Journal of Solid State Chemistry xxx (xxxx) xxx



Contents lists available at ScienceDirect

Journal of Solid State Chemistry



journal homepage: www.elsevier.com/locate/jssc

Self-assembly of three novel entangled polyoxometalate-based coordination polymers with redox properties

Jun-Jie Fu¹, Jian-Gang Wo¹, Yu-Hui Luo^{*}, A-Di Xie, Ji Wu, Yuan-Yuan Zhang^{**}, Yi-Bo Zhao, Dong-En Zhang

Address: School of Environmental and Chemical Engineering, Jiangsu Ocean University, Lianyungang, 222000, PR China

ARTICLE INFO	A B S T R A C T
Keywords: Entanglement Hydrothermal reaction Polycatenation Interdigitation Polythreading Electrocatalyst	Three novel entangled coordination polymers (CPs), namely, $[Cu_4(BPB)_5(HPW_{12}O_{40})_2] \cdot 2H_2O$ (JOU-15), $[Cu_3(BPB)_3PW_{12}O_{40}]$ (JOU-16), and $[Cu_3(BPB)_3PW_{12}O_{40}]$ (JOU-17), have been successfully synthesized by combining flexible N-donor ligands and Keggin type polyoxometalates with copper ion under hydrothermal conditions. Structural characterizations show that JOU-15 features an unusual $1D + 1D \rightarrow 2D$ entangled network with the coexistence of polycatenation and interdigitation. JOU-16 exhibits a fascinating self-catenated three-dimensional framework with a new point symbol of $(4^4 \cdot 6^{10} \cdot 8)(6^5 \cdot 8)(6^6)$. JOU-17 displays a novel $1D + 3D + 3D \rightarrow 3D$ entangled framework with features of both polycatenation and polythreading. In addition, the electrochemical properties of these compounds have also been studied.

1. Introduction

Coordination polymers (CPs), which represent a class of designable materials based on metal ions and organic ligands, have been wildly studied for their potential applications in luminescence, catalysis, and sensing [1–8]. As a meaningful class of this field, entangled CPs are attracting increasing interest for their aesthetic structures and enhanced properties [9–12]. Up to now, many efforts have been payed to the rational design and synthesis of entangled CPs, and some fascinating entangled forms have been reported, such as polycatenation, polythreading and polyknotting [13–15]. However, the preparation of new types of entangled structures is still a hard task in coordination chemistry because the assembly system is very complex and may be affected by many factors.

Polyoxometalates (POMs) are attracting more and more interests for their significant applications in, for instance, catalysis, biotechnology and optics [16–20]. POMs with abundant surface oxygen atoms not only can act as templates, but also can act as O-donor ligands to coordinate with metal ions. It has been noticed that the combination of POMs and CPs can produce composites with enhanced properties [21,22]. Many POM-based CPs have been reported so far [19,23–25]. However, it remains challenges to design and synthesize POM-based entangled CPs with specific properties. Take Keggin type $\left[PW_{12}O_{40}\right]^{3-}$ (PW₁₂) as an example, it can only stable within acidic pH range, but the low pH value may not conducive to the coordination reaction [26]. On the other hand, PW₁₂ are composed of up to 53 atoms. The large molecular volume and rigid steric hindrance would hinder the formation of CPs with complex structure. In our previous work, we found that N-donor ligands with flexible methylene groups can exhibit variable conformations and can act as excellent ligands for the construction of entangled POM-based CPs [27-29]. For one thing, flexible nitrogen heterocyclic ligands have strong coordination ability. For another, the flexible structure of these ligands can adapt to the rigid steric hindrance of POMs. In this work, we aim to prepare POM-based CPs with novelty entangled forms. Compounds 1, 4-bis((3,5-dimethyl-1H-pyrazol-4-yl)-methyl)benzene (BPB) and 4, 4'-bis((3,5-dimethyl-1H-pyrazol-4-yl)methyl)biphenyl (BPBP) (Scheme 1) were selected as organic ligands for their following advantages. Firstly, the ligands with flexible methylene groups may form a variety of different conformations and are beneficial to generating entangled structure. Secondly, the pyrazolo groups of the ligands contain two adjacent nitrogen atoms can form different coordination modes. Thirdly, the pyrazolo groups can form hydrogen bonds to further stabilize the supramolecular architectures.

