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# Two new silver(I) coordination polymers with 4,4'-bipyridine and two perfluoro- $\beta$ -diketonates

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# 1. Introduction

The rational design and synthesis of novel, discrete and polymeric metal-organic hybrid frameworks have remained an important research focus in recent years [1–4], due to their fascinating coordination architectures and their potential applications in various fields, including gas storage, conductivity, catalysis, photophysics, photochemistry, fluorescence, magnetism and biological properties [5-8]. Although the synthesis of such coordination polymers (CPs) is mainly based on the self-assembly of suitable metal ions and the structural characterization of organic building blocks, it is also highly influenced by numerous other factors such as the solvent system, temperature, counter ions with different bulk or coordination abilities, template, metal/ligand ratio and even pH [9–12]. Besides these aspects, non-covalent interactions such as hydrogen bonding,  $\pi$ - $\pi$  interactions, and metal-metal interactions play an important role in the construction of supramolecular structures [13,14]. Although it is possible to get some control on the structures by a judicious choice of the metal ions, a circumspect consideration of the geometry of the organic ligands and the orientations of the donor groups, the prediction and control of the supramolecular assembly of molecules remains a compelling challenge. On the other hand, the employment of mixed ligands during the self-assembly process has gradually become a powerful approach, which is expected to result in frameworks with more diverse structural motifs compared to using a single type of ligand.

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# ABSTRACT

Two coordination polymers (CPs) based on a Ag<sup>l</sup>/perfluoro- $\beta$ -diketonate/N-donor ligand, [Ag(4,4'-bpy)(h-fa)]<sub>n</sub>, (1) and [Ag(4,4'-bpy)(ttfa)]<sub>n</sub> (2), where 4,4'-bpy is 4,4'-bipyridine, Hhfa is hexafluoroacetylacetone, and Httfa is thenoyltrifluoracetylacetone, were prepared and characterized by elemental analysis, IR and <sup>1</sup>H NMR spectroscopy as well as X-ray crystallography and electrochemical properties were studied. The complexes display 1D CPs structurally quite similar to another. The adjacent chains are further interlinked *via* Ag...Ag, Ag...O contacts to generate 1D ladder (double chains) structures. Abundant weak interactions, such as  $\pi$ ... $\pi$ , C—H...F, C—H...O and F...F interactions, provide additional assembly forces, leading to 3D supramolecular networks for 1 and 2.

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To design and synthesize metal–organic coordination networks based on coordination bonds and non-covalent interactions (such as hydrogen-bonding interactions), the interactive information stored in the ligand, as well as the coordination geometry of the metal ions, should be taken into account. 4,4'-bpy is a neutral linear bifunctional ligand widely used as an excellent spacer in the construction of metal–organic coordination polymer architectures [15–19]. Furthermore, both exo-bidentate N-donor ligands, such as 4,4'-bipyridine and the O-donor ligands, such as di-, tri- and tetra-carboxylates, are excellent synthons that have been employed for the design of functional solid materials [20,21]. In metallo-assembled architectures, the dominant factor that controls the final supra-molecule is usually the metal–ligand interaction [22]. Therefore any structure with weak interactions [23] must fulfill the requirements of the primary synthon obtained from the metal–ligand interactions.

The Ag(I) center, with closed-shell configuration, lacks strong coordination preferences, and thus, non-covalent weak interactions involved in the overall structure observed (topology, geometry and packing arrangement) may have a strong effect and determine the organization of the supra-molecular networks [24–27]. Although many reports about the use of 4,4'-bpy as a synthon to construct Ag-containing hybrid frameworks have been presented in recent literature [15–19], Ag(I) complexes with  $\beta$ -diketonates and/or other ancillary ligands have rarely received attention [28–31]. In this paper, we present the syntheses, structures (including weak interactions), and properties of two new Ag(I) coordination polymers, namely [Ag(4,4'-bpy)(hfa)]<sub>n</sub>, (1) and [Ag(4,4'-bpy)(ttfa)]<sub>n</sub> (2), 4,4'-bpy: 4,4'-bipyridine, Hhfa: hexafluoroacetylacetone, Httfa: thenoyltrifluoracetylacetone.

