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基于 3,6-二(2-(4-氧化苯并吡嗪基))-4,5-二氮杂-3,5-辛二烯配体的两个离散型 Ag(I)配合物的合成与晶体结构

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摘要:3,6-二(2-(4-氧化苯并吡嗪基))-4,5-二氮杂-3,5-辛二烯配体(L)与银盐室温下反应得到了 2 个结构新颖的离散型配位化合物$[Ag_8(L)_8](BF_4)_8\cdot CH_2Cl_2\cdot 3CH_3OH$ (**1**)和$[Ag_4(L)_4](PF_6)_4\cdot CH_2Cl_2$ (**2**)。通过红外、元素分析、X 射线单晶衍射等检测手段对所得配合物进行了表征。结果表明,2 个配合物皆以二聚体的形式存在。未配位的平衡阴离子与二聚体通过氢键连接成一维或二维结构。

关键词:双席夫碱配体;离散型化合物;氢键

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Syntheses and Crystal Structures of Two Discrete Complexes Generated from 3,6-Bis(2-(4-oxide-quinoxaline)-yl)-4,5-diaza-3,5-octadiene and Ag(I) Salt

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Abstract: Two novel discrete complexes with Ag(I) centers based on the double Schiff-base ligand, 3,6-bis(2-(4-oxide-quinoxaline)-yl)-4,5-diaza-3,5-octadiene (L), have been synthesized. The obtained Ag(I) complexes, $[Ag_8(L)_8](BF_4)_8\cdot CH_2Cl_2\cdot 3CH_3OH$ (**1**) and $[Ag_4(L)_4](PF_6)_4\cdot CH_2Cl_2$ (**2**), were fully characterized by infrared spectroscopy, elemental analysis, and single-crystal X-ray diffraction. Both complexes exist as dimers. Through hydrogen bonds, uncoordinated counter ions and discrete molecular complex building blocks formed one-dimensional (1D) or two-dimensional (2D) frameworks. CCDC:1838857, **1**; 1838858, **2**.

Keywords: double Schiff-base ligand; discrete compound; hydrogen bond

0 Introduction

Due to their novel structural topologies and potential applications in gas storage[1-2], adsorption and separation[3-4], luminescence[5-7], catalysis[8-10] and magnetic properties[11], pronounced interest has been focused on new discrete compounds and coordination polymers based on polydentate organic ligands. Of all

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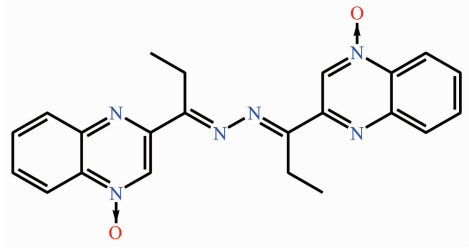
factors in the process of constructing coordination compounds, such as coordination orientation of metal ions, counter- anions, template effect of solvent, the most important is the coordination ability, length, geometry and conformation of the organic ligands[12]. Therefore, for a long time, a variety of organic ligands have been synthesized and used as building blocks to construct CPs with novel topological structures. One of continuing project in our laboratory has been the development of organometallic coordination compounds generated from double Schiff-base ligands with pyridine, pyrazine, and quinoxaline diazene as the terminal binding groups[13]. Our previous research demonstrated that such types of ligands were very useful to construct novel polymeric and discrete complexes due to their zigzag conformation of the spacer moiety (-RC=N-N=CR-) between two terminal coordination groups[14]. Moreover, Ag(I), as a soft Lewis acid, may adopt various coordination modes such as linear, trigonal planar, trigonal pyramidal, and tetrahedral coordination geometries [15]. In this context, we design a double Schiff-base ligand, 3,6-bis(2-(4-oxide-quinoxaline)-yl)-4, 5-diaza-3, 5-octadiene (L) (Scheme 1) [15]. More novel coordination compounds may be obtained with the quinoxaline-*N*-oxide as the terminal binding groups. Additionally, the O atoms of quinoxaline-*N*-oxide can serve as potential binding sites and H-bond acceptors forming hydrogen bonds with solvent molecules. In this paper, based on this novel functional ligand, two silver complexes, $[Ag_8(L)_8](BF_4)_8\cdot CH_2Cl_2\cdot 3CH_3OH$ (**1**) and $[Ag_4(L)_4](PF_6)_4\cdot CH_2Cl_2$ (**2**), are successfully synthesized and the crystal structures are determined. As reported in other articles[16], the complex hydrogen bonding systems exist in the above two complexes.



Scheme 1　Schiff-base ligand used in the construction of coordination compounds

1　Experimental

1.1　Materials and measurements

$AgBF_4$ and $AgPF_6$ (Acros) were purchased and used as obtained without further purification. The ligand L was synthesized according to the literature[15]. Infrared (IR) samples were prepared as KBr pellets, and spectra were obtained in the 400~4 000 cm^{-1} range using a Perkin-Elmer 1600 FT-IR spectrometer. Elemental analyses were performed on a Perkin-Elmer model 2400 analyzer.

