



Cite this: *Chem. Commun.*, 2016, 52, 10004

Received 22nd June 2016,  
Accepted 19th July 2016

DOI: 10.1039/c6cc05224j

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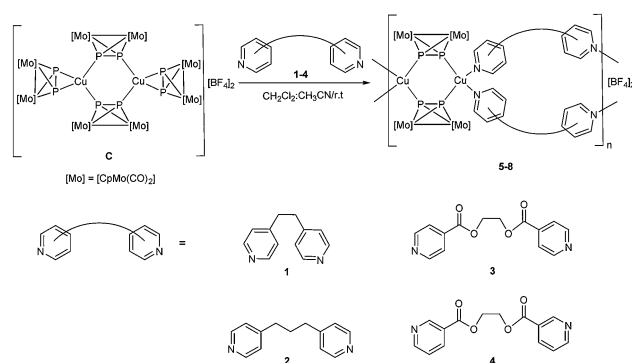
# Facile synthesis of one-dimensional organometallic–organic hybrid polymers based on a diphosphorus complex and flexible bipyridyl linkers†

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The selective synthesis of a series of new “ladderlike” one-dimensional organometallic–organic hybrid polymers is shown. The polymers are obtained from the reaction of the diphosphorus ligand complex [Cp<sub>2</sub>Mo<sub>2</sub>(CO)<sub>4</sub>(η<sup>2</sup>-P<sub>2</sub>)] with the copper salt [Cu(CH<sub>3</sub>CN)<sub>4</sub>]BF<sub>4</sub> in the presence of flexible organic bipyridyl linkers in high selectivity. This unique behaviour is supported by DFT calculations.

In recent years, coordination polymers have attracted significant attention due to their intriguing network topologies<sup>1,6</sup> and unique properties.<sup>2,6</sup> The coordination polymers are assembled *via* the coordination of organic ligands usually bearing N, O or S donor atoms to metal ions.<sup>3</sup> Yet, the understanding of the supramolecular aggregation processes is still limited, as many factors influence the formation of the final products. Those factors can be external (solvent systems, pH values, temperatures, crystallisation techniques, and template involved)<sup>4,6</sup> or internal (the geometry or the position of the donor atoms of the ligands and counteranions involved).<sup>5,6</sup> One way to avoid the low selectivity of the assembling reactions and direct the synthesis towards targeted products is the use of pre-designed precursors.<sup>7</sup> Another way is to utilise rigid linkers,<sup>8</sup> as the use of flexible linkers often leads to unpredictable frameworks<sup>9</sup> due to their conformational freedom.<sup>10</sup> Recently, C. Lescop *et al.* succeeded in the selective synthesis of tetranuclear metallacycles based on mixed rigid and flexible linkers.<sup>7a</sup> In addition, several groups have synthesized dinuclear metallacycles using flexible ditopic linkers.<sup>11</sup> In all these examples, the authors have benefited from the metal-directed self-assembly process to build their targeted inorganic–organic metallacycles. Therefore, the question arises whether it is possible to

use flexible organic linkers to control a regular arrangement in the solid state. Obviously, the used interplay of linkers/nodes will then play a decisive role. In this field, our group has previously reported a new approach by using P<sub>n</sub> ligand complexes as organometallic connectors between metal centers allowing the formation of one- and two-dimensional coordination polymers.<sup>12</sup> Moreover, one of those P<sub>n</sub> ligand complexes, the tetrahedrane complex [Cp<sub>2</sub>Mo<sub>2</sub>(CO)<sub>4</sub>(η<sup>2</sup>-P<sub>2</sub>)] (Cp = C<sub>5</sub>H<sub>5</sub>) (**A**), has been reacted with Ag<sup>I</sup> and Cu<sup>I</sup> salts in the presence of *trans*-1,2-di(pyridine-4-yl)ethene to give unprecedented organometallic–organic hybrid polymers.<sup>13</sup> Herein, we present the reaction between the P<sub>2</sub> ligand complex **A**, the [Cu(CH<sub>3</sub>CN)<sub>4</sub>]BF<sub>4</sub> (**B**), and the flexible ditopic linkers **1–4** (Scheme 1). Due to the different possible arrangements of the flexible linkers<sup>10</sup> and different coordination modes of the P<sub>2</sub> ligand complex<sup>14</sup> towards the Cu<sup>I</sup> cation, a large number of combinations is expected resulting in a large variety of accessible networks. However, those reactions yielded selectively the novel one-dimensional organometallic–organic coordination polymers **5–8** (Scheme 1, Fig. 2), where, to the best of our knowledge, no general approach has yet been reported to synthesize selectively coordination polymers based on flexible organic linkers and organometallic nodes.



