

## 基于柔性多元羧酸配体构筑的两例过渡金属 配位聚合物的合成、结构及性质

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**摘要:** 以柔性配体 5-(吡啶-2-甲氧基)-间苯二甲酸为主配体在水热条件下合成了 2 例过渡金属配位聚合物  $[\text{Cu}(\text{L})\cdot\text{H}_2\text{O}]_n$  (**1**),  $[\{\text{Co}(\text{L})\cdot\text{H}_2\text{O}\}_2\cdot 5\text{H}_2\text{O}]_n$  (**2**) ( $\text{H}_2\text{L}$ =5-(吡啶-2-甲氧基)-间苯二甲酸), 并通过 X 射线单晶衍射、红外光谱、X 射线粉末衍射、元素分析和热重分析方法对其进行表征。结构分析表明: 配合物 **1** 为单斜晶系  $P2_1/n$  空间群的二维平面结构, 并呈现 2-节点(3,4)-连接的拓扑网络。**2** 为三斜晶系,  $P\bar{1}$  空间群的一维链状结构, 在分子间氢键的作用下构筑出三维超分子网络结构。同时对配合物 **1** 和 **2** 进行了发光性质的研究。

**关键词:** 5-(吡啶-2-甲氧基)-间苯二甲酸; 水热反应; 柔性配体; 荧光

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## Two Transition Metal Coordination Complexes Based on a Flexible Pyridinecarboxylate Ligand: Syntheses, Structures, and Properties

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**Abstract:** Two transition metal coordination complexes  $[\text{Cu}(\text{L})\cdot\text{H}_2\text{O}]_n$  (**1**),  $[\{\text{Co}(\text{L})\text{H}_2\text{O}\}_2\cdot 5\text{H}_2\text{O}]_n$  (**2**) ( $\text{H}_2\text{L}$ =5-(pyridin-2-ylmethoxy)-isophthalic acid) were synthesized through hydrothermal method. They were characterized by single-crystal, IR, PXRD, elemental and TGA analyses. Structural analysis indicated that the complexes **1** and **2** were linked into infinite structures bridged by organic acid ligands. **1** crystallizes in the monoclinic system with  $P2_1/n$  space group and features a 2D layered structure, which possesses a 2-nodal (3,4)-connected topology; **2** crystallizes in triclinic system  $P\bar{1}$  space group with a 1D structure and further are connected to 3D supramolecular structure via hydrogen bonds. Moreover, compounds **1**~**2** exhibited photoluminescence in the solid state at room temperature. CCDC: 1430584, **1**; 1430585, **2**.

**Keywords:** 5-(pyridin-2-ylmethoxy)-isophthalic acid; hydrothermal reaction; flexible ligand; fluorescence

Crystal engineering of metal-organic frameworks (MOFs) have attracted intense interest not only for their intriguing architectures and topologies<sup>[1]</sup>, but also for their potential applications as functional materials in the field of luminescence, molecular recognition,

magnetism, catalysis, gas storage and so on<sup>[2-8]</sup>. In this aspect, considerable progress has been made on the theoretical prediction and network-based approaches for controlling the topology and geometries of the networks to produce useful functional materials<sup>[9-12]</sup>.

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But so far, how to reasonably design and synthesize metal-organic frameworks with anticipated structures remain a great challenge to chemists. It is quite difficult to select an appropriate organic ligand with suitable shape, functionality, flexibility, and symmetry, which helps us obtain the target products<sup>[13]</sup>. Therefore, systematic research on this topic is still very necessary for understanding the roles of the factors in the formation of metal-organic frameworks.

Pyridinecarboxylic ligand and their derivatives, exhibiting excellent coordination ability and diverse coordination modes, have been extensively employed to construct MOFs<sup>[14-17]</sup>. However, only a few compounds based on the flexible pyridinecarboxylate ligands have been reported<sup>[18-23]</sup>. Among them, 5-(pyridin-2-ylmethoxy)-isophthalic acid as a multifunctional organic ligand, contains a flexible -CH<sub>2</sub>-O- spacer between the pyridyl and phenyl ring, which not only makes it exhibits various coordination modes in the process of self-assembly but also can adopt a suitable configuration according to the requirements of metal ions. Here we selected flexible 5-(pyridin-2-ylmethoxy)-isophthalic acid (H<sub>2</sub>L)<sup>[24]</sup> as organic ligand, to react with different transition metal ions (Cu(II), Co(II)) under hydrothermal conditions, and successfully obtained two new coordination polymers, namely [Cu(L)·H<sub>2</sub>O]<sub>n</sub> (**1**) and {[Co(L)H<sub>2</sub>O]<sub>2</sub>·5H<sub>2</sub>O}<sub>n</sub> (**2**). All crystal structures have been determined by single-crystal X-ray diffraction, IR, elemental, PXRD and TGA analyses. Photoluminescence properties of two complexes have been studied.

