A New Class of Self-Assembled Copper(I) Complexes from a Bipyrazine-Bipyridine Ligand Strand

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In the present work, the synthesis of a new ligand strand and its ability to undergo helical Cu^I complexes are described. Three type of complexes have been detected. The nature of these complexes were confirmed by ^1H-NMR and ESI-MS.

Keywords: 2,2'-bipyrazine, copper(I) complexes, self-assembly

INTRODUCTION

Achieving spontaneous and selective formation of self-assembled systems is one of the major goals in supramolecular chemistry. Of recent interest is the formation of beautiful helical inorganic architectures by self assembly from polybipyridine ligands with transition-metal ions [1]. Most of these structures, as helicates, [2] rings, [3] grids [4] and rotaxanes, [5] have been generated from bipyridine, phenanthroline [6] and recently from bipyrimidine units [7]. Recently, Lehn et al. [2] demonstrated the synthesis of racemic double helices from achiral oligobipyridines. More recently, synthesis of preferentially one-handed Cu^I helices by introduction of a chiral center [8] or by chiral templating and oligobipyridine strand elongation [9], opened access to enantiopure topological head-to-head Cu^I double helices.

By changing the chemical nature of the heterocyclic strand, a possible control of the directionality may be obtained. Recent results report that introduction of substituents asymmetrically in homostrand bpy–bpy ligands induces a sense of directionality in the helicate self assembly with a sterically head-to-tail or head-to-head favoured form [10]. Furthermore, linear ligands containing a sequence of three bipyridine (B) and terpyridine (T) units are shown to form homo- or hetero-nuclear duplex helicates with Cu^I, Cu^{II} and Fe^{II} ions [11]. Among them, the case of [(BTB) $Cu^{II}Cu^{II}Cu^{II}$(TBT)] is of particular interest since it represents a case of translation of a given sequence of B and T units into the complementary sequence by virtue of the heterotopic B <–> T correspondence established by the five-coordinate Cu^{II} ions which act as translator.

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A further possible interesting step is the synthesis of ligands containing different binding subunits in a given sequence, (*e.g.*, unsubstituted subunits having methyl-terminated strand-extremities and the same number of inner coordination sites) and the study of their metal complexing behavior.

RESULTS

We illustrate here this work by the synthesis of a new dimer **4** containing a 6-methyl-2,2′-bipyrazine (bpz) and a 6-methyl-2,2′-bipyridine (bpy) unit connected by an oxapropylene bridge and we present some results obtained in its self-assembly into Cu^I complexes. The 6,6′-disubstituted-2,2′-bipyrazine unit appeared recently in the literature [12, 13] and to our knowledge, it has not been used until now in self organization processes leading to helicates. Ligand **4** was synthesized in 56% yield [14] by treatment of the monohydroxymethyl bipyrazine **3** with NaH in anhydrous tetrahydrofuran (THF) at 0°C for 45 min, followed by addition of one equivalent of monobromomethyl bipyridine [15] and heating at 40°C for 24h to give a mixture, chromatographied on alumina (eluent 0.4% MeOH/ CH_2Cl_2). Compound **3** was previously prepared, by treatment of a monochloromethyl bipyrazine [16] in CH_3CN/H_2O in presence of Na_2CO_3 or NaOH(1N) at 60°C for 24h. A chromatography on silica (eluent 1% MeOH/ CH_2Cl_2) gave the monohydroxymethyl bipyrazine in 45% yield. The new compounds **3** and **4** gave spectral (^1H-NMR, ^{13}C-NMR, EI-MS) and microanalytical data in agreement with the assigned structures.