**Scheme 1** The reaction of the dimeric complex **C** with the flexible organic linkers **1–4**. Synthesis of the one-dimensional organometallic–organic coordination polymers **5–8**.

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† Electronic supplementary information (ESI) available: Experimental details, synthesis and characterisation and details of the DFT calculations. CCDC 1487111–1487114. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c6cc05224j



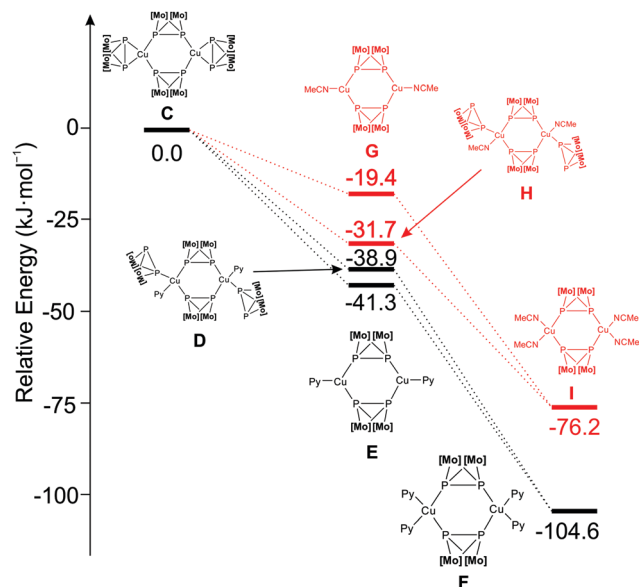


Fig. 1 Energy diagram of the reaction of **C** with pyridine and  $\text{CH}_3\text{CN}$ . The positive charges, ligands added or cleaved are not depicted.  $[\text{Mo}] = \text{CpMo}(\text{CO})_2$ .

Recently,<sup>15</sup> we have shown that the reaction of the copper salt **B** and the  $\text{P}_2$  ligand complex **A** affords a compound **C** that possesses a dimeric  $[\text{Cu}_2(\text{A})_4][\text{BF}_4]_2$  structure in the solid state with two  $\mu\text{-}\eta^1\text{:}\eta^1$  bridging ligands **A** and two ligands **A** in  $\eta^2$  side-on coordination (Fig. 1, Scheme 1). In order to study the dimer **C** as a suitable precursor for the selective synthesis of organometallic–organic hybrid polymers, DFT calculations have been performed at the B3LYP/def2-TZVP level of theory. Accordingly, the substitution of the terminal ligands **A** in the preformed dimeric complex **C** by pyridine as a model ligand, leading to **F**, is exothermic ( $-104.6 \text{ kJ mol}^{-1}$ ) in solution (Fig. 1). In contrast, the substitution by dichloromethane (**Q**) is endothermic by  $87.4 \text{ kJ mol}^{-1}$  (Fig. S22 in ESI†). Just like pyridine, acetonitrile can also substitute the terminal ligands **A** in **C**, but the reaction is less exothermic than in the case of pyridine ( $-76.2 \text{ kJ mol}^{-1}$ ; Fig. 1). The substitution of the terminal ligands **A** in **C** leading to **D** and **H** is more favoured for pyridine than for acetonitrile. This indicates that, starting from the dimer **C**, it should be possible to synthesise organometallic–organic hybrid polymers by reacting it with pyridine-based multitopic ligands. In addition, the tuning of the final outcome of the reactions should also be attainable.

