation and two perchlorate counterions. The structure of **1** (Figure 1) confirms the reaction of nickel(II)-hydrazone complex, $[Ni(L^1)](ClO_4)_2$, with pyridine-2-aldehyde to form a neutral 15-membered azamacrocyclic ligand. In the complex dication, the pentadentate neutral ligand coordinates to the metal ion by two secondary amines (N2 and N3), two hydrazone nitrogens (N1 and N4), and the pyridine nitrogen atom (N7). The ligand spans the metal ion to form a distorted square-pyramidal geometry (τ = 0.14),[32] with the pyridine nitrogen atom N7 occupying the axial position at the Ni−N7 distance of 2.009(4) Å. The Ni−N bond distances in the basal plane fall in the range 2.036(4)−2.108(4) Å, indicating the high-spin nickel(II) complex (Table 2).[19] These four nitrogen atoms are almost coplanar (max deviation ±0.08 Å) with the nickel(II) ion displaced by 0.243 Å from their mean-plane toward the apical pyridine nitrogen. It is worthy of note that the coordinated amine nitrogens N2 and N3 have opposite chirality.

The six-membered chelate ring, formed upon coordination of hydrazone nitrogens (N1 and N4) to the nickel center, adopts a boat conformation. The other chelate rings are twisted in nature. The axial coordination of pyridine nitrogen N7 allows the formation of a 2.2.2-metallamacrobicyclic ring consisting of the metal ion, the pyridine and hydrazone nitrogens, the bridgehead carbon C9, and one pyridine carbon atom. The pyridine ring N7 forces one of the $C(CH_3)_2$ groups (on the N3 side) to assume a different conformation with respect to that on the N2 side, likely dictated by steric crowding. This arrangement is completely different from the macrocyclic systems of the ligand derived from hydrazone and carbonyl compounds.[17]

Table 3. Selected Bond Distances (Å) and Angles (deg) for 2

Cu(1)−N(1)	2.055(12)	Cu(2)−N(11)	2.036(14)
Cu(1)−N(2)	2.007(14)	Cu(2)−N(12)	2.076(14)
Cu(1)−N(3)	2.066(13)	Cu(2)−N(13)	2.033(13)
Cu(1)−N(4)	2.036(13)	Cu(2)−N(14)	2.037(14)
Cu(1)−N(7)	2.119(12)	Cu(2)−N(17)	2.102(13)
N(1)−Cu(1)−N(2)	91.0(6)	N(11)−Cu(2)−N(12)	92.4(6)
N(1)−Cu(1)−N(3)	174.8(6)	N(11)−Cu(2)−N(13)	150.5(6)
N(1)−Cu(1)−N(4)	92.2(6)	N(11)−Cu(2)−N(14)	90.6(6)
N(1)−Cu(1)−N(7)	83.6(5)	N(11)−Cu(2)−N(17)	89.0(5)
N(2)−Cu(1)−N(3)	83.9(6)	N(12)−Cu(2)−N(13)	85.8(6)
N(2)−Cu(1)−N(4)	152.0(6)	N(12)−Cu(2)−N(14)	176.8(6)
N(2)−Cu(1)−N(7)	120.2(6)	N(12)−Cu(2)−N(17)	97.0(5)
N(3)−Cu(1)−N(4)	92.4(6)	N(13)−Cu(2)−N(14)	91.0(6)
N(3)−Cu(1)−N(7)	98.8(6)	N(13)−Cu(2)−N(17)	120.5(6)
N(4)−Cu(1)−N(7)	87.8(5)	N(14)−Cu(2)−N(17)	84.3(6)

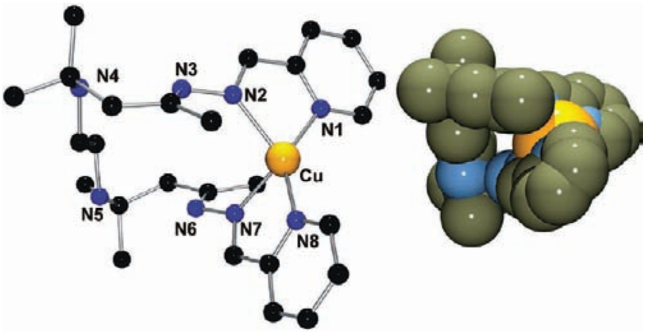


Figure 2. Molecular structure of the cationic part of copper(I) complex (**3**) and its space-filling representation showing the metallamacrocyclic cavity (right).