## 1 Experimental

### 1.1 Materials and physical measurements

The reagents were used directly as supplied commercially without further purification. Elemental analyses (C, H, N) were determined with a Perkin-Elmer model 240C automatic instrument. Infrared spectra on KBr pellets were recorded on a Bruker Equinox-55 spectrometer in the range of 4 000~400 cm<sup>-1</sup>. Luminescence spectra for the solid samples were investigated with a Hitachi F-4500 fluorescence spectrophotometer. The X-ray powder diffraction

pattern was recorded with a Rigaku D/Max III diffractometer (40 kV, 40 mA), using Cu K $\alpha$  radiation ( $\lambda$ =0.015 42 nm) with a  $2\theta$  range of 5°~50°. Thermal analysis was determined with a Netzsch STA 449C microanalyzer under flowing N<sub>2</sub> atmosphere at a heating rate of 10 °C·min<sup>-1</sup>.

### 1.2 Synthesis of [Cu(L)·H<sub>2</sub>O]<sub>n</sub> (**1**)

Compound **1** was obtained as blue stick-shaped crystals by treatment of Cu(NO<sub>3</sub>)<sub>2</sub> with H<sub>2</sub>L under the hydrothermal system. A mixture of Cu(NO<sub>3</sub>)<sub>2</sub>·3H<sub>2</sub>O (0.05 mmol, 0.012 1 g), H<sub>2</sub>L ligand (0.05 mmol, 0.013 7 g), H<sub>2</sub>O (9.0 mL), and NaOH (25%, 0.1 mL) solution was stirred under air atmosphere for half an hour. Then the mixture was transferred to a 25 mL stainless steel reactor with Teflon liner and held at 145 °C for 72 h. The reaction system was cooled to room temperature at a rate of 5 °C·h<sup>-1</sup>. A large amount of compound **1** were obtained in 46% yield based on Cu(NO<sub>3</sub>)<sub>2</sub>·3H<sub>2</sub>O. Anal. Calcd. for CuC<sub>14</sub>H<sub>11</sub>NO<sub>6</sub>(%): C, 47.67; H, 3.14; N, 3.97. Found (%): C, 47.58; H, 3.09; N, 3.96. IR (KBr, cm<sup>-1</sup>): 3 201(m), 2 939(w), 1 616(m), 1 557(s), 1 361(s), 1 275(m), 1 235(w), 1 165(w), 1 117(m), 1 050(s), 921(m), 770 (m), 720(s).

### 1.3 Synthesis of {[Co(L)H<sub>2</sub>O]<sub>2</sub>·5H<sub>2</sub>O}<sub>n</sub> (**2**)

After pH value of the solution was adjusted to 7 with NaOH (1 mol·L<sup>-1</sup>), the mixture of Co(NO<sub>3</sub>)<sub>2</sub>·6H<sub>2</sub>O (0.05 mmol, 0.014 6 g), H<sub>2</sub>L (0.05 mmol, 0.013 7 g) and H<sub>2</sub>O (10 mL) were placed in a 25 mL Teflon-lined stainless steel reactor under autogenous pressure at 95 °C for 36 h. After the reaction system was cooled to room temperature, purple prism-shaped blocks were obtained, washed with distilled water, and dried. (Yield: 56% based on Co(NO<sub>3</sub>)<sub>2</sub>·6H<sub>2</sub>O). Anal. Calcd. for Co<sub>2</sub>C<sub>28</sub>H<sub>32</sub>N<sub>2</sub>O<sub>17</sub>(%): C 42.76, H 4.10, N 3.56; Found (%): C 42.59, H 4.29, N 3.36. IR (KBr, cm<sup>-1</sup>): 3 733(m), 3 665(w), 3 090(m), 2 925(m), 2 849(m), 1 619(m), 1 557(s), 1 451(m), 1 354(s), 1 230(m), 1 047 (m), 770(s), 716(m), 614(m), 456(w).