1.2　Synthesis of 1

A solution of $AgBF_4$ (23.1 mg, 0.12 mmol) in CH_3OH (8 mL) was slowly diffused into a solution of L (12.0 mg, 0.03 mmol) in CH_2Cl_2 (8 mL). Yellow crystals are formed in about 7 days in 50.7% yield (based on $AgBF_4$). Anal. Calcd. for $C_{180}H_{174}B_8N_{48}O_{19}F_{32}Ag_8Cl_2$(%): C, 43.70; H, 3.52; N, 13.60. Found(%): C, 43.26; H, 3.45; N, 13.79. IR (KBr pellet, cm^{-1}): 3 449 (s), 1 636 (m), 1 575 (w), 1 524 (w), 1 490 (w), 1 457 (w), 1 401 (s), 1 249 (w), 1 218 (w), 1 085 (m), 910 (w), 856 (w), 771 (w), 625 (w).

1.3　Synthesis of 2

A solution of $AgPF_6$ (30.3 mg, 0.12 mmol) in CH_3OH (8 mL) was slowly diffused into a solution of L (12.0 mg, 0.03 mmol) in CH_2Cl_2 (8 mL). Yellow crystals were formed in about 7 days in 24.3% yield (based on $AgPF_6$). Anal. Calcd. for $C_{89}H_{82}N_{24}O_8F_{24}P_4Ag_4Cl_2$(%): C, 39.58; H, 3.04; N, 12.45. Found(%): C, 38.65; H, 3.15; N, 11.61. IR (KBr pellet, cm^{-1}): 3 417 (s), 3 120 (w), 1 638 (m), 1 617 (m), 1 578 (m), 1 522 (w), 1 492 (m), 1 459 (w), 1 400 (s), 1 375 (s), 1 277 (w), 1 250 (w), 1 216 (w), 1 136 (w), 1 098 (w), 1 050 (w), 982 (w), 942 (w), 910 (w), 838 (s), 771 (m), 557 (m).

1.4　Determination of crystal structure

Suitable single crystals of **1** and **2** were selected and mounted in air onto thin glass fibers. X-ray intensity data were measured at 298(2) K on a Bruker SMART APEX CCD-based diffractometer (Mo $K\alpha$ radiation, λ=0.071 073 nm). The raw frame data for **1** and **2** were integrated into SHELX-format reflection files and corrected for Lorentz and polarization effects using SAINT[17]. Corrections for incident and diffracted

beam adsorption effects were applied using SADABS[18]. None of the crystals showed evidence of crystal decay during data collection. The structures were solved by a combination of direct methods and difference Fourier syntheses and structural analysis refined against F^2 by the full-matrix least squares technique. Crystallographic data for **1** and **2** are listed in Table 1. Selected bond lengths and bond angles are listed in Table 2. Hydrogen bond lengths and bond angles are listed in Table 3.

CCDC:1838857, **1**; 1838858, **2**.

Table 1 Crystallographic data for 1 and 2

Complex	1	2
Formula	$C_{180}H_{174}B_8N_{48}O_{19}F_{32}Ag_8Cl_2$	$C_{89}H_{82}N_{24}O_8F_{24}P_4Ag_4Cl_2$
Formula weight	4 942.01	2 698.05
Crystal system	Orthorhombic	Triclinic
Space group	*Pbca*	$P\bar{1}$
a / nm	1.501 40(1)	1.535 4(4)
b / nm	1.835 08(1)	1.930 6(5)
c / nm	3.679 0(1)	2.040 6(6)
α / (°)		104.926(4)
β / (°)		99.426(4)
γ / (°)		98.671(4)
V / nm^3	10.136 3(2)	5.647(3)
Z	2	2
D / (g·cm^{-3})	1.619	1.587
μ(Mo *K*α) / mm^{-1}	0.885	0.888
F(000)	4 960	2 692
GOF on F^2	1.044	0.973
R_1[a], wR_2[b] [$I>2\sigma(I)$]	0.061 5, 0.174 6	0.060 4, 0.154 4
R_1, wR_2 (all data)	0.108 7, 0.198 1	0.100 6, 0.170 6
Largest difference peak and hole / (e·nm^{-3})	960 and −1 070	1 770 and −1 230