# 2. Experimental

# 2.1. Physical measurements

IR spectra were recorded as KBr pellets using a Perkin–Elmer 597 and a Nicolet 510P spectrophotometer. Elemental analyses (C, H, N) were performed using a Carlo ERBA model EA 1108 analyzer. Solution <sup>1</sup>H NMR spectra were recorded on a BRUKER DRX-500 AVANCE spectrometer at 500 MHz using d<sub>6</sub>-dimethyl-sulfoxide as solvent. Thermogravimetrical analysis (TGA) was performed in N<sub>2</sub> atmosphere with a flow rate of 20 ml/min on a Seiko Instruments thermal analyzer from 20 to 800 °C, with a heating rate of 10 °C/min in the ceramic crucibles. Cyclic voltammetry was performed using an Autolab potentiostat/galvanostat 101. The working electrode was a glassy carbon disk (2.0 mm diameter), a Pt wire was used as a counter electrode. The working electrode potentials were measured versus a quasi-reference electrode of a platinum wire (all electrodes from Azar Electrode).

# 2.2. Preparation of $[Ag(4,4'-bpy)(hfa)]_n$ (1)

A mixture of Ag<sub>2</sub>O (116 mg, 0.5 mmol), 4,4'-bpy (156 mg, 1 mmol) and Hhfa (208 mg, 1 mmol) was stirred in a CH<sub>3</sub>OH—H<sub>2</sub>O mixed solvent (15 ml, v/v: 1/1). Then, an aqueous NH<sub>3</sub> solution (25%) was poured into the mixture to give a clear solution. The resultant solution was allowed to evaporate slowly in darkness at room temperature for several days to give colorless crystals of **1** (yield, 54%). The crystals were washed with a small volume of cold CH<sub>3</sub>OH and diethyl ether. Anal. Calc. for C<sub>15</sub>H<sub>9</sub>AgF<sub>6</sub>N<sub>2</sub>O<sub>2</sub>: C, 38.21; H, 1.91; N, 5.94. Found: C, 38.37; H, 2.01; N, 5.68%. IR (KBr) (cm<sup>-1</sup>): 3090 (m), 1618 (s), 1560 (s), 1515 (s), 1473 (s), 1348(m), 1316 (m), 1248, 1187, 1132 (m), 767 (m), 649 (w), 512 (w), 487 (m). <sup>1</sup>H NMR (DMSO,  $\delta$ ): 8.72 (d, 4H, pyridyl), 7.88 (d, 4H, pyridyl), 5.29 (s, 1H, =CH— of hfa<sup>-</sup>).

#### Table 1

Crystal	l data	and	structure	refinement	for 1	l and	2.
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		1	2	
Identification code		$[Ag(4,4'-bpy)(hfa)]_n$	[Ag(4,4'-bpy)(ttfa)] <sub>n</sub>	
	Empirical formula	$C_{15}H_9AgF_6N_2O_2$	$C_{18}H_{12}AgF_3N_2O_2S$	
	Formula weight	471.11	485.23	
	Crystal system	Monoclinic	Monoclinic	
	Space group	P2 <sub>1</sub> /c (No. 14)	C2/c (No. 15)	
	Unit cell dimensions	a = 9.118(1) Å	<i>a</i> = 10.834(1) Å	
		b = 20.181(2) Å	b = 20.262(2) Å	
		c = 18.109(3) Å	c = 16.752(2) Å	
		$\beta = 101.98(1)^{\circ}$	$\beta = 107.73(1)^{\circ}$	
	Volume	3259.8(7) Å <sup>3</sup>	3502.4(6) Å <sup>3</sup>	
	Ζ	8	8	
	Density (calculated)	$1.920 \text{ g cm}^{-3}$	$1.840 \mathrm{g}\mathrm{cm}^{-3}$	
	Absorption coefficient	$1.313 \text{ mm}^{-1}$	$1.317 \text{ mm}^{-1}$	
	F(000)	1840	1920	
	$\theta$ range for data	2.50-28.11	2.01-27.30	
	collection			
	Index ranges	$-10 \leqslant h \leqslant 10$	$-13 \leqslant h \leqslant 13$	
		$-26 \leqslant k \leqslant 26$	$-26 \leqslant k \leqslant 25$	
		$-23 \leqslant l \leqslant 23$	$-21 \leqslant l \leqslant 21$	
	Reflections collected	38,313	24,552	
	Independent reflections	7394[R(int) = 0.0607]	3901[R(int) = 0.0319]	
	Completeness to theta	93.1%	98.9%	
	Data/restraints/ parameters	7394/0/470	3901/0/245	
	Goodness-of-fit on F <sup>2</sup>	0.947	1.053	
	Final R $[I_0 > 2\sigma(I_0)]$	Rl = 0.0432,	Rl = 0.0386,	
		wR2 = 0.0967	wR2 = 0.1118	
	R indices (all data)	R1 = 0.0870,	R1 = 0.0482,	
		wR2 = 0.1102	wR2 = 0.1169	
	Largest diff. peak, hole	0.722, –0.410 e Å	0.745, –0.752 e Å	