Herein, three POM-based CPs, namely, [Cu4(BPB)5(HPW12O40)2].

https://doi.org/10.1016/j.jssc.2020.121839

Received 1 October 2020; Received in revised form 26 October 2020; Accepted 27 October 2020 Available online xxxx 0022-4596/© 2020 Elsevier Inc. All rights reserved.

Please cite this article as: J.-J. Fu et al., Self-assembly of three novel entangled polyoxometalate-based coordination polymers with redox properties, Journal of Solid State Chemistry, https://doi.org/10.1016/j.jssc.2020.121839

^{*} Corresponding author.

^{**} Corresponding author.

E-mail addresses: luoyh@jou.edu.cn (Y.-H. Luo), zhangyy@jou.edu.cn (Y.-Y. Zhang).

¹ These two authors contributed equally.



Scheme 1. Structures of BPB and BPBP.

 $2H_2O$ (**JOU-15**, JOU stands for Jiangsu Ocean University), [Cu₃(BPB)₃PW₁₂O₄₀] (**JOU-16**), and [Cu₃(BPBP)₃PW₁₂O₄₀] (**JOU-17**), have been synthesized under hydrothermal conditions. Structural analyses reveal that these compounds exhibit novelty entangled networks. In addition, the electrochemical properties of these compounds have also been investigated.

2. Results and discussions

2.1. Structure of JOU-15

Structural analyses reveal that **JOU-15** displays a novel $2D + 2D \rightarrow 2D$ entangled framework with features of both polycatenation and

interdigitation. The asymmetric unit of JOU-15 contains four crystallographic independent copper ions. All copper atoms in JOU-15 are detected to be +1 oxidation state with the bond valence sums (BVS) calculation [30,31]. As shown in Fig. 1a, all of Cu ions are three-coordinated by two nitrogen atoms from BPB ligands and one oxygen atom from PW12 anions in approximate "T" shaped coordination geometry (Cu-N 1.85(2) - 1.93(3) Å, Cu-O 2.694(3) - 2.875(4) Å). Five BPB ligands are connected by four Cu ions to form linear coordination fragments, which are further connected by PW12 anions to generate 1D ladder-shape chains (Fig. 1b). Thereafter, these ladder-shape chains interpenetrate with each other to form a $1D + 1D \rightarrow 2D$ polycatenation (Fig. 1c-d). Fascinatingly, monocoordinated BPB ligands with protonated pyrazole groups distributed on both sides of the ladder-shape chains. These monocoordinated BPB ligands act as arms to form a $1D + 1D \rightarrow 2D$ interdigitation (Fig. 1e). Thus, JOU-15 exhibits a $1D \rightarrow 2D$ polycatenated and interdigitated network. It is worth noting that JOU-15 represents the first example of POM-based CPs with both $1D + 1D \rightarrow 2D$ polycatenated and $1D + 1D \rightarrow 2D$ interdigitated phenomenon. The 2D entangled layers accumulate to form a supramolecular structure. In addition, the space of the supramolecular structure is occupied by the lattice water molecules. These lattice water molecules connect the 2D entangled layers through hydrogen-bonding interactions between oxygen atoms of POMs (O1W...O69 3.085(5), O2W...O40 3.062(4) and O3W...O77 2.866(3) Å) and nitrogen atoms of BPB ligands (N1...O1W 2.587(5), N2...O2W 2.695(5), N10...O80 2.894(2) Å and N9...O3W 2.764(3) Å) (Fig. S1).