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

Table 2 Selected bond lengths (nm) and bond angles (°) of complexes 1 and 2

1					
Ag(1)-N(10)	0.242 3(5)	Ag(1)-N(3)	0.242 7(5)	Ag(2)-N(5)	0.224 6(5)
Ag(1)-N(1)	0.223 6(5)	Ag(2)-N(4)	0.243 4(5)	Ag(2)-N(7)	0.222 4(5)
Ag(1)-N(11)	0.224 4(5)	Ag(2)-N(9)	0.239 6(5)		
N(1)-Ag(1)-N(11)	158.6(17)	N(1)-Ag(1)-N(10)	127.9(17)	N(1)-Ag(1)-N(3)	69.68(17)
N(10)-Ag(1)-N(3)	96.4(16)	N(11)-Ag(1)-N(10)	69.5(16)	N(11)-Ag(1)-N(3)	125.1(17)
N(5)-Ag(2)-N(4)	69.4(17)	N(5)-Ag(2)-N(9)	127.9(18)	N(7)-Ag(2)-N(4)	134.4(18)
N(7)-Ag(2)-N(5)	152.4(18)	N(7)-Ag(2)-N(9)	69.9(17)	N(9)-Ag(2)-N(4)	97.6(17)
2					
Ag(1)-N(11)	0.223 7(4)	Ag(1)-N(1)	0.226 4(4)	Ag(1)-N(3)	0.237 3(4)
Ag(1)-N(10)	0.247 3(4)	Ag(2)-N(5)	0.220 8(5)	Ag(2)-N(7)	0.222 3(5)
Ag(2)-N(4)	0.237 4(5)	Ag(2)-N(9)	0.239 8(5)	Ag(3)-N(23)	0.228 4(5)
Ag(3)-N(13)	0.222 3(4)	Ag(3)-N(15)	0.241 5(5)	Ag(3)-N(22)	0.236 9(4)
Ag(4)-N(17)	0.224 8(5)	Ag(4)-N(19)	0.225 2(5)	Ag(4)-N(16)	0.239 4(5)
Ag(4)-N(21)	0.235 3(5)				

Continued Table 2

N(11)-Ag(1)-N(1)	148.98(16)	N(11)-Ag(1)-N(3)	129.24(14)	N(1)-Ag(1)-N(3)	68.71(15)
N(11)-Ag(1)-N(10)	69.13(16)	N(1)-Ag(1)-N(10)	138.76(15)	N(3)-Ag(1)-N(10)	99.54(15)
N(5)-Ag(2)-N(7)	147.89(17)	N(5)-Ag(2)-N(4)	70.95(16)	N(7)-Ag(2)-N(4)	137.19(15)
N(5)-Ag(2)-N(9)	129.72(15)	N(7)-Ag(2)-N(9)	69.25(16)	N(4)-Ag(2)-N(9)	100.02(15)
N(23)-Ag(3)-N(13)	139.91(17)	N(23)-Ag(3)-N(15)	124.90(17)	N(13)-Ag(3)-N(15)	70.09(17)
N(23)-Ag(3)-N(22)	71.28(17)	N(13)-Ag(3)-N(22)	146.62(17)	N(15)-Ag(3)-N(22)	103.97(15)
N(17)-Ag(4)-N(19)	134.95(19)	N(17)-Ag(4)-N(16)	70.44(16)	N(19)-Ag(4)-N(16)	149.63(18)
N(17)-Ag(4)-N(21)	131.3(2)	N(19)-Ag(4)-N(21)	70.20(18)	N(16)-Ag(4)-N(21)	107.35(16)

Table 3　Structural parameters of hydrogen bonds for complexes 1 and 2

D–H···A	*d*(D-H) / nm	*d*(H···A) / nm	*d*(D···A) / nm	∠DHA / (°)
		1		
C(24)–H(24) ···O(1)	0.093	0.257	0.330 5(9)	136.0
C(2)–H(2)···O(2)	0.093	0.230	0.311 4(8)	146.4
C(43)–H(43)···O(4)^{i}	0.093	0.254	0.331 6(9)	141.5
C(35)–H(35A)···F(3)^{ii}	0.097	0.260	0.348 3(10)	150.0
C(11)–H(11F)···F(5)	0.096	0.262	0.328 9(10)	125.1
		2		
C(5)–H(5)···O(1)^{ii}	0.093	0.237	0.319	146
C(76)–H(76A)···O(2)	0.097	0.245	0.339	162
C(73)–H(73)···O(2)	0.093	0.244	0.328	151
C(51)–H(51)···O(3)	0.093	0.262	0.350	158
C(7)–H(7)···O(5)	0.093	0.249	0.335	154
C(10)–H(10B)···O(5)	0.097	0.292	0.366	134
C(55)–H(55A)···O(6)^{iii}	0.096	0.277	0.353	137
C(57)–H(57A)···O(6)	0.097	0.294	0.364	130
C(24)–H(24A)···O(7)^{iv}	0.097	0.269	0.347	138
C(27)–H(27)···O(7)	0.093	0.261	0.340	143
C(82)–H(82)···O(8)^{v}	0.093	0.265	0.336	134
C(79)–H(79B)···O(8)	0.097	0.230	0.315	146
C(44)–H(44C)···F(23)	0.096	0.246	0.324	139
C(86)–H(86)···F(24)	0.093	0.279	0.348	131
C(10)–H(10B)···F(21)	0.097	0.266	0.343	137
C(55)–H(55C)···F(21)	0.096	0.287	0.376	156
C(87)–H(87)···F(22)	0.093	0.249	0.335	153
C(57)–H(57B)···F(22)	0.097	0.272	0.364	160
C(77)–H(77C)···F(14)	0.096	0.245	0.335	155
C(14)–H(14)···F(16)	0.093	0.251	0.341	161
C(68)–H(68)···F(13)	0.093	0.286	0.370	151
C(23)–H(23C)···F(5)^{xi}	0.096	0.276	0.367	158
C(23)–H(23C)···F(3)^{xi}	0.096	0.253	0.336	145
C(21)–H(21A)···F(1)^{xi}	0.097	0.274	0.364	154
C(10)–H(10A)···F(7)	0.097	0.239	0.327	150
C(76)–H(76B)···F(12)^{xii}	0.097	0.287	0.355	164
C(78)–H(78C)···F(12)^{xii}	0.096	0.260	0.359	133