#### 2.3. Preparation of $[Ag(4,4'-bpy)(ttfa)]_n$ (2)

Complex **2** was synthesized in the same way as complex **1** using Httfa (222 mg, 1 mmol) in place of Hhfa. Anal. Calc. for  $C_{18}H_{12}AgF_{3-}N_2O_2S$ : C, 44.51; H, 2.47; N, 5.77. Found: C, 44.37; H, 2.29; N, 5.59%. IR (KBr) (cm<sup>-1</sup>): 3075 (m), 1625 (s), 1585 (s), 1520 (s), 1495 (s), 1352(m), 1256, 1194, 1142 (m), 785 (m), 666 (w). <sup>1</sup>H NMR (DMSO,  $\delta$ ): 8.72 (d, 4H, pyridyl), 7.85 (d, 4H, pyridyl), 7.55–7.70 (m, 2H, thiophen), 7.07 (d, 1H, thiophen), 5.86 (s, 1H, =CH— of ttfa<sup>-</sup>).

# 2.4. Crystallography

# 2.4.1. Structure determination

Data collection for X-ray structure determinations (Table 1) were performed on a STOE IPDS I (2)/II (1) diffractometers using graphite-monochromated Mo K $\alpha$  radiation (0.71073 Å). The data

Table 2						
Selected	bond	lengths/Å	and	angles/°	for 1	and 3

1		2	
Ag1–N18 <sup>iii</sup>	2.200(3)	Ag1-N11	2.232(3)
Ag1-N11	2.204(3)	Ag1-N18 <sup>iv</sup>	2.232(3)
Ag1-032 <sup>i</sup>	2.592(4)	Ag1-O26 <sup>ii</sup>	2.511(3)
Ag1-034 <sup>i</sup>	2.618(4)	Ag1–O28 <sup>ii</sup>	2.522(3)
Ag1···O44 <sup>ii</sup>	3.046(3)	Ag1…026 <sup>i</sup>	2.902(3)
Ag2-N21	2.198(3)	$Ag1 \cdots Ag^{v}$	3.307(5)
Ag2–N28 <sup>iii</sup>	2.203(3)	N11—Ag1—N18 <sup>iv</sup>	162.73(12)
Ag2-O42 <sup>ii</sup>	2.585(4)	N11-Ag1-026 <sup>ii</sup>	102.38(10)
Ag2–O44 <sup>ii</sup>	2.629(3)	N18 <sup>iv</sup> —Ag1—O26 <sup>ii</sup>	94.82(11)
Ag2···O34 <sup>i</sup>	3.018(3)	N11–Ag1–O28 <sup>ii</sup>	91.71(11)
Ag1···Ag2	3.250(7)	N18 <sup>iv</sup> —Ag1—O28 <sup>ii</sup>	95.43(11)
N18 <sup>iii</sup> —Ag1—N11	163.79(1)	026 <sup>ii</sup> —Ag1—028 <sup>ii</sup>	70.82(8)
N18 <sup>iii</sup> —Ag1—O32 <sup>i</sup>	92.01(1)		
N11—Ag1—O32 <sup>i</sup>	96.34(1)	i: −0.5 + <i>x</i> , 0.5 + <i>y</i> , <i>z</i>	
N21—Ag2—N28 <sup>iii</sup>	164.73(1)	ii: 0.5 − <i>x</i> , 1.5 − <i>y</i> , − <i>z</i>	
N21—Ag2—O42 <sup>ii</sup>	92.12(1)	iv: −1 + <i>x</i> , 2 − <i>y</i> , −0.5	+ <i>z</i>
N28 <sup>iii</sup> —Ag2—O42 <sup>ii</sup>	94.03(1)	v: $-x$ , $2 - y$ , $-z$	
i: −1 + <i>x</i> . <i>v</i> . <i>z</i>			

