Rational serendipity: “undirected” synthesis of a large \{Mn^{II}_{10}Cu^{II}_{5}\} complex from pre-formed Mn^{II} building blocks†

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Use of an aminopolyalcohol-based Mn^{II} complex in solvothermal Cu^{II} chemistry leads to a rare example of a high nuclearity heterometallic \(\{Mn^{III}_{32}Cu^{II}\}\) system, in which four Cu^{II}(H$_4$Edte) units trap an inner \(\{Mn^{III}_{10}Cu^{II}\}\) oxide core.

High-symmetry, high-nuclearity transition metal complexes have always been a source of fascination for coordination chemists. This is not simply because of the interesting chemical and physical properties that such molecules can often display, applications range from catalysis to magnetism, but also because of the synthetic challenges involved in isolating such systems. One well-established method for preparing high nuclearity complexes is to employ flexible multidentate organic ligands (or combinations thereof) which can simultaneously chelate and bridge, in simple one-pot reactions with appropriate metal ions. Polyalkoxide ligands have yielded beautiful examples of homometallic systems including; a \(\{Mn_{12}\}\) truncated cube, a \(\{Mn_{19}\}\) complex and in \(\{Mn_{32}\}\) truncated cube, recently possessed the largest spin ground state known; 83/2, 6 a \(\{Mn_{19}\}\) complex 6 beautiful examples of homometallic systems including; a metallic \(\{Mn^{III}_{12}Cu^{II}\}\) system, in which four Cu^{II}(H$_4$Edte) units trap an inner \(\{Mn^{III}_{10}Cu^{II}\}\) oxide core.

The main issue with this approach however is that it is difficult, if not impossible, to predict the structure of the resulting products \textit{a priori}. Indeed, this method is frequently referred to in the literature as “serendipitous self-assembly”. In an effort to transcend this serendipity and gain some degree of control over product formation, one can react pre-formed complexes which feature multiple (and vacant) ligand binding sites capable of coordinating additional metal ions. This is particularly useful for assembling heterometallic complexes and constitutes a kind of synthetic “half-way house”, between serendipitous self-assembly at one extreme and the more rigid building-block approach exemplified by cyanometallate chemistry at the other (so-called “rational design”). Aminopolyalcohol ligands are ideally suited to constructing systems in this manner, since they can form stable \([M(H_{6}L)]\) monometallic complexes in which one or more of the alkoxide arms remain protonated and thus amenable to later coordination, thereby facilitating cluster nucleation.

To this end, we have previously investigated the coordination chemistry of the ligand bis-tris propane \((H_{6}L = \{2,2′′′-(propane-1,3-diyldiimin)bis[2-(hydroxymethyl)-propane-1,3-diol]}\), demonstrating that a pre-formed mononeric Cu^{II} complex of H$_4$L can be used to trap a cuboctahedral manganese oxide core, thereby directing the synthesis of a large \(\{Mn^{III}_{12}Mn^{II}_{6}Cu^{II}_{5}\}\) complex (Scheme 1). Here, we demonstrate that the coordination chemistry of H$_4$L’s smaller cousin H$_4$Edte \((2,2′′′′-(1,2-ethanediyldinitrilo)tetraethanol, Scheme 1 right) is much less predictable (though no less interesting), by presenting the synthesis, structure and magnetic characterisation of the \([Cu^{II}(H_{4}Edte)]-capped \{Mn^{III}_{10}Cu^{II}\}\) complex; \([Mn^{III}_{10}Cu^{II}[O_4(O_2CPh)_2][HEdte]_4(H_2O)_4][NO_3]_4\cdot7MeOH\cdot13H_2O (2) – the unexpected product of a reaction initially intended to produce large \(\{Mn_{n}(H_{4}Edte)\}\)-capped Cu^{II} complexes (Scheme 1) as part of our investigation into core-shell molecular interfaces.

