The synthesis of the heterocubane cluster \([\{\text{CpMn}\}_4(\mu_3-P)_4]\) as a tetrahedral shaped starting material for the formation of polymeric coordination compounds\(^\dagger\ddagger\$\)

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Thermolysis of \([\text{CpMn}\eta^6\text{-cht}]]\) with \(\text{P}_4\) in 1,3-diisopropylbenzene leads to the formation of the heterocubane \([\text{Cp}_4\text{Mn}_4\text{P}_4]\) (1) in high yields, as a rare example of ‘naked’ phosphorus containing complexes of manganese. Compound 1 is characterized and studied by DFT calculations and reflection measurements. 1D coordination polymers \([\{\text{CpMn}_4(\mu_3-P)_2\}(\text{CuX})\}_n\) (2-CI: X = Cl; 2-Br: X = Br) are obtained in the reaction with \(\text{CuX}\). Furthermore, it is shown that all four \(\text{P}\) atoms in 1 can be addressed for a coordination towards cyamtenre resulting in \([\{\text{CpMn}_4(\mu_3-P)_2(\text{CpMn}\text{CO})_2\}_n\] (3a: \(n = 1\); 3b: \(n = 2\); 3c: \(n = 3\); 3d: \(n = 4\)), and shows that 1 is a tetra-topic building block in coordination chemistry.

In the last few decades, the field of \(\text{P}_n\) ligand complexes\(^1\) has been well established in chemistry.\(^2\) Within this area, we demonstrated that \(\text{P}_n\) ligand complexes in combination with monovalent coinage metal salts are perfect starting materials to construct supramolecular assemblies. Especially, using the complexes \([\{\text{CpMo}(\text{CO})_2\}_2(\mu_3^2-P)_2\}_2\) and \([\{\text{CpFe}(\eta^3\text{-P})_3\}]\) (\(\text{Cp}^* = \text{C}_5\text{Me}_5\)) together with \(\text{CuX}\) (\(X = \text{Cl}, \text{Br}, \text{I}\)), a wide spectrum of pseudo-0D,\(^3\) 1D\(^4\) or 2D\(^5\) frameworks could be realized. For the formation of 3D architectures, ideally multtopic linkers with an appropriate symmetry (e.g. \(T_{h}, O_{h}\)) would be needed. All attempts to construct 3D scaffolds by using \(\text{P}_n\) ligand complexes have failed so far.\(^5\)

The existence of a restricted number of clusters and complexes of manganese with substituent-free \(\text{P}\) atoms motivated us to prepare such compounds.\(^6\) Very recently we reported on the synthesis of the two triple decker sandwich complexes \([\{\text{Cp}^{\text{BlG}}\text{Mn}\}_2(\mu_3^3-\text{P}_3)\}]\) and \([\{\text{Cp}^{\text{BlG}}\text{Mn}\}_2(\mu_3^2-P)_2\}_2\] (\(\text{Cp}^{\text{BlG}} = \text{C}_5(4-n\text{BuC}_6\text{H}_4)\)) via the thermolysis of \([\text{Cp}^{\text{BlG}}\text{Mn}(\text{cht})]\] (cht = cycloheptatriene) with \(\text{P}_4\).\(^6\) Substitution of the sterically demanding \(\text{Cp}^{\text{BlG}}\) ligand by the usual Cp ligand should alter the product outcome dramatically.

In general, \(\text{Mn}^{IV}\) ions are very promising candidates for future warm white LEDs due to their emission in the red range of the visible spectrum and large intensities in some host lattices, but their luminescence is mainly investigated by doping in oxidic or fluoridic solid state materials.\(^7\) For the cluster presented in this communication the electronic situation is quite different, but the formal manganese oxidation state is also IV. Therefore we investigated the optical properties of 1. Herein we report on the synthesis and characterization of the heterocubane cluster \([\{\text{CpMn}_4(\mu_3-P)_4\}]\) (1) and the first coordination studies of 1 with \(\text{CuX}\) (\(X = \text{Cl}, \text{Br}\)) resulting in 1D coordination polymers. It is also shown that the coordination of all four \(\text{P}\) atoms in 1 towards metals can be generally achieved.