ii: -x, 0.5 + y, -0.5 - z

iii: -1 + x, 1.5 - y, -0.5 + z



**Fig. 1.** (I) Cyclic voltammograms of 1.0 mM (a) AgNO<sub>3</sub>, (b) **2** and (c) **1** at glassy carbon electrode in DMSO, Supporting Electrolyte 0.1 M TBAP and scan rate 100 mV s<sup>-1</sup>.

were corrected for Lorentz and polarization effects. A numerical absorption correction based on crystal-shape optimization was applied for all data [32]. The programs used in this work are Stoe's X-Area [33], including X-RED and X-Shape for data reduction and absorption correction [34], and the WinGX suite of programs [35], including SIR-92 [36] and SHELXL-97 [37] for structure solu-

tion and refinement. The hydrogen atoms were placed in idealized positions and constrained to ride on their parent atom. The last cycles of refinement included atomic positions for all atoms, anisotropic thermal parameters for all non-hydrogen atoms and isotropic thermal parameters for all of the hydrogen atoms. Selected interatomic distances and angles are given in Table 2.



Fig. 2. Fragment of the (one-dimensional) coordination polymer of 1.



Fig. 3. Fragment of the (one-dimensional) coordination polymer of 2.

Table 3Intermolecular interactions for 1 and 2.

A···H−B	A···H	A···B	A···H—B
	(A)	(A)	(°)
1			
F312H111C111	2.612	3.289(2)	129.82
(-1 - x, -1/2 + y, -1/2 - z)			
044H17—C17 (1 + x, 1.5 – y, 1/2 + z)	2.558	3.317(3)	139.07
F453…H17—C17 (1 + x, 1.5 – y, 1/2 + z)	2.583	3.407(3)	147.97
F452…H112—C112	2.516	3.388(3)	156.30
034…H22—C22	2.641	3.389(3)	137.97
F352…H22—C22	2.639	3.521(3)	158.54
F451H12—C12 $(-1 - x, -1/2 + y, -1/2 - z)$	2.558	3.290(3)	135.86
F412H27–C27 $(-x, -1/2 + y, -1/2 - z)$	2.641	3.176(3)	117.29
F453F411 $(-1 + x, y, z)$	-	2.884	-
$\pi \cdots \pi$ (slipped face-to-face)	-	3.347	-
$\pi \cdots \pi$ (slipped face-to-face) (in double chains)	-	3.489	-
2			
O26 - H17 - C17 (1 - x, y, 1/2 - z)	2.674	3.389(3)	134.08
O26…H112−C112 (− <i>x</i> , 2 − <i>y</i> , − <i>z</i> )	2.607	3.347(3)	136.88
$O28 \cdots H110 - C110 (1 - x, 2 - y, -z)$	2.582	3.034(4)	110.41
F291H22–C22 $(1/2 + x, 1.5 - y, -1/2 + z)$	2.530	3.249(2)	134.26
F291F291 ( $-x, y, -1/2 - z$ )	-	2.878(1)	-
$\pi$ $\pi$ (slipped face-to-face) (in double chains)		3.467	

#### 3. Results and discussion

# 3.1. Spectroscopic studies, TG and CV behavior

The IR spectra display the characteristic absorption bands for 4,4'-bpy ligands and the  $\beta$ -diketonate anion. The relatively weak absorption bands at around 3090 and 3075 cm<sup>-1</sup> are due to the C–H modes involving the aromatic ring hydrogen atoms. The IR