Based on this information, complex **C** was reacted with the 4,4'-bipyridine (**1–3**) or 3-3'-bipyridine (**4**) linkers bearing flexible ( $\text{C}_2\text{H}_4$ , **1**), ( $\text{C}_3\text{H}_6$ , **2**), ( $\text{C}_4\text{H}_4\text{O}_4$ , **3** and **4**) linkages in a 1:2 stoichiometry in a mixture of  $\text{CH}_2\text{Cl}_2$  and  $\text{CH}_3\text{CN}$  at room temperature resulting in the formation of the coordination polymers **5–8** as orange or red crystalline solids in good to high (65–94%) yields (Scheme 1). In either case, the same products could also be selectively isolated when all the components were mixed together using different stoichiometries (1 or 3 equivalents) of the organic linker, which suggest that the products **5–8** are thermodynamically favoured, even passing other possible intermediates.

The derivatives **5–8** are slightly soluble in donor solvents like  $\text{CH}_3\text{CN}$ , but insoluble in other common organic solvents like  $\text{CH}_2\text{Cl}_2$ , THF and *n*-pentane. The compounds **5–8** were crystallized at room temperature from pentane diffusion into  $\text{CH}_2\text{Cl}_2/\text{CH}_3\text{CN}$  solutions of the crude reaction mixtures and characterised by single crystal X-ray structural analysis (Tables S1–S5, ESI†). Unexpectedly, despite the various lengths of spacers between the pyridyl fragments and the different positions of the donor atoms in the linkers **1–4**, the assemblies **5–8** are 1D coordination polymers (Fig. 2). In the derivatives **5–8**, each side-on coordinating ligand **A** present in the parent dimer **C** is substituted by the pyridine functions of two linker molecules. As a consequence, 1D polymers are formed with  $\text{Cu}_2(\text{A})_2$  repeating units, which are linked together *via* the organic connectors (Fig. 2). Within those repeating units, each copper ion comprises a distorted tetrahedral environment of two P and two N atoms. Interestingly, in the polymeric chains of **5** and **7**, each of the Cu centers of the  $\text{Cu}_2\text{P}_4$  six-membered rings participates in a different metallacyclic fragment, while they participate in similar metallacyclic repeating units in the derivatives **6** and **8**. In other words, the derivatives **5** and **7** can be described as infinite dinuclear metallacyclic chains formed by  $\text{Cu}_2(\text{5})_2$  metallacycles connected to each other *via*  $\text{Mo}_2\text{P}_2$  ligands, while the derivatives **6** and **8** are infinite tetranuclear metallacyclic chains where the  $\text{Mo}_2\text{P}_2$  ligands are a part of the metallacycles. The P–P bond lengths in the derivatives **5–8** are in the range between 2.072(2) and 2.086(2) Å, comparable to those of the non-coordinated ligand **A** (2.079(6) Å) and slightly shortened compared to that of the complex **C** (2.094(2)–2.159(2) Å). The Cu–P bonds of the derivatives **5–8** vary in a wider range (2.261(1)–2.307(1) Å) and are also shortened as compared to those of the parent dimer **C** (2.260(2)–2.385(2) Å). The  $\text{Cu}_2\text{P}_4$  six-membered rings in all derivatives **5–8** are nearly planar, with folding angles of (4.4–7.9°). In the assemblies **5–8**, the central flexible linkages have an *anti*-“*anti-periplanar*” and *gauche*-“*synperiplanar*” and conformations for the linkers **1–3** and **4**, respectively (Fig. 2). The coordination polymers possess virtual porosity, with cavities having “*circular*” (**5–7**) and “*rectangular*” (**8**) meshes of maximum diameters ranging between 1.02 and 1.47 nm and minimum diameters ranging between 0.32 and 0.73 nm.