### 1.4 Crystallographic data collection and refinement

Diffraction experiments for compound **1~2** were carried out with Mo K $\alpha$  radiation using a BRUKER SMART APEX CCD diffractometer ( $\lambda$ =0.071 073 nm)

by using  $\varphi$ - $\omega$  scan technique with a potential of 40 kV and a current of 40 mA fitted with a graphite monochromator in the parallel mode (175 mm collimator with 0.5 mm pinholes). All intensity data were corrected for Lorentz and polarization effects (SAINT)<sup>[25]</sup>, and empirical absorption corrections based on equivalent reflections were applied (SADABS)<sup>[26]</sup>. The structure was solved using direct methods and successive Fourier difference synthesis (SHELXS-97)<sup>[27]</sup>,

and refined using the full-matrix least-squares method on  $F^2$  with anisotropic thermal parameters for all non-hydrogen atoms (SHELXL-97)<sup>[28]</sup>. The crystal data and the structure refinement of compounds are summarized in Table 1. Selected bond lengths and angles are listed in Table 2. Possible hydrogen bond geometries of complex **2** are listed in Table 3. All of the nonhydrogen atoms were refined anisotropically.

CCDC: 1430584, **1**; 1430585, **2**.

Table 1 Crystal data and structure parameters for complexes 1~2

Compound	<b>1</b>	<b>2</b>
Empirical formula	CuC <sub>14</sub> H <sub>11</sub> NO <sub>6</sub>	Co <sub>2</sub> C <sub>28</sub> H <sub>32</sub> N <sub>2</sub> O <sub>17</sub>
Formula weight	352.78	786.42
Crystal system	Monoclinic	Triclinic
Space group	$P2_1/n$	$P\bar{1}$
$a$ / nm	0.897 8(4)	0.809 3(6)
$b$ / nm	1.180 4(5)	0.930 1(6)
$c$ / nm	1.221 7(6)	1.090 5(7)
$\alpha$ / (°)	90	94.630(2)
$\beta$ / (°)	92.456 3(15)	101.347(2)
$\gamma$ / (°)	90	107.800(2)
$V$ / nm <sup>3</sup>	1.293 5(10)	0.757 6(9)
$Z$	4	1
Size / mm	0.221×0.093×0.072	0.21×0.20×0.19
$D_c$ / (g·cm <sup>-3</sup> )	1.812	1.724
$\mu$ / mm <sup>-1</sup>	1.720	1.182
$F(000)$	716	404
Reflections, collected	19 855, 2 981	10 516, 2 687
$R_{int}$	0.078 5	0.051 5
Goodness-of-fit on $F^2$	0.995	1.123
$R^a$ [ $I > 2\sigma(I)$ ]	$R_1=0.038$ 3, $wR_2=0.09$	$R_1=0.041$ 3, $wR_2=0.096$ 1
$R^a$ (all data)	$R_1=0.067$ 3, $wR_2=0.103$ 4	$R_1=0.048$ 3, $wR_2=0.100$ 8

$$^a R_1 = \sum ||F_o| - |F_c|| / \sum |F_o|; wR_2 = [\sum w(F_o^2 - F_c^2)^2 / \sum w(F_o^2)^2]^{1/2}$$

Table 2 Selected bond lengths (nm) and angles (°) for 1~2

Compound <b>1</b>					
Cu(1)-O(2)	0.194 3(2)	Cu(1)-N(1)	0.199 8(2)	Cu(1)-O(4)	0.195 7(19)
Cu(1)-O(1)	0.243 4(2)	Cu(1)-O(6)	0.197 0(2)	Cu(1)-O(5)	0.264 8(1)
O(2)-Cu(1)-O(4)	87.95(8)	O(6)-Cu(1)-N(1)	88.79(9)	O(2)-Cu(1)-O(6)	93.43(9)
O(2)-Cu(1)-O(1)	97.73(9)	O(4)-Cu(1)-O(6)	170.54(9)	O(4)-Cu(1)-O(1)	95.78(7)
O(2)-Cu(1)-N(1)	173.27(9)	O(6)-Cu(1)-O(1)	93.31(9)	O(4)-Cu(1)-N(1)	90.91(9)
O(5)-Cu(1)-O(1)	148.602(1)	O(5)-Cu(1)-O(6)	115.834(1)	O(5)-Cu(1)-O(2)	92.188(1)
O(5)-Cu(1)-N(1)	92.563(1)	O(5)-Cu(1)-O(4)	54.733(1)		

