Notes

S- and NH- Bridging Pyridine- and Pyrimidine-Based Ligands for 2 × 2, 3 × 3 and 4 × 4 Molecular Grids: Evidence of [2 × 2]Zn(II) Grids

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Supramolecular arrays generated by self-assembly of metal ions and organic ligands are of interest in the field of supramolecular chemistry.[1] A certain class of coordination arrays such as molecular-helicates, -racks and -grids can potentially be developed into information storage devices by switching the redox states of metal ions.[2] The topology of the complex can be controlled by the coordination chemistry of metals and the chemical structure of the organic ligands. Heterocyclic ligands containing nitrogen donor such as pyridine, pyrimidine and pyridazine derivatives have received much attention due to their ability to bind metal ions and to produce complexes in many forms and geometries. Lehn and colleagues employed rigid ligands such as 3,6-bis(2'-pyridyl)pyridazine[3] and 6,6'-bis[2-(6-methylpyridyl)]-3,3'-bipyridazine[4] which can chelate Cu(I) and Ag(I) ions in a bidentate fashion and form **[2 × 2]Cu(I)** and **[3 × 3]Ag(I)** molecular grids, respectively. However, there are still needs of more flexible and efficient ligands for generating larger molecular grids and for facilitating the fabrication of molecular electronics. This can be fulfilled by adding bridging groups such as S or NH between each binding site of a heterocyclic ligand. The sulfide bridge can support the grid formation on gold surface and the NH group (when it is reduced to N^-) can be used to regulate the charge of the synthesized molecular grids. Furthermore, both S and NH can be used as donor providing an appropriate geometry in metal ion coordination. This article describes the synthesis of ligands containing pyridine and pyrimidine units with 2-4 available binding sites bridging by sulfide or NH group to accommodate metal ions possessing 4-6 coordination. The formation of 2 × 2 molecular grids with Zn(II) was also investigated.

Experimental Section

Materials and Physical Measurements. Dichloromethane was dried by the standard procedure.[5] Bis-trifluorosulfonatezinc(II), 2-mercaptopyridine, 4,6-dichloropyrimidine and anhydrous *N*,*N*-dimethylformamide were purchased from Aldrich Chemical Company. 2-Methyl-4,6-dichloropyrimidine,[6] 2-mercapto-4,6-dimethylpyridine,[7,8] 4,6-dimercaptopyrimidine,[9] *N*-trimethylsilyl-2-amino-4,6-dimethyl pyridine[10] and compound **1**[11] were prepared according to the published procedures. Unless otherwise noted, reactions were performed under argon or nitrogen atmosphere.

NMR spectra were recorded at 200 MHz on a Bruker AC200 NMR spectrometer and at 500 MHz on a Geol NMR spectrometer. The FAB mass spectra were obtained on a VG-Analytical ZAB HF apparatus. In a typical experiment, a solution (CH_2Cl_2/CH_3CN, 95/5 v/v) of **Zn-1**, **Zn-2** or **Zn-3** was introduced into the MS machine. UV-visible spectra were recorded on a Spectronic 3000 array spectrophotometer.

Preparation of 2-Methyl-4,6-di(2-mercapto-4,6-dimethylpyridyl)pyrimidine, 2. Under argon atmosphere, 2-mercapto-4,6-dimethylpyridine (2.80 g, 20 mmol) was added to an ethanolic solution (30 mL) of Na (0.50 g, 22 mmol). The mixture was stirred until the sodium metal dissolved. Then, an ethanolic solution (30 mL) of 2-methyl-4,6-dichloropyrimidine (1.63 g, 10 mmol) was added, and the reaction mixture was heated at reflux for 4 h. The suspension was evaporated to dryness. The residue was subsequently redissolved in ether (100 mL) and heated at reflux for another 15 min. The suspension was filtered through a short alumina column (10 cm, 4 cm dia.) employing ether as an eluant. The solvent was removed by rotary evaporator, and an oily residue was obtained. The residue was redissolved in ether (10 mL) and *n*-hexane (30 mL) was then layered on. The mixture was left at -10 °C overnight. The product **2** crystallized as colorless crystal which was subsequently washed with n-pentane (30 mL) and dried. (2.06 g, 56%) ^{1}H NMR (200 MHz, δ in $CDCl_3$): 7.20 (d, J = 1.2, 2H); 6.90 (d, J = 1.2, 2H); 6.61 (s, 1H); 2.53 (s, 3H); 2.39 (s, 6H); 2.28 (s, 6H). UV/vis (nm): 245, 292. FAB MS (M^+, m/z): 369.