The perchlorate anions in **1** are involved in weak hydrogen bonding interactions with the amine nitrogen N3 and with hydrazone nitrogens N5 and N6 via N−H···O, resulting in the formation of a one-dimensional hydrogen-bonded polymeric network where the cationic units are held together by a perchlorate bridge (Figure S1, Supporting Information).

Although diffraction data for **2** were obtained at low θ angle, the structural determination allowed the clarification of some relevant geometrical features (Figure S2, Supporting Information). In this case, the unit cell contains two independent cations having the metal ion in a distorted square pyramidal geometry, with the Cu−N(pyridine) axial bond distances (mean ca. 2.11 Å) longer, as expected, than the corresponding Ni−N7 of **1** (Table 3). A peculiar aspect of the independent complexes of **2** is represented by both of the $C(CH_3)_2$ groups that assume a conformation with a methyl pointing on the side of the pyridine ring, in contrast to what is observed in **1**. This likely induces distortions in the basal plane, and the four nitrogen

Table 4. Selected Bond Distances (Å) and Angles (deg) for 3

Cu−N(1)	2.000(3)	Cu−N(8)	1.990(3)
Cu−N(2)	2.120(3)	Cu−N(7)	2.137(4)
N(2)−N(3)	1.398(5)	N(6)−N(7)	1.419(5)
N(2)−C(6)	1.274(5)	N(7)−C(21)	1.261(5)
N(1)−Cu−N(2)	81.03(13)	N(2)−Cu−N(7)	102.55(13)
N(7)−Cu−N(8)	80.71(13)	N(1)−Cu−N(8)	140.37(14)
N(1)−Cu−N(7)	120.95(14)	N(8)−Cu−N(2)	129.64(14)

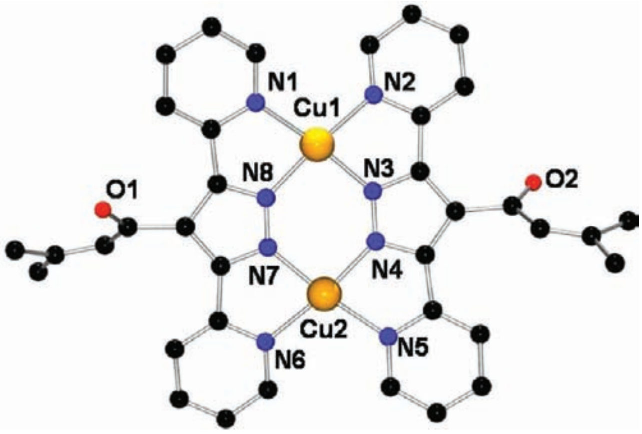


Figure 3. Ball and stick view of the complex cation of **4** with atom labeling scheme. The coordinated perchlorates at Cu1 are not shown for clarity.

atoms display a slight tetrahedral distortion, being positioned alternatively above and below their mean-plane (±0.26 Å), with the copper(II) ion displaced by 0.253 Å from this plane toward the apical pyridine N donor.

Complex **3** is a mononuclear tetracoordinate copper(I) complex and crystallizes in the chiral space group $P2_1$ (Table 1) with three perchlorate counterions and a solvent methanol molecule. The structure of the cationic complex, having a pseudo C_2 symmetry axis passing through the copper ion and in between the N4/N5 atoms, confirms the formation of a new ligand L^3 as a result of the ring-opening of the macrocyclic ligand L^2 during the reaction with pyridine-2-aldehyde (Figure 2). The coordination environment around the copper center is best described as distorted tetrahedral. The metal ion is coordinated by the hydrazone nitrogens N2 and N7 and the pyridine nitrogen atoms N1 and N8 from L^3 with Cu−N bond distances that average to 2.128(4) Å for the former, significantly longer than the mean value of 1.995(3) Å measured for the pyridine donors. The distortion of the tetrahedral geometry of the metal center is evident from the interligand bite angles in the range of 102.55(13)−140.37(14)°, the chelating bite angles being 81.03(13) and 80.71(13)° (Table 4).

This binding motif of the protonated form of L^3 forms a 15-membered metallamacrocycle in the complex cation, creating a small cavity in the chirally twisted structure of **3**. The protonation of the amine nitrogens during the reaction accounts for the cleavage of L^2 upon insertion of the second pyridine-imine moiety coordinating the copper(I) ion. The amine nitrogens N4 and N5 are found to be protonated and are involved in hydrogen bonding interactions either with solvent methanol or perchlorate counterions (Figure S3, Supporting Information).