Continued Table 3

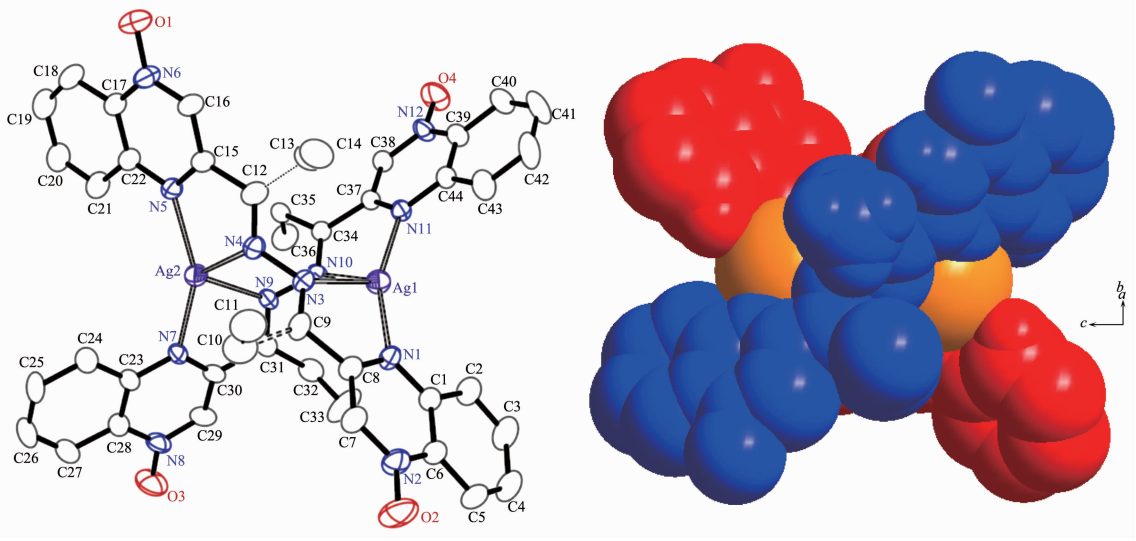
C(65)–H(65)···F(6)^{xiii}	0.093	0.251	0.324	135
C(79)–H(79A)···F(6)^{xiii}	0.097	0.250	0.335	147
C(37)–H(37)···F(16)^{xiv}	0.093	0.270	0.348	142
C(43)–H(43A)···F(18)^{xv}	0.097	0.257	0.333	136
C(77)–H(77C)···F(18)^{xv}	0.096	0.266	0.339	133
C(14)–H(14)···F(17)^{xvi}	0.093	0.258	0.326	130
C(69)–H(69)···F(15)^{xvii}	0.093	0.248	0.327	142
C(76)–H(76B)···F(8)	0.097	0.268	0.349	141
C(46)–H(46)···F(8)	0.093	0.260	0.346	153

Symmetry codes: ^{i} x+1/2, y, −z+3/2; ^{ii} x−1, y, z for **1**; ^{ii} −x, 1−y, 1−z; ^{iii} 1−x, 2−y, 1−z; ^{iv} −1+x, −1+y, z; ^{v} 2−x, 2−y, −z; ^{xi} −1+x, y, z; ^{xii} 1−x, 1−y, −z; ^{xiii} x, 1+y, z; ^{xiv} 1−x, 1−y, −z; ^{xv} −1+x, y, z; ^{xvi} 1−x, 1−y, 1−z; ^{xvii} 2−x, 2−y, 1−z for **2**.

2 Results and discussion

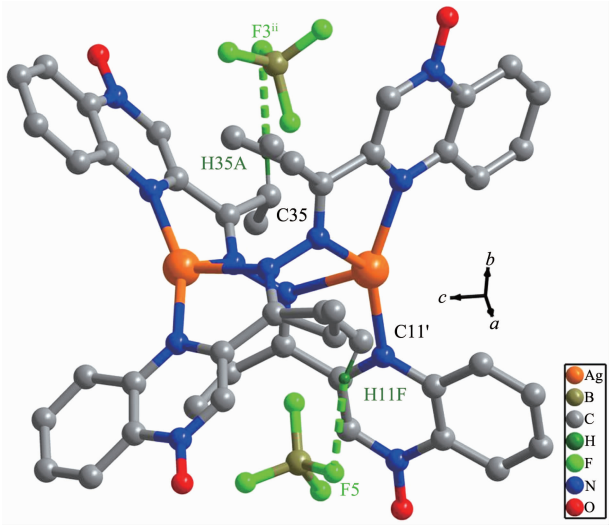
2.1 Structural analysis of $[Ag_8(L)_8](BF_4)_8\cdot CH_2Cl_2\cdot 3CH_3OH$ (1)