Preparation of 4,6-Di-(4,6-dimethl-2-pyridylamino)-2-methylpyrimidine, 3. A 1.6 M hexane solution (10 mL) of n-butyllithium was added slowly to a cool (-50 °C) toluene solution (20 mL) of *N*-trimethylsilyl-2-amino-4,6-dimethylpyridine (3.11 g, 16 mmol). The solution was gradually warmed to room temperature, then heated to 50 °C and a toluene solution (10 mL) of 2-methyl-4,6-dichloropyrimidine (1.30 g, 8.0 mmol) was subsequently added dropwise. A deep red solution was formed and LiCl started to precipitate. The mixture was heated at reflux for 48 h and cooled to room temperature. A methanolic solution (20 mL) of KF (4.0 g, 68.8 mmol) was then added, and the mixture was held at 60 °C for 30 min. The mixture was consequently evaporated to dryness. The products were eluted with acetone through a short silica gel column. The orange-brown solid obtained after evaporation of the eluant contained the starting material, the monosubstituted pyrimidine and the desired compound **3**. Another chromatographic separation of the compounds (alumina, CH_2Cl_2/EtOAc 1 : 1) yielded a yellow solid which was recrystallized from ether/n-hexane (1 : 1) at -15 °C. (0.83 g, 31%). ^1H NMR (200 MHz, δ in $CDCl_3$): 7.76 (d, 2H); 7.08 (d, 2H); 6.60 (s, 1H); 2.49 (s, 3H); 2.41 (s, 6H); 2.28 (s, 6H). UV/vis (nm): 260, 292, 313. FAB MS (M^+, m/z): 335.

Preparation of 4,6-Di(4-mercapto-6-chloropyrimidyl) pyrimidine, 4. Into a mixture of 4,6-dichloropyrimidine (4.47 g, 30 mmol), 4,6-dimercaptopyrimidine (0.72 g, 5 mmol) and potassium carbonate (1.38, 10 mmol) was added anhydrous dimethylformamide (50 mL). Benzene (*ca*. 1 mL) was subsequently added to aid in condensation of the volatile pyrimidine. The mixture was heated at 100-110 °C for 1.5 h and was then cooled to room temperature. The solvent was removed by a rotary evaporator. The product was then separated on an alumina (neutral) column using methylene chloride as eluant (0.97 g, 54%). ^1H NMR (200 MHz, δ in $CDCl_3$): 7.80 (s, 2H); 8.02 (s, 1H); 8.88 (s, 2H); 8.99 (s, 1 H). FAB MS (M^+, m/z): 368.9.

Preparation of Compound 5. Into a mixture of 2-mercaptopyridine (0.77 g, 6.90 mmol), potassium carbonate (0.47 g, 3.45 mmol) and acetone (40 mL) was added **4** (0.50 g, 1.38 mmol). The mixture was stirred at room temperature under argon blanket for 7 h and the solvent was then evaporated to dryness. The mixture was redissolved in a small amount of CH_2C1_2 and placed on an alumina column. Elution with 5% acetone in CH_2Cl_2 yielded an oily yellow compound which can be solidified upon adding n-hexane and standing at 18 °C overnight. (0.24 g, 43%). ^1H NMR (500 MHz, δ in $CDCl_3$): 7.35 (m, 2H); 7.55 (d, J = 1.2, 2H); 7.65 (m, 2H); 7.78 (m, 2H); 8.67 (m, 2H); 8.71 (d, J = 1.2, 2H). FAB MS (M^+, m/z): 408.9.

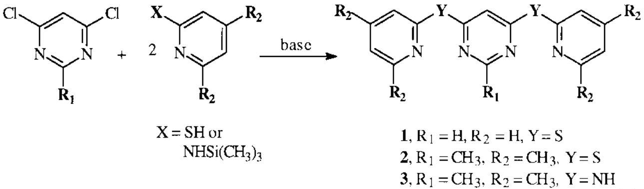
Preparation of Compound 6. In a similar fashion as the synthesis of **5**, the reaction between compound **4** (0.22 g, 0.59 mmol) and 2-mercapto-4,6-dimethylpyridine (0.25 g, 1.77 mmol) in the presence of potassium carbonate (0.16 g, 1.18 mmol) in acetone (25 mL) resulted in compound **6** (0.12 g, 45%). ^1H NMR (200 MHz, δ in $CDCl_3$): 2.23 (s, 6H); 2.51 (s, 6H); 7.03 (d, J = 1.2, 2H); 7.29 (d, J = 1.2, 2H); 7.41 (d, J = 1.2, 2H); 8.63 (d, J = 1.2, 2H). FAB MS (M^+, m/z): 465.1.