Table 5. Selected Bond Distances (Å) and Angles (deg) for 4[a]

Cu(1)−N(1)	2.018(3)	Cu(2)−N(5)	2.035(3)
Cu(1)−N(2)	2.034(3)	Cu(2)−N(6)	2.022(3)
Cu(1)−N(3)	1.937(3)	Cu(2)−N(4)	1.929(3)
Cu(1)−N(8)	1.936(3)	Cu(2)−N(7)	1.924(3)
Cu(1)−O(11)	2.445(3)	Cu(2)−O(1)′	2.460(3)
Cu(1)−O(34)	2.751(7)	Cu(2)−O(2)″	2.625(3)
N(3)−N(4)	1.330(4)	N(7)−N(8)	1.327(4)
N(1)−Cu(1)−N(2)	107.57(10)	N(5)−Cu(2)−N(6)	108.51(11)
N(1)−Cu(1)−N(3)	171.75(12)	N(5)−Cu(2)−N(7)	164.42(12)
N(1)−Cu(1)−N(8)	79.56(10)	N(5)−Cu(2)−N(4)	79.15(11)
N(2)−Cu(1)−N(3)	79.10(10)	N(6)−Cu(2)−N(7)	79.84(11)
N(2)−Cu(1)−N(8)	169.34(12)	N(6)−Cu(2)−N(4)	169.44(13)
N(3)−Cu(1)−N(8)	94.55(11)	N(7)−Cu(2)−N(4)	94.48(11)
N(1)−Cu(1)−O(11)	89.55(11)	N(4)−Cu(2)−O(1)′	92.08(11)
N(2)−Cu(1)−O(11)	92.45(10)	N(5)−Cu(2)−O(1)′	99.47(10)
N(3)−Cu(1)−O(11)	85.25(12)	N(6)−Cu(2)−O(1)′	79.64(10)
N(8)−Cu(1)−O(11)	95.56(11)	N(7)−Cu(2)−O(1)′	94.93(11)
N(1)−Cu(1)−O(34)	80.66(17)	N(4)−Cu(2)−O(2)″	99.83(11)
N(2)−Cu(1)−O(34)	87.32(18)	N(5)−Cu(2)−O(2)″	81.14(10)
N(3)−Cu(1)−O(34)	104.86(18)	N(6)−Cu(2)−O(2)″	88.73(10)
N(8)−Cu(1)−O(34)	86.05(18)	N(7)−Cu(2)−O(2)″	86.03(11)
O(11)−Cu(1)−O(34)	169.64(17)	O(1)′-Cu(2)−O(2)″	167.95(8)

[a] Symmetry code (′) at $-x + 1/2$, $-y + 1/2$, $-z$; (″) at $-x + 1/2$, $-y + 1/2$, $-z + 1$.

The structure of **4** shows the formation of a dinuclear complex with a pyrazolate bridged dimeric copper(II) core. The formation of a substituted pyrazole ligand (HL^4) during the reaction of **2** with pyridine-2-aldehyde is verified by the X-ray structural determination (Figure 3). Each copper ion shows a distorted octahedral coordination sphere and is coordinated by two pyrazole and two pyridine nitrogen atoms from the ligand in the equatorial plane. The Cu−N(pyridine) bond lengths are in the range of 2.018(3)−2.035(3) Å, slightly longer than those relative to the pyrazolate donors in between 1.924(3)−1.937(3) Å (Table 5). The axial positions of Cu(1) center are occupied by two perchlorate oxygen atoms; those of Cu(2), on the other hand, are occupied by oxygen atoms (O1 and O2) of the 3-methyl-2-butenoyl group of two symmetry related complexes. The Cu(1)−O(11) and Cu(1)−O(34) distances are 2.445(3) and 2.751(7) Å, and the Cu(2)−O(1)′ and Cu(2)−O(2)″ are 2.460(3) and 2.625(3) Å, respectively. All these values are indicative of weak interactions between the metal centers and the perchlorate and carbonyl oxygens.