spectra of the compounds showed strong bands at 1618, 1625 cm<sup>-1</sup> and at 1515, 1520 cm<sup>-1</sup>, assigned to the v(C=O) and v(C=C) stretching of hfa<sup>-</sup> and ttfa<sup>-</sup> anions. These bands are at significantly lower energies than those found for free Hhfac, Httfa (1689 and 1675 cm<sup>-1</sup>) are indicative of  $\beta$ -diketonate chelation to Ag(I). The absorption bands with variable intensity in the frequency range 1560, 1585 cm<sup>-1</sup> correspond to the aromatic ring vibrations of the ligands (4,4'-bipyridine). The absorption bands in the frequency range 1260–1130 cm<sup>-1</sup> correspond with the C–F modes of the  $\beta$ -diketonates [9]. The <sup>1</sup>H NMR spectra of the DMSO solutions of **1** and **2** display two different protons of the 4,4'-bipy ligand at 8.7 and 7.8 ppm and the singlets at 5.25 and 5.89 ppm of =CH– protons of the hfa<sup>-</sup> and ttfa<sup>-</sup> anions, respectively. In **2**, distinct peaks at 7.55–7.70 and 7.07 ppm were assigned to the three protons of the thiophen ring of the ttfa<sup>-</sup> anions.

In order to investigate the thermal stability of all the silver complexes, TGA was performed on them in a N<sub>2</sub> atmosphere. The TG curves show that complexes 1 and 2 exhibit similar decomposition pathways. The TGA curves illustrate no weight loss up to 285 °C for 1 and up to 220 °C for 2, demonstrating that 1 and 2 are retained up to these temperatures. The thermal decomposition of the compounds occurs in two steps: The first step (sharp endothermic decomposition) in the temperature range 285-295 °C (almost 70 wt.%) for 1 and 215-225 °C (almost 60 wt.%) for 2, the second step in the temperature range 295-500 °C (almost 7 wt.%) for 1 and 25-500 °C (almost 18 wt.%) for 2, corresponds to the decomposition of the compounds (TG curve of 2, as example, in Fig. S1). The mass loss calculations as well as the microanalyses of the solid residues suggest that the residue left as a final decomposition product of the complexes is metallic silver, and the total mass loss of 21.10% for 1 (Calc. 22.93%) and 22.00% for 2 (Calc. 22.27%),



Fig. 4. Packing diagram of 1 viewing down the a axis with intermolecular interactions shown as dotted lines.

respectively, agrees well with the proposed structures. These results indicate that **1** have good thermal stability and accord with the conclusion reported that a fluorinated substituent in a ligand leads to an improved thermal and oxidative stability and increases the volatility of the complex [38].

The electrochemical behavior of the complexes is studied using the cyclic voltammetric technique in DMSO containing 0.1 M tetrabutylammonium perchlorate. Fig. 1 (curve a) shows the cyclic voltammograms (CV) of AgNO<sub>3</sub> in the desired solution. The curves (b) and (c) are the cyclic voltammograms of 1 and 2, respectively, under the same conditions. All the cyclic voltammograms exhibit a cathodic peak  $(C_1)$  in negative scan mode and a corresponding anodic peak  $(A_1)$  in positive scan mode. The cathodic peaks are due to the reduction of the silver ion (Ag<sup>+</sup>), and the anodic peaks are related to the oxidation of Ag produced at the electrode surface. As seen in this Figure, the cathodic peak potential of the complexes shifts to more negative values (-58 mV), which indicates the good interaction and stability of the silver ion in the complex structures. Based on these results, the interactions of the desired ligands with silver are about ten times stronger than the interaction of DMSO [39]. It should be noted that Ag<sup>+</sup> is strongly solvated in DMSO and its interactions are comparable with some cryptants (Electrochemistry in nonaqueous solutions, Kosukelzutsu). Additionally, the voltammetric study of the complexes with time show their good kinetic stability.

# 3.2. Description of the crystal structures of 1 and 2

Single-crystal X-ray diffraction analysis reveals that complexes **1** and **2** crystallize in the monoclinic space groups P2<sub>1</sub>/c and C2/c,

