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Note

Synthesis and characterization of bifunctional oligo-α-aminopyridines and their copper(II) complexes

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Abstract

The synthesis of two new bifunctional oligo-α-aminopyridine ligands, *N*-(6-{6-[3-(6-amino-pyridin-2-ylamino)-phenylamino]-pyridin-2-ylamino}-pyridin-2-yl)-4-methylbenzenesulfonamide (apppm) and *N*-(6-{6-[3-(6-bromo-pyridin-2-ylamino)-phenylamino-pyridin-2-yl-amino]-pyridin-2-yl)-4-methylbenzenesulfonamide (bpppm), by double aminated couplings and Pd-catalization is presented in this paper. $NaNH_2$ was used as a critical base in the first step of the aminated coupling for synthesizing the key building block *N*-(6-bromo-pyridin-2-yl)-pyridine-2,6-diamine (bppd) in 96% yield. Pyridine was then used in the second step of the aminated coupling for 4-toluenesulphonyl chloride and bppd. Finally, the monoamination was facilitated by the palladium-catalyzed Buchwald's coupling reaction, and subsequently the corresponding metal complexes of these bifunctional ligands were constructed. The single-crystal X-ray crystallographic data of the complex $[Cu(apppm)(ClO_4)(H_2O)](ClO_4)\cdot 2THF$ (**1**), $[Cu(bpppm)](ClO_4)_2\cdot (H_2O)_{5/3}\cdot (CH_3CN)_{1/3}$ (**3**), and the related salt $[H(appm)](ClO_4)\cdot THF$ (**2**), were prepared and characterized. In complex **1**, Cu(II) coordinates with the three nitrogen atoms of the pyridine rings, with the oxygen atom of the *p*-toluenesulphonyl group, strongly with the oxygen of the water molecule, and weakly with the oxygen atom of the perchlorate anion, and shows a distorted octahedral geometry. However, in the complex **3**, Cu(II) bonds to N(1), N(3), N(5), and N(7) of the ligand bpppm toughly and exhibits a twisted square planar geometry.

Keywords: Oligo-α-aminopyridine; Palladium-catalyzed; Distorted 6-coordinated octahedral geometry

1. Introduction

Organometallic reagents have often been utilized to catalyze the formation of carbon–nitrogen bond of heteroaromatics. Nitrogen-containing heteroaromatics have fascinating and versatile bonding properties, and their unique features have been well applied to organic chemistry, polymer chemistry, and supramolecular chemistry [1,2]. In particular, the growing applications of oligo-aminopyridines are observed in areas such as material science and industrial pharmacology [3]. Thus, the synthesis of oligo-aminopyridines has attracted many chemists' interests recently. Using catalytic palladium complexes, Migita has synthesized aminopyridines [4], Buchwald's [5] and Hartwig's groups [6] have reported various primary and secondary amines with dihalides to give products in high yields, Kanbara has prepared high mass material poly(aryleneamine)s [7], and Beletskaya has produced selective aryl-substituted polyamines [8]. It was noticed that bases and catalysts also play important roles, for examples, sterically hindered bases, LiO^tBu, NaO^tBu, and KO^tBu; and the chelating biphosphine ligand, 1,1′-bis-(diphenylphosphino)ferrocene (DPPF) [5e]; and the racemic catalyst 2,2′-bis(diphenylphosphenyl)-1,1′-binaphtyl (BINAP) [6b].

This work focuses on the synthesis of the bifunctional oligo-α-aminopyridines, *N*-(6-{6-[3-(6-amino-pyridin-2-ylamino)-phenylamino]-pyridin-2-ylamino}-pyridin-2-

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yl)-4-methylbenzenesulfonamide (apppm) and *N*-(6-{6-[3-(6-bromo-pyridin-2-ylamino)-phenylamino]-pyridin-2-ylamino}-pyridin-2-yl)-4-methylbenzenesulfonamide (bpppm), and the structure–property relationship of the corresponding Cu(II) complexes [Cu(apppm)(ClO_4)-(H_2O)](ClO_4)·2THF (**1**), and [Cu(bpppm)](ClO_4)$_2$·(H_2O)$_{5/3}$·(CH_3CN)$_{1/3}$ (**3**). The reason of choosing copper metal was originated from the need to understand the copper proteins [9], and bifunctional oligo-α-aminopyridines were selected for their structural features to learn the multibinding capabilities [10–12]. Based on the literature survey, the coordination study of Cu(II) complexes with the aminopyridines have illustrated variety of geometries, such as tetrahedral [10a], square planar [10b], square pyramid [10b], trigonal planar [10g], and distorted octahedral [10f].

In order to obtain more information of the coordinated geometries of Cu(II) and bifunctional oligo-α-aminopyridines, we have synthesized two new ligands, apppm and bpppm. Two new metal complexes, **1** and **3**, and its related salt [H(appm)](ClO_4)·THF (**2**) were synthesize and characterized in details with single X-ray crystallographic analysis.

2. Experimental

2.1. Chemicals and general procedures

Benzene, THF, and toluene were pre-dried, and freshly distilled from sodium suspension. All starting chemicals were purchased from Aldrich. All procedures were carried out in Ar and using standard high-vacuum techniques.

2.2. Physical measurements

The infrared spectra were recorded on a Nicolet Fourier Transform IR MAGNA-IR 500 spectrophotometer in the range of 500–4000 cm^{-1} using KBr disk technique. UV–Vis spectra were recorded on a Hewlett–Packard (HP) 8453 spectrophotometer. Maximum absorptions were recorded (in CH_3OH) and listed in the form of λ_{max} (nm) [ε (M^{-1} cm^{-1})]. The ^1H and ^{13}C NMR spectra were measured on a Bruker Avance-400 MHz spectrometer. Elemental analysis was performed on a Perkin–Elmer CHN analyzer 2400. Fast atom bombardment mass (FAB MS) spectra were obtained on a JEOL-SX 102A mass spectrometer with *m*-nitrobenzyl alcohol (*m*-NBA) as the matrix.