Preparation of Compound 7. Into a mixture of 2-mercaptopyridine (0.25 g, 2.30 mmol), potassium carbonate (0.16 g, 1.18 mmol) and dry CH_2C1_2 (20 mL) was added **4** (0.22 g, 0.59 mmol). The mixture was stirred at room temperature under argon blanket for 18 h. The solvent was then evaporated to dryness. The residue was redissolved in a small amount of CH_2Cl_2 and placed on an alumina column. Elution with 5% acetone in CH_2C1_2 yielded an oily product which was crystallized as white crystal upon adding *n*-hexane into its CH_2C1_2 solution (0.09 g, 32%). ^1H NMR (500 MHz, δ in $CDCl_3$): 7.36 (m, 2H); 7.61 (d, J = 1.2, 2H); 7.67 (m, 2H); 7.78 (m, 2H); 7.94 (d, J = 1.2, 1H); 8.67 (m, 2H); 8.75 (d, J = 1.2, 1H); 8.80 (d, J = 1.2, 2H). FAB MS (M^+, m/z): 518.9.

Preparation of Compound 8. In a similar manner as the synthesis of **7**, the reaction between 2-mercapto-4,6-dimethylpyridine (0.21 g, 1.50 mmol) and **4** (0.14 g, 0.37 mmol) in the presence of potassium carbonate (0.13 g, 0.93 mmol) in dry dichloromethane (25 mL) yielded compound **8** as white solid (0.09 g, 43%). ^1H NMR (200 MHz, δ in $CDCl_3$): 2.34 (s, 6H); 2.52 (s, 6H); 7.03 (s, 2H); 7.30 (s, 2 H); 7.47 (d, J = 1.2, 2H); 7.94 (d, J = 1.2, 1H); 8.63 (d, J = 1.2, 1H); 8.76 (d, J = 1.2, 2H). FAB MS (M^+, m/z): 575.1.

Results and Discussion

Synthesis. Ligands for 2 × 2 molecular grids containing sulfur and amine bridges were basically prepared from nucleophilic aromatic substitution reactions between 2-methyl-4,6-dichloropyrimidine and mercaptopyridine or aminopyridine as shown in Eq. (1). The ligand **1**, was synthesized according to the procedure reported by Chen *et al.*[11] Similarly, nucleophilic substitution of chloride in 2-methyl-4,6-dichloropyrimidine by 2 equivalent of 2-mercapto-4,6-dimethylpyridine produced the sulfur bridging ligand **2** in 56% yield. Both ^1H NMR and FAB MS confirm the desired molecular structure.

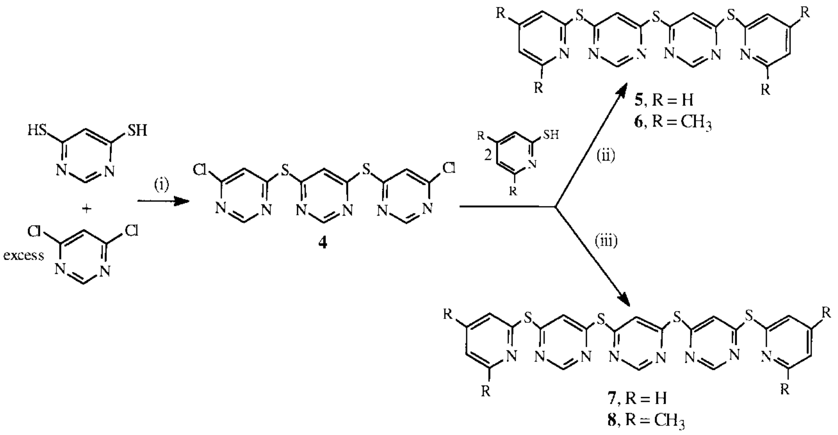


(1)

The amine bridging ligand, **3**, however, requires more steps for preparation than the analogue **2** does. The starting 2-amino-4,6-dimethylpyridine needed to be protected by a trimethylsilyl group before the substitution reaction took place. The reaction of the protected ligand with 4,6-dichloro-2-methylpyrimidine in the presence of n-butyllithium yielded the ligand **3** in 31%. The FAB mass spectrum of the ligand **3** gave a very strong signal (100%) at 335 m/z, and ^1H NMR spectrum also agreed well with the proposed structure. In addition, compared to **1** and **2**, the ligand **3** showed an intense blue fluorescence absorption at 254 nm.