The reaction of the ligand **4** with the required amounts of $[Cu(CH_3CN)_4]$ $[PF_6]$ in anhydrous CH_3CN leads spontaneously to a deep-red solution. Crystallized Cu^I complexes are red needles, stable toward oxygen. They were obtain by slow evaporation of a CH_3CN/H_2O (20%) solution. Some needles appeared suitable in a first approximation for X-ray diffraction analysis

and were used to resolve the structure. Unfortunately, it was a mixture of co-crystallized complexes and, despite many attempts to crystallize **5**, the main product in this mixture, we were unable to obtain pure crystals. The electrospray mass spectrum (ESI-MS) confirms this observation and shows a mixture with the following composition: [LCu] $[PF_6]$ **5**, for 85%, (m/z = 446.6), along 15% of $[L_2Cu]$ $[PF_6]$ **8**, (m/z = 831.1), (Fig. 1, top left). A more detailed analysis of the peak corresponding to m/z = 446.6 (Fig. 1, top left), reveals the presence of small amounts of another complex (peaks separated by 0.5 m/z units) that correspond to the di-charged ion $[L_2Cu_2]^{2+}/2$ of an homo- or hetero-site double helix complex as **6** (or **7**); (Fig. 1, bottom left). The mono-charged ion of (L_2Cu_2) $[PF_6]_2$, (m/z = 894) was not detected in the ESI-MS and MALDI recorded spectra [14].

Nevertheless, a column chromatography of the raw material was realized and allows us to separate a mixture of products **5+6** (or **7**); (*ca.* 77%, yield) and a minor product corresponding to the pure complex $[L_2Cu]$ $[PF_6]$ **8**(basic alumina, eluent 0.5% MeOH/ CH_2Cl_2, yield = 21%, TLC (10% MeOH/90% CH_2Cl_2), Rf = 0.45. Unfortunately, all attempts to separate totally **5** from the minor product **6**(or **7**) by chromatography have failed. Chemical properties of **8** are found very different from **5**. Contrary to **5**, the compound **8** is destroyed by exposition to air (a blue-light coloration of oxidized Cu^{II} is obtained in 24 hours). This latter feature confirms the poor stability of the complex structure $[L_2Cu]$ $[PF_6]$ of **8**. The electrospray mass spectrum corroborates this structure (m/z = 831.0, Fig. 1, bottom right).

The ^1H-NMR spectra of the complexes **5** to **8** are very different from those of the free ligand. Looking first at the spectrum of **8** $[L_2Cu^+]$, (Fig. 2b), we can observe the presence of two ligands in the structure. By comparison with dimer **4**, (Fig. 2a) half of the peaks in the spectrum of **8** is identical to those of the free ligand and represent the protons of the uncomplexed units (one bpz
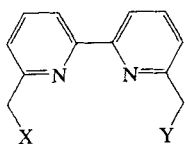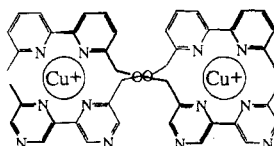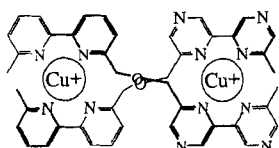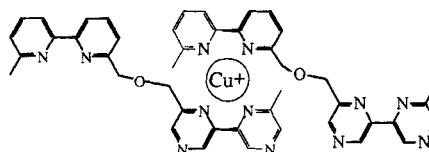
1 : X, Y = H
2 : X= Cl, Y = H
3 : X = OH, Y = H
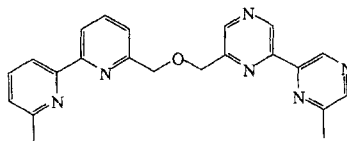
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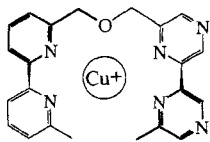
5

6

7

8

and one bpy). The other half is shifted from their initial position and represents the protons of the two units engaged in the Cu^I complex (see assignements Fig. 2b , of the free (f) and complexed (c) corresponding resonances). On complex formation, protons signals are shifted upfield and most importantly the O—CH which appear as two singlets in the free ligand (Fig. 2a), becomes a four peaks system (Fig. 2b). In 8 half of the O—CH_2 protons have become non equivalent in the complex and lie in the shielding regions of bipyrazine and bipyridine groups. The other half, assuming a tetrahedral distorded geometry of the copper complexed units, doesn't be modified, regards to their far position from the metal center as it might be illustrated in Figure 3. Absence of a strong splitting of the O—CH_2 protons lying near the metal center in a structure as 8 might be also interpreted as a rapid racemization of such a

relative flexible structure. Furthermore, analyzing the methyl protons part (not represented here), two peaks are present for each methyle at 2.56 and 2.59 ppm in 4 and four peaks are found in 8 showing two unchanged signals (methyls of the free units) and two others at 2.61 and 2.09 ppm (methyls of the complexed units) [14], indicating an oriented complexation of the two ligands around one copper atom, as drawn for 8.