2.3. The preparation of ligands

2.3.1. The synthesis of N-(6-bromo-pyridin-2-yl)-pyridine-2,6-diamine (bppd)

To a 2 L two-necked round-bottomed flask, 2,6-diaminopyridine (20.00 g, 0.18 mol), sodium amide (11.91 g, 0.31 mol), and anhydrous toluene (600 mL) were added. The mixture was stirred and refluxed for 24 h. Subsequently, dibromopyridine (36.18 g, 0.15 mol) in toluene (300 mL) was added drop by drop to this solution over 1 h, and the whole solution was refluxed for another 48 h. The hot reaction mixture ($\sim$85 °C) was quenched by water (300 mL, $\sim$25 °C) and then extracted with hot toluene (4 × 1 L), and the combined organic solution was dried over anhydrous $MgSO_4$ and filtered. The filtrate was concentrated in vacuo, and the residue was purified by flash chromatography (silica gel 60–300 mesh) to obtain the desired product bppd as white solids in 96% yield (38.85 g, m.p. 112 °C) and 2% yield of side product bbppd (see Section 2.3.2). *Anal*. Calc. for $C_{10}H_9BrN_4$: C, 45.28; H, 3.39; N 21.13. Found: C, 45.41; H, 3.21; N, 20.94%. IR (KBr): 3448, 3310, 3198, 1635, 1562, 1516, 1352, 1418, 1155, 1122 cm^{-1}. ^1H NMR of bppd (400 MHz, Me_2SO-d_6): δ 9.54 (s, 1H, NH), 8.04 (d, 1H, aromatic H_a), 7.51 (t, 1H, aromatic H_b), 7.28 (t, 1H, aromatic H_c), 6.97 (d, 1H, aromatic H_d), 6.56 (d, 1H, aromatic H_e), 5.99 (d, 1H, aromatic H_f), 5.78 (s, 2H, NH_2). ^{13}C NMR (100 MHz, Me_2SO-d_6): δ 158.0, 154.5, 152.3, 139.8, 139.7, 139.4, 119.2, 109.7, 101.4, 100.7. MS (FAB) [*m*/*z*]: [265 $(M+1)^+$]. UV–Vis (CH_3OH): 329 ($\varepsilon = 3.85 \times 10^4$), 270 ($\varepsilon = 3.05 \times 10^4$), 229 ($\varepsilon = 2.21 \times 10^4$), 206 nm ($\varepsilon = 4.44 \times 10^4$).

2.3.2. The synthesis of N,N′-bis-(6-bromo-pyridin-2-yl)-pyridine-2,6-diamine (bbppd)

It is a side product with an optimized yield of 40% (0.64 g) from another trial where 2,6-diaminopyridine (5.00 g, 0.05 mol) and dibromopyridine (21.71 g, 0.09 mol) were employed under the previously described experimental conditions. *Anal*. Calc. for $C_{15}H_{11}Br_2N_5$: C, 42.76; H, 2.61; N 16.63. Found: C, 42.94; H, 2.47; N, 16.38%. IR (KBr): 3254, 3167, 3066, 1609, 1514 cm^{-1}. ^1H NMR (400 MHz, Me_2SO-d_6): δ 9.83 (s, 2H, NH), 7.85 (d, 2H, aromatic H_d), 7.57 (t, 3H, aromatic H_{a+e}), 7.03 (m, 4H, aromatic H_{b+c}). ^{13}C NMR (100 MHz, Me_2SO-d_6): δ 154.4, 151.9, 140.6, 139.4, 138.6, 118.8, 110.6, 104.0. MS (FAB) [*m*/*z*]: [421.9 $(M+1)^+$]. UV–Vis (CH_3OH): 339 ($\varepsilon = 2.11 \times 10^4$), 266 ($\varepsilon = 1.98 \times 10^4$), 204 nm ($\varepsilon = 2.27 \times 10^4$).

2.3.3. The synthesis of N-[3-(3-bromo-phenylamino)-phenyl]-4-methyl-benzenesulfonamide (bppm)

To a 500 mL two-necked round-bottomed flask, a solution of bppd (7.40 g, 28 mmol) in anhydrous pyridine (20 mL) was loaded, then 4-toluenesulphonyl chloride (10.64 g, 55.82 mmol) in pyridine (20 mL) was

added to this solution, and the mixture was stirred at room temperature (r.t.) for 2 h. To this reaction mixture, 20% NaOH was added dropwise until the pH reached 9. The crude product was extracted with EtOAc (3×100 mL) and then was washed with water (3×100 mL). The water layer was extracted with EtOAc (2×100 mL) again. The combined organic layer was dried over anhydrous $MgSO_4$ and allowed to stand overnight. After filtration, the solution was concentrated in vacuo to obtain the desired compound bppm in 95% yield (11.11 g) without further purification. *Anal*. Calc. for $C_{17}H_{15}BrN_4O_2S$: C, 48.69; H, 3.58; N 13.37. Found: C, 48.68; H, 3.60; N, 13.24%. IR (KBr): 3448, 3237, 3066, 1589, 1523, 1437, 1372, 1155, 1089 cm^{-1}. ^1H NMR (400 MHz, Me_2SO-d_6): δ 10.92 (s, 1H, SO_2NH_a), 9.90 (s, 1H, NH_b), 8.32 (d, 1H, aromatic H_c), 7.80 (d, 2H, aromatic H_d), 7.57 (dd, 2H, aromatic H_{e+f}), 7.30 (d, 2H, aromatic H_g), 7.05 (d, 1H, aromatic H_h), 6.79 (d, 1H, aromatic H_i), 6.54 (d, 1H, aromatic H_j), 2.27 (s, 3H, CH_3). MS (FAB) [*m*/*z*]: [421 $(M+1)^+$]. UV–Vis (CH_3OH): 325 ($\varepsilon = 3.79 \times 10^4$), 270 ($\varepsilon = 3.36 \times 10^4$), 225 ($\varepsilon = 3.20 \times 10^4$), 205 nm ($\varepsilon = 5.46 \times 10^4$).