Continued Table 2

Compound 2					
Co(1)-O(2)#1	0.199 7(2)	Co(1)-O(1W)	0.205(2)	Co(1)-O(5)#2	0.200 5(2)
Co(1)-N(1)	0.205 1(2)	Co(1)-O(1)#2	0.241(2)		
O(2)#1-Co(1)-O(5)#2	104.06(9)	O(2)#1-Co(1)-N(1)	119.57(9)	O(2)#1-Co(1)-O(1W)	101.05(9)
O(5)#2-Co(1)-N(1)	123.31(9)	O(5)#2-Co(1)-O(1W)	96.16(9)	O(1W)-Co(1)-N(1)	108.00(9)
O(1)-Co(1)-O(5)#2	82.72(2)	O(1)-Co(1)-O(1W)	177.97(3)	O(1)-Co(1)-O(2)#1	80.88(2)
O(1)-Co(1)-N(1)	71.37(2)				

Table 3 Hydrogen-bonding geometries for compound 2

D-H...A	d(D-H) / nm	d(H...A) / nm	d(D...A) / nm	∠DHA / (°)
O1W-H1WA...O3W#3	0.088	0.184	0.267 4(5)	158
O1W-H1WB...O2#2	0.087	0.185	0.272 2(3)	172
O2W-H2WA...O2W#5	0.085	0.255	0.314 8(6)	128
O2W-H2WB...O4#1	0.085	0.208	0.279 9(4)	141
O3W-H3WA...O3#4	0.085	0.238	0.295 7(6)	125
O3W-H3WB...O2W#5	0.085	0.215	0.283 1(5)	138
O4W-H4WA...O3#4	0.085	0.197	0.281 5(6)	171
O4W-H4WB...O2W#5	0.085	0.205	0.289 5(8)	174

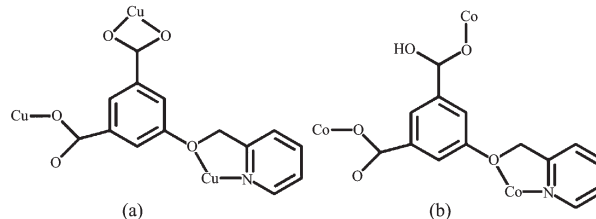
Symmetry codes: #1: 1-x, 1-y, 1-z; #2: 1+x, y, z; #3: x, -1+y, z; #4: -x, 1-y, 1-z; #5: 1-x, 1-y, -z

## 2 Results and discussion

### 2.1 Description of the structure of $[\text{Cu}(\text{L}) \cdot \text{H}_2\text{O}]_n$ (1)

X-ray single-crystal diffraction analysis reveals that **1** crystallizes in the monoclinic system with  $P2_1/n$  space group and features a 2D layered structure. Compound **1** asymmetric unit contains one crystallographically independent Cu(II) ions, one individual  $\text{L}^{2-}$  ligand as well as one coordinated water molecule. As shown in Fig.1a. Cu1 is six-coordinated by five oxygen and one nitrogen atom: one oxygen from coordinated water molecule and four carboxylate oxygen, one nitrogen atom from three different **L** ligands, displaying a distorted octahedral coordination geometry. The Cu-O distances are 0.194 3(2)~0.264 8(1) nm and the Cu-N distance is 0.199 8(2) nm, which are similar to the reported Cu-based compound<sup>[29-30]</sup>. Each **L** links three different Cu(II) centers in tridentate bridging mode with two carboxyl groups adopting  $\mu^2\text{-}\eta^1\text{:}\eta^1\text{:}\eta^1$ -bridging coordination mode (Scheme 1a). A 2D polymeric layer of **1** is generated by the extension of cyclic motif connectivity (Fig.1b). Further, the 2D

layers arrange in an offset way in the 3D supramolecular network along the *b* axis (Fig.1d). In order to fully understand the structure of compound **1** clearly, the topological method is used to simplify the structure. Further analysis suggests that such a subnet could be described as a simple 2D 2-nodal (3,4)-connected topology net with the point symbol of  $\{4.8\}^2$ , in which each  $\text{L}^{2-}$  ligands sever as the 3-connected linkers, while the Cu(II) center acts as a 4-connected node (Fig.1c).