2.2. Structure of JOU-16

Single-crystal X-ray diffraction analyses indicate that **JOU-16** shows a 3D self-catenated framework. There are one and a half Cu(I) ions, three



Fig. 1. (a) Coordination environment of Cu ions in **JOU-15**. Symmetry codes: #1 x, -1 + y, z. (b) View of the 1D ladder-shape chain with monocoordinated BPB ligands distribute on both sides. (c) Topological illustration of 1D \rightarrow 2D polycatenated and interdigitated network. (d) The interlocking between polycatenated ladder-shape chains to give a rotaxane-like motif. (e) Structural representation of 1D + 1D \rightarrow 2D interdigitated phenomenon in **JOU-15**. The PW₁₂ anions in all pictures are depicted as polyhedral representative.

J.-J. Fu et al. half BPB ligands and half PW₁₂ anion in the asymmetric unit of **JOU-16**. The P atom in the centre of PW12 cluster lies on an inversion centre, with four disordered oxygen atoms (O1, O2, O3, O4) directly bond to it. All copper atoms in JOU-16 are in +1 oxidation state, which was calculated by the BVS calculation [30,31]. As shown in Fig. 2a, Cu1 is four-coordinated by two nitrogen atoms from BPB and two oxygen atoms from PW₁₂ in a distorted tetrahedral coordination geometry (Cu1-N1 1.827(19) Å, Cu1-N3 1.851(15) Å, Cu1-O20 2.703(4) Å), whereas Cu2 is four-coordinated by two nitrogen atoms from BPB and two oxygen atoms from PW12 in a plane quadrilateral coordination geometry (Cu2-N5 1.83(2) Å, Cu2–O6 2.868(2) Å). PW12 anions are connected by Cu⁺ to form 2D layers (Fig. 2b), which are further linked into a 3D framework by BPB ligands (Fig. 2c). Interestingly, the framework of JOU-16 displays a self-penetrating phenomenon. As far as we know, self-catenated POM-based CPs are still rare reported [28,29,32]. From the topological view, PW12 anions coordinated by six Cu ions can be reduced to 4-connected nodes. Binuclear Cu1 ions connect two PW12 clusters and four other

binuclear Cu1 ions can be considered as 6-connected nodes. Cu2 ions

connect two PW_{12} clusters and two other Cu2 ions can also be simplified as 4-connected nodes. Thus, **JOU-16** shows a new type of (4,4,5)-con-

nected network with $(4^4 \cdot 6^{10} \cdot 8)(6^5 \cdot 8)(6^6)$ topology (Fig. 2d).

2.3. Structure of JOU-17

When BPB was replaced with a longer ligand BPBP, compound **JOU-17** was obtained with an entirely different framework. Structural analyses reveal that **JOU-17** represents a novel $1D + 3D + 3D \rightarrow 3D$ entangled framework with features of both polycatenation and polythreading. The asymmetric unit of **JOU-17** contains three Cu(I) ions, three BPBP ligands and one PW₁₂ anion. Copper atoms in **JOU-17** are also in +1 oxidation state. As shown in Fig. 3a, Cu1 and Cu2 ions are

three-coordinated by two nitrogen atoms from BPBP and one oxygen atom from PW12 in approximate "T" shaped coordination geometries, whereas Cu3 is two-coordinated by two nitrogen atoms from BPBP in a linear coordination geometry. Cu1 ions are connected by BPBP ligands to form 1D zigzag chains, whereas Cu2 ions are connected by BPBP ligands to form left- and right-handed single-helical chains (Fig. 3b, c and 3d). These chains are cross-linked by PW12 through weak Cu-O bonds to generate a 3D network (Fig. 3e). Topologically, binuclear Cu1 ions connect two binuclear Cu2 ions and four other binuclear Cu1 ions can be reduced to 6-connected nodes. Binuclear Cu2 ions connected two binuclear Cu1 ions and four other binuclear Cu2 ions can also be considered as 6-connected nodes. PW12 anions and BPBP ligands can be considered as linear linkers. Thus, the framework of JOU-17 can be simplified as a (6,6)-connected network with the pcu topology (Fig. 3f). Interestingly, the large pores of the framework allow pair of networks interpenetrate with each other to generate a $3D + 3D \rightarrow 3D$ polycatenation (Fig. 3g). More fascinatingly, Cu3 ions are connected by BPBP ligands to form leftand right-handed single-helical chains (Fig. 3h-i), which penetrate throughout the remaining channels of JOU-17 to generate a $1D + 3D \rightarrow$ 3D polythreading network. Thus, compound JOU-17 exhibits a 1D + 3D+ 3D \rightarrow 3D polycatenation and polythreading network. As far as we know, JOU-17 is the first POM-based CPs with both $3D + 3D \rightarrow 3D$ interpenetrated and $1D + 3D \rightarrow 3D$ polythreading motifs.