2.3.4. The synthesis of (N-(6-{6-[3-(6-amino-pyridin-2-ylamino)-phenylamino]-pyridin-2-ylamino}-pyridin-2-yl)-4-methyl-benzenesulfonamide) (apppm)

To a two-necked round-bottomed flask (250 mL), bppm (5.00 g, 11.92 mmol) in C_6H_6 (200 mL) and $Pd_2(dba)_3$ (0.11g, 0.12 mmol) were loaded, and the mixture was stirred for 20 min. Then BINAP (0.15 g, 0.24 mmol), and NaO^tBu (3.44 g, 35.76 mmol) were added to the reaction mixture. After stirring for 30 min, 2,6-diaminopyridine (2.86 g, 26.23 mmol) was then added. The resulting mixture was stirred at 80 °C for 3 days, then cooled to r.t. and quenched with aq. $(NH_4)_2SO_4$ solution. The crude product was extracted with EtOAc (3×200 mL), and the combined organic layer was dried over anhydrous $MgSO_4$. The filtrate was concentrated in vacuo, and the residue was purified by flash chromatography on silica gel. The desired compound apppm was obtained as white solids in 60% yield (3.19 g), m.p. 240 °C. *Anal*. Calc. for $C_{22}H_{21}N_7O_2S$: C, 59.06; H, 4.69; N 21.92. Found: C, 59.11; H, 4.64; N, 21.70%. IR (KBr): 3467, 3382, 3323, 3212, 3047, 1661, 1615, 1586, 1576, 1444, 1366, 1319, 1155 cm^{-1}. ^1H NMR (400 MHz, Me_2SO-d_6): δ 10.74 (br, 1H, SO_2NH_a), 8.77–9.03 (br, 2H, NH_{b+o}), 7.81 (d, 2H, aromatic H_c), 7.48 (br, 2H, aromatic H_{d+e}), 7.30 (d, 2H, aromatic H_g), 7.20 (m, 1H, aromatic H_f), 7.10 (m, 4H, aromatic $H_{j+k+l+m}$), 6.42 (br, 1H, aromatic H_i), 5.99 (d, 1H, aromatic H_n), 5.67 (br, 2H, NH_2), 2.27 (s, 3H, CH_3). MS (FAB) [*m*/*z*]: [448 $(M+1)^+$]. UV–Vis (CH_3OH): 375 ($\varepsilon = 1.87 \times 10^4$), 336 ($\varepsilon = 2.66 \times 10^4$), 260 ($\varepsilon = 2.11 \times 10^4$), 221 ($\varepsilon = 2.19 \times 10^4$), 204 nm ($\varepsilon = 2.52 \times 10^4$).

2.3.5. The synthesis of N-(6-{6-[3-(6-bromo-pyridin-2-ylamino)-phenylamino]-pyridin-2-ylamino}-pyridin-2-yl)-4-methyl-benzenesulfonamide (bpppm)

To a two-necked round-bottomed flask (500 mL), bppm (5.00 g, 11.92 mmol) in C_6H_6 (300 mL) was loaded, and then $Pd_2(dba)_3$ (0.33 g, 0.36 mmol) was added, and the mixture was stirred for 20 min. Then BINAP (0.45 g, 0.72 mmol), and NaO^tBu (3.44 g, 35.76 mmol) were added to the reaction mixture. After stirring for 30 min, bppd (2.86 g, 26.23 mmol) was then added. This mixture was stirred at 80 °C for 3 days, then cooled to r.t., and quenched with aq. $(NH_4)_2SO_4$ solution (100 mL). The crude product was extracted with EtOAc (3×250 mL). The combined organic phase was dried over $MgSO_4$ and subsequently filtered and concentrated in vacuo. The residue was purified by flash chromatography over silica gel to produce the desired product bpppm in 40% yield (2.87 g). *Anal*. Calc. for $C_{27}H_{23}BrN_8O_2S$: C, 53.73; H, 3.81; N 18.57. Found: C, 53.74; H, 3.81; N, 18.50%. IR (KBr): 3449, 3348, 3254, 1663, 1602, 1447, 1219, 1179 cm^{-1}. ^1H NMR (400 MHz, Me_2SO-d_6): δ 10.74 (s, 1H, SO_2NH_a), 9.77 (s, 1H, NH_b), 9.10 (s, 2H, NH_{c+d}), 8.15 (d, 1H, H_e), 7.81 (d, 2H, H_f), 7.53 (m, 6H, $H_{g+h+i+j+k+l}$), 7.32 (d, 2H, H_m), 7.04 (m, 3H, H_{n+o+p}), 6.87 (d, 1H, H_q), 6.47 (d, 1H, H_r), 2.49 m (s, 3H, CH_3). MS (FAB) [*m*/*z*]: [605 $(M+1)^+$]. UV–Vis (CH_3OH): 374 ($\varepsilon = 2.33 \times 10^4$), 341 ($\varepsilon = 3.30 \times 10^4$), 256 ($\varepsilon = 2.96 \times 10^4$), 204 nm ($\varepsilon = 3.61 \times 10^4$).

2.4. The preparation of Cu(II) complexes **1**, and **3**, and the related salt **2**

2.4.1. The synthesis of [Cu(apppm)(ClO_4)(H_2O)](ClO_4)·2THF (**1**)

Apppm (0.10 g, 0.22 mmol), $Cu(ClO_4)_2 \cdot 6H_2O$ (0.13 g, 0.34 mmol), and THF (30 mL) were placed in a round-bottomed flask (50 mL). The mixture was stirred at r.t. for 2 h. A violet powder product was isolated by filtration in 80% yield (0.16 g). The single crystal of **1** was obtained from the mixed DMF–THF/Et_2O by slow diffusion techniques. *Anal*. Calc. for $C_{30}H_{39}Cl_2CuN_7O_{13}S$: C, 41.28; H, 4.47; N 11.24. Found: C, 41.35; H, 4.40, N; 11.08%. IR (KBr): 3341, 3241, 3153, 1636, 1575, 1454, 1132, 1085 cm^{-1}. MS (FAB) [*m*/*z*]: [1119 ($2apppm + 2Cu^{2+} + ClO_4^-$)]. UV–Vis ($CH_3OH$): 381 ($\varepsilon = 7.654 \times 10^3$), 340 ($\varepsilon = 2.27 \times 10^4$), 247 ($\varepsilon = 1.60 \times 10^4$), 231 ($\varepsilon = 1.61 \times 10^4$), 204 nm ($\varepsilon = 2.23 \times 10^4$).