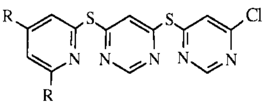
In the similar fashion as ligands **1-3**, ligands for 3 × 3 and 4 × 4 molecular grids, **5-8**, can be synthesized essentially from nucleophilic aromatic substitution reactions of mercaptopyridine on the chloro leaving groups of 4,6-di(4-mercapto-6-chloropyrimidyl)pyrimidine, **4**, as shown in Scheme 1. The compound **4** was obtained in 54% from the reaction of 4,6-dimercaptopyrimidine with an excess amount of 4,6-dichloropyrimidine in dry DMF in the presence of potassium carbonate. ^1H NMR and FAB MS of **4** agree well with the molecular structure.

Reactions between **4** and 2-mercaptopyridine or 2-mercapto-4,6-dimethylpyridine should give ligands for 4 × 4 molecular grids. However, we found that products obtained

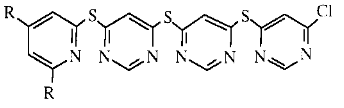


Scheme 1. Synthetic procedures for ligands for 3 × 3 and 4 × 4 molecular grids. (i) K_2CO_3/DMF (ii) K_2CO_3/acetone (iii) K_2CO_3/CH_2Cl_2.

from such reactions depend largely on solvents employed. At room temperature, the reaction carried out in acetone solution gave the three-binding-site ligands **5** and **6** (43% and 45%, respectively) as main products while reactions in CH_2Cl_2 gave the four-binding-site ligands, **7** and **8**, in 32% and 43%, respectively. Upon heating or refluxing the above reaction in chloroform resulted in disintegrated products, **9** and **10**, and monoalkylated products, **11** and **12**.

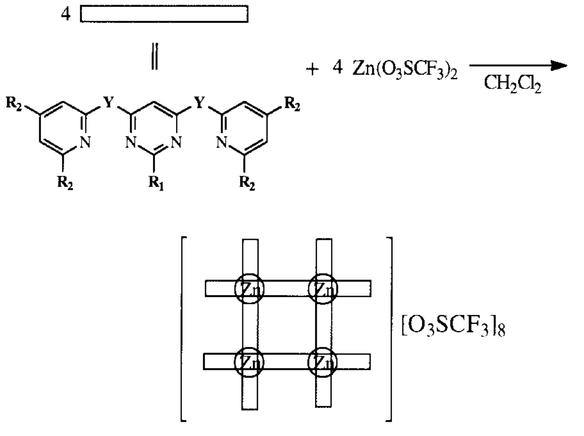


9, R = H
10, R = CH_3



11, R = H
12, R = CH_3

2 × 2 Molecular Grid Formation. In order to obtain molecular grids, we decided to use a 4-coordinate metal ion, Zn(II), for self-assembly of ligands **1-3** to confine the shape of the complex to a square grid fashion. Non-coordinate anion, triflate, was used as counter anion so that the counter anion would not interfere with the coordination sphere of the metal ion. The general procedure for preparation of 2 × 2 molecular grids is shown in Eq. (2). Under inert atmosphere, $Zn(O_3SCF_3)_2$ (0.363 g, 0.1 mol) was added into a solution (CH_2Cl_2, 25 mL) of ligand **1** (0.298 g, 1 mmol). White solid of **Zn-1** precipitated after stirring for 30 minutes (0.612 g, 92%). The solid turned slightly yellow after standing for several days in air. In a similar fashion, $Zn(O_3SCF_3)_2$ (0.040 g, 0.11 mmol) was added into a CH_2Cl_2 solution (5 mL) of Ligand **2** (0.037 g, 0.10 mmol) and the mixture was stirred for 24 hours. The white solid of **Zn-2** precipitated from the solution and was separated by filtration (0.044 g, 60%). **Zn-3** (0.073 g, 74%) also precipitated from the stirred solution of Ligand **3** (0.033 g, 0.1 mmol) and $Zn(O_3SCF_3)_2$ (0.036 g, 0.1 mmol).



