Cages on a plane: a structural matrix for molecular ‘sheets’

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Introduction

Paramagnetic metal ions arranged in triangular topologies have long held academic interest in the field of molecule-based magnetism,\(^1\) since they can lead to the observation of, for example, ferromagnetic exchange in partial cubanes,\(^2\) tuneable exchange between metal ions separated by two atom bridges,\(^3\) antisymmetric exchange effects in heterometallic 3d-4d complexes,\(^4\) and geometric spin frustration in antiferromagnetically coupled cages\(^5\) and 2-3D materials (e.g. the kagomé lattice) possessing high symmetry.\(^6\)

In 3d transition metal chemistry the molecular triangle is most commonly found in one of two structure types: a) the oxo-centred planar triangle \([\text{M}O_2]^{\text{n}+}\), as personified by the basic metal carboxylates,\(^7\) where all four atoms lie on (or nearly on) the same plane, or b) the \([\text{M}O_4]^{\text{n}+}\) partial cubane where the metal ions and O-atoms lie on different planes, i.e. a cube missing one metal vertex. The latter moiety also often acts as the building block for the creation of large and (occasionally) very large molecules whose structures conform to molecular ‘sheets’, i.e. the metallic skeleton of the complex grows in 2D. From a structural/synthetic perspective this is simple to understand as a series of O-bridged, edge- and vertex-sharing metal triangles (Figure 1). For example, two edge-sharing triangles form tetranuclear \([\text{M}_4\text{O}_7]^{\text{n}+}\) or \([\text{M}_4\text{O}_8]^{\text{n}+}\) butterflies or partial cubanes (Figure 1a-b), with detailed magneto-structural correlations developed for Fe\(^8\) and Mn.\(^9\) Such triangles and butterflies/partial cubanes are by far the most common building blocks seen in large cages containing multiple 3d \(\text{M}^{\text{III}}\) ions (n > 4).

Continued edge-sharing growth in just one dimension/direction from triangle to butterfly/partial cubane to larger species results in the formation of molecular rods (Figure 1c), a pertinent example being the use of tripodal alcohol ligands to direct the formation of \(\text{Mn}_6\), \(\text{Mn}_7\), \(\text{Mn}_9\), \(\text{Mn}_{12}\) complexes.\(^10\) Growth in two dimensions/directions leads to planar disc-like complexes (Figures 1d-i), the most common of which is the Anderson-type wheel. This structure describes a centred hexagon, with homometallic,\(^11\) heterometallic,\(^12\) homovalent\(^13\) and heterovalent\(^14\) examples known. Larger complexes are somewhat unusual, but are all characterised by beautiful structural aesthetics, the presence of the Anderson moiety at the core of their metallic skeletons, and interesting physical properties. For example, \([\text{Ni}_{10}]^{\text{(I)}}\) (Figure 1e) is a rare example of a large nuclearity Ni single-molecule magnet (SMM),\(^15\) mixed-valent \([\text{Cr}_{12}]^{13/14}\) cages (Figures 1f-g) display ferromagnetic exchange interactions between the Co\(^{\text{II}}\) ions,\(^16\) \([\text{Fe}_{21/22}]^{\text{III}}\) is an example of a trapped/molecular mineral phase with S ≥ 33/2,\(^17\) two \([\text{Mn}_{18}]^{\text{II}}\) cages possess a similar brucite-like core (Figure 1h), one displaying intramolecular ferrimagnetic exchange and long range magnetic order,\(^18a\) and the other being a very rare example of a Mn-alkoxide, while \([\text{Co}_{26}]^{\text{II}}\) was the first polynuclear Co\(^{\text{II}}\) species to exhibit slow relaxation of the magnetization (Figure 1i).\(^19\) It is also interesting to note a common thread in the synthesis of each of these species: the use of alkoxide-based bridging ligands.
We recently reported a small family of Anderson-type complexes of general formula \([\text{M}^{III}\text{M}^{II}\text{hmp})_{12}]^{4+}\) \((\text{M}^{III} = \text{Cr} \text{ or Al} \text{ and M}^{II} = \text{Ni} \text{ or Zn})\). Herein we report expansion of this family to include \(\text{M}^{III} = \text{Cu}, \text{Co}, \text{Mn} \text{ and Fe},\) and \(\text{M}^{II} = \text{Al} \text{ and Cr},\) alongside the serendipitous self-assembly of the related, but larger complex \([\text{Al}^{III}\text{Cu}^{II}\text{Cu}^{III}(\text{OH})_{12}\text{hmp})_{12}]^{8+}\text{(NO}_3^-)_2\). 