2.4.2. Synthesis of [H(appm)](ClO_4)·THF (**2**)

To a round-bottomed flask (50 mL), apppm (0.10 g, 0.22 mmol), 70% of $HClO_4$ (0.03 mL, 0.35 mmol), and THF (30 mL) were loaded. This reaction mixture was stirred at r.t. for 2 h. The protonated compound **2** was isolated by filtration of the THF solution in 80% yield (0.10 g). The crystal of **2** was obtained from THF/

hexane system. *Anal*. Calc. for $C_{26}H_{30}ClN_7O_7S$: C, 50.32; H, 4.84; N 15.80. Found: C, 50.41; H, 4.80; N, 15.69%. IR (KBr): 3523, 3429, 1615, 1461, 1152, 1105 cm^{-1}. MS (FAB) [*m*/*z*]: [619 (apppm + Cu^{2+} + ClO_4^-)]. UV–Vis (CH_3OH): 340 ($\varepsilon = 3.31 \times 10^3$), 226 ($\varepsilon = 4.90 \times 10^3$), 204 nm ($\varepsilon = 5.89 \times 10^3$).

2.4.3. Synthesis of [Cu(bpppm)](ClO4)2·(H2O)5/3·(CH3CN)1/3 (3)

To a round-bottomed flask (50 mL), bpppm (0.10 g, 0.16 mmol) and $Cu(ClO_4)_2 \cdot 6H_2O$ (0.09 g, 0.24 mmol), and THF (15 mL) were loaded. The mixture was stirred at r.t. for 2 h. The copper complexes were isolated by filtration in 75% yield (0.12 g). The reddish-violet crystal **3** was obtained from CH_3CN/ether by diffusion techniques. *Anal*. Calc. for $C_{27.67}H_{27.33}BrCl_2CuN_{8.33}O_{11.67}S$: C, 36.50; H, 3.00; N 12.82. Found: C, 36.69; H, 3.00; N, 12.54%. IR (KBr): 3415, 3073, 1649, 1454, 1226, 1119 cm^{-1}. MS (FAB) [*m*/*z*]: [766 (bpppm + Cu^{2+} + ClO_4^-)]. UV–Vis (CH_3OH): 394 ($\varepsilon = 3.32 \times 10^3$), 350 ($\varepsilon = 1.21 \times 10^4$), 335 ($\varepsilon = 1.12 \times 10^4$), 235 ($\varepsilon = 1.08 \times 10^4$), 204 nm ($\varepsilon = 1.88 \times 10^4$).

2.5. Crystallography

Data collection for ligand bppd and compound **1** were carried out on a Siemens SMART diffractometer with a CCD detector (150 K), on a NONIUS CAD4 diffractometer (295 K) for compound **2**, and on a KappaCCD (150 K) for compound **3**. All measurements were carried out under Mo Ka radiation ($\lambda = 0.71073$ Å), and the cell parameters were listed in Table 2. The structures of bppd, **1**, **2** and **3** were identified by direct methods and refined with full-matrix least-square methods on F^2 by SHELXL-97 (G.M. Sheldrick, 1997, University of Göttinggen, Germany). All of the nonhydrogen atomic positions were located in different Fourier maps and refined anisotropically. The hydrogen atoms attached to nitrogen atoms were located and refined isotropically. The rest of hydrogen atoms attached to the carbon atoms were placed in their geometrically generated positions.

3. Results and discussion

3.1. The synthesis of ligands bppd and bbppd

Ligand bppd was the key building block to prepare our final target ligands apppm and bpppm. The synthesis of ligand bppd was first tried via palladium-catalyzed amination of diaminopyridine and dibromopyridine. However, the attempt was not successful, and only unexpected polymers [7] or the β-elimination side products were obtained as reported previously [5f]. The failure may be due to both of the starting materials being active under the reaction conditions. Less than 40% of bppd was obtained when various bulky bases, such as NaO^tBu or KO^tBu, and chelating agents like BINAP, DPPP, and 1,1′-bis(diphenylphosphino)ferrocene were added into the reaction mixture in the absence of palladium catalyst. However, the yield of bppd was optimized to 96% by using $NaNH_2$ as a base in the first aminated step after many trials (Scheme 1). It may be noted that since $NaNH_2$ ($pK_a \sim 33$) is a stronger base than KO^tBu ($pK_a \sim 19$), the formation of products favor to facilitate by employing $NaNH_2$.

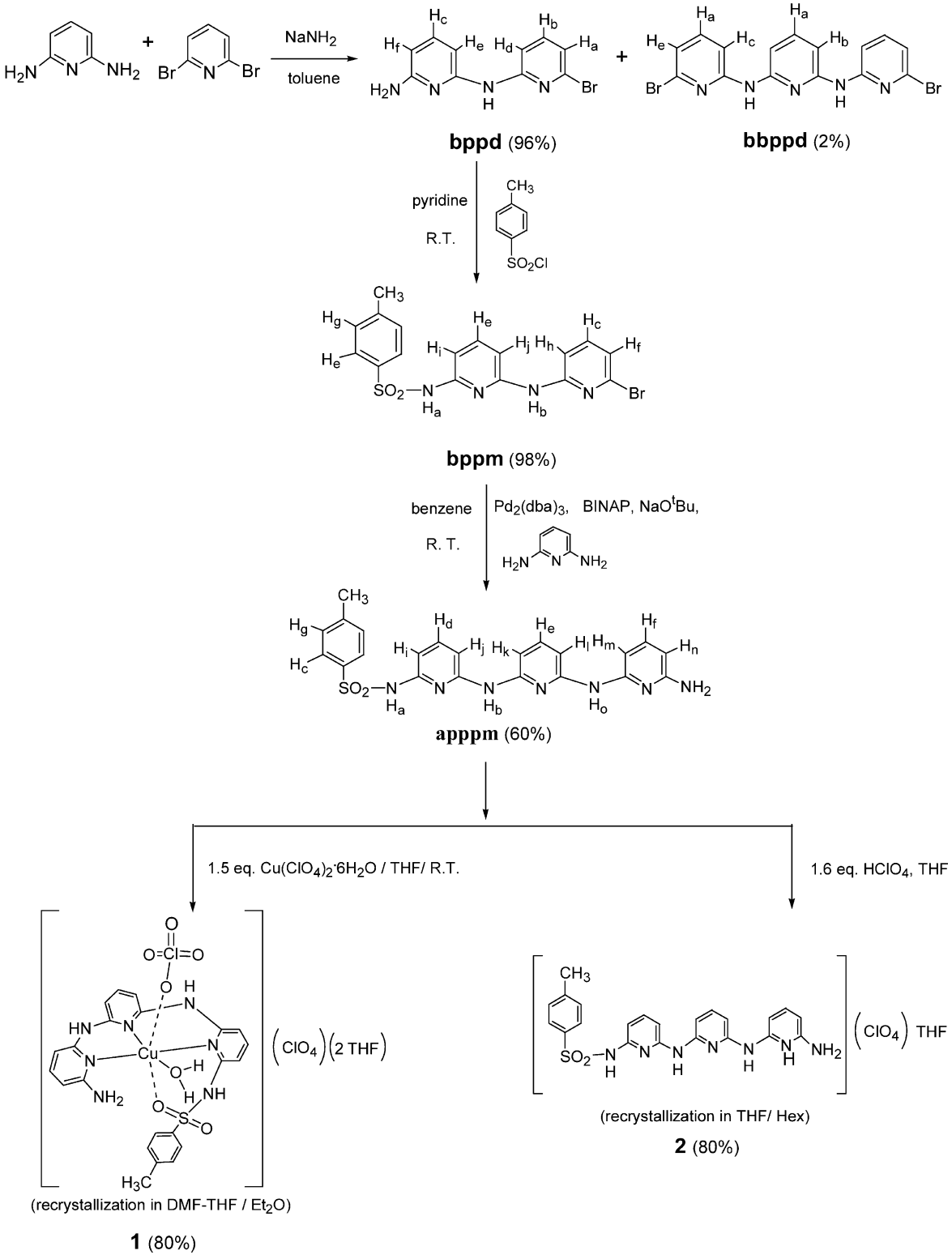
Compound bbppd, a side product (2%) from the first aminated step with $NaNH_2$ treatment, is a potential bifunctional oligo-α-aminopyridine ligand. The yield was optimized to achieve 40% under 1:2 molar ratio of 2,6-diaminopyridine and 2,6-dibromopyridine. Ligand bbppd has a C_2 fold symmetry, thus only half carbons of the skeleton were observed in the ^{13}C NMR.