This coordination motif of the bis(bidentate) ligand makes a metallamacrocycle at the two copper centers with a Cu···Cu separation of 3.9329(7) Å. The macrocycle is not completely planar, but, in order to avoid steric clashes between the aromatic protons α to the pyridine nitrogens N1/N2 and similarly N5/N6, the two monoanionic ligands (which have coplanar atoms within ±0.16 Å, excluding the methylpropenyl ketone fragment) are tilted to form a dihedral angle of 22.02(9)°. The pyrazolate ring is strictly planar in the copper(II) complex of 3,5-di(2-pyridyl)pyrazole ligand.[33,34] Similar deformations are observed in some pyrazolate bridged dimetallic complexes and in bischelated square planar [Pd(bpy)$_2$]$^{2+}$ and [Pd(Phen)$_2$]$^{2+}$ complexes.[24,35]

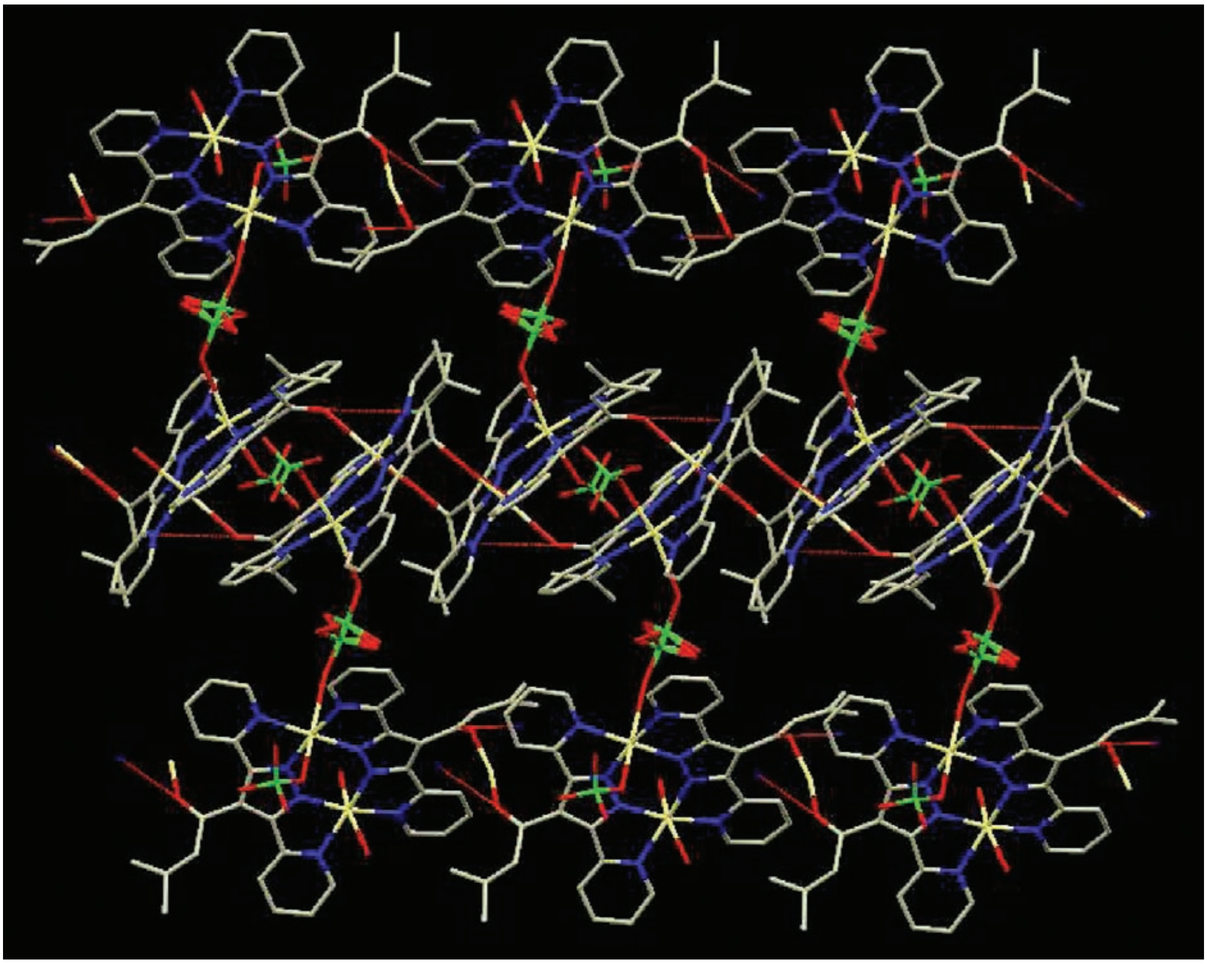


Figure 4. Crystal packing showing the 2D coordination polymeric network in **4**.