Reaction of Mn(NO$_3$)$_3$·4H$_2$O with H$_4$Edte in MeCN yields a light-pink precipitate which can be recrystallised from EtOH via Et$_2$O vapour diffusion to yield pink needle-like crystals of \([Mn(H_{4}Edte)][NO_3]\) [1, see ESI† for details]. Complex 1 (Fig. S1†) crystallises in the orthorhombic space group \(Pbca\), with its structure describing a single H$_4$Edte ligand coordinated to a single Mn$^{II}$ ion via its two N and four O donor atoms (the latter of which all remain protonated). The Mn$^{II}$ ion is heptacoordinate and in distorted capped octahedral geometry \((C_{3v}, \text{ChSM} = 0.932)\), with a single terminal monodentate NO$_3$$^-$ ligand, which along with a uncoordinated NO$_3$$^-$ anion maintain charge balance (see cif file and Tables S1 and S2† for full details). Heating of 1 in a methanolic solution of Cu(OAc)$_2$·2H$_2$O and Na$_2$O$_2$CPh under solvothermal conditions, yields small dark brown block-like crystals of 2 after slow evaporation of
the filtered mother liquor over a period of 6 weeks (see ESI† for details). The use of 1 under these conditions was essential to isolate 2. Compound 2 crystallises in the tetragonal space-group I41/a (Fig. S2, Table S3†). Bond lengths and angles pertinent to the discussion herein are given in Table S4.† The structure of 2 is complex and unusual (Fig. 1a). We suggest that it is best thought of as comprising; two pairs of symmetry equivalent \{CuII(H1Edte)}-capped corner-sharing oxo-centered pseudo-\{MnIII\} triangles, that form two heavily distorted square-based \{MnIII\} square pyramids which are stacked and off-set with respect to one another, and in-turn linked at their square faces by a single CuII ion (Fig. 1b). All Mn ions are hexacoordinate, exhibit distorted octahedral coordination geometries and are in the +3 oxidation state, as confirmed by a combination of bond length considerations, BVS calculations (Table S3†) and charge balance. Two \(\eta^1:\eta^1:\mu_3\)-benzoate ligands link two pairs of MnIII ions (Mn1–Mn2 and Mn1–Mn3), creating two edges of each \{MnIII\} sub-unit, with the \(\eta^2\)-O arm facilitating corner sharing between triangles (via Mn1) to create each \{\{MnIII\}\} pyramid” (see Fig. 1). The remaining edge of each triangular sub-unit is completed by a single µ-bridging H2O ligand. Although a rare occurrence in Mn chemistry, there are previous reports of polymetallic complexes which feature Mn ions bridged by H2O ligands.\(^{13}\) The Jahn–Teller (JT) axes of the MnIII ions lie along the edges of the \{MnIII\} triangle (again something of an unusual occurrence, see Fig. 1d), with the central \(\mu_3\)-O\(^{2–}\) anion within each deviating ~0.16 Å from the mean \{MnIII\} planes. Each \{MnIII\}\(\mu_3\)-triangle is capped on its face by a single \{CuII(H1Edte)} unit, which employs three of its deprotonated alkoxide arms to coordinate to the triangular face (one to each MnIII ion), with the resulting CuII–O–MnIII angles all falling within an extremely narrow range \(\langle zCu-O-Mn = 120.34(13)–121.03(13)\rangle\). The remaining R–O arm of each Edte ligand remains protonated and unbound, exhibiting significant crystallographic disorder. Each CuII ion within the \{CuII(H1Edte)} units is pentacoordinate and in an \{O2N2\} coordination environment, with continuous shape measurements revealing a heavily distorted coordination geometry which is best described as square pyramidal \(\langle C_{4v}, \text{ChSM} = 2.298\rangle\).\(^{12a,14}\)

Four \(\eta^1:\eta^1:\mu\)-benzoate ligands link the square faces of the two \{MnIII\} pyramids at their corners (Mn2/Mn3 and symmetry equivalents), with a single CuII ion (Cu2) lying at the centre of the “\{MnIII\} cubane” created by the joining of the square faces of the two \{MnIII\} sub-units. This CuII ion is ligated by four \(\mu_3\)-O\(^{2–}\) ligands, which link the CuII ion to the eight MnIII ions of the \{MnIII\} cubane, and is in distorted square-planar geometry \(\langle D_{4h}, \text{ChSM} = 1.172\rangle\).\(^{12a,15}\) The distance between Cu2 and the
mean Mn
III
 planes created by the square faces of the two \{Mn
III
\} pyramids is just 1.6 Å, with the corresponding distance between Cu2 and Mn1/Mn1′ being ~3.1 Å. The entire cluster is ~18.5 Å at its widest point with the largest intramolecular metal-metal separation being ~10.5 Å (Cu1–Cu1′/Cu1–Cu1′′). The charge on the complex is balanced by four lattice NO3
−
 anions.