The room temperature  $^{31}\text{P}$  NMR spectra in  $\text{CD}_3\text{CN}$  of the complexes **5–8** show broad signals centered at  $-51.5$  (**5**),  $-53.4$  (**6**) and  $-48.2$  (**7** and **8**) ppm, which are upfield shifted as compared to the free  $\text{P}_2$  ligand complex **A** ( $-43.2$  ppm) and comparable to the signal of the dimer **C** ( $-49.1$  ppm, Table S6, ESI†). Their room temperature  $^1\text{H}$  NMR spectra (Fig. S9–S12, ESI†) present simple sets of signals with a 1:1 ratio of **A**:**L** (**L** = **1–4**), which suggest the formation of supramolecular assemblies with  $\text{Cu}_2(\text{A})_2\text{L}_2$  repeating units. The  $^{13}\text{C}$  NMR spectra show also typical sets of signals corresponding to the bipyridine linkers and the **A** ligands (Fig. S13–S16, ESI†). The  $^{19}\text{F}$  NMR spectra of all complexes are featured by two signals centered at *ca.*  $-150.5$ , and  $-151.8$  ppm, which correspond to the  $\text{BF}_4$  counteranions (Table S6, ESI†). The IR spectra exhibit two strong bands at *ca.*  $\nu(\text{CO}) \approx 1920$  and  $1980 \text{ cm}^{-1}$ , which can be attributed to the carbonyl groups of the **A** moieties.