Looking now at the ^{1}H-NMR spectrum (2c) of 5 + 6 (or 7) recorded first at room temperature, one can notice several broad lines and unresolved resonances in CD_3CN. In order to verify whether the presence of one component in dynamic exchange really exists in the mixture, low temperature measurements have been performed until $-20°C$ (freezing temp.). 1D spectrum (Fig. 2d) and 2D COSY (Figs. 4a-c), are showing a good resolution of all the lines, with appearance of aromatic and most importantly
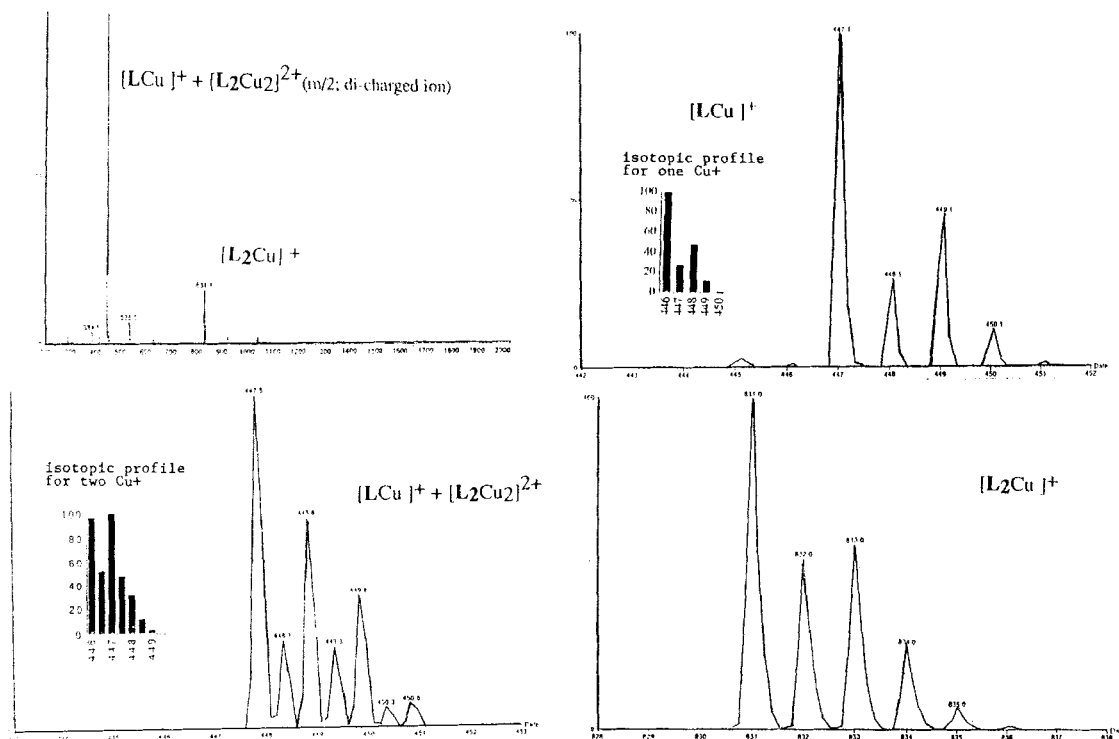
FIGURE 1   ESMS spectra of the complexes 5, 6 (or 7) and 8: top left = whole spectrum; top right = detailed peak of 5, $[LCu]^+$; bottom left = detailed peak for 6 (or 7), $[L_2Cu_2]^{2+}/2$; bottom right = detailed peak of 8 $[L_2Cu]^+$.