Scheme 1 Coordination modes of **L** ligand in compounds **1**~**2**

### 2.2 Description of the structure of $\{[\text{Co}(\text{L})\text{H}_2\text{O}]_2 \cdot 5\text{H}_2\text{O}\}_n$ (2)

The single crystallographic analysis reveals that complex **2** crystallizes in triclinic system  $P\bar{1}$  space group. The asymmetric unit of complex **2** is made up

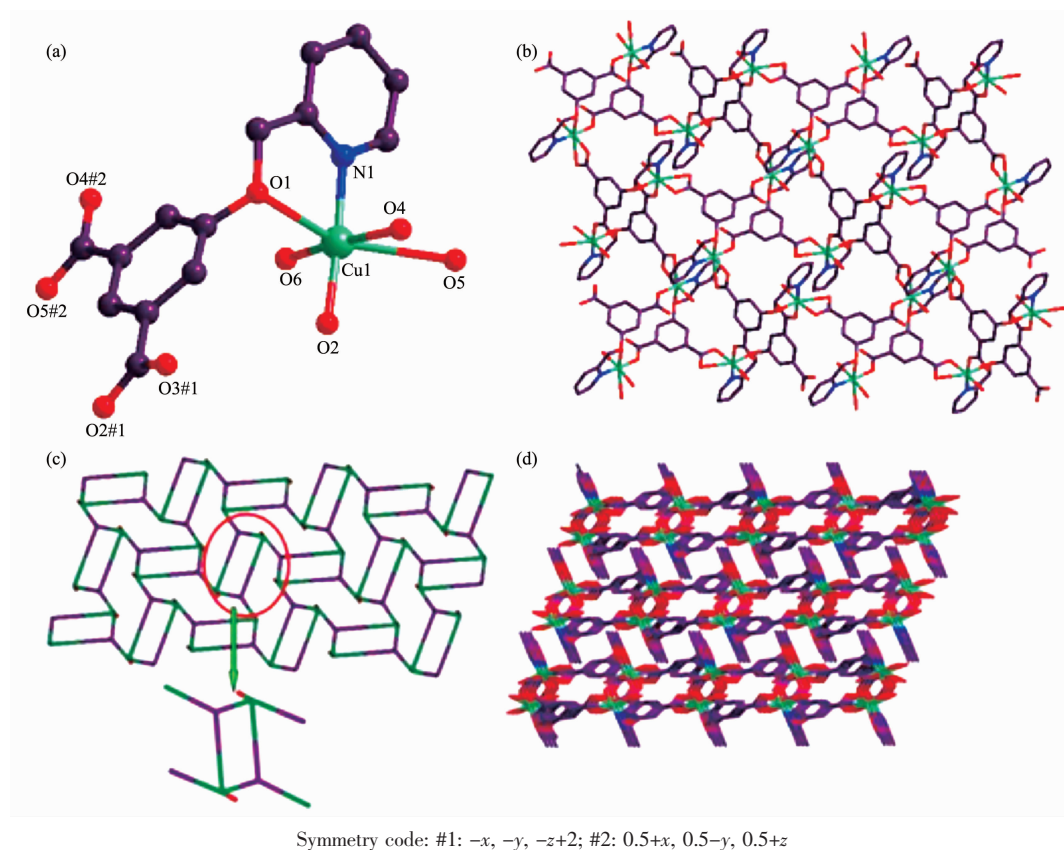


Fig.1 (a) View of the coordination environments of Cu(II) ions in **1**; (b) 2D polymeric layer of **1**; (c) Schematic view of the 2D 2-nodal (3,4)-connected topology net with the point symbol of  $\{4.8^2\}$  in **1**; (d) View of 3D supramolecular network along the  $b$  axis