**Experimental**

**Materials and physical measurements**

All chemicals were procured from commercial suppliers and used as received (reagent grade). Elemental analyses for C, H, N and metal ions were performed by Medac Ltd.

**Synthesis of \([\text{Cr}^{II}\text{Co}^{III}\text{hmp})_{12}]^{4+}\text{(ClO}_4^-)_9\text{MeOH} (1)**

\(\text{Co(ClO}_4^-)_2\cdot6\text{H}_2\text{O} (0.366 \text{ g, 1 mmol})\) and \(\text{CrCl}_3\cdot6\text{H}_2\text{O} (0.133 \text{ g, 0.5 mmol})\) were dissolved with \(\text{NaOMe} (0.162 \text{ g, 3 mmol})\) in \(\text{MeOH} (24 \text{ ml})\) to give a clear brown solution. Upon full dissolution, \(\text{Hhmp} (0.285 \text{ ml, 3 mmol})\) was added dropwise giving a colour change to red. The reaction was left overnight with continuous stirring. 12 ml samples of the resulting dark red solution were heated in Teflon-lined autoclaves at 100°C for 12 hours. After slowly cooling to room temperature the reaction vessels were allowed to sit undisturbed for 24 hours yielding dark brown, plate-shaped crystals suitable for X-ray diffraction. Yield 0.041 g \((8.7\% \text{ by Fe weight})\). Anal. Calcd \((\%)\) for \(\text{Cu}_3\text{Cu}_2\text{Cr}_2\text{N}_3\text{O}_2\text{MeOH}:\) C 44.36, H 3.60, Cr 4.95, Fe 12.01, N 7.43.

**Synthesis of \([\text{Cr}_5\text{Mn}_2\text{hmp})_{12}]^{8+}\text{(ClO}_4^-)_9\text{MeOH} (3)**

\(\text{Mn(ClO}_4^-)_2\cdot6\text{H}_2\text{O} (0.365 \text{ g, 1 mmol})\) and \(\text{Cr(ClO}_4^-)_2\cdot6\text{H}_2\text{O} (0.229 \text{ g, 0.5 mmol})\) were dissolved with \(\text{NaOMe} (0.162 \text{ g, 3 mmol})\) in \(\text{MeOH} (24 \text{ ml})\) to give a light pink cloudy solution. Upon full dissolution, \(\text{Hhmp} (0.285 \text{ ml, 3 mmol})\) was added dropwise and the reaction was left overnight with continuous stirring. 12 ml samples of the resulting dark purple/red solution were heated in Teflon-lined autoclaves at 100°C for 12 hours. After slowly cooling to room temperature the reaction vessels were allowed to sit undisturbed for 24 hours yielding pale purple hexagonal crystals suitable for X-ray diffraction. Yield 0.021 g \((4.4\% \text{ by Mn weight})\). Anal. Calcd \((\%)\) for \(\text{Cr}_2\text{H}_2\text{ClCr}_2\text{Mn}_2\text{N}_2\text{O}_2\text{C}:\) C 41.70, H 3.50, Cr 5.01, Mn 13.25, N 8.10; found: C 41.52, H 3.66, Cr 4.98, Mn 13.02, N 8.33.