2.4. Synthesis and structural comparison

In this work, we used copper ions as metal centres, Keggin-type PW_{12} as inorganic functional ligands, and flexible N-donor Ligands with different lengths as organic linkers to prepare three entangled CPs. Although all title compounds are hydrothermal synthesized with Cu(II) salt as reactant, the copper is in +1 oxidation state in the products. This



Fig. 2. (a) Coordination environment of Cu ions in **JOU-16**. Symmetry codes: #1 - *x*, 1 - *y*, - *z*; #2 - *x*, -*y*, 2 - *z*; #3 1 - *x*, -*y*, 1 - *z*; #4 1 - *x*, -*y*, - *z*; #5 -*x*, 1 - *y*, 1 - *z*. (b) View of the 2D layered structure constructed by Cu ions and PW₁₂ anion. (c) View of the 3D framework of **JOU-16**. The self-penetrating motifs are highlighted in pink. (d) Topological view of **JOU-16**. Red ball represents binuclear Cu1 ions, green ball represents Cu2 ions, and blue ball stands for PW₁₂. The PW₁₂ anions in all pictures are depicted as polyhedral representative. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



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Fig. 3. (a) Coordination environment of Cu ions in JOU-17. Symmetry codes: #1 1 - x, 1 - y, 1 - z. (b) View of the 1D zigzag chain of Cu1-BPBP. (c) and (d) View of the left- and right-handed Cu2-BPBP chains. (e) View of the 3D framework of JOU-17. (f) Topological view of JOU-17. (g) Structural representation of $1D + 3D + 3D \rightarrow 3D$ entangled network of JOU-17. The penetrated Cu3-BPBP chains are highlighted in red and black, respectively. (h) and (i) View of the left- and right-handed Cu3-BPBP chains. The PW12 anions in all pictures are depicted as polyhedral representative. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

may be attributed to the in situ reduction of Cu(II) to Cu(I) under hydrothermal condition with the presence of nitrogen heterocyclic ligands. This phenomenon has also been noticed in some other reaction conditions [24,25,33,34].

Initially, a $1D + 1D \rightarrow 2D$ entangled framework of **JOU-15** was successfully prepared with the coexistence of polymerization and interdigitation by using BPB as a ligand. All copper ions in JOU-15 exhibit three coordinated T-shaped configurations, whereas BPB ligands show both monodentate and bidentate coordination modes to connected copper ions into an interpenetrating structure. When the pH value of the reaction solution was reduced, a self-interpenetrating 3D framework JOU-16 was obtained. Two crystallographically independent copper ions in JOU-16 were tetrahedral coordinated to form a distorted tetrahedral and a plane quadrilateral coordination geometry, respectively, while BPB ligands were all bidentate coordinated. These results indicate that pH value is important to the formation of CPs' structure. In compounds JOU-15 and JOU-16, BPB presents six and three kinds of coordination configurations, respectively (Fig. S2). This result reveals that the flexible ligand with -CH₂- groups can show various configurations to adapt to the rigid steric hindrance of POMs, and then to form complex entanglement. When BPB was replaced with a longer ligand BPBP, a novel 1D + 3D + 3D \rightarrow 3D entangled framework with the features of both polycatenation and polythreading was prepared. These results not only prove that the structure of CPs can be affected by changing the length of ligands, but also further confirm that ligands contain -CH2- groups could show high flexibility.