(2)

Zn-1, R_1 = H, R_2 = H, Y = S
Zn-2, $R_1 = CH_3$, $R_2 = CH_3$, Y = S
Zn-3, $R_1 = CH_3$, $R_2 = CH_3$, Y = NH

There are a few structural methods such as X-ray crystallography, NMR and mass spectroscopy used in characterization of supramolecular structures.[12] Unfortunately, the single crystals of **Zn-1**, **Zn-2** and **Zn-3** complexes cannot be obtained due to hygroscopic nature of the Zn(II) complexes. Many research groups have used various mass spectrometry techniques such as electrospray and coldspray ionization mass spectrometry for determining self-assembly inorganic architectures.[13] We have found that FAB MS is the most appropriate technique for our complexes. The calculated charged peaks of [2 × 2]Zn grids of our ligands are shown in Table 1. FAB mass spectrum of **Zn-1** showed an intense signal (100% relative abundance) at m/z 512.9 corresponding to $[Zn_4(C_{14}H_{10}N_4S_2)_4(O_3SCF_3)_4]^{4+}$ and a low intensity peak (20%) at m/z 1174.8 due to the $[Zn_4(C_{14}H_{10}N_4S_2)_4(O_3SCF_3)_6]^{2+}$ species. Mass spectrum of **Zn-2** possessed an intense signal (100%) at 582.9 m/z corresponding to $[Zn_4(C_{19}H_{20}N_4S_2)_4(O_3SCF_3)_4]^{4+}$ and a very weak signal (4%) at m/z 1314.7 corresponding to $[Zn_4(C_{19}H_{20}N_4S_2)_4(O_3SCF_3)_6]^{2+}$. The amine

Table 1. Expected Multiply-Charged Peaks of [2 × 2]Zn(II) Grids in FAB Mass Spectra (trf = triflate ion)

Charged species	Calculated m/z		
	L = **1**	L = **2**	L = **3**
$[Zn_4L_4(trf)_7]^{+}$	2498.4	2779.0	2642.6
$[Zn_4L_4(trf)_6]^{2+}$	1174.7	1314.9	1246.8
$[Zn_4L_4(trf)_5]^{3+}$	733.4	826.9	781.5
$[Zn_4L_4(trf)_4]^{4+}$	512.8	582.9	548.8

bridged molecular grid, **Zn-3**, showed FAB MS signals at m/z 548.7 (100%) and at m/z 1246.7 (1%) corresponding to $[Zn_4(C_{19}H_{22}N_6)_4(O_3SCF_3)_4]^{4+}$ and $[Zn_4(C_{19}H_{22}N_6)_4(O_3SCF_3)_6]^{2+}$ species, respectively. Thus, FAB MS was able to detect only +2 and +4 charged species of **Zn-1**, **Zn-2** and **Zn-3** complexes. These charged species may be the most stable ones existing in conditions used for FAB measurement.

Besides FAB MS, other techniques such as NMR spectroscopy can be used to support the formation of molecular grids. Due to the insolubility of grid complexes, $Zn(O_3SCF_3)_2$ (0.02 mmol) was added directly to solutions ($CDCl_3$) of ligands **1-3** (0.02 mmol) in NMR tubes. The mixture was left to stand overnight before ^{1}H NMR spectrum of the mixture was recorded. All except **Zn-2** precipitated out of the solution. Therefore, only **Zn-2** can be elucidated by ^{1}H NMR. Although ^{1}H NMR spectrum of the complex **Zn-2** showed the same pattern as that of the free ligand **2**, the chemical shifts before and after complexation changed dramatically.[14] The shifting of signals is pertinent to the results obtained from complexation studies of ligands containing N donor groups towards Zn^{2+} by ^{1}H NMR titrations in which all signals also shifted downfield upon addition of Zn^{2+}.[15] The result thus indicates that Zn^{2+} ions coordinate to the ligand **2** and the complex **Zn-2** possesses a symmetric structure of the 2×2 grid.

^{1}H NMR and FAB mass spectral data indicated that ligands **1-3** were able to react with $Zn(O_3SCF_3)_2$ and gave 2x2 molecular grids. We are currently find the way to make 3x3 and 4x4 molecular grids from ligands **5-8** which will require more advanced and powerful techniques for characterization and will report the results in due course.

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14. ^{1}H NMR after complexation are 7.49 (d, J = 1.2, 2H); 7.28 (d, J = 1.2, 2H); 7.22 (s, 1H); 2.67 (s, 3H); 2.71 (s, 6H); 2.48 (s, 6H).
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