**Synthesis of \([\text{Cr}_5\text{Cu}_2\text{hmp})_{12}]^{8+}\text{(ClO}_4^-)_9\text{MeOH} (4)**

\(\text{Cu(ClO}_4^-)_2\cdot6\text{H}_2\text{O} (0.371 \text{ g, 1 mmol})\) and \(\text{Cr(NO}_3^-)_3\cdot9\text{H}_2\text{O} (0.200 \text{ g, 0.5 mmol})\) were dissolved with \(\text{NaOMe} (0.162 \text{ g, 3 mmol})\) in \(\text{MeOH} (24 \text{ ml})\) to give a pale green solution. Upon full dissolution, \(\text{Hhmp} (0.285 \text{ ml, 3 mmol})\) was added dropwise giving a colour change to dark green/blue. The reaction was left overnight with continuous stirring. 12 ml samples of the resulting dark green solution were heated in Teflon-lined autoclaves at 100°C for 12 hours. After slowly cooling to room temperature the reaction vessels were allowed to sit undisturbed for 24 hours and the resulting solutions were left
to slowly evaporate over 5 days, yielding light purple, plate-shaped crystals suitable for X-ray diffraction. Yield 0.104 g (20.4% by Cu weight). Anal. Calcd (% for C$_{27}$H$_{72}$Cl$_6$Cr$_3$Cu$_2$N$_{12}$O$_{26}$: C 42.35, H 3.55, Cr 5.09, Cu 15.56, N 9.60; found: C 41.85, H 3.40, Cr 5.09, Cu 15.38, N 9.37.

**Synthesis of [Al$_2$Co$_2$(hmp)$_2$](ClO$_4$)$_2$·9MeOH (5)**

Co(ClO$_4$)$_2$·6H$_2$O (0.366 g, 1 mmol) and Al(NO$_3$)$_3$·9H$_2$O (0.188 g, 0.5 mmol) were dissolved with NaOMe (0.162 g, 3 mmol) in MeOH (24 ml) to give a pink solution. Upon full dissolution, hmp (0.285 ml, 3 mmol) was added dropwise giving a colour change to red. The reaction was left overnight with continuous stirring. 12 ml samples of the resulting solution were heated in Teflon-lined autoclaves at 100°C for 12 hours. After slowly cooling to room temperature the reaction vessels were allowed to sit undisturbed for 24 hours yielding pale brown, plate-shaped crystals suitable for X-ray diffraction. Yield 0.289 g (70.7% by Co weight). Anal. Calcd (% for C$_{27}$H$_{72}$Al$_2$Co$_2$N$_2$O$_{26}$: C 42.31, H 3.55, Al 2.64, Co 14.42, N 8.22; found: C 41.81, H 3.38, Al 2.50, Co 14.34, N 7.99.

**Synthesis of [Cu$_3$Al$_4$(hmp)$_2$](ClO$_4$)$_2$(NO$_3$)$_2$·21MeOH (6)**

Cu(ClO$_4$)$_2$·6H$_2$O (0.371 g, 1 mmol) and Al(NO$_3$)$_3$·9H$_2$O (0.188 g, 0.5 mmol) were dissolved with NaOMe (0.162 g, 3 mmol) in MeOH (24 ml) to give a turquoise solution. Upon full dissolution, hmp (0.285 ml, 3 mmol) was added dropwise giving a colour change to dark blue. The reaction was left overnight with continuous stirring. 12 ml samples of the resulting solution were heated in Teflon-lined autoclaves at 100°C for 12 hours. After slowly cooling to room temperature the dark blue solution was left to slowly evaporate yielding dark blue, block-shaped crystals suitable for X-ray diffraction. Yield 0.078 g (26.7% by Al weight). Anal. Calcd (% for Cu$_3$H$_{12}$Al$_4$Cl$_4$Cu$_2$N$_{12}$O$_{64}$: C 31.27, H 3.97, Al 5.14, Cu 14.12, N 6.23; found: C 30.89, H 3.87, Al 5.11, Cu 14.30, N 6.20.

**X-ray crystallography**

Single crystal X-ray diffraction data for samples 1-6 were collected using a Rigaku Oxford Diffraction SuperNova diffractometer with MoK$_\alpha$ (1 & 5-6) or CuK$_\alpha$ (2-4) radiation. Experimental details are given in Table S1 in the Supplementary Information. An Oxford Cryosystems Cryostream 700+ low temperature device was used to maintain a crystal temperature of 120.0 K for all experiments. The structures were solved using ShelXT and refined with version ShelXL interfaced through Olex2 (1-2, 4-6), or Superflip and refined using ShelXL (3). All non-hydrogen atoms were refined using anisotropic displacement parameters. H atoms were placed in calculated positions geometrically and refined using the riding model except for some in compound 6 which were refined freely. CCDC: 1855222-1855227.