respectively. Each asymmetric unit contains one Ag(I) ion, one 4,4'bpy ligand and one hfa and ttfa anion. A twofold axis runs through the midpoint of the C–C bond of the 4,4'-bpy ligand. As shown in Figs. 2 and 3, the four-coordinated Ag(I) ion, which adopts a distorted tetrahedral geometry with bond angles ranging from 96.34° to 163.79° for 1 and 91.71° to 162.7 ° for 2, is coordinated by two N atoms from two different  $\mu$ -4,4'-bpy ligands and two O atoms from one hfa or ttfa anion. The distortion of the tetrahedron is indicated by the calculated value of the  $\tau_4$  parameter introduced by Houser and co-workers [40] to describe the geometry of a four coordinated metal system, which are 0.74 in 1 and 0.67 in 2 (for a perfect tetrahedral geometry  $\tau_4 = 1$ ). The two delocalized C=O groups of the hfa and ttfa anions are coordinated to the Ag(I) ion in a  $\eta\text{-}0,0'\text{-}chelating$  mode. The Ag– $N_{bipy}$  bond lengths range between 2.198(3)-2.203(3) Å for 1 and 2.232(3) Å for 2, which are comparable with those in Ag(I)-bpy complexes [41]. The Ag1–O bond length (2.585(4)-2.629(3) for 1 and 2.511(3), 2.521(3) for 2) is compatible with those in Ag(I) complexes containing oxygen ligator atoms [42], and the average Ag–O bond length in 1 is longer than in **2**. On the other hand, the Ag–N bond length in **1** is shorter than in 2. In addition to the strong coordinative bonds, there are weak Ag...O bonds (Ag1-O44 (-x, y + 1/2, -z + 1/2)) and Ag2-O34 with distances of 3.046 and 3.018 Å for **1** and Ag1–O26 (x + 1/2, y + 1/2, z) with a distance of 2.902 Å for **2**). These are slightly longer, but still fall in the secondary bonding range (the sum of van der Waals radii of Ag and O is 3.24 Å). The separation of Ag...Ag are 3.250 Å for 1 and 3.307 Å for 2, which is longer than the Ag...Ag distance in silver metal, but obviously shorter than twice the van der Waals radius of Ag(I) [43]. As shown in Figs. 2 and 3, a pair of



Fig. 5. Packing diagram of 2 viewing down the c axis with intermolecular interactions shown as dotted lines.

adjacent Ag-bpy single chains are linked into a double chain by weak Ag...O and Ag...Ag interactions.

Intermolecular, intramolecular and  $\pi$ - $\pi$  stacking interactions are observed in 1 and 2. They seem to be responsible for the packing of the complexes. An inspection of the data of 1 and 2 for weak directional intermolecular interactions using the programs PLA-TON and MERCURY, which were used for calculating the supramolecular interactions, has shown that there are O...H-C and C-H...F interactions [44,45] (Table 3). Fig. 4 shows the packing of the molecules of **1** in the crystal highlighting of some of the weak intermolecular interactions. The H…O and H…F separations range from 2.516 to 2.674 Å, which indicates moderate-to-strong hydrogen bonds [46]. The packing of the molecules of **1** and **2** in the solid state exhibits interesting self-assembled structure topologies through different  $\pi$ - $\pi$  stacking modes with interlayer distances of 3.347. 3.489 Å in **1** and 3.467 Å in 2 (see also Ref. [47]). The centroid-to-centroid separations between neighboring aromatic rings are exhibiting typical slipped  $\pi$ - $\pi$  stacking interactions in an offset fashion. Thus, a three-dimensional hydrogen-bonded and layerpacked network is constructed, as is illustrated for 1 and 2 Figs. 4 and 5. The two aryl ring planes of "4,4'-bpy" form an angle of 17.89° for 1 and 38.94° for 2. It seems reasonable to assume that the differences in the distorted aryl ring planes of "4,4'-bpy" around the silver atoms between **1** and **2** result from the network of directed intermolecular interactions detected in the reported structure. The formation of 3D networks is governed by the above-mentioned directed intermolecular interactions.

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#### Appendix A. Supplementary data

Full cif depositions, excluding structure factor amplitudes, reside with the Cambridge Crystallography Data center, CCDC-826097 for **1**, CCDC-826096 for **2**. Copies of the data can be obtained, free of charge, on application from CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: +44 1223 336033 or e-mail: deposit@ccdc.cam.ac.uk). Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.molstruc. 2011.08.059.