2.5. PXRD measurements and thermal analyses

Powder X-ray diffractions (PXRD) were used to confirm the crystalline phase purity of the title compounds (Fig. S3), while thermogravimetric analysis (TGA) were carried out to investigate their thermal stability (Fig. S4). The measured and simulated PXRD patterns matched well confirm their phase purity.

For **JOU-15**, the first weight loss from 180 to 200 °C may be due to the release of water molecules (obsd 0.67%, calcd 0.48%). A further weight loss started at about 370 °C is due to the decomposition of the framework. For compounds **JOU-16** and **JOU-17**, only one weight loss was obtained both started at about 400 °C. This may be due to the decomposition of the framework.

2.6. Electrochemical experiments

Electrochemical performances of the title compounds were studied by using compound modified glassy carbon electrode (GCE) as the working electrode. 2 mg powder of compound, 2 mg carbon black (CB) and 20 μ L of Nafion (5% solution in ethanol) were mixed in 2 mL ethanol and ultrasonic treated for several hours to obtain a slurry. 10 μ L of the slurry was added on the surface of GCE and dried under room temperature. The cyclic voltammograms (CVs) of all compounds were recorded in 0.5 M H₂SO₄ aqueous solution in a potential range of -720 to -100 mV. As shown in Fig. 4a, d and 4g, the CV curves of JOU-15-GCE, JOU-16-GCE

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Fig. 4. (a), (d) and (g) shows the CV curves of JOU-15-GCE, JOU-16-GCE and JOU-17-GCE at different scan rates, respectively. (b) and (h) The cathodic peak (III) and anodic peak (III)' currents of JOU-15-GCE and JOU-17-GCE are all proportional to the scan rates. (e) The cathodic peak (III) and anodic peak (III)' currents of JOU-16-GCE and JOU-17-GCE are all proportional to the scan rates. (e) The cathodic peak (III) and anodic peak (III)' currents of JOU-16-GCE were proportional to the square root of scan rates. (C), (f) and (i) represents the CV curves of JOU-15-GCE, JOU-16-GCE and JOU-17-GCE in 0.5 M H₂SO₄ solution containing 0.0–8.0 mmol L⁻¹ NaNO₂, respectively. Scan rate: 100 mV s⁻¹.

and JOU-17-GCE show three pairs of reversible redox peaks. The mean peak potentials ($E_{1/2} = (E_{pa} + E_{pc})/2$) were detected to be -0.254, -0.448, and -0.637 V for JOU-15, -0.255, -0.479 and -0.635 for JOU-16, -0.243, -0.453 and -0.643 for JOU-17, respectively (Scan rate: 100 mV s⁻¹). When the scan rate was increased, the cathodic peak potentials of CV curves shift to the negative direction, while the corresponding anodic peak potentials shift to the positive direction. For JOU-15-GCE and JOU-17-GCE, the currents of peaks III and III' are proportional to scan rates, indicating that the redox processes of JOU-15-GCE and JOU-17-GCE are surface controlled (Fig. 4b and h). On the other hand, the peak currents of JOU-16-GCE are proportional to the square root of scan rates, indicating that the redox procedures of JOU-16-GCE are diffusion controlled (Fig. 4e) [35].

In addition, JOU-15, JOU-16 and JOU-17 display electrocatalytic activities toward the nitrite reduction (Fig. 4c, f and 4i). As the concentration of nitrite increase, all reduction peak currents of JOU-15-GCE, JOU-16-GCE and JOU-17-GCE substantially grow, indicating that all the reduced species in GCEs can effectively electro catalyze the reduction of nitrite. In contrast, direct electrochemical reduction of nitrite usually requires a large overpotential [29], and almost no response could be obtained at a CB modified GCE. To verify the stability and recycling of these modified GCEs, multiple CV curves were tested (Fig. S5). The CV curves before and after fifty cycles were almost coincident, indicating that these modified GCEs were stable and recyclable.