methylene protons splitting resonances. These results confirm the complexation with the copper atom and the presence of more than one component in solution. The methylene protons display several patterns which could be organized as ca. four AB systems of various intensity between 4.25 ppm to 3.25 ppm, two of them representing the O—CH₂—bpy and O—CH₂—bpz groups of one complex. The COSY allows to understand in this sense direct correlations between components of AB systems in one hand, between heterocyclic protons and in other hand, between O—CH₂ protons and are reported in Figure 2d. In correlation with the ES-MS results, the NMR data confirm the presence of two complexes 5+6 (or 7) in the sample. Nevertheless, it remains uncertain actually to affirm from these results whether the structure for $[L_2Cu_2]$ $[PF_6]_2$ is 6 or 7.

DISCUSSION

By comparison with the earlier results obtained on oligobipyridine Cu^I complexes, a ligand possessing bidendate alternate heterosites as 4, seems to follow a different self-assembly process. Surprisingly, and contrary to oligobipyridine strands, the bpz-bpy ligand is able to bind Cu^I ion, so as to form the mononuclear mono stranded complex 5. In this species the Cu^I ion probably binds the ligand molecules in a distorted tetrahedral geometry as previously found in the case of parent substances [2]. Among the complexes, the dinuclear double stranded helicate 6 (or 7) was also obtained as a minor product in the reaction. Very surprisingly, the presence of a complex $[L_2Cu]$ $[PF_6]$ 8 is detected and isolated. Recently, literature reports in this sense the formation of a similar
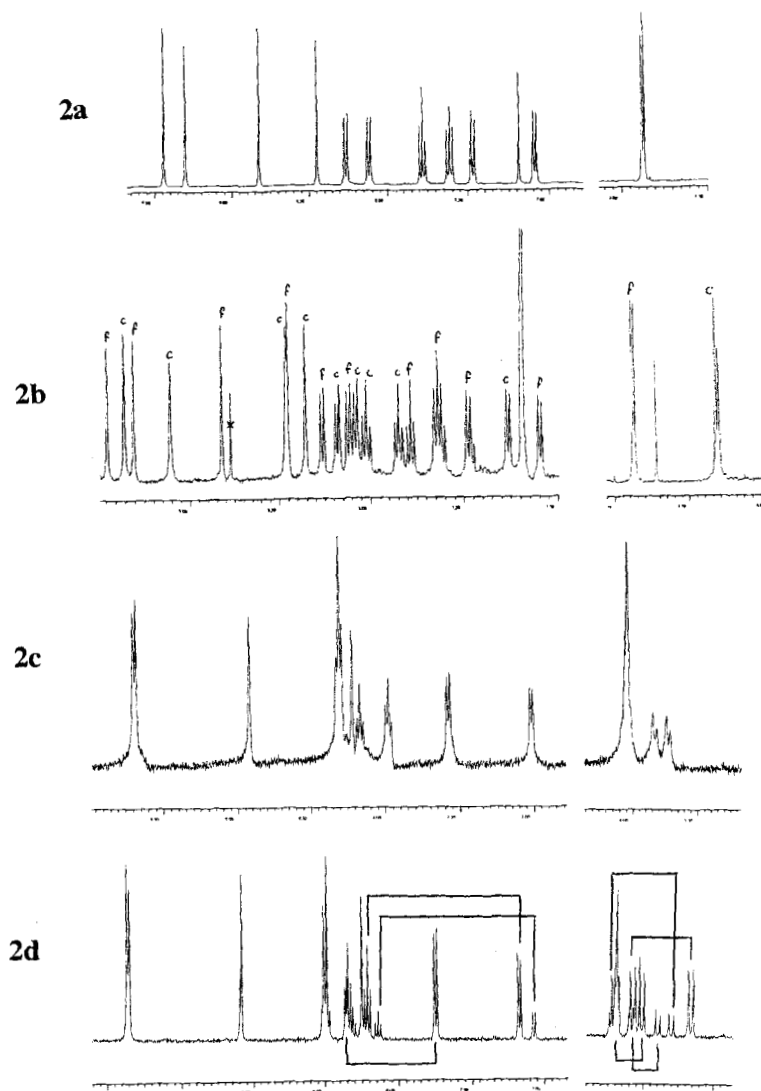
FIGURE 2   400 MHz ^{1}H NMR spectra of the ligand 4 (2a), the complex 8 (2b*) in CDCl$_3$ and complexes 5+6 (or 7): (2c) at 25°C, (2d) at-20°C in CD$_3$CN. *(f) = labelled protons of the free units, (c) = labelled protons of the complexed units.