## References

- [1] G. Férey, Chem. Soc. Rev. 37 (2008) 191.
- [2] L.J. Murray, M. Dinca, J.R. Long, Chem. Soc. Rev. 38 (2009) 1294.
- [3] K. Koh, A.G. Wong-Foy, A.J. Matzger, Angew. Chem., Int. Ed. 47 (2008) 677.
- [4] Z. Wang, S.M. Cohen, Chem. Soc. Rev. 38 (2009) 1315.
- [5] J.L.C. Rowsell, E.C. Spencer, J. Eckert, J.A.K. Howard, O.M. Yaghi, Science 309 (2005) 1350.
- [6] O. Shekhah, H. Wang, M. Paradinas, C. Ocal, B. Schupbach, A. Terfort, D. Zacher, R.A. Fischer, C. Woll, Nat. Mater. 8 (2009) 481.
- [7] M.D. Allendorf, C.A. Bauer, R.K. Bhakta, R.J.T. Houk, Chem. Soc. Rev. 38 (2009) 1330.

- [8] C.-Y. Su, C.-L. Chen, J.-Y. Zhang, B.-S. Kang, Silver(I) coordination polymers, in: M.-C. Hong, L. Chen (Eds.), Design and Construction of Coordination Polymers, John Wiley & Sons, Inc., Hoboken, NJ, USA, 2009 (Chapter 5).
- [9] S. Bureekaew, S. Horike, M. Higuchi, M. Mizuno, T. Kawamura, D. Tanaka, N. Yanai, S. Kitagawa, Nat. Mater. 8 (2009) 831.
- [10] B. Wang, A.P. Côté, H. Furukawa, M. O'Keeffe, O.M. Yaghi, Nature 453 (2008) 207.
- [11] D. Sun, G.G. Luo, N. Zhang, J.H. Chen, R.B. Huang, L.R. Lin, L.S. Zheng, Polyhedron 28 (2009) 2983.
- [12] A.N. Khlobystov, A.J. Blake, N.R. Champness, D.A. Lemenovskii, A.G. Majouga, N.V. Zyk, M. Schröder, Coord. Chem. Rev. 222 (2001) 155.
- [13] G. Meyer, A. Berners, I. Pantenburg, Z. Anorg. Allg. Chem. 632 (2006) 34.
- [14] J.W. Steed, D.R. Turner, K.J. Wallace, Core Concepts in Supramolecular Chemistry and Nanochemistry, John Wiley and Sons Ltd., 2007 (Chapter 1).
- [15] J. Zhang, Y.-C. Shen, Y.-Y. Qin, Z.-J. Li, Y.-G. Yao, CrystEngComm 9 (2007) 636.
- [16] Y.-Q. Yu, W. Zhan, T.E. Albrecht-Schmitt, Inorg. Chem. 46 (2007) 10214.
- [17] L. Cunha-Silva, R. Ahmad, M.J. Carr, A. Franken, J.D. Kennedy, M.J. Hardie, Cryst. Growth Des. 7 (2007) 658.
- [18] Z.-X. Lian, J.-W. Cai, C.-H. Chen, Polyhedron 26 (2007) 2647.
- [19] S.E.-D.H. Etaiw, M.M. El-Bendary, J. Coord. Chem. 63 (2010) 1038.
- [20] B.H. Ye, M.L. Tong, X.M. Chen, Coord. Chem. Rev. 249 (2005) 545.
- [21] C.N.R. Rao, S. Natarajan, R. Vaidhyanathan, Angew. Chem., Int. Ed. Engl. 43 (2004) 1466.
- [22] B.R. Manzano, F.A. Jalon, M.L. Soriano, M.C. Carrion, M.P. Carranza, K. Mereiter, A.M. Rodriguez, A. De la Hoz, A. Sanchez-Migallon, Inorg. Chem. 47 (2008) 8957.
- [23] A. Decken, C. Knapp, G.B. Nikiforov, J. Passmore, J.M. Rautiainen, X.-P. Wang, X.-Q. Zeng, Chem. Eur. J. 15 (2009) 6504.
- [24] C.-L. Chen, C.-Y. Su, Y.-P. Cai, H.-X. Zhang, A.-W. Xu, B.-S. Kang, H.C. zur Loye, Inorg. Chem. 42 (2003) 3738.
- [25] M.J. Hannon, C.L. Painting, E.A. Plummer, L.J. Childs, N.W. Alcock, Chem. Eur. J. 8 (2002) 2226.
- [26] J.R. Price, Y.-H. Lan, G.B. Jameson, S. Brooker, Dalton Trans. (2006) 1491.
- [27] A.M. Stadler, N. Kyritsakas, G. Vaughan, J.M. Lehn, Chem. Eur. J. 13 (2007) 59.
- [28] P.A. Vigato, V. Peruzzo, S. Tamburini, Coord. Chem. Rev. 253 (2009) 1099.
- [29] S.C. Ngo, K.K. Banger, P.J. Toscano, J.T. Welch, Polyhedron 21 (2002) 1289.
- [30] K.-M. Chi, K.-H. Chen, H.-C. Lin, K.-J. Lin, Polyhedron 16 (1997) 2147.
- [31] (a) K. Akhbari, A. Morsali, Cryst. Growth Des. 7 (2007) 2024;