3. Conclusions

Three POM-based CPs with novel entanglements have been successfully synthesized and structurally characterized. Compound **JOU-15** shows an unusual $1D + 1D \rightarrow 2D$ entangled network with fascinating

features of both polycatenation and interdigitation. Compound **JOU-16** represents a self-catenated 3D framework with new $(4^4 \cdot 6^{10} \cdot 8)(6^5 \cdot 8)(6^6)$ topology. Compound **JOU-17** displays a novel $1D + 3D + 3D \rightarrow 3D$ entangled framework with features of both polycatenation and polythreading. In addition, the results of electrochemical experiments suggest that these compounds may be new candidates as electrocatalysts for nitrite reduction. The successful synthesis of these compounds provides valuable clues for systematically assembly of functional entangled POM-based CPs.

4. Experiments

4.1. Synthesis of BPB and BPBP

BPB and BPBP were prepared according to the reported method with revisions [36]. In a 1000 mL three-necked round flask, a certain amount of trimethylchlorosilane (31.5 g for BPB and 40.2 g for BPBP) were dissolved in 400 mL acetonitrile under N2 atmosphere. Then sodium iodide (43.44 g for BPB and 55.5 g for BPBP) and 5.8 g of acetylacetone were added to the solution successively. At this time, orange suspension appeared, and the temperature of the solution was reduced to 0 °C. After that, corresponding aldehydes (3.9 g of p-benzaldehyde for BPB and 8 g of 4,4'-biphenyldicarboxyldehyde for BPBP) was added followed by warming the solution to room temperature. The reaction mixture was stirred at room temperature for 6 h and at 60 °C for 10 h, respectively. After the reaction was cooled to room temperature, a dark brown mixture was obtained. Pour the dark brown mixture into a separating funnel containing 800 mL of distilled water. The crude product was extracted three times with 150 mL ether, and the dark brown organic phase was repeatedly washed (about seven times) with 100 mL (10 wt%) sodium

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thiosulfate aqueous solution until the colour of the solution changed from dark brown to light yellow. The obtained solution was evaporated and concentrated at 40 $^{\circ}$ C under vacuum. Thereafter, the obtained concentrate was poured into 500 mL boiling distilled water and stirred until the ether was completely removed. The white powder of intermediate product was obtained by filtration.

The white powder of intermediate product (\sim 2.0 g for BPB and \sim 8.0 g for BPBP) and hydrazine hydrate solution (4 mL, 80%) were dissolved in 100–200 mL ethanol, and stirred for 24 h at room temperature. The white powder of BPB or BPBP was obtained by filtering, washing repeatedly with ethanol, and drying in vacuum. Yield: 1.7 g for BPB and 7.2 g for BPBP. These white powdered products were used directly without further purification.

4.2. Synthesis of JOU-15

A mixture of PW₁₂ (0.03 mmol, 100 mg), BPB (0.03 mmol, 10 mg), CuCl₂·2H₂O (0.1 mmol, 17 mg), H₂O (10 mL) and NaOH (1 mol/L, 30 µL) was added into an 18 mL Teflon-lined reactor and heated at 180 °C for three days. Red block crystals were collected by ultrasonically cleaning the sample, washing with distilled water several times, filtrating, and drying in air. The pH value of reaction solution was about 5.0. Yield: ca. 35% (based on BPB). IR (KBr, cm⁻¹): ν = 3448 (s), 3365 (m), 2989 (m), 2951 (m), 2916 (m), 2827 (m), 2780 (m), 1610 (s), 1488 (s), 1443 (s), 1414 (s), 1367 (s), 1277 (m), 1170 (m), 1122 (m), 1081 (m), 988 (w), 887 (m), 812 (s), 772 (s), 670 (s), 609 (m).

4.3. Synthesis of JOU-16

JOU-16 was synthesized with a similar method to **JOU-15** except that HCl (1 mol/L, 30 μ L) was used instead of NaOH. Red plate crystals were collected by hand picking. The pH value of reaction solution was about 3.5. Yield: ca. 10% (based on BPB). **JOU-15** can also be isolated under this condition. IR (KBr, cm⁻¹): $\nu = 3435$ (s), 3368 (m), 2994 (m), 2949 (m), 2915 (m), 2825 (m), 2716 (m), 1598 (s), 1493 (s), 1439 (s), 1363 (s), 1277 (m), 1172 (m), 1119 (m), 1077 (s), 986 (w), 895 (m), 821 (s), 776 (s), 615 (s), 513 (m).