There are intramolecular H-bonding interactions between the η1O atoms of the η1η2μ3-benzoate ligands and the H-atoms of coordinated H2O ligands (O6–O9 = 2.808(4) Å). These same H2O ligands also form intermolecular H-bonds with the O atoms of disordered MeOH solvent molecules (O9⋯O1M = 2.58(9) Å). The protonated arms of Edte ligands also form an extensive network of intermolecular H-bonding contacts, with the O-atoms of NO3
−
 counter ions (O12⋯O42 = 3.16(2) Å), which in-turn, are H-bonded to disordered MeOH solvent molecules (O13⋯O1M = 2.756(17) Å). The closest intercluster contacts are between the aromatic rings of the η1η2μ3-benzoate ligands of neighbouring clusters (~3.56 Å), with the shortest intercluster metal–metal separation being between the Cu
II
 ions of \{Cu
II
(H2Edte)\} units (~9.24 Å, see Fig. S3† for packing diagram).

To the best of our knowledge 2 represents just the fifth reported example of a discrete heterometallic Mn/Cu complex of nuclearity greater than ten.11,16 It is also an extremely rare example of a high nuclearity Mn/Cu system featuring Mn exclusively in the +3 oxidation state—the only other example being the \{Mn
6
III
Cu
10
II
\} system of Oshio and co-workers.16a

It is interesting to note that despite the use of the \{Mn
III
(H2Edte)\} unit as a starting material, the Edte ligands in 2 encapsulate Cu and not Mn. This was unexpected, and our initial intention had been to assemble Mn-capped oxo-bridged Cu
II
 complexes using \{Mn
III
(H2Edte)\}, in a similar fashion to our previous work using Cu-bis-tris-propane building blocks (see Scheme 1).17 One can only assume that under solvothermal conditions the \{Cu
II
(H2Edte)\} unit is more thermodynamically stable than the corresponding \{Mn
III
(H2Edte)\} one. Studies are currently underway to examine the structural integrity of \{Mn
III
(H2Edte)\} building blocks under a variety of reaction conditions, in an effort to better understand, and hence exploit, this ligand for the controlled assembly of heterometallic structures.

The magnetic susceptibility of 2 (χ) was measured from 290 K down to 1.8 K in an applied field of 0.1 T, with the results plotted in Fig. S3† as the χMT vs. T product (see Fig. S6† for the corresponding M vs. H plot). The χMT value of 30.64 cm3 K mol−1 at 290 K, is close to the theoretical value of 31.47 cm3 K mol−1 expected for ten Mn
III
 and five Cu
II
 non-interacting ions; Mn
III
 (S = 2, g = 1.98) and Cu
II
 (S = 1/2, g = 2.1). This value decreases steadily until around 100 K, before decreasing more sharply to reach a minimum value of 3.1 cm3 K mol−1 at 1.8 K. This behaviour is indicative of dominant antiferromagnetic exchange interactions between the constituent spin carriers. Unfortunately, despite the high symmetry of the cluster the sheer number of distinct M–L–M exchange pathways precludes any meaningful quantitative analysis of the susceptibility data. AC susceptibility studies in the 10–1.8 K temperature range in a 3.5 G field at oscillating at frequencies up to 1300 Hz, do not reveal any frequency dependence in the out-of-phase component of the AC susceptibility (χ′′), indicating that 2 does not exhibit slow relaxation of the magnetisation in the temperature regime investigated. The lack of slow relaxation behaviour is perhaps unsurprising given the presence of dominant antiferromagnetic exchange interactions and the relative orientation of the JT axes of the Mn
III
 ions in the structure.

Use of the pre-formed building block \{Mn
III
(H2Edte)\} in solvothermal Cu
II
 chemistry has led to isolation of a fascinating \{Mn
III
Cu
II
\} complex, an extremely rare example of a heterometallic Mn/Cu system featuring Mn ions exclusively in the +3 oxidation state. Despite our initial intention to “direct” the assembly of \{Mn
III
(H2Edte)\}-capped Cu
II
 complexes, as part of an investigation into core-shell molecular interfaces and magnetic behaviour, the resulting molecule was a consequence of serendipity with the Edte ligands in the structure of 2 found to encapsulate Cu and not Mn. These results suggest that the structural integrity of molecular building blocks derived from flexible multidentate chelates must be carefully considered if any degree of synthetic control is to be maintained, but also that “undirected” synthesis can nevertheless produce fascinating new molecules.

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Notes and references


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