Complex **1** was obtained as yellow crystals in CH_2Cl_2/CH_3OH mixed solvent system using combination of L and $AgBF_4$ (metal-to-ligand molar ratio 4:1) at room temperature. The X-ray single-crystal analysis reveals that **1** crystallizes in the orthorhombic space group *Pbca* and exists as a dimer. Complex **1** possesses a dinuclear chiral double-helical structure with the Ag···Ag distance of 0.439 6 nm. As indicated in Fig.1, the asymmetric unit contains two crystallographic Ag(I) centers, two L ligands, two BF_4^- anions, a quarter CH_2Cl_2, and 0.75 CH_3OH molecule. Each Ag(I) center lies in a distorted tetrahedral coordination environment defined by two quinoxaline N-donors and two Schiff-base N-donors from two quadridentate ligands, respectively. The dihedral angle between two terminal benzene rings is 79.94°. BF_4^- anions are bonded to the $[Ag_2L_2]^{2+}$ unit through weak F···H–C bonds (F(3)···H(35A)–C(35), F(3)···H(35A) 0.260 nm, F(5)···H(11F)–C(11′), F(5)···H(11F) 0.262 nm, Fig.2). In the solid state, through three sets of hydrogen-bonding systems, the dinuclear subunits are linked together to give one-dimensional helical chains extending along the crystallographic *c* axis, which arrange in the crystallographic *bc* plane in parallel (Fig.3).



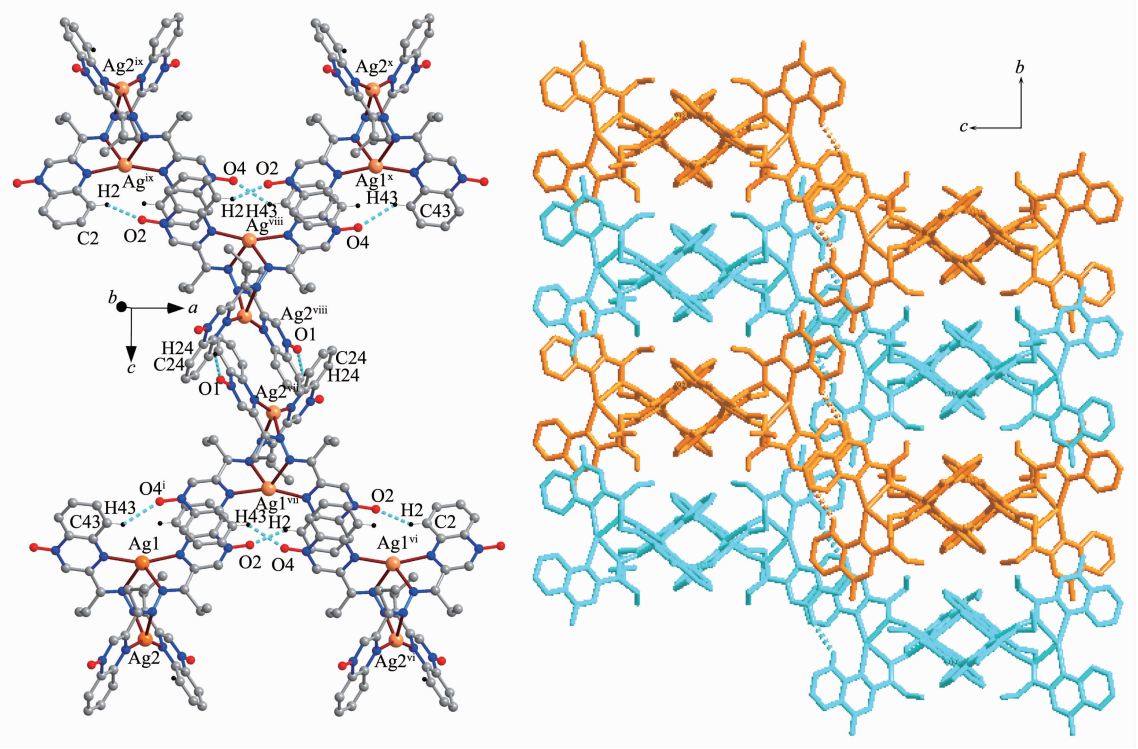
Probability of displacement ellipsoids: 30%; Two strands are colored as red and blue, respectively

Fig.1 ORTEP figure (left) and space-filling model (right) of **1**



Symmetry codes: ii $x-1, y, z$

Fig.2　Hydrogen-bonds (dotted lines) between BF_4^- anions and $[Ag_2L_2]^{2+}$ unit