complex in a head-to-head arrangement around one zinc (II) atom [17] and also the formation of a predominant heterodinuclear complex in solution. Moreover, a recent synthesis of an homo-oligobipyrazine (bpz3) strand in our group [18] shows, as the oligobipyridine do, the formation of a trinuclear *double stranded helicate* of Cu^I and so, shows the particularity of the self assembling process encountered with the mixed ligand strand regards to homonuclear ones.

Results of the literature [10] obtained with asymmetric quatenarypyridines (substituted by donor groups in position 4 of the py's) have demonstrated that the assembling process is dependent on the methyl–methyl interstrand steric interactions and that introduction of bulky *tert*-butyl substituents led to the head to head unique configuration.

In our case, excepting the methyl substituents at each end of the strand, no other substituents
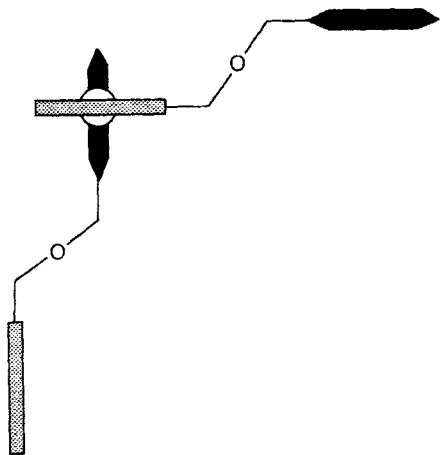
FIGURE 3   Schematic representation of one probable geometry for 8.

are introduced in any position and therefore it cannot be proposed that a steric factor is acting on the assembling selectivity. The sole difference between the two heterocycles is of electronic order. The prefered obtention of the mono heteronuclear complex 5 and a probable hetero-dinuclear assembly as 6 is not clear actually as well as the special obtention of 8. Off-set the initial attractive preference, there is no evidence here of a secondary repulsive interaction inducing this prefered directionnality as it was found for the asymmetric quaterpyridines examples.

Refering to the conclusions of previous works describing redox properties of Ru(II) tris-chelate complexes [19, 20] of either bipyridine and
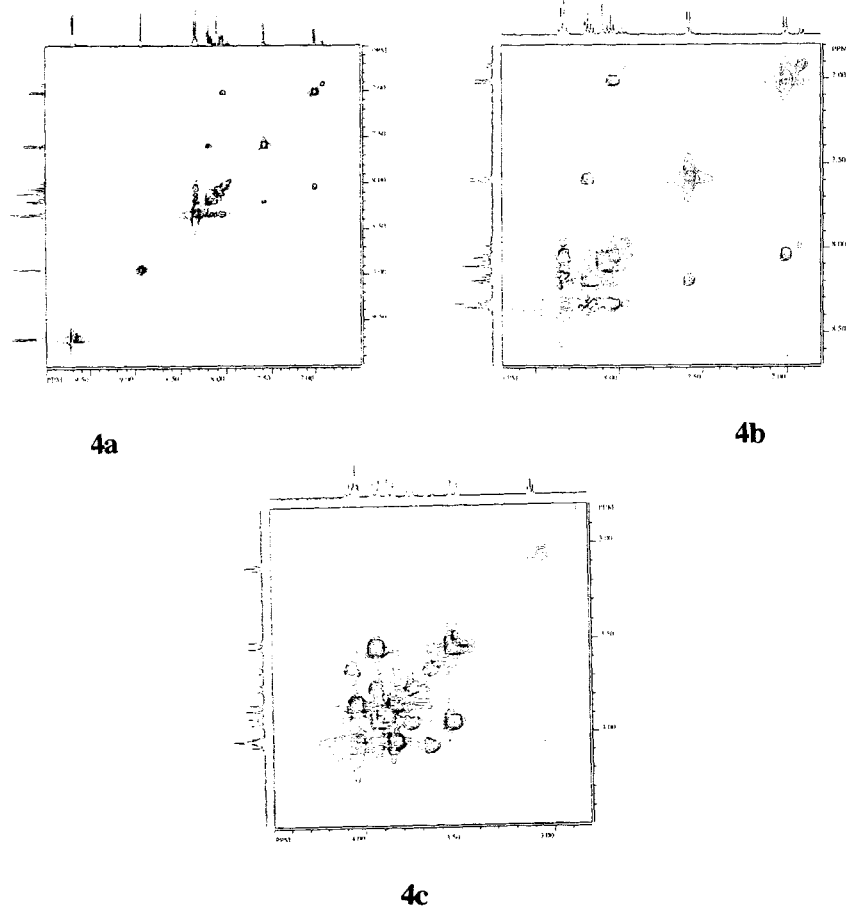
4a