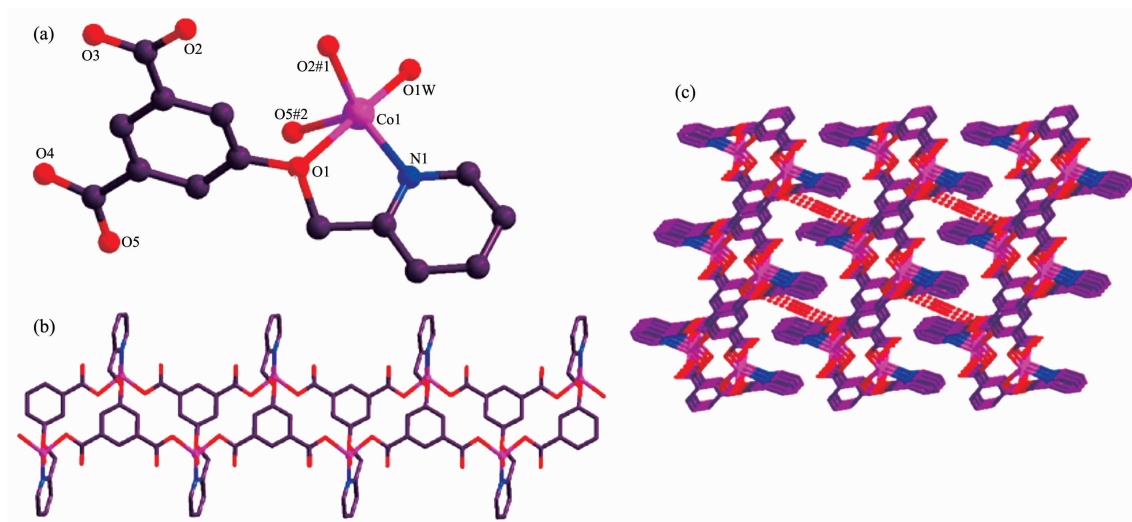


Fig.2 (a) View of the coordination environments of Co(II) ions in **2**; (b) Representation of an infinite 1D distorted ladder chain; (c) View of 3D network by linkage of hydrogen bonds

of one Co(II) ion, one L ligand and one coordination water molecule. As shown in Fig.2a, the Co(II) adopts five-coordinated by three oxygen atoms from three

different  $L^{2-}$  ligand, one coordinated water, and one pyridine nitrogen atom, displaying a distorted trigonal bipyramidal coordination geometry. The Co-O distances

are in the range of 0.199 7(2)~0.241(2) nm, and the Co-N distance is 0.205 1(2) nm, respectively. In **2**, each  $L^{2-}$  ligand with the dihedral angle of  $70.82^\circ$  between the pyridine and benzene rings connects three different Co(II) ions in a  $\mu_3-O',O'',O'''$ , N coordination mode (Scheme 1b). Similar to the compound **1**, there is an isolated  $[Co_2L_2]$  metallocyclic motif by the connection L ligands and metal atoms, which are expanded to form a 1D ladder (Fig.2b). The different structures between **1** and **2** are due to the different coordination modes of carboxyl group. Furthermore, the presence of hydrogen-bonds is essential to link the

1D network to construct a 3D polymer network (Fig. 2c). The free water molecules and the -COO group of  $L^{2-}$  ligands are responsible for hydrogen bonding.

### 2.3 PXRD and thermal stability analyses

In order to confirm the phase purity of the bulk materials at room temperature, PXRD experiments on the bulk materials of **1~2** have been carried out (Fig.3). Because the experimental patterns match well with simulated patterns base on the crystal data, the synthesized crystals of **1~2** are regarded as the pure phases.

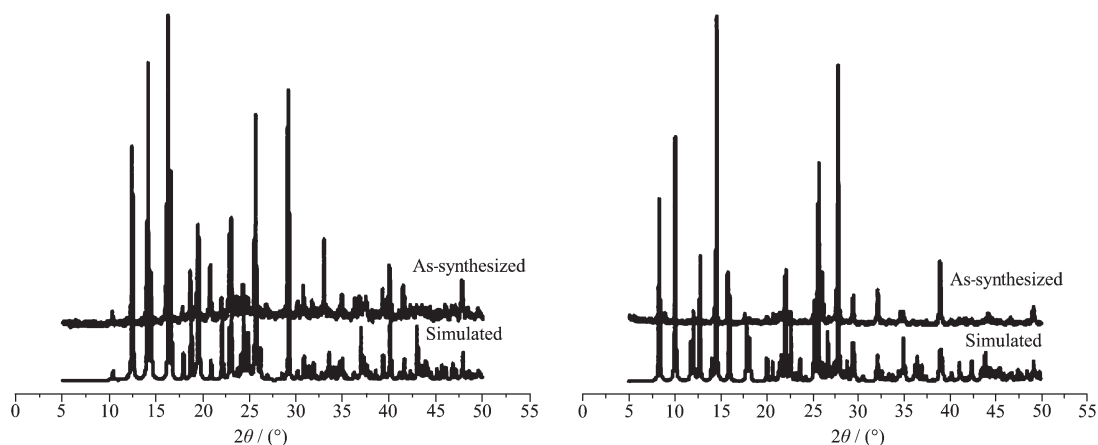


Fig.3 PXRD patterns of complexes **1** (left) and **2** (right)