4.4. Synthesis of JOU-17

JOU-17 was synthesized with a similar method to **JOU-16** except that BPB was replaced by BPBP (0.03 mmol, 12.5 mg). The pH value of reaction solution was about 3.5. Red block crystals were obtained with a yield of 30% (based on BPBP). IR (KBr, cm⁻¹): $\nu = 3400$ (s), 2990 (m), 2920 (m), 2830 (m), 1600 (s), 1500 (s), 1430 (s), 1360 (s), 1170 (m), 1080 (m), 981 (m), 898 (w), 810 (w), 662 (m), 619 (s), 520 (m).

CRediT authorship contribution statement

Jun-Jie Fu: Crystal growth. Jian-Gang Wo: Crystal growth. Yu-Hui Luo: Writing - original draft. A-Di Xie: Software and characterization. Ji Wu: Software and characterization. Yuan-Yuan Zhang: Resources. Yi-Bo Zhao: Supervision. Dong-En Zhang: Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was financially supported by the Natural Science Fund of

Jiangsu Province (BK20171263); the Six Talents Peak Project of Jiangsu Province (XCL-009); the Foundation of Jiangsu Key Laboratory of Function Control Technology for Advanced Materials (AM201902); and the Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://do i.org/10.1016/j.jssc.2020.121839.