(b) F. Pointillart, P. Herson, K. Boubekeur, C. Train, Inorg. Chim. Acta 361 (2008) 373;

(c) L. Zanotto, F. Benetollo, M. Natali, G. Rossetto, P. Zanella, S. Kaciulis, A. Mezzi, Chem. Vap. Deposition 10 (2004) 207.

- [32] X-Shape 1.06, Crystal Optimisation for Numerical Absorption Correction (C), STOE & Cie GmbH Darmstadt, 1999.
- [33] X-Area 1.16, Stoe & Cie GmbH Darmstadt, 2003.
- [34] X-RED 1.22, Stoe Data Reduction Program (C), Stoe & Cie GmbH Darmstadt, 2001.
- [35] L.J. Farrugia, J. Appl. Crystallogr. 32 (1999) 837.
- [36] A. Altomare, G. Cascarano, C. Giacovazzo, J. Appl. Crystallogr. 26 (1993) 343.
  [37] G.M. Sheldrick, SHELXL-97; Programs for Crystal Structure Analysis, University
- of Göttingen, 1997. [38] J.B. Yu, L. Zhou, H.J. Zhang, Y.X. Zheng, H.R. Li, R.P. Deng, Z.P. Peng, Z.F. Li, Inorg.
- Chem. 44 (2005) 1611. [39] I.M. Kolthoff, E.B. Sandel, E.J. Meehan, S. Brukenestein, Ouantitative Chemical
- [39] I.M. Kolthoff, E.B. Sandel, E.J. Meenan, S. Brukenestein, Quantitative Chemica Analysis, fourth ed., Macmillan, London, 1971.
- [40] L. Yang, D.R. Powell, R.P. Houser, J. Chem. Soc., Dalton Trans. (2007) 955.
- [41] X.-F. Zheng, L.-G. Zhu, Inorg. Chim. Acta 365 (2011) 419.
- [42] D. Sun, G.-G. Luo, N. Zhang, Q.-J. Xu, R.-B. Huang, L.-S. Zheng, Polyhedron 29 (2010) 1243.
- [43] A. Bondi, J. Phys. Chem. 68 (1964) 441.
- [44] A.C. Moro, F.W. Watanabe, S.R. Ananias, A.E. Mauro, A.V.G. Netto, A.P.R. Lima, J.G. Ferreira, R.H.A. Santos, Inorg. Chem. Commun. 9 (2006) 493.
- [45] J.W. Steed, J.L. Atwood, Supramolecular Chemistry, J. Wiley, Chichester, 2000.
  [46] (a) L.A. Barrios, G. Aromi, A. Frontera, D. Quinonero, P.M. Deya, P. Gamez, O. Roubeau, E.J. Shotton, S.J. Teat, Inorg. Chem. 47 (2008) 5873;

(b) C.A. Hollis, L.R. Hanton, J.C. Morris, C.J. Sumby, Cryst. Growth Des. 9 (2009) 2911.

[47] (a) T. Dorn, C. Janiak, K. Abu-Shandi, CrystEngComm 7 (2005) 633;
 (b) S. Banerjee, A. Ghosh, B. Wu, P.-G. Lassahn, C. Janiak, Polyhedron 24 (2005) 593;

(c) S. Banerjee, B. Wu, P.-G. Lassahn, C. Janiak, A. Ghosh, Inorg. Chim. Acta 358 (2005) 535.