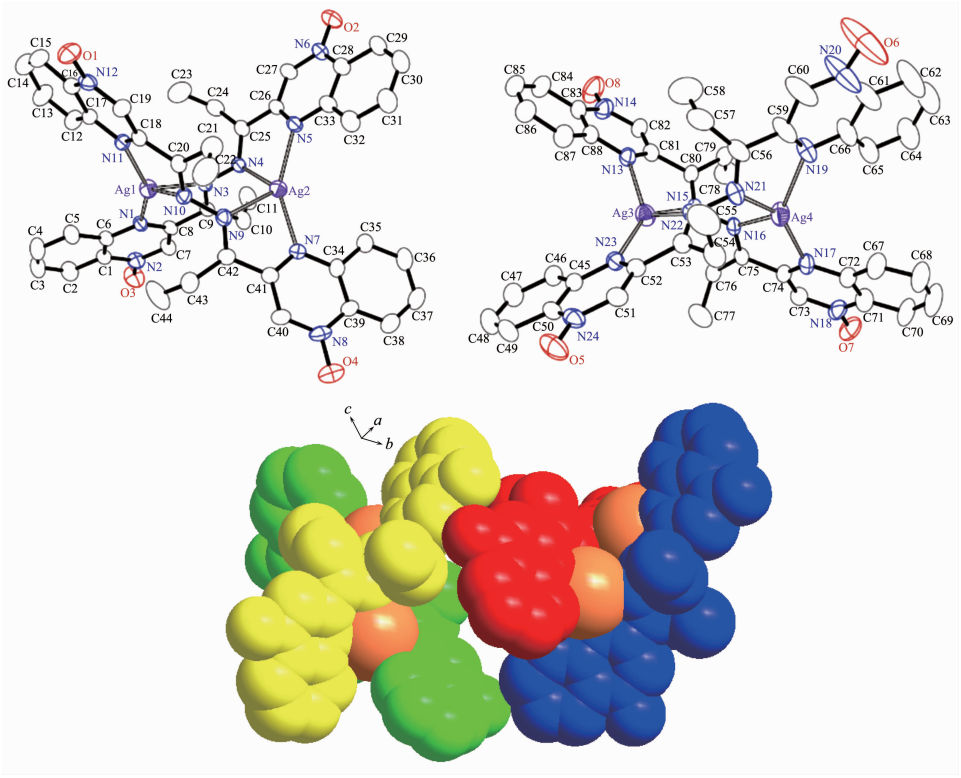
Hydrogen bonds are shown as orange and blue dotted lines; Symmetry codes: i $x+1/2, y, -z+3/2$; vi $1+x, y, z$; vii $x+1/2, y, -z+3/2$; viii $-x+1/2, -y+2, -z+1/2$; ix $-x, -y+2, -z+1$; x $-x+1, -y+2, -z+1$

Fig.3　One-dimensional helical chains of **1** (left) and crystal packing of **1** (right)

2.2　Structural analysis of $[Ag_4(L)_4](PF_6)_4 \cdot CH_2Cl_2$ (2)

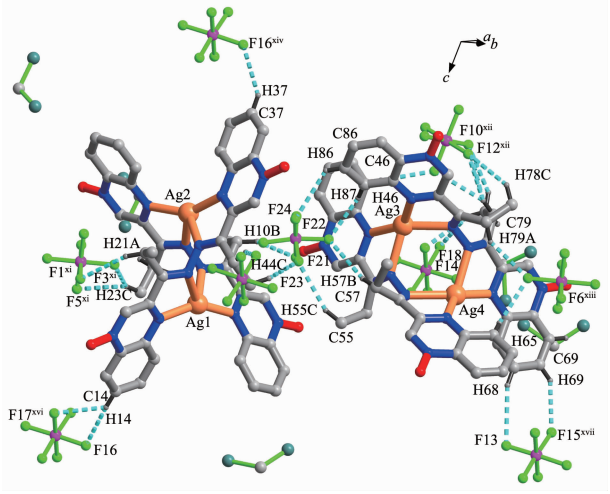
The reaction of L with $AgPF_6$ in methanol/methylene chloride at room temperature afforded discrete complex **2** in 24.3% yield. Single-crystal analysis reveals that complex **2** contains four types of crystallographic independent Ag(I) ions (Fig.4). Each Ag(I) ion is four-coordinated in an approximately tetrahedral coordination environment, which is defined by two quinoxaline N-donors and two Schiff-base N-donors from two quadridentate ligands. The Ag-N bond distances are in a range of 0.220 8 (5)~0.247 3(4)

nm, all of which are within the range of those reported for other Ag(I) complexes with N donors[19]. The dihedral angles between two terminal benzene rings are 60° and 75° , respectively. Additionally, the complex features diverse non-clsssical hydrogen bonding interactions (Fig.5). PF_6^- anions are bonded to the $[Ag_2L_2]^{2+}$ units through weak F···H–C bonds (Table 3). As shown in Fig.6, the dinuclear subunits are linked together into a two-dimensional net extending in the crystallographic *bc* plane through complicated hydrogen-bonding systems. These networks stack in an -ABAB- sequence along the crystallographic *a* axis (Fig.7).