The co-thermolysis (20 min) of \([\text{CpMn}\eta^6\text{-cht}]]\) (cht = cycloheptatriene) and \(\text{P}_4\) in 1,3-diisopropylbenzene (DIB) results in the formation of \([\text{Cp}_4\text{Mn}_4\text{P}_4]\] (1) (eqn (1)). After solvent removal, extraction with \(\text{CH}_2\text{Cl}_2\) and cooling to \(-35\, ^\circ\text{C}\), 1 is obtained as dark red to brown needle shaped crystals in yields of about 73%. Decomposition is observed at longer reaction times (metal mirror).

\[\text{eqn (1)}\]

Heterocubanes of the formulae \(\text{M}_4\text{E}_4\) (\(\text{M} = \text{metal fragment}; \text{E} = \text{‘naked’ element of the 15th or 16th group}) have been well known in chemistry for decades. In particular, O, S and N atoms show a high tendency to form this structural motif.
Therefore, hundreds of such compounds could be characterized until now. Additionally, a very large number of Se and Te containing heterocubanes have been published. However, only very few phosphorus derivatives are known. Structural characterization was possible for three similar cobalt compounds [[Co(P3)]4(µ3-P)]

(A: CoR = C8H5; B: CoR = C8H4Bu; C: CoR = C8H5C6H4Bu)\(^6\) and the tungsten cluster [W(CO)6(CpW)(µ3-P)(µ3-P)]\(^4\) (DI).\(^9\) Schumann et al. also proposed a heterocubane structure for (PhSnP)\(^4\).\(^10\) Structural similarities can also be found for [(CpFe)\(^4\)(P2)]\(^{11}\), [(Cp*Ni)\(^3\)(µ3-P)(µ3-P)]\(^4\), \([(Cp*Cp)\(^4\)(µ3-P)]\(^4\), and \([(Cp*Cp)\(^4\)(µ3-P)]\(^4\).\(^14\) Heterocubane clusters with substituent-free As units are also known, but very rare.\(^11,15\)

Both the \(^1\)H NMR and the \(^31\)P\(^{1}\)H) NMR spectra (CD\(_2\)Cl\(_2\)) of 1 show singlets at 4.58 ppm and 82.7 ppm, respectively, in the expected regions. In contrast, the \(^31\)P\(^{1}\)H) NMR spectrum of 1 shows an extremely low-field shifted singlet at 1079.8 ppm (slightly broadened, \(\delta_{P1/2} = 31.3\) Hz). Astonishingly, the signal is about 230 ppm to 600 ppm low field shifted compared to A–D.

The NMR data indicate a highly symmetric molecule, which is confirmed by single crystal X-ray diffraction (Fig. 1). Compound 1 crystallizes with one solvent molecule CH\(_2\)Cl\(_2\) from concentrated CH\(_2\)Cl\(_2\) solutions in the monoclinic space group C2/c. The core of 1 can be described as a Mn\(_4\) tetrahedron, wherein the faces are capped by P atoms, resulting in a heterocubane structure. In comparison, the central cores of the structures of A, C and D are much more distorted from a perfect cube structure than 1 is. The four Mn atoms in 1 are coordinatively saturated by Cp ligands. The Mn–Mn and Mn–P bond lengths vary from 2.6914(8) Å to 2.7320(6) Å and from 2.2249(9) Å to 2.2411(10) Å, respectively.

The number of valence electrons of the Mn atoms can be calculated classically to be 18 and the Mn centers have a formal oxidation state of +4, but 1 could be better described to contain a [Mn\(_2\)P\(_4\)]\(^{10}\) cluster. To gain more insight into the electronic oxidation state of +4, but calculated classically to be 18 and the Mn centers have a formal oxidation state of +4. The Mn–Mn bond order is close to unity (0.92). The molecular Wiberg bond index indicates a Mn–Mn bond order of 0.33, while the Mn–P bond order is close to unity (0.92). The molecular orbitals (MO) as well as the localized molecular orbitals (LMO) of 1 show the presence of Mn\(_2\)P\(_4\) four centre bonds (2e\(^-\)) and the presence of lone pairs at the phosphorus atoms (Fig. 2 and Fig. S18 and S19, ESI\(^\)§).

The results of the optical measurements fit well to the findings of the theoretical calculations. No emission of compound 1 could be observed neither in the visible range nor in the IR range (down to 1600 nm) even at 10 K. This can be explained by the different spin multiplicities of the ground and excited states which causes low emission intensity due to the spin selection rule. On the other hand the large number of electronic states in relatively small energetic distances causes non-radiative transitions rather than emission of radiation.

The room temperature reflection spectrum of 1 is depicted in Fig. 3. Besides some vibrational transition in the IR range the electronic transitions of the basis of the DFT calculations described above can be detected in the reflection spectrum. In detail, the first singlet–triplet electronic transition at about 1700 nm and also the one of the next higher electronic state identified by the DFT calculations to be at about 930 nm could be detected (Fig. 3).