4b

4c

FIGURE 4   2D ^{1}H NMR COSY of 5+6 (or 7) at $-20°$C in CD_3CN : (4a, b) = aromatic protons (4c) = methylene protons.

bipyrazine it appears that it was also necessary to consider σ- and most importantly π-bonding effects as important factors for bonding heterocyclic ligands to a metal. The importance of π-bonding effects in related ligands have been rationalized on the basis of ligands types that withdraw or donate electrons through $d\pi$-π^* interactions. It was notably stressed on the role of $d\pi$-π^* back-bonding to stabilized the metal $d\pi$ orbitals. Although, these effects have not been proved to occur in case of the above described copper complexes, it constitute in our opinion good criterions to analyze the results.

The present observations extend the earlier ones and show that new inorganic complexes can be generated on the basis of the structural design developed. Nevertheless, further studies must be envisaged to complete these first results, from organic, inorganic and physical points of view and they are such as: -the separation of **5** and **6** (or **7**) if possible, and X-rays resolution of each structure, -double helix wrapping of homodinuclear mixtures, syntheses of extended length chains having heterocyclic units different combinatories (*e.g.*, a strand as bpy-bpz-bpy) in order to study their self organization by complexation with Cu^I ions. These experiments are actually in progress.

Acknowledgments

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[14] All new compounds were characterized by ^1H NMR and mass spectrometry. **3**: ^1H NMR (400, 1 MHz, CDCl$_3$, 25°C): $\delta = 9.45$ (*s*, 1H), 9.31 (*s*, 1H), 8.64 (*s*, 1H), 8.47 (*s*, 1H), 4.87 (*s*, 2H), 2.60 (*s*, 3H). MS (EI): *m/z* 202 (M$^+$); C$_{10}$H$_{10}$N$_4$O (202.1): calcd C 59.37, H 4.98, N 27.70; found C 59.14, H 5.04, N 27.81. **4**: ^1H NMR (400, 1 MHz, CDCl$_3$, 25°C): $\delta = 9.44$ (*s*, 1H), 9.30 (*s*, 1H), 8.82 (*s*, 1H), 8.45 (*s*, 1H), 8.26 (*d*, 1H, $^3J(H,H) = 8$ Hz), 8.12 (*d*, 1H, $^3J(H,H) = 8$ Hz), 7.78 (*t*, 1H, $^3J(H,H) = 8$ Hz), 7.60 (*t*, 1H, $^3J(H,H) = 8$ Hz), 7.47 (*d*, 1H, $^3J(H,H) = 8$ Hz), 7.09 (*d*, 1H, $^3J(H,H) = 