3.2. The crystal stucture and properties of the key building block bppd

The single crystal of compound bppd was obtained from a mixture of ethyl acetate and hexane by the layer diffusion technique. Four pairs of the intermolecular hydrogen bondings were observed through N4···N1A (3.004 Å), N3···N2A (3.571 Å) and N2···N3A (3.571 Å), N1···N4A (3.004 Å) in sequential order within a dimer (Fig. 1). Two middle hydrogen bondings are longer than the terminal ones because the middle ones have more constraint in packing formation. There are two other intermolecular hydrogen bondings observed: one was constructed through the hydrogen atom of the 'amine end' to the 'Br atom' of another molecule (bppd) at the adjacent layer, and the other from the 'Br atom' to the 'NH_2 end' of another molecular (bppd) at the same surface.

It was also observed that all (bppd) molecules possessed the head-to-tail packing, and there was no distinct π–π interaction (it usually occurs at ~3.4 Å) between the pyridine planes in the layered structure (Fig. 2). In the case of bppd, the dihedral angle between Br–pyridine and NH_2–pyridine is 32.89°, and both Br–pyridine and NH_2–pyridine can form the 'least square planes' individually. The 'least square plane' for Br–pyridine is 4.20 Å (dihedral angle = 0°), and for NH_2–pyridine is 2.47 Å (dihedral angle = 0°).

Based on the NMR study, the chemical shift of the N–*H* group in the skeleton backbone appeared at 9.54 ppm, and this peak did not show clear change caused by intermolecular hydrogen bondings in various concentrations. This was presumably because that the dimer formation was favored under the tested concentrations. Ligand bppd (in CH_3OH) also showed high absorption in the UV–Vis region 206–329 nm; this phenomena represented the occurrence of the π to π* allowed



Scheme 1. The synthesis of compounds **1** and **2**.

transition. In the IR spectra of bppd, several N–H peaks were observed from a solid KBr pallet (3448, 3310, 3199, 3108, and 3093 cm^{-1}); however, they became only two peaks in CH_2Cl_2 solution (3505 and 3403 cm^{-1}) in the region of 3000–3600 cm^{-1}. The previous observation is due to different degrees of hydrogen bonding influences to the N–H stretches. It is consistent with that there are two sets (four pairs) of

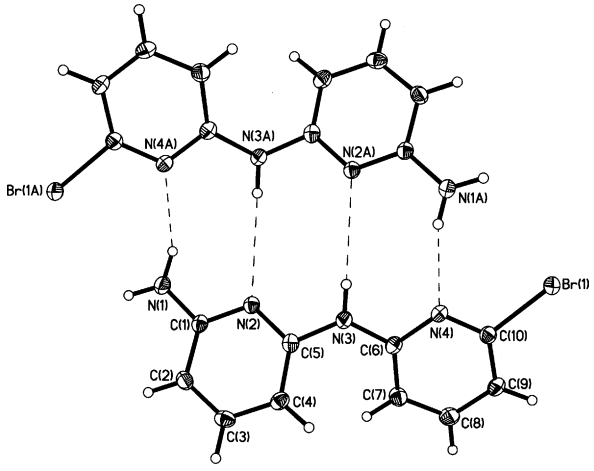


Fig. 1. The ORTEP structure and atom labeling of ligand bppd.

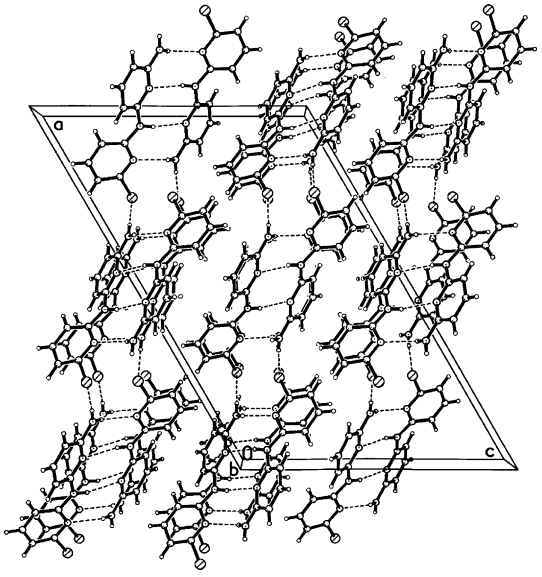


Fig. 2. The crystal packing of ligand bppd.

intermolecular hydrogen bondings exhibit within a dimer from the crystallographic evidence (Fig. 1).