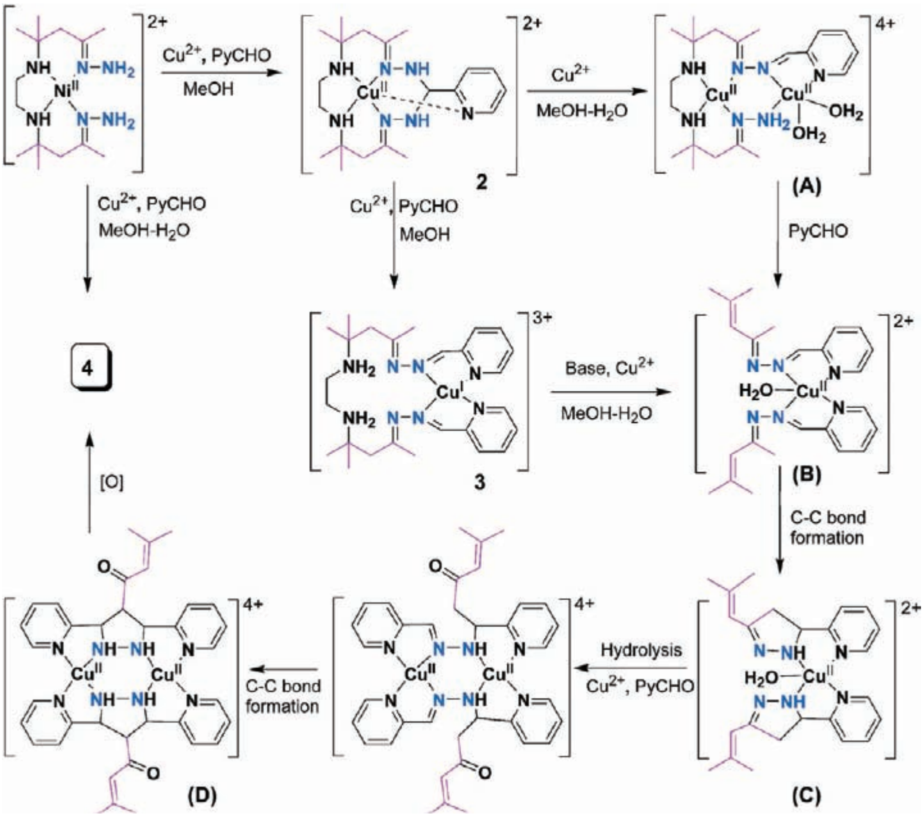
In the crystal, the complexes are connected by Cu−O-(carbonyl) (along axis *c*) and Cu−OClO$_3$ (along axis *a*) interactions, forming a two-dimensional (2D) polymeric arrangement as shown in Figure 4, taking into account that the latter interactions involve crystallographic disordered perchlorate anions.

Formation of Macrocylic Ligand (L^2) and Pyrazole (HL^4) from 4,4,9,9-Tetramethyl-5,8-diazadodecane-2,11-dione Dihydrazone (L^1). The nickel(II)-dihydrazone complex, [Ni(L^1)]-(ClO$_4$)$_2$, has been shown to react with aliphatic and aromatic aldehydes and ketones to form azamacrocycles.[17] In this study, reactivity of the dihydrazone with pyridine-2-aldehyde was studied in the presence of nickel(II) and copper(II) salts. The metal ions act as templates in the cyclization reaction, forming a new macrocycle ligand containing a pendant pyridine donor. While the nickel(II) macrocycle is obtained irrespective of the amount of pyridine-2-aldehyde used, different copper complexes are obtained during the reaction of [Ni(L^1)](ClO$_4$)$_2$ with copper(II) perchlorate and pyridine-2-aldehyde, depending upon the reaction condition and the stoichiometry of reagents.

The transformation of the azamacrocycle L^2 (or dihydrazone ligand L^1) to a substituted pyrazole ring HL^4, mediated by copper(II) ion, is unprecedented and involves C−C bond forming reactions. The most common method for the synthesis of pyrazole derivatives is the reaction between 1,3-diketone and hydrazine.[36] A number of other methods that do not require 1,3-diketones have also been employed for the synthesis of pyrazoles.[37−40] Despite other synthetic methods for the preparation of a pyrazole ring, there is no reported procedure where a pyrazole ring is synthesized via copper(II)-mediated C−C bond formation reaction in a pathway described in this work.