**Magnetic data**

Magnetic susceptibility and magnetisation measurements were performed on powdered, polycrystalline samples of 1-6 in the $T = 2$-300 K and $B = 0$-7 T temperature and field ranges on a Quantum Design MPMS XL SQUID magnetometer equipped with a 7 T dc magnet. Hexadecane was employed to prevent potential torquing of the crystallites. Diamagnetic corrections were applied to all data using Pascal’s constants.

**EPR Spectroscopy**

EPR spectra of 6 were measured at Q-band on a Bruker EMX spectrometer.

**Results and discussion**

**Structural description**

There are two unique structure types present in 1-6; compounds 1-5 possess the [M$_1$] Anderson-type structure, while 6 is an [M$_{13}$] cluster containing an Anderson core capped on each of its six edges by an additional metal ion. Crystallographic details for all complexes are given in Table S1, with pertinent bond lengths and angles provided in Tables 1-3. We begin with a generic description of complexes 1-5. Complexes 1-3 and 5 are isostructural, crystallising in the trigonal space group $R3$ with the asymmetric unit (ASU) containing only the central metal ion, one outer metal ion, two hmp ligands and two ClO$_4$ anions. The structure (Figures 2-3) is that of a centred metal hexagon in which the two M$^{11}$ ions are...
disordered around the outer [M₆] wheel. There are therefore two distinct metal sites in the [MIII₂MII₅] cluster, the central metal ion is always an MII ion (Co (1, 5), Fe (2), Mn (3)), which is bridged to the outer metal ions by six symmetry equivalent µ-OR groups from six hmp ligands. The central ion thus has a symmetry imposed, octahedral (D₃d) [MII₆O₆] coordination sphere. The outer metal ions are all also symmetry equivalent, crystallographic disorder resulting in the MIII ions being equally distributed around all six positions, each with a 2/3 MII, 1/3 MIII occupancy, with an average charge of +2.33. This was modelled as a 5:2 substitutional disorder ratio of metal centres by splitting the unique site into two separate parts with identical, constrained co-ordinates and anisotropic displacement parameters, and by fixing the occupancies such that they sum to give a 5:2 ratio of MII to MIII. The disorder gives three distinct structural isomers with the MIII ions occupying outer ring positions 1, 2, 1, 3 or 1, 4 in a ratio of 2:2:1 (Figure 3).

Around the ring, the metal ions are connected by one µ-OR (hmp) group on the ‘outside’ of the wheel and one µ-OR (hmp-) group on the ‘inside’ of the wheel. Two terminally bonded N-atoms from the hmp ligands complete the octahedral coordination spheres on each metal ion. A total of twelve hmp ligands therefore ‘frame’ the metal-oxygen core, six sitting above and six sitting below the metal ion plane. Charge balance is maintained through the presence of four ClO₄⁻ anions. Two sit one above / one below the plane of the metal core with their O-atoms closely associated to the three methylene groups of the hmp ligands, with Cl-O···H(CH₂) distances of approximately 2.6 Å. These interactions occur between cations lying above and below the ClO₄⁻ ion creating offset cation-anion columns down the c-axis of the unit cell. The remaining two ClO₄⁻ anions sit parallel to the plane of the cage, with analogous inter-molecular cation-anion interactions creating H-bonded sheets in the ab plane. The overall result is an aesthetically pleasing topology reminiscent of a hexagonal close packed (hcp) array of cages viewed down the c-axis (Figure S1).

Compound 4 (Figure 5) crystallises in the monoclinic space group I2/a, with half the molecular formula in the ASU. The structure is analogous to that seen for 1-3 and 5 but with the important exception that the two CrIII sites in the outer wheel...
are now not disordered, instead being localised in the 1,4 positions, i.e. trans to each other. The reason for this, and the lowering of crystallographic symmetry, is not clear but may be associated with the presence of Jahn-Teller (JT) distortions at the four peripheral CuII sites (Cu2-N3 = 2.032 Å; Cu2-O6 = 2.402 Å; Cu3-N6 = 2.080 Å; Cu3-O2 = 2.345 Å), and at the central CuII site (Cu1-O3/O3′ = 2.213 Å). Charge balance is maintained through the presence of two ClO4- and two NO3- anions. The cation-anion interactions are largely similar to that seen above, with the molecules forming layers in the ab plane, with the NO3- anions lying between the planes and the ClO4- anions lying within the planes. However in this case the cations are not offset, instead they sit directly above/below nearest neighbours along the c-axis of the unit cell (Figure S2-S3).