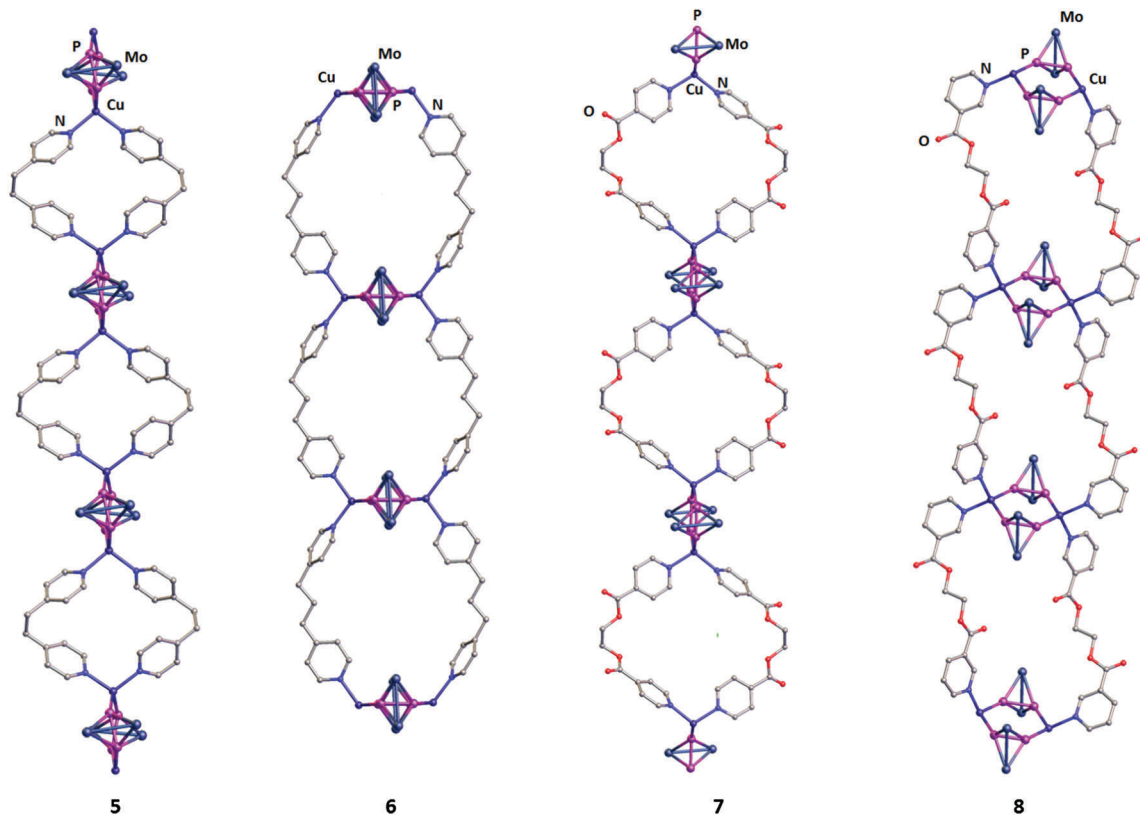


Fig. 2 Sections of the 1D coordination polymers **5–8**. Cp and CO ligands, hydrogen atoms as well as minor parts of the disordered fragments are omitted for clarity.

The results obtained demonstrate a new approach for the selective synthesis of novel 1D organometallic–organic hybrid polymers **5–8** based on the reaction of the organometallic  $P_2$  ligand complex  $[Cp_2Mo_2(CO)_4(\eta^2-P_2)]$  (**A**), the copper salt  $[Cu(CH_3CN)_4]BF_4$  (**B**) and the flexible pyridine-based linkers **1–4**. This is possible due to the liability of the  $\eta^2$ -coordinated  $P_2$  units, which could be easily substituted by the pyridine-based organic linkers **1–4**. In these aggregation reactions, the flexibility of the linkers **1–4** plays a “positive role” instead of the usual “destructive role” in directing the synthesis towards selective product formation since those linkers can easily adopt their backbones to afford the thermodynamically favored polymers. Current investigations focus on the use of rigid linkers with defined lengths and functionalities. The reactions of those linkers with the  $P_2$ -based dimer precursor **C** are expected to be directionally leading to selective products with the possibility of a fine tuning and control of the sizes of the cavities formed. In addition, the incorporated functionalities could play a role in the host–guest chemistry of defined host molecules.

The European Research Council *via* Grant ERC-2013-AdG 339072 is gratefully acknowledged for the comprehensive support of this work.

## Notes and references

- 1 (a) X.-Y. Dong, C.-D. Si, Y. Fan, D.-C. Hu, X.-Q. Yao, Y.-X. Yang and J.-C. Liu, *Cryst. Growth Des.*, 2016, **16**, 2062–2073; (b) R. Haldar and T. K. Maji, *Chem. Rev.*, 2014, **114**, 7557–7580; (c) R. Haldar and