3.3. The synthesis and properties of the bifunction oligo-α-aminopyridine ligands apppm and bpppm

Ligands apppm and bpppm were obtained via several steps starting from the key building block bppd. The purposes of introducing a *p*-toluenesulphonyl substitutent (Ts) into the ligands apppm and bpppm, is not only for protecting the end amino group of bppd from self-dimerization during the second aminated step, but also for stabilizing the formation of metal complex **1** by direct coordinating through the oxygen atom in the Ts group (Scheme 1). It is different from the previously reported case in which a direct formation of nitrogen–metal bond of the similar ligand is observed in $[Cu_3^I L_2]^-$ [12]. Sulphonylation of ligand bppd yielded the quantitative ligand bppm in the second step of the aminated coupling. The ligand bppm was used next for apppm synthesis without further purification.

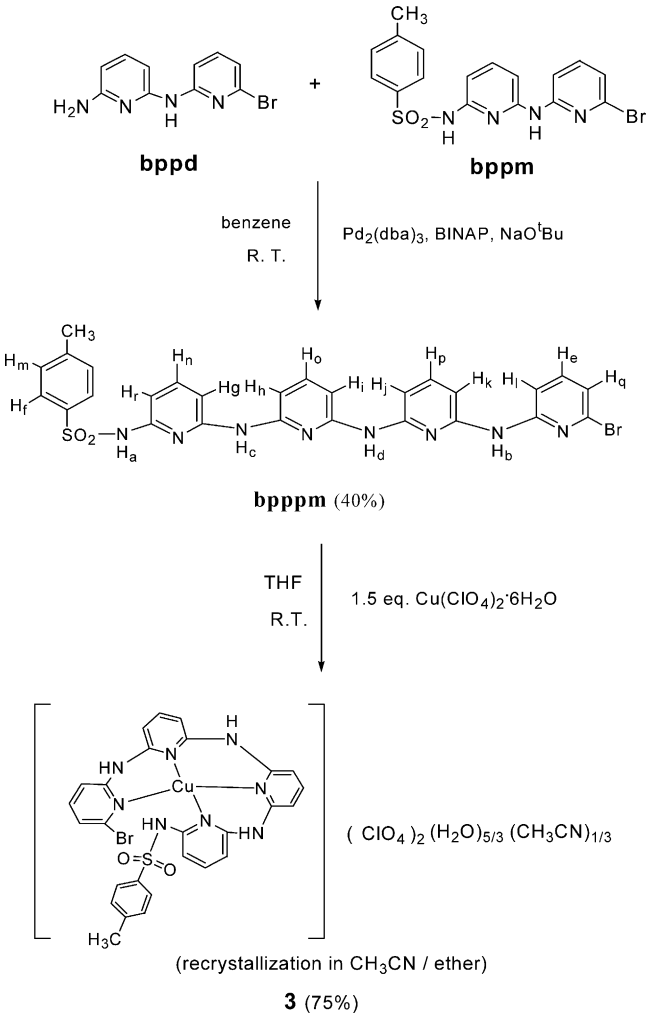
The bifunctional oligo-α-aminopyridine apppm was obtained in a yield of 60% by the Buchwald's palladium-catalyzed coupling of bppm and 2,6-diaminopyridine. To get the higher yield in apppm, it was critical to avoid the formation of the side products, such as polymers and the elimination products, by not mixing $Pd_2(dba)_3$, BINAP and NaO^tBu at the very beginning of the reaction. Based on the NMR study, strong intermolecular hydrogen bonding was observed in ligand apppm, the very broad peaks ($\delta = 8.8–9.5$) were recorded. The chemical shifts of these peaks were subjected to change in different concentrations of sample in d_6-DMSO. However, this feature was totally absent in the compounds bppd, bppm and bpppm. Both bppd and apppm showed strong hydrogen bondings and might serve as potential building blocks for the self-assembling materials [13], supramolecular tubes [14], and artificial ion channels [15].

In a similar approach, the bifunctional oligo-α-aminopyridine bpppm was obtained in a relatively low yield (40%) by coupling of bppd and bppm in similar palladium-catalyzed Buchwald's conditions. Attempts to improve the yields were not successful by manipulating the substrate ratios, or catalytic systems and solvents.

3.4. The preparation and crystallographic properties of copper complexes *1*, and *3*, and the salt *2*

The 6-coordinated copper complex **1** was synthesized by mixing $Cu(ClO_4)_2 \cdot 6H_2O$ and apppm in a molar ratio 1.5:1, and its violet single crystal was obtained from the mixed solvent DMF–THF/Et_2O by slow diffusion techniques. The protonated salt **2** was obtained by mixing $HClO_4$ and apppm in a molar ratio of 1.6:1, and its crystal was obtained from the THF/hexane by similar diffusion techniques (Scheme 1). The synthetic route for the compound **3** is illustrated in Scheme 2. The reddish-violet crystal of copper complex **3** could not be obtained from the previously reported DMF–THF/Et_2O system; however, it could be generated from CH_3CN/ether system by the diffusion techniques.

The single-crystal X-ray crystallographic analysis of compound **1** reveals that the Cu(II) is coordinated with the three nitrogen atoms of pyridine moieties with the distance of 1.965(5), 2.042(5), 2.061(5) Å, respectively. Besides, Cu(II) in **1** is also coordinated: (i) with an oxygen atom of the ligand apppm [2.377(4) Å]; (ii) strongly with one oxygen of the water molecule [1.951(5) Å]; and (iii) weakly with the oxygen atom of perchlorate anion [2.511(2) Å] (Fig. 3). The electronic configuration of the Cu(II) of compound **1** was $[Ar]3d^9$, and this



Scheme 2. The synthesis of compound **3**.