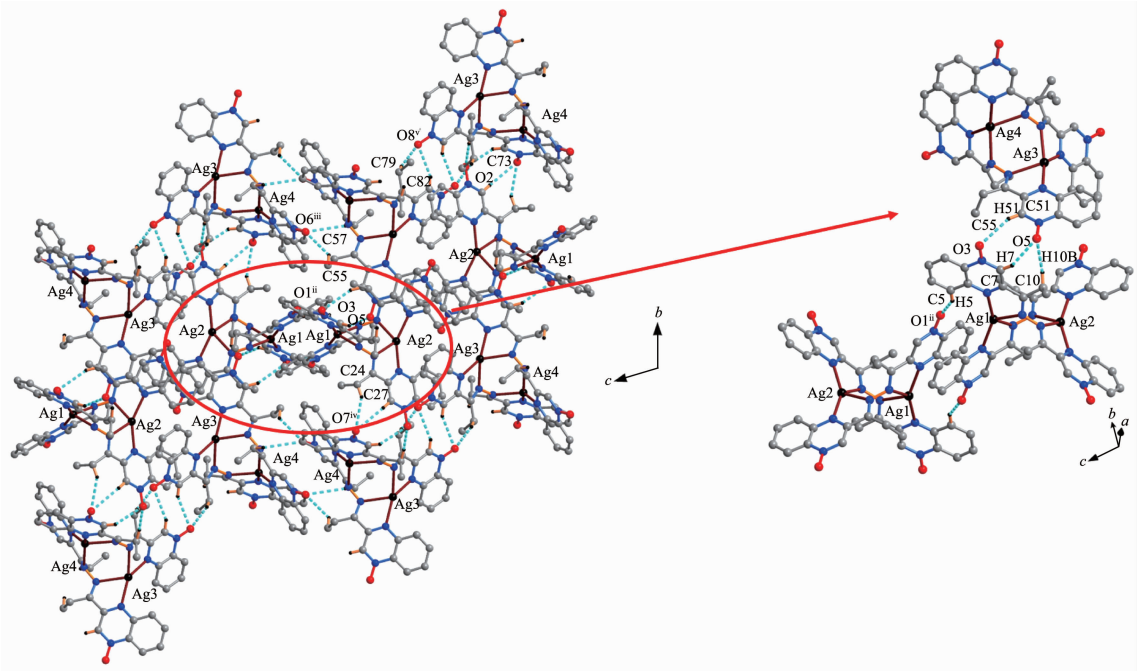
Probability of displacement ellipsoids: 30%; Four strands are colored as green, yellow, red and blue respectively

Fig.4 ORTEP figure (top) and space-filling model (below) of **2**



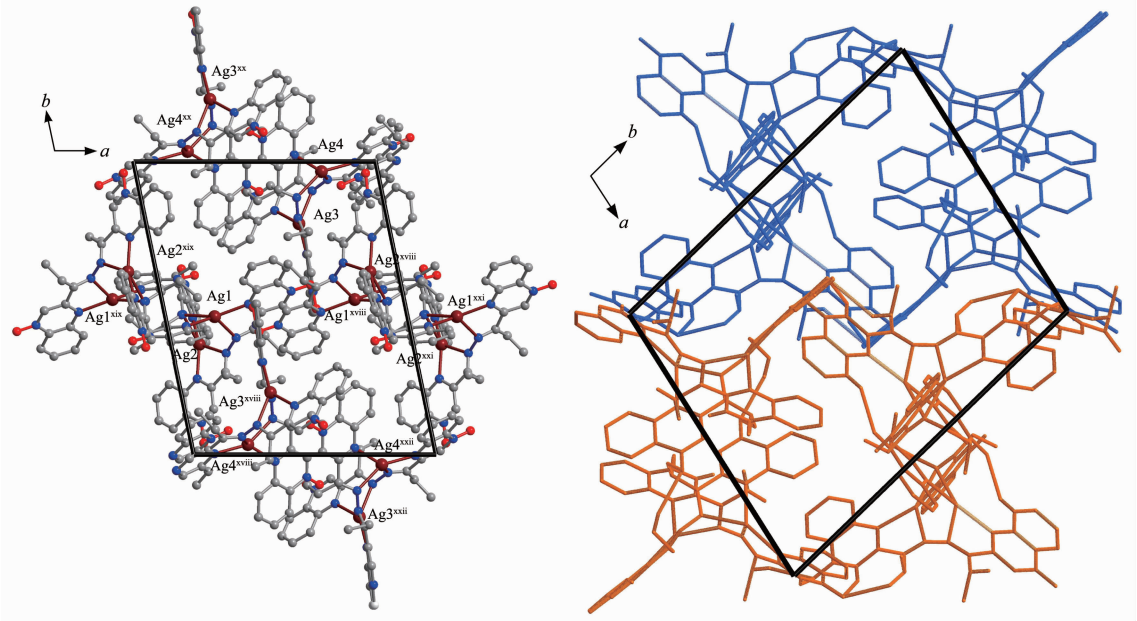
Hydrogen bonds are shown as blue dotted lines; Symmetry codes: [xi] −1+*x*, *y*, *z*; [xii] 1−*x*, 1−*y*, −*z*; [xiii] *x*, 1+*y*, *z*; [xiv] 1−*x*, 1−*y*, −*z*; [xv] −1+*x*, *y*, *z*; [xvi] 1−*x*, 1−*y*, 1−*z*; [xvii] 2−*x*, 2−*y*, 1−*z*