- T. K. Maji, *Z. Anorg. Allg. Chem.*, 2014, **640**, 1102–1108; (d) W.-Q. Kan, J. Yang, Y.-Y. Liu and J.-F. Ma, *CrystEngComm*, 2012, **14**, 6271–6281; (e) J. Guo, D. Sun, L. Zhang, Q. Yang, X. Zhao and D. Sun, *Cryst. Growth Des.*, 2012, **12**, 5649–5654; (f) W. L. Leong and J. J. Vittal, *Chem. Rev.*, 2011, **111**, 688–764.
- 2 (a) S.-I. Noro, J. Mizutani, Y. Hijikata, R. Matsuda, H. Sato, S. Kitagawa, K. Sugimoto, Y. Inubushi, K. Kubo and T. Nakamura, *Nat. Commun.*, 2015, **6**, 5851; (b) K. Banerjee, S. Roy, M. Kotal and K. Biradha, *Cryst. Growth Des.*, 2015, **15**, 5604–5613; (c) Z. Zhou, C. He, J. Xiu, L. Yang and C. Duan, *J. Am. Chem. Soc.*, 2015, **137**, 15066–15069; (d) X. Yan, T. R. Cook, J. B. Pollock, P. Wei, Y. Zhang, Y. Yu, F. Huang and P. J. Stang, *J. Am. Chem. Soc.*, 2014, **136**, 4460–4463; (e) J. Heine and K.-M. Buschbaum, *Chem. Soc. Rev.*, 2013, **42**, 9232–9242.
- 3 (a) T. R. Cook, Y.-R. Zheng and P. J. Stang, *Chem. Rev.*, 2013, **113**, 734–777; (b) S. Park, S. Y. Lee, K.-M. Park and S. S. Lee, *Acc. Chem. Res.*, 2012, **3**, 391–403.
- 4 (a) R. S. Patil, A. M. Drachnik, H. Kumari, C. L. Barnes, C. A. Deakne and J. L. Atwood, *Cryst. Growth Des.*, 2015, **15**, 2781–2786; (b) B. Liu, N. Li, W.-P. Wu, H. Miao, Y.-Y. Wang and Q.-Z. Shi, *Cryst. Growth Des.*, 2014, **14**, 1110–1124; (c) K. P. Rao, M. Higuchi, J. Duan and S. Kitagawa, *Cryst. Growth Des.*, 2013, **13**, 981–985; (d) C.-P. Li, J.-M. Wu and M. Du, *Chem. – Eur. J.*, 2012, **18**, 12437–12445; (e) C.-P. Li, J.-M. Wu and M. Du, *CrystEngComm*, 2012, **14**, 2748–2755.
- 5 (a) K. Tripuramallu, P. Manna and S. K. Das, *CrystEngComm*, 2014, **16**, 4816–4833; (b) R.-J. Wei, J. Tao, R.-B. Huang and L.-S. Zheng, *Eur. J. Inorg. Chem.*, 2013, 916–926; (c) H. T. Chifotides, I. D. Giles and K. R. Dunbar, *J. Am. Chem. Soc.*, 2013, **135**, 3039–3055; (d) F.-J. Liu, D. Sun, H.-J. Hao, R.-B. Huang and L.-S. Zheng, *Cryst. Growth Des.*, 2012, **12**, 354–361.
- 6 W. L. Leong and J. J. Vittal, *Chem. Rev.*, 2011, **111**, 688–764.
- 7 (a) W. Shen, M. El Sayed Moussa, Y. Yao and C. Lescop, *Chem. Commun.*, 2015, **51**, 11560–11563; (b) S. Wang, T. Zhao, G. Li, L. Wojtas, Q. Huo, M. Eddaoudi and Y. Liu, *J. Am. Chem. Soc.*, 2010, **132**, 18038–18041; (c) B. Nohra, Y. Yao, C. Lescop and R. Réau, *Angew. Chem., Int. Ed.*, 2007, **46**, 8242–8245; (d) R. D. Sommer,