8$ Hz), 4.88 (*s*, 2H), 4.87 (*s*, 2H), 2.59 (*s*, 3H), 2.56 (*s*, 3H); ^{13}C NMR (200 MHz, CDCl$_3$, 25°C): $\delta = 158.2$, 157.5, 156.3, 155.7 (C2, C6, C2', C6', bpz), 153.4, 152.9, 148.7, 148.5, (C2, C6, C2', C6', bpy), 145.3, 144.0, 142.3, 140.6 (C3, C4, C3' C4', bpz), 137.9, 137.3 (C4, C4', bpy), 123.6, 121.5, 120.3, 118.5 (C3, C5, C3', C5', bpy), 74.7 (CH$_2$, bpz), 72.2 (CH$_2$, bpy), 24.9 (CH$_3$, bpz), 21.9 (CH$_3$, bpy); MS (EI): *m/z* 384 (M$^+$). C$_{22}$H$_{20}$N$_6$O (384.2): calcd C 68.72, H 5.24, N 21.86; found C 68.64, H, 5.22, N 21.73. **5** and **6** (or **7**): ^1H NMR (400, 1 MHz, CD$_3$CN, 25°C): $\delta = 9.72$ (*s*, 1H), 9.70 (*s*, 1H), 8.92 (*s*, 1H), 8.40 – 8.25 (*m*, 3H), 8.20 (*s*, 1H), 8.16 (*t*, 0.5H), 7.97 (*t*, 0.8H), 7.57 (*d*, 1H), 7.02 (*d*, 0.8H), 4.07 (*m*, 3H), 3.85 (*d*, large, 0.1H), 3.75 (*d*, large, 0.1H), 2.80 (*t*, 0.2H), 2.3–2.0 (4*s*, 12H). ^1H NMR (400, 1 MHz, CD$_3$CN, −20°C): $\delta = 9.85$ (*s*, 1H), 9.82 (*s*, 1H) 9.10 (*s*, 1H), 8.50 (*m*, 2H), 8.35 (*m*, 1H), 8.25 (*s*, 0.5H), 8.20 (*t*, 0.5H), 8.15 (*t*, 0.2H), 7.75 (*d*, 1H), 7.17 (*d*, 0.8H), 7.07 (*d*, 0.2H), 4.25–4.15 (*m*, 2H), 4.07 (*dd*, 0.3H), 4.02 (*d*, 0.3H), 3.90 (*d*, 0.1H), 3.80 (*d*, 0.1H), 3.65 (*d*, 0.3H), 3.27 (*t*, 0.2H), 2.80–2.10 (4*s*, 12H). MS (ES$^+$ in CH$_3$CN): *m/z* 446.6 (LCu$^+$ + L$_2$Cu2^{2+}/2). MS (MALDI in THF): *m/z* 447

(LCu⁺), 517 (LCu⁺ + THF). **8** TLC (10% MeOH/90% CH_2Cl_2), $Rf = 0.45$; ¹H NMR (400, 1 MHz, $CDCl_3$, 25°C): $\delta = 9.44$ (s, 1H), 9.36, (s, 1H), 9.31 (s, 1H), 9.11 (s, 1H), 8.82 (s, 1H), 8.46 (s, 1H), 8.45 (s, 1H), 8.36 (s, 1H), 8.26 (d, 1H, $^3J(H, H) = 8Hz$), 8.18 (d, 1H, $^3J(H, H) = 8Hz$), 8.12 (d, 1H, $^3J(H, H) = 8Hz$), 8.08 (d, 1H, $^3J(H, H) = 8Hz$), 8.02 (t, 1H, $^3J(H, H) = 8Hz$), 7.85 (t, 1H, $^3J(H, H) = 8Hz$), 7.79 (t, 1H, $^3J(H, H) = 8Hz$), 7.64 (t, 1H, $^3J(H, H) = 8Hz$), 7.48 (d, 1H, $^3J(H, H) = 8Hz$), 7.26 (d, 1H, $^3J(H, H) = 8Hz$), 7.10 (d, 1H, $^3J(H, H) = 8Hz$), 4.87 (d, 4H), 4.72 (s, 1H), 4.33 (s, 1H), 4.32 (d, 2H), 2.61 (s, 3H), 2.59 (s, 3H), 2.56 (s, 3H), 2.09 (s, 3H). MS (ES⁺ in CH_3CN): m/z 831.1 (L_2Cu^+).

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