Fig.5 Hydrogen-bonding systems between PF_6^- anions and $[Ag_2L_2]^{2+}$ unit



Hydrogen bonds are shown as blue dotted lines; Symmetry codes: [ii] $-x$, $1-y$, $1-z$; [iii] $1-x$, $2-y$, $1-z$; [iv] $-1+x$, $-1+y$, z; [v] $2-x$, $2-y$, $-z$

Fig.6　Two dimensional hydrogen-bonded nets found in **2**



Symmetry codes: [xviii] $1-x$, $1-y$, $1-z$; [xix] $-x$, $1-y$, $1-z$; [xx] $1-x$, $2-y$, $1-z$; [xxi] $1+x$, y, z; [xxii] x, $-1+y$, z

Fig.7　Two dimensional nets stack parallel to crystallographic *ab* plane

3　Conclusions

In summary, a double Schiff-base ligand, namely 3,6-bis(2-(4-oxide-quinoxaline)-yl)-4,5-diaza-3,5-octadiene (L), was used as a polydentate ligand to coordinate with transition metal ions. Two novel discrete complexes with Ag(I) centers have been synthesized and structurally characterized. Both complexes exist as dimers and the frameworks were formed via hydrogen bonding interactions between uncoordinated counter ions and the discrete building blocks. Further investigations on supramolecular compounds based on the double Schiff-base ligand with new structures and multifunctional properties are ongoing in our group.

References:

[1] Xie Z G, Ma L Q, Lin W B, et al. *J. Am. Chem. Soc.*, **2010**, **132**:922-923

[2] Myunghyun P, Hye J P, Thazhe K, et al. *Chem. Rev.*, **2012**, **112**:782-835

[3] Liu Q K, Ma J P, Dong Y B. *J. Am. Chem. Soc.*, **2010**,**132**: 7005-7017

[4] Li J R, Julian S, Zhou H C. *Chem. Rev.*, **2012**,**112**:869-932

[5] Wang M S, Guo S P, Li Y, et al. *J. Am. Chem. Soc.*, **2009**, **131**:13572-13573

[6] Cui Y J, Yue Y F, Chen B L, et al. *Chem. Rev.*, **2012**,**112**: 1126-1162

[7] Ren X H, Wang P, Cheng J Y, et al. *J. Mol. Struct.*, **2018**, **1161**:145-151

[8] Zhao C W, Ma J P, Dong Y B, et al. *Green Chem.*, **2013**,**15**: 3150-3154

[9] Cheng J Y, Ding F W, Dong Y B, et al. *ChemPlusChem*, **2016**,**81**:743-751

[10]Minyoung Y, Renganathan S, Kimoon K. *Chem. Rev.*, **2012**, **112**:1196-1231

[11]Zhang W, Xiong R G. *Chem. Rev.*, **2012**,**112**:1163-1195

[12]Cook T R, Zheng Y R, Stang P J. *Chem. Rev.*, **2013**,**113**: 734-777

[13]Dong Y B, Wang L, Ma J P, et al. *Cryst. Growth Des.*, **2006**, **6**:2475-2485

[14]Dong Y B, Cheng J Y, Ma J P, et al. *Cryst. Growth Des.*, **2005**,**5**:585-591

[15]Cheng J Y, Wang P, Dong Y B, et al. *Chem. Commun.*, **2014**,**50**:13672-13675

[16]YU Qin(余沁), WANG Da-Peng(王大鹏), WANG Hai-Ying(王海英), et al. *Chinese J. Inorg. Chem.*(无机化学学报), **2017**,**33**(12):2345-2350

[17](a)Sheldrick G M. *SHLXTL Ver.* 5.1, Bruker Analytical X-ray Systems, Inc., Madison, Wisconsin, USA, **1997**.

(b)*SMART Ver.* 5.625 and *SAINT+ Ver.* 6.02*a*, Bruker Analytical X-ray Systems, Inc., Madison, Wisconsin, USA, **1998**.

[18]Sheldrick G M. *SADABS*, University of Göttingen, Germany, **1996**.

[19]NI Tian-Jun(倪天军), YUAN Qiang-Tao(苑强涛), ZHANG Wei(张伟), et al. *Chinese J. Inorg. Chem.*(无机化学学报), **2017**,**33**(12):2177-2185