Complex 6 crystallises in the trigonal space group R3, with the ASU containing the central CuII ion (Cu2), one AlIII ion, one outer CuII ion (Cu1), two OH ions (O3, O4), two hmp ligands, one ClO4- anion and 1/3 of an NO3- anion (Figure 4b). The central core contains an Anderson-like [CuIIAlIII] wheel with an octahedral CuII ion (Cu2-O3 = 2.043Å) in the central position bridged to a ring of six AlIII ions through six μ3-OH ions. D3d symmetry is imposed on Cu2 as it sits on a special position with a 3-fold axis and an inversion centre. The AlIII ions are further bridged to each other via six μ-OH ions (O4), and to edge-capping CuII ions (Cu1) through the μ-hmp ligands. The AlIII ions are thus in octahedral geometries with [AlO6] coordination spheres, while the peripheral CuII ions are square-based pyramidal with [CuN4O3] coordination spheres, the fifth site being occupied by a ClO4- ion (Cu1-O5 = 2.637 Å). When viewed parallel to the central Anderson motif, it is clear that the metallic skeleton is not fully planar, with the six peripheral CuII ions (Cu1) sitting alternately above and below the plane (Figure 6). As these are chelated by the hmp ligands the latter also sit (six) above and (six) below the [CuAl] moiety. The packing of the molecules of 6 in the crystal (Figures S4-S5) is akin to that seen for complexes 1-3 and 5, with offset columns of cations along the c-axis, the charge balancing NO3- counter ions lying between the sheets of cations present in the ab plane. Nearest inter-cluster contacts exist between aromatic rings on neighbouring molecules with C(AR)-C(AR) separations of ~3.4 Å, C(AR)-H(CAR) of ~2.8 Å and C(AR)-O(ClO4) of ~3 Å. Note that the closest intermolecular Cu...Cu distance is ~8.5 Å (see magnetism and EPR sections below).

| Table 1 Pertinent structural parameters for the Mcentral-Mouter di-alkoxo bridge in 1-5. r = M-O bond length, φ = M-O-M bridging angle. |
|---|---|---|
| M-M (Å) | r (Å) | φ (°) |
| 1 | 3.148 | 2.059-2.151 | 95.40-98.23 |
| 2 | 3.182 | 2.126-2.162 | 98.80-97.70 |
| 3 | 3.236 | 2.108-2.170 | 96.60-98.48 |
| 4 | 3.156-3.188 | 2.067-2.213 | 88.59-102.89 |
| 5 | 3.133 | 2.036-2.133 | 95.49-98.47 |

| Table 2 Pertinent structural parameters for the Mouter-Mcentral di-alkoxo bridge in 1-5. r = M-O bond length, φ = M-O-M bridging angle. |
|---|---|---|
| M-M (Å) | r (Å) | φ (°) |
| 1 | 3.156 | 1.987-2.151 | 97.09-104.73 |

Dc magnetic susceptibility (χM) measurements were carried out on powdered polycrystalline samples of compounds 1-6 in a B = 0.1 T applied magnetic field over the temperature range T = 2-300 K, and are plotted as the χM product versus T in Figures 7-8.