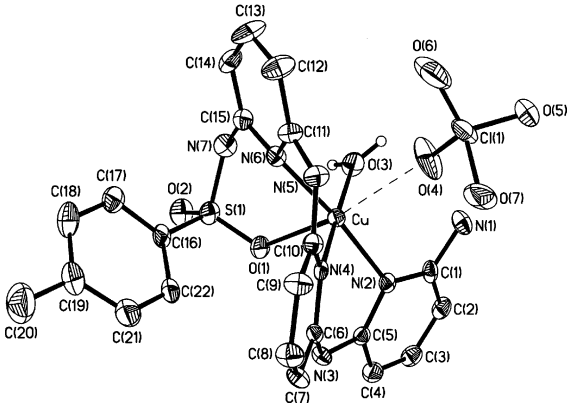


Fig. 3. The ORTEP structure of the cation part of compound **1**.

molecule showed a slightly distorted octahedral geometry resulting from the strong interactions between the metal center and both of water and the perchlorate [16]. In addition, the anti–anti conformation of N(2)–N(3)–N(4) and the twisted syn–anti conformation of N(4)–N(5)–N(6) played important roles as well. The geometry of compound **1** is different from the tetrahedral [10a], square planar [10b], square pyramid [10b], or trigonal planar [9g] ones for most of commonly related complexes. Based on the packing structure of compound **1**, it is known that another ClO_4^- and two THF joined the formation of this particular molecular cell, and only parts of hydrogen bondings are depicted in Fig. 4 for the reason of legibility.

As indicated by the structures of compound **2** (Fig. 5), the protonated position was performed at the N(2), and the distance of the hydrogen bonding was reported in Table 1. Besides, the conformation of compound **2** for N(2)–N(3)–N(4) is anti–anti, and that of N(4)–N(5)–N(6) is anti–syn. The crystal packing of compound **2** is shown in Fig. 6. The hydrogen bondings of this compound were not all drawn to avoid the complication for legibility reason.

The crystal structure for Cu(II) in the compound **3** displayed surprisingly a twisted square planar geometry despite of the great similarities between the ligands apppm and bpppm. This may be due to all nitrogen atoms in bpppm have the trans–trans conformation so that the backbone structure of the ligand without any skewness is most favored. The bond lengths between Cu(1)–N(1), Cu(1)–N(3), Cu(1)–N(5), and Cu(1)–N(7) are 1.985, 1.952, 1.959, 1.972 Å, respectively basing on the X-ray structure of compound **3** as shown in Fig. 7. The detailed comparisons of all hydrogen bondings for the compounds **1**–**3** are shown in Table 1, where only compound **2** possessed two intramolecular hydrogen bondings. For comparisons, the X-ray crystallographic data of the compounds bppd, **1**, **2**, and **3** are listed in the Table 2, where the space groups of bppd, **1**, and **2** are monoclinic, and that of **3** is triclinic.

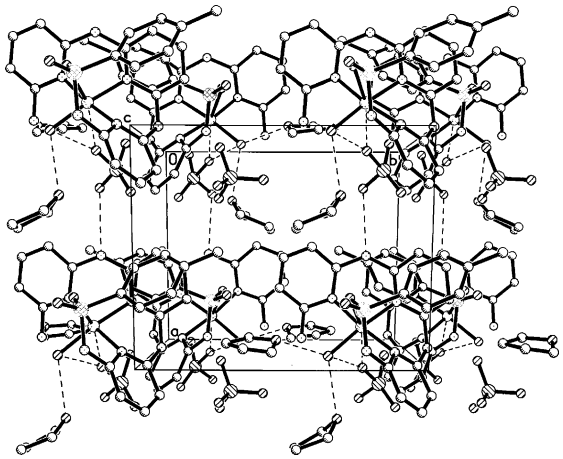


Fig. 4. The crystal packing of compound **1**.

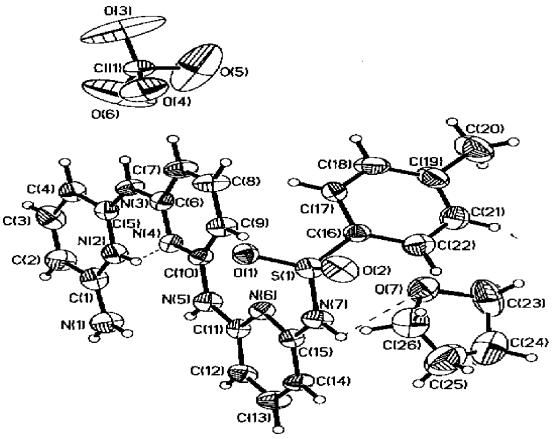


Fig. 5. The ORTEP structure and atom labeling of compound **2**.

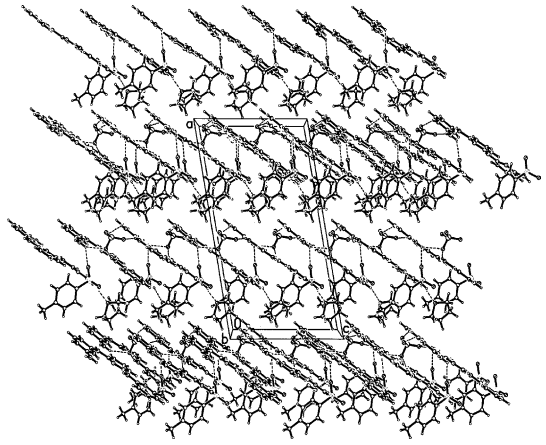


Fig. 6. The crystal packing of compound **2**.

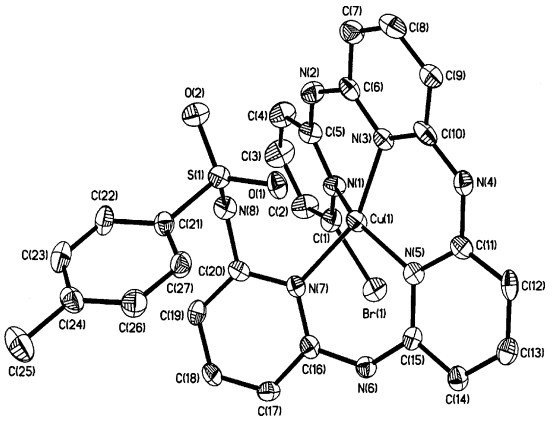


Fig. 7. The ORTEP structure of the cation in compound **3**.

4. Conclusion

This work presents the synthesis of the bifunctional oligo-α-aminopyridines with optimized yields by employing the base-induced reactions ($NaNH_2$ and pyridine) and the Buchwald's palladium-catalyzed coupling. The compounds **1**–**3** and the ligands bppd and apppm have all shown intermolecular hydrogen bondings. The single X-ray crystallographic data of the new bifunctional oligo-α-aminopyridine metal complexes, $[Cu(apppm)(ClO_4)(H_2O)](ClO_4)\cdot 2THF$ (**1**) and $[Cu(bpppm)](ClO_4)_2\cdot(H_2O)_{5/3}\cdot(CH_3CN)_{1/3}$ (**3**), were prepared and characterized. Based on the X-ray diffraction study of these copper complexes, a distorted octahedral geometry in **1** and a twisted square planar geometry in **3**.