References

- J. Gao, X. Qian, R.B. Lin, R. Krishna, H. Wu, W. Zhou, B. Chen, Angew. Chem. Int. Ed. 59 (2020) 4396–4400.
- [2] J.S. Qin, D.Y. Du, M. Li, X.Z. Lian, L.Z. Dong, M. Bosch, Z.M. Su, Q. Zhang, S.L. Li, Y.Q. Lan, S. Yuan, H.C. Zhou, J. Am. Chem. Soc. 138 (2016) 5299–5307.
- [3] K. Kadota, N.T. Duong, Y. Nishiyama, E. Sivaniah, S. Kitagawa, S. Horike, Chem. Sci. 10 (2019) 6193–6198.
- [4] X. Pei, H.B. Bürgi, E.A. Kapustin, Y. Liu, O.M. Yaghi, J. Am. Chem. Soc. 141 (2019) 18862–18869.
- [5] A.X. Zhu, Q.Y. Yang, S. Mukherjee, A. Kumar, C.H. Deng, A.A. Bezrukov, M. Shivanna, M.J. Zaworotko, Angew. Chem. Int. Ed. 58 (2019) 18212–18217.
- [6] W.W. Xiong, Q.C. Zhang, Angew. Chem. Int. Ed. 54 (2015) 11616–11623.
 [7] P. Li, F.F. Cheng, W.W. Xiong, Q.C. Zhang, Inorg. Chem. Front. 5 (2018) 2693–2708.
- [8] F.F. Cheng, J.N. Zhu, M.Y. Zhao, Z.J. Ma, W.W. Xiong, J. Solid State Chem. 278 (2019) 120904.
- [9] T.K. Maji, R. Matsuda, S. Kitagawa, Nat. Mater. 6 (2007) 142–148.
 [10] J. Liang, X.L. Wang, Y.Q. Jiao, C. Qin, K.Z. Shao, Z.M. Su, Q.Y. Wu, Chem. Commun.
- 49 (2013) 8555–8557. [11] D. Balestri, P. Scilabra, C. Carraro, A. Delledonne, A. Bacchi, P.P. Mazzeo,
- L. Carlucci, P. Pelagatti, CrystEngComm 21 (2019) 6365–6373.
- [12] Z.J. Ma, W. Li, J.M. Yu, Z.Z. Zhang, X.Q. Zhu, W.W. Xiong, X.Y. Huang, J. Solid State Chem. 285 (2020) 121248.
- [13] L. Carlucci, G. Ciani, D.M. Proserpio, Coord. Chem. Rev. 246 (2003) 247-289.
- [14] J. Yang, J.F. Ma, S.R. Batten, Chem. Commun. 48 (2012) 7899–7912.
 [15] J. Zhao, D.S. Li, X.J. Ke, B. Liu, K. Zou, H.M. Hu, Dalton Trans. 41 (2012)
- 2560–2563.
- [16] M. Samaniyan, M. Mirzaei, R. Khajavian, H. Eshtiagh-Hosseini, C. Streb, ACS Catal. 9 (2019) 10174–10191.
- [17] J.S. Qin, D.Y. Du, W. Guan, X.J. Bo, Y.F. Li, L.P. Guo, Z.M. Su, Y.Y. Wang, Y.Q. Lan, H.C. Zhou, J. Am. Chem. Soc. 137 (2015) 7169–7177.
- [18] Z. Zhang, Y. Tao, H. Tian, Q. Yue, S. Liu, Y. Liu, X. Li, Y. Lu, Z. Sun, E. Kraka, S. Liu, Chem. Mater. 32 (2020) 5550–5557.
- [19] W.W. He, S.L. Li, H.Y. Zang, G.S. Yang, S.R. Zhang, Z.M. Su, Y.Q. Lan, Coord. Chem. Rev. 279 (2014) 141–160.
- [20] W. Li, J.N. Zhu, N.N. Shen, W.W. Xiong, X.Y. Huang, CrystEngComm 21 (2019) 971–980.
- [21] J. Song, Z. Luo, D.K. Britt, H. Furukawa, O.M. Yaghi, K.I. Hardcastle, C.L. Hill, J. Am. Chem. Soc. 133 (2011) 16839–16846.
- [22] L. Li, J.R. Wang, Y. Hua, Y. Guo, C. Fu, Y.N. Sun, H. Zhang, J. Mater. Chem. C 7 (2019) 38–42.
- [23] S. Taleghani, M. Mirzaei, H. Eshtiagh-Hosseini, A. Frontera, Coord. Chem. Rev. 309 (2016) 84–106.
- [24] D. Li, P. Ma, J. Niu, J. Wang, Coord. Chem. Rev. 392 (2019) 49–80.
 [25] X.X. Lu, Y.H. Luo, Y.S. Liu, W.W. Ma, Y. Xu, H. Zhang, CrystEngComm 18 (2016) 3650–3654.
- [26] A.V. Anvushin, A. Kondinski, T.N. Parac-Vogt, Chem. Soc. Rev. 49 (2020) 382–432.
- [27] Y.H. Luo, X.X. Lu, H. Zhang, CrystEngComm 16 (2014) 7865–7868.
- [28] X.X. Lu, Y.H. Luo, Y. Xu, H. Zhang, CrystEngComm 17 (2015) 1631-1636.
- [29] Y.H. Luo, X.Y. Yu, H. Zhang, CrystEngComm 16 (2014) 6664-6669.
- [30] I.D. Brown, D. Altermatt, Acta Crystallogr. B 41 (1985) 244–247.
- [31] R.L. Meyer, R. Love, W.W. Brennessel, E.M. Matson, Chem. Commun. 56 (2020) 8607–8610.
- [32] X. Wang, A. Tian, X. Wang, RSC Adv. 5 (2015) 41155-41168.
- [33] D. Li, X. Ma, Q. Wang, P. Ma, J. Niu, J. Wang, Inorg. Chem. 58 (2019) 15832–15840.
- [34] Y.H. Luo, Z.L. Lang, X.X. Lu, W.W. Ma, Y. Xu, H. Zhang, Inorg. Chem. Commun. 72 (2016) 13–16.
- [35] X.L. Wang, X.T. Sha, G.C. Liu, N.L. Chen, Y. Tian, CrystEngComm 17 (2015) 7290–7299.
- [36] A. Tăbăcaru, C. Pettinari, F. Marchetti, S. Galli, N. Masciocchi, Cryst. Growth Des. 14 (2014) 3142–3152.