Some mechanistic insight into the formation of the pyrazole ligand can be gleaned from the reaction of **2** with copper(II) perchlorate and pyridine-2-aldehyde in the absence of a base, where L^2 is transformed to L^3 (Scheme 2). It is important to note that, in this reaction, copper(II) gets reduced to copper(I) and subsequently a mononuclear copper(I) complex (**3**) is isolated. The ligand L^3 could not be synthesized independently from L^1 in the absence of copper(II) salt. Moreover, complex **3** is not isolated during the reaction of **2** with copper(II) perchlorate and pyridine-2-aldehyde in the presence of a base. Complex **3** further reacts with copper(II) perchlorate and pyridine-2-aldehyde in the presence of a base to form complex **4**. On the other hand, when complex **2** is allowed to react with an excess amount of nickel(II) salts and pyridine-2-aldehyde, nickel(II) complex of the pyrazolate ligand is not isolated.

The copper(II) macrocycle (**2**) gets cleaved upon protonation of the amine nitrogens in the reaction condition. The macrocyclic complex (**2**) is stable in methanol−water but is unstable in the presence of an excess copper(II) salt. This has been established from the ESI-MS of the reaction solution after treatment of **2** with copper(II) perchlorate in methanol−water, Scheme 2. Proposed Mechanism for the Formation of Pyrazole Complex 4



where the characteristic ion peak for **2** at $m/z = 534.84$ was not observed (Figure S4, Supporting Information). It is worth mentioning here that **3**, isolated from methanol, is not isolated from a methanol—water solvent mixture. In methanol, a copper(II)-coordinated methanol molecule is expected to generate a proton which protonates the amine nitrogens. The methoxide then abstracts the hydrazone proton to cleave the macrocycle. The resulting copper(II) species is expected to be strongly oxidizing and gets reduced to copper(I).

The progress of the reaction in methanol—water was monitored by ESI-MS to get an insight into the involvement of different species in the reaction pathway. The formation and decay of a number of ion peaks were observed during the reaction, and those peaks were assigned according to their m/z values and their isotope distribution patterns (Figures S5—S7, Supporting Information). On the basis of these results, a mechanism is proposed in Scheme 2. A water-coordinated copper(II) species (**A**) is initially formed after cleavage of the macrocycle (Figure S5, Supporting Information). Complex **A** reacts immediately with pyridine-2-aldehyde, and a second pyridine-imine moiety is inserted to the ligand backbone for coordination with copper(II) ion. Species **A** is not stable and undergoes $C—N_{amine}$ bond cleavage resulting in the formation of species **B** (Figure S6, Supporting Information). The enolizable mesityloxide-hydrazone group in **B** then attacks the carbon atom of a pyridine-imine moiety to form a C—C bond. The ring in **C** gets hydrolyzed, and another pyridine-imine group is formed, followed by another C—C bond formation (Figure S7, Supporting Information). The pyrazolidine complex (**D**) is oxidized further to form complex **4** of the pyrazolate ligand, L^4.

CONCLUSIONS

We have isolated and characterized a nickel(II) and a copper(II) complex of a new 15-membered azamacrocyclic ligand upon reaction of dihydrazone complexes with pyridine-2-aldehyde. The copper(II) complex of the azamacrocyclic ligand further reacts with pyridine-2-aldehyde in the presence of copper(II) perchlorate to give different complexes depending upon the reaction conditions. The formation of a mononuclear copper(I) complex and of a pyrazolate bridged dimeric copper(II) coordination polymer indicates the role played by the pendant pyridine arm and the metal ion in directing the course of the reactivity of the macrocyclic complexes. A new pyrazole, 3,5-di(2-pyridyl)-4-(3-methyl-2-butenoyl)pyrazole, is isolated in the transformation reaction. The formation of a copper(I) complex is implicated in the reaction pathway. The isolation of the 3,4,5-trisubstituted pyrazole reported in this work points to a novel method for the synthesis of pyrazoles from three isolated carbon sources via C—C bond forming reaction.

ASSOCIATED CONTENT

Supporting Information. Crystallographic data in CIF file format, molecular structures, and ESI-MS data. This material is available free of charge via the Internet at http://pubs.acs.org.

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