Table 1
The comparisons of selected hydrogen bonding distances (Å) for compounds **1**–**3**

Types of bonding	**1**	**2**	**3**
	$[Cu(apppm)(ClO_4)(H_2O)](ClO_4)\cdot 2THF$	$[H(appm)](ClO_4)\cdot THF$	$[Cu(bpppm)](ClO_4)_2\cdot(H_2O)_{5/3}\cdot(CH_3CN)_{1/3}$
Intermolecular			
	$(H_2O)O3\cdots O12$ (THF) (2.659 Å)	N2···N4 (2.695 Å)	N4···O11 (ClO_4) (2.556 Å)
	$(H_2O)O3\cdots O13$ (THF) (2.655 Å)	(THF)O7···N7 (1.957 Å)	N6···O11 (ClO_4) (2.986 Å)
	$(ClO_4)O4\cdots N6$ (ligand) (3.319 Å)	$(ClO_4)O5\cdots N5$ (3.371Å)	N10···O25 (ClO_4) (3.199 Å)
	$(ClO_4)O5\cdots N3$ (ligand) (2.954 Å)	$(ClO_4)O5\cdots N1$ (3.158 Å)	N10···O31 (H_2O) (2.940 Å)
	$(ClO_4)O6\cdots N3$ (ligand) (3.311 Å)	$(SO_2)O1\cdots N1$ (2.387 Å)	N12···O35 (ClO_4) (2.867 Å)
	$(ClO_4)O6\cdots N5$ (ligand) (3.222 Å)		N12···O30′ (ClO_4) (3.130 Å)
	$(ClO_4)O7\cdots N5$ (ligand) (2.943 Å)		N14···O22 (ClO_4) (3.029 Å)
	$(ClO_4)O9\cdots N7$ (ligand) (2.974 Å)		N14···O23 (ClO_4) (3.235 Å)
			N16···O32 (H_2O) (2.884 Å)
			N18···O32 (H_2O) (2.978 Å)
			N20···O18 (ClO_4) (2.963 Å)
			N22···O24 (ClO_4) (2.893 Å)
			N22···O21 (ClO_4) (3.244 Å)
			N22···O35 (ClO_4) (3.283 Å)
			N24···O31 (H_2O) (2.912 Å)
Intramolecular			
		$(ClO_4)O4\cdots N3$ (3.029 Å)	
		$(ClO_4)O4\cdots N1$ (3.230 Å)	

Table 2
The crystallographic data of compounds bppd, **1**, **2** and **3**

Parameters	Ligand	**1**	**2**	**3**
	Bppd	[Cu(apppm)(ClO_4)(H_2O)]-(ClO_4)·2THF	[H(appm)]-(ClO_4)·THF	[Cu(bpppm)](ClO_4)$_2$·(H_2O)$_{5/3}$·(CH_3CN)$_{1/3}$
Empirical formula	$C_{10}H_9BrN_4$	$C_{30}H_{39}Cl_2CuN_7O_{13}S$	$C_{26}H_{30}ClN_7O_7S$	$C_{27.67}H_{27.33}BrCl_2CuN_{8.33}O_{11.67}S$
Formula weight	265.12	872.18	620.08	909.66
Temperature (K)	150	150	295	150
Radiation λ (Å)	0.71073	0.71073	0.71073	0.71073
Crystal system	monoclinic	monoclinic	monoclinic	Triclinic
Space group	*C*2/*c*	*Pc*	*Cc*	$P\bar{1}$
Dimension (mm^3)	0.30 × 0.25 × 0.20	0.30 × 0.15 × 0.03	0.25 × 0.12 × 0.05	0.23 × 0.15 × 0.15
Unit cell dimensions				
a (Å)	24.8531(2)	9.5897(1)	22.922(5)	12.0709(2)
b (Å)	5.69390(10)	11.4034(1)	10.205(2)	17.5632(3)
c (Å)	16.4191(2)	17.5163(1)	12.795(3)	24.9333(5)
α (°)	90	90	90	72.8798(9)
β (°)	120.512	104.696(1)	100.69(3)	86.8801(9)
γ (°)	90	90	90	87.4533(7)
V (Å^3)	2001.73(5)	1852.83(3)	2941.1(10)	5042.00(16)
Z	8	2	4	6
D_{calc} (g cm^{-3})	1.759	1.563	1.400	1.798
μ (mm^{-1})	4.076	0.863	0.257	2.136
Diffractometer	SMART CCD	SMART CCD[b]	NONIUS CAD4	KappaCCD
θ Range (°)	1.90–27.50	1.79–26.38	1.81–25.00	1.26–25.00
T_{min}/T_{max}	0.4031/0.4861	0.6776/0.8621	0.8703/0.9527	0.657/0.738
Independent reflections	2312 (R_{int} = 0.0172)	7045 (R_{int} = 0.0369)	2592	17724 (R_{int} = 0.0777)
Goodness-of-fit on F^2	1.066	1.053	1.009	1.035
R_1 [a]/wR_2 [$I > 2\sigma(I)$]	0.0203/0.0549	0.0626/0.1474	0.0519/0.1340	0.0913/0.2320

[a] The functions minimized during least-squares cycles were $R = \Sigma\,||F_o| - |F_c||/\Sigma\,|F_o|$. $R_w(F_o^2) = [\Sigma\{w(F_o^2 - F_c^2)^2\}/\Sigma\,\{w(F_o^2)^2\}]^{1/2}$.

5. Supplementary material

Crystallographic data for the structural analysis have been registered in the Cambridge Crystallographic Data Center, CCDC Nos. 178279–81, for compounds bppd, **1**, and the salt **2**, respectively and CCDC No. 199290, for the compound **3**. Copies of this information may be obtained free of charge from The Director, CCDC, 12 Union Road, Cambridge, CB2 1EZ, UK (fax: +44-1223-336-033; e-mail: deposit@ccdc.cam.ac.uk or www: http://www.ccdc.cam.ac.uk).

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