To study the thermal stabilities of two complexes, thermal gravimetric analysis (TGA) of complexes **1~2** was carried out under  $N_2$  atmosphere (Fig.4). As for **1**, the weight loss of 5.97% (Calcd. 5.11%) before 150  $^\circ C$  reveals the exclusion of coordinated water molecule. Then the framework begins to decompose until 650  $^\circ C$ , corresponding to the loss of L ligands. The remaining

weight of 21.08% might be CuO component (Calcd. 22.55%). For **2**, the weight loss of 15.32% (Calcd. 16.04%) in the range of 30~210  $^\circ C$  reveals the exclusion of water molecule. The removal of organic ligands occurs from 149 to 658  $^\circ C$ , and the remaining weight of 19.31% might be CoO component (Calcd. 19.06%).

### 2.4 Luminescence properties

The solid-state luminescence behaviors of  $H_2L$  ligand and complexes **1~2** are investigated at room temperature (Fig.5). The  $H_2L$  ligand displays two emission bands at 381 and 472 nm ( $\lambda_{ex}=280$  nm), which can be assigned to  $\pi-\pi^*$  transition fluorescence in nature. As shown in Fig.5, the fluorescent emissions are observed at 408 and 462 nm for **1**, 390 and 449 nm for **2** upon excitation at 280 nm, respectively. The main peaks in **1** and **2** are similar to those of free  $H_2L$ , which can be propably ascribed to  $\pi-\pi^*$  intraligand transitions of  $L^{2-}$  ligand according to the literature<sup>[31-32]</sup>.

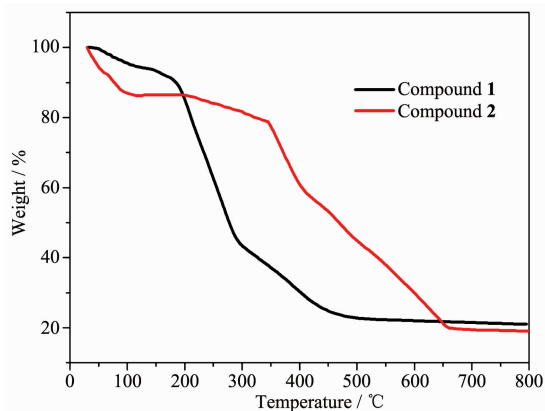


Fig.4 TGA curves of complexes **1~2**



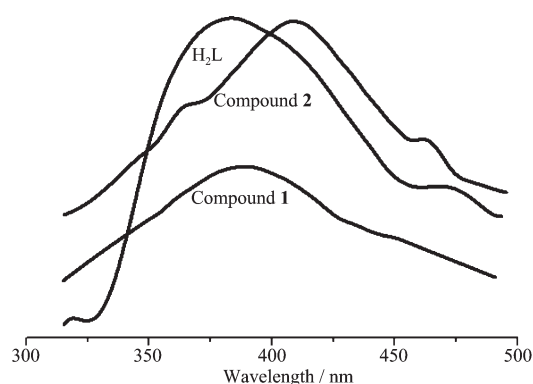


Fig.5 Solid-state photoluminescent spectra of free  $H_2L$ , **1** and **2**

### 3 Conclusions

Based on flexible pyridinecarboxylate ligands (5-(pyridin-2-ylmethoxy)-isophthalic acid), the Cu(II)/Co(II) metal-organic frameworks **1**~**2** have been constructed successfully through hydrothermal method. Compound **1** exhibits a 2D layered structure, which possesses a 2-nodal (3,4)-connected topology. Compound **2** shows a 1D chain structure, which is connected to 3D supramolecular structure via hydrogen bonds. Complexes **1**~**2** display different motifs due to different coordination modes of  $H_2L$ . Finally, these interesting observations prompt us to further research the rational synthetic strategy to obtain new crystalline materials with special properties and structures.