- A. L. Rheingold, A. J. Goshe and B. Bosnich, *J. Am. Chem. Soc.*, 2001, **123**, 3940–3952.
- 8 (a) H.-N. Wang, G.-G. Shan, H.-B. Li, X.-L. Wang, H.-T. Cao and Z.-M. Su, *CrystEngComm*, 2014, **16**, 2754–2759; (b) A. N. Khlobystov, A. J. Blake, N. R. Champness, D. A. Lemenovskii, A. G. Majouqa, N. V. Zyk and M. Schröder, *Coord. Chem. Rev.*, 2001, **222**, 155–192; (c) M. Fujita, K. Umamoto, M. Yoshizawa, N. Fujita, T. Kusukawa and K. Biradha, *Chem. Commun.*, 2001, 509–518; (d) B. J. Holliday and C. A. Mirkin, *Angew. Chem., Int. Ed.*, 2001, **40**, 2022–2043.
- 9 (a) L. Liu, C. Huang, X. Xue, M. Li, H. Hou and Y. Fan, *Cryst. Growth Des.*, 2015, **15**, 4507–4517; (b) L.-P. Xue, X.-H. Chang, L.-F. Ma and L.-Y. Wang, *RSC Adv.*, 2014, **4**, 60883–60890; (c) M.-M. Dong, L.-L. He, Y.-J. Fan, S.-Q. Zang, H.-W. Hou and T. C. W. Mak, *Cryst. Growth Des.*, 2013, **13**, 3353–3364; (d) Q. Sun, Y.-Q. Wang, A.-L. Cheng, K. Wang and E.-Q. Gao, *Cryst. Growth Des.*, 2012, **12**, 2234–2241; (e) T.-F. Liu, J. Lü and R. Cao, *CrystEngComm*, 2010, **12**, 660–670.
- 10 (a) Y. Wen, T. Sheng, Z. Xue, Z. Sun, Y. Wang, S. Hu, Y. Huang, J. Li and X. Wu, *Cryst. Growth Des.*, 2014, **14**, 6230–6238; (b) D. Deng, L. Liu, B.-M. Ji, G. Yin and C. Du, *Cryst. Growth Des.*, 2012, **12**, 5338–5348; (c) M. L. Hernández, M. K. Urriaga, M. G. Barandika, R. Cortés, L. Lezama, N. de la Pinta, M. I. Arriortua and T. Rojo, *J. Chem. Soc., Dalton Trans.*, 2001, 3010–3014; (d) M. L. Hernández, M. G. Barandika, M. K. Urriaga, R. Cortés, L. Lezama and M. I. Arriortua, *J. Chem. Soc., Dalton Trans.*, 2000, 79–84; (e) T. L. Hennigar, D. C. MacQuarrie, P. Losier, R. D. Rogers and M. J. Zaworotko, *Angew. Chem., Int. Ed.*, 1997, **36**, 972–973.
- 11 (a) S. Karthikeyan, R. Nagarajprakash, G. Satheesh, C. A. Kumar and B. Manimaran, *Dalton Trans.*, 2015, **44**, 17389–17398; (b) P. Crosshans, A. Jouaiti, V. Bulach, J.-M. Planeix, M. W. Hosseini and N. Kyritsakas, *Eur. J. Inorg. Chem.*, 2004, 453–458; (c) B. Chatterjee, J. C. Noveron, M. J. E. Resendiz, J. Liu, T. Yamamoto, D. Parker, M. Cinke, C. V. Nguyen, A. M. Arif and P. J. Stang, *J. Am. Chem. Soc.*, 2004, **126**, 10645–10656.
- 12 (a) F. Dielmann, A. Schindler, S. Scheuermayer, J. Bai, R. Merkle, M. Zabel, A. V. Virovets, E. V. Peresypkina, G. Brunklaus, H. Eckert and M. Scheer, *Chem. – Eur. J.*, 2012, **18**, 1168–1179; (b) M. Scheer, *Dalton Trans.*, 2008, 4372–4386; (c) J. Bai, A. V. Virovets and M. Scheer, *Angew. Chem., Int. Ed.*, 2012, **41**, 1737–1740; (d) J. Bai, E. Leiner and M. Scheer, *Angew. Chem., Int. Ed.*, 2002, **41**, 783–786.
- 13 (a) B. Attenberger, E. V. Peresypkina and M. Scheer, *Inorg. Chem.*, 2015, **54**, 7021–7029; (b) B. Attenberger, S. Welsch, M. Zabel, E. Peresypkina and M. Scheer, *Angew. Chem., Int. Ed.*, 2011, **50**, 11516–11519.
- 14 S. Welsch, C. Lescop, G. Balázs, R. Réau and M. Scheer, *Chem. – Eur. J.*, 2011, **17**, 9130–9141.
- 15 M. Fleischmann, S. Welsch, E. V. Peresypkina, A. V. Virovets and M. Scheer, *Chem. – Eur. J.*, 2015, **21**, 14332–14336.