The four P atoms in 1 are pyramidal and bear a lone pair each. This should be a perfect building block for the formation of three-dimensional networks. By slow diffusion of CH\(_2\)CN solutions of CuX (X = Cl, Br) into CH\(_2\)Cl\(_2\) solutions of 1, some black needle-shaped crystals and plenty of off-white to brown voluminous, amorphous powder were obtained. The reaction with a 1 : 1 stoichiometry of 1 and CuX results in a still coloured
molecule CH$_2$Cl$_2$ co-crystallizes per formula unit, which is not observed. With angular sums around the Cu centres of 359.8 atoms. In 2-Br to CuX units resulting in a trigonal planar coordination of the Cu atoms. In the case for 2-Br, the mono-coordination product is obtained and in a 1 : 4 stoichiometry the tri- and tetra-coordination derivative occurs.

For the formation of three-dimensional networks, the coordination of all four P atoms in 1 is necessary. To check whether this is possible at all, 1 was reacted with [CpMn(CO)$_2$(thf)], and in fact, the coordination of up to four P atoms can be achieved, resulting in the formation of \([[(\text{CpMn})_4]\mu_3-P_4] (\text{CuX})_n] (3a: n = 1; 3b: n = 2; 3c: n = 3; 3d: n = 4). In a 1 : 1 stoichiometry the mono- and di-coordination product is obtained and in a 1 : 4 stoichiometry the tri- and tetra-coordination derivative occurs. Compounds 3a–d can be separated by column chromatography. However, complex 3a elutes together with the unreacted cluster 1.

All four compounds were crystallized as solvates from concentrated CH$_2$Cl$_2$ solutions. The molecular structures are depicted in Fig. 5. The average bond lengths between the P atoms and the \([\text{CpMn(CO)}_2] \) fragments increase with the degree of coordination (3a: 2.260 Å; 3b: 2.262 Å; 3c: 2.272 Å; 3d: 2.287 Å). The steric parameters of the heterocubane cores are also affected by the coordination. While the average Mn–Mn and Mn–P bond lengths in 3a are almost identical in comparison to 1, they indication for almost perfect planarity. The polymeric strands are orientated in parallel with respect to each other.

The off-white powder was found to be amorphous, as indicated by X-ray powder diffraction. Also $^{31}$P($^1$H) MAS NMR did not show any signals. To further analyse the amorphous powder, it was washed several times with CH$_3$CN and dried carefully in a vacuum. To get a hint of the composition, elemental analyses were carried out. With the assumption of complete removal of the solvent and excess of CuX, the result fits best for a 1 : CuX ratio of roughly 1 : 3. This might be a hint for the coordination of more than two of P atoms to CuX and the formation of a 3D structure.

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increase steadily from 3b to 3d (1: av. Mn–P 2.235 Å, av. Mn–Mn 2.713 Å; 3d: av. Mn–P 2.258 Å, av. Mn–Mn 2.757 Å). The increase in the Mn–Mn and Mn–P bond lengths effectively results in an expansion of the heterocubane cages. The volumes of the Mn₄P₄ cages vary in the same way as the bond lengths. With just one coordination it remains almost unaffected, but starting from the second coordination in 3b the volume increases constantly \(V(1) = 9.159 \, \text{Å}^3; V(3a) = 9.151 \, \text{Å}^3; V(3b) = 9.333 \, \text{Å}^3; V(3e) = 9.372 \, \text{Å}^3; V(3d) = 9.490 \, \text{Å}^3\). The core overall expands by 3.5%.

In conclusion, we have reported on the synthesis of the novel cluster \([\text{Cp}_4\text{Mn}_4\text{P}_4]\) (1) with a central heterocubane structure in good yields, which is a good building block for promoting higher-dimensional aggregation. Compound 1 was characterized by X-ray diffraction, spectroscopic measurements and DFT calculations. Reaction with CuX (X = Cl, Br) leads to the formation of 1D coordination polymers with the zigzag-like structural motif. As a proof of concept it was demonstrated that all four P atoms in 1 can be addressed for coordination, which was exemplified by the coordination of \{\text{CpMn(CO)}_3\}_2 moieties. An interesting cluster volume expansion is observed, correlating with the degree of coordination. The formation of 3D networks starting from 1 will be the focus of future work.

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Notes and references

1 Complexes, mainly of transition metals, with unsubstituted P₄ ligands. P atoms are only bound to the metal atoms and/or other P atoms.
5 Very recently we were able to construct the first 3D scaffolds containing P₄ ligand complexes, however by using additional multi-topic organic linkers cf. B. Attenberger, E. V. Peresypkina and M. Scheer, Inorg. Chem., 2015, 54, 7021–7029.
16 The obtained crystals of the reactions with a different stoichiometry show the same crystal structures.
17 The heterocubane scaffold is broken up into one Mn₄ pyramid and four Mn₄P pyramids for the volume calculations (Heron's formula and \(V = 1/3 \times b \times h\)).