### References:

- [1] Cao X Y, Lin Q P, Qin Y Y, et al. *Cryst. Growth Des.*, **2009**,**9** (1): 20-23
- [2] ZHANG La-Ying(张腊莹), XU Kang-Zhen(徐抗震), SONG Ji-Rong(宋纪蓉), et al. *Chinese J. Inorg. Chem.*(无机化学学报), **2010**,**26**(5):899-904
- [3] Batten S R, Robson R. *Angew. Chem. Int. Ed.*, **1998**,**37**(11): 1460-1494
- [4] Han S D, Chen Y Q, Zhao J P, et al. *CrystEngComm*, **2014**,**16**:753-756
- [5] Horcajada P, Gref R, Baati T, et al. *Chem. Rev.*, **2012**,**112**: 1232-1268
- [6] Wu Y, Yang G P, Zhao Y, et al. *Dalton Trans.*, **2015**,**44**: 3271-3277
- [7] Yang G P, Hou L, Ma L F, et al. *CrystEngComm*, **2013**,**15**: 2561-2578
- [8] Zhang Y, Ju W, Xu X, et al. *CrystEngComm*, **2014**,**16**:5681-5688
- [9] Yaghi O M, O'Keeffe M, Ockwig N W, et al. *Nature*, **2003**,**423**:705-714
- [10] Nagaraja C M, Ugalea B, Chanthapally A, et al. *CrystEngComm*, **2014**,**14**:4085-4090
- [11] LI Yun-Tao(李运涛), ZHANG Ya-Nan(张亚男), HAI Xiao(海啸), et al. *Chinese J. Inorg. Chem.*(无机化学学报), **2013**,**29**(11):2475-2479
- [12] Zhang Y N, Dang B J, Wang Y, et al. *Inorg. Chem. Comm.*, **2015**,**61**:89-92
- [13] Ferey G, Mellot C, Serre C. *Science*, **2005**,**309**(5743):2040-2042
- [14] ZHANG Ya-Nan(张亚男), DANG Bei-Jun(党蓓君), HAI Xiao(海啸), et al. *Chinese J. Inorg. Chem.*(无机化学学报), **2014**,**30**(8):1931-1937
- [15] Sun J Y, Weng L H, Zhou Y M, et al. *Angew. Chem. Int. Ed.*, **2002**,**41**:4471-4476
- [16] Wei Y L, Hou H W, Li L K, et al. *Cryst. Growth Des.*, **2005**,**5**:1405-1412
- [17] Lin X, Blake A J, Wilson C, et al. *J. Am. Chem. Soc.*, **2006**,**128**:10745-10751
- [18] Shekhah O, Liu J, Fischer R A, et al. *Chem. Soc. Rev.*, **2011**,**40**(2):1081-1106
- [19] Ren P, Liu M L, Zhang J, et al. *Dalton Trans.*, **2008**,**35**: 4711-4713
- [20] Zhang X, Cheng J K, Chen F, et al. *Inorg. Chem. Comm.*, **2011**,**14**:358-361
- [21] Meng Q H. *Inorg. Chem. Comm.*, **2014**,**49**:82-85
- [22] Xing G E, Zhang Y, Zhang S F, et al. *J. Coord. Chem.*, **2015**,**68**:2006-2013
- [23] Zhang X, Cheng J K, Yin P X, et al. *J. Mol. Struct.*, **2011**,**990**:1-5
- [24] Jack M H, Saeed M, Ali A S. *Inorg. Chem.*, **2004**,**43**:1810-1812
- [25] Sheldrick G M. *SADABS, Program for Empirical Absorption Correction of Area Detector Data*, University of Göttingen, Germany, **1997**.
- [26] *APEX II Software Version 6.3.1*, Bruker AXS Inc., Madison, WI, **2004**.
- [27] Sheldrick G M. *SHELXS-97, Program for X-ray Crystal Structure Solution*, University of Göttingen, Germany, **1997**.
- [28] Sheldrick G M. *SHELXL-97, Program for X-ray Crystal Structure Refinement*, University of Göttingen, Germany, **1997**.
- [29] Zheng B H, Ming Y Z, Yuan D Q, et al. *CrystEngComm*, **2011**,**13**:6945-6949
- [30] Guo X G, Yang W B, Wu X Y, et al. *CrystEngComm*, **2013**,**15**:3654-3663
- [31] Chu Q, Liu G X, Huang Y Q, et al. *Dalton Trans.*, **2007**,**38**: 4302-4311
- [32] Zhang Y N, Wang Y Y, Hou L, et al. *CrystEngComm*, **2010**,**1**:1-13