For complexes 1-5 the experimental room temperature values of χM are close to the Curie constants expected for five and two non-interacting MIII and MII ions, respectively; 1: 19.6 cm³K mol⁻¹ (expected 16.2 cm³K mol⁻¹, gc = 2.00, gc = 2.30); 2: 17.7 cm³K mol⁻¹ (expected 18.2 cm³K mol⁻¹, gc = 2.00, gc = 2.20); 3: 25.4 cm³K mol⁻¹ (expected 25.6 cm³K mol⁻¹, gc = 2.00); 4: 6.1 cm³K mol⁻¹ (expected 6.0 cm³K mol⁻¹, gc = 2.00, gc = 2.20); 5: 13.7 cm³K mol⁻¹ (expected 12.4 cm³K mol⁻¹, gc = 2.00, gc = 2.30). The temperature dependence of χM for all five complexes down to approximately T = 25 K is rather similar, all decreasing slowly with decreasing temperature. For complex 1 the value of χMT then plateaus at a value of 17.0 cm³K mol⁻¹, before decreasing to a value of 14.2 cm³K mol⁻¹ at 2 K. For complexes 3 and 5 the value of χMT increases to maximum values of 19.7 and 14.4 cm³K mol⁻¹, respectively. For complexes 2 and 4 the value of χMT continues to decrease, reaching T = 2 K values of 7.8 and 0.5 cm³K mol⁻¹, respectively. The behaviour in each case is therefore consistent with the presence of competing exchange interactions, as observed and quantified for the structurally
analogous [Cr2Ni5(hmp)2]4+ family of complexes.20 The positional disorder of the CrIII ions and resulting different isomers, the large number of different exchange interactions and, in the case of complexes, 1, 2, 5, the zero-field splitting effects of the MII ions precludes any detailed/quantitative analysis of the susceptibility data. Magnetisation (M) versus field data, collected for 1-5 in the $T = 2$-7 K and $B = 0.5$-7 T temperature and field ranges (Figures S6-S10) are consistent with this picture, in each case $M$ rising rapidly with increasing $B$ without reaching saturation.

\[ \chi_B T = \sum_s - \sum_3 - 50 t \text{ca}_B, 1 - xx_6 2 6 M. \]

Figure 8 Plot of the $\chi_B T$ product versus $T$ for complex 6 in an applied field, $B = 0.1$ T. Inset: Plot of the magnetisation (M) versus field ($\chi$) data for complex 6 in the indicated field and temperature ranges. The solid black lines represent the simultaneous fit of the experimental susceptibility and magnetisation data.

The dc susceptibility and magnetisation data for complex 6 is shown in Figure 8. The high temperature $\chi_B T$ value of 3.06 cm$^3$ K mol$^{-1}$ is close to that expected for seven non-interacting ($s = \frac{5}{2}$) CuII ions with $g = 2.20$ (3.2 cm$^3$ K mol$^{-1}$). This value remains constant in the $T = 400$ - 25 K temperature regime, before falling to a value of 1.7 cm$^3$ K mol$^{-1}$ at $T = 2$ K. This is consistent with the presence of very weak antiferromagnetic exchange interactions between the CuII ions, as would be expected from the presence of a 3-atom (Cu-O-M-O-Cu) bridge between neighbouring paramagnetic sites.24 The data is invariant in measurements performed at different field strengths (Figure S11). The $\chi_B T$ and magnetisation data were fitted simultaneously using isotropic spin-Hamiltonian (1) and the exchange interaction scheme depicted in Figure 9, where the indices $i$ and $j$ refer to the interacting CuII ions, $\mu_B$ is the Bohr magneton, $B$ is the applied magnetic field, $g$ is the $g$-factor of the CuII ions (fixed from the EPR with $g_{11} = 2.21$ and $g_2 = 2.06$), $\hat{S}$ is a spin operator and $J$ is the isotropic exchange interaction. Using this model, the best fit parameter was found to be $J = -0.47$ cm$^{-1}$. This value is similar to that previously observed for Cu(II) ions bridged via diamagnetic metal ions (-O-M-O-) moieties.24

\[ \hat{H} = \mu_B B \sum_i g_i \hat{S}_i - 2 \sum_{i<j} J_{ij} \hat{S}_i \hat{S}_j \]  

Given the very small value of $J$, fitting was also attempted using a model in which intermolecular interactions (see the EPR section below) were also included via a mean-field approach, but all solutions remained inferior to that given above.

**EPR Spectroscopy**

EPR spectra of a powdered sample of complex 6, measured at Q-band (ca. 34 GHz; Figure 10), are consistent with tetragonal Cu(II) centres with near axially-symmetric $g$-values with “$g_2” = 2.06 and “$g_1” = 2.21. There is no resolution of any fine structure and the spectra change little with variable temperature (beyond simple Curie behaviour), consistent with any intramolecular exchange interactions being very weak. However, there is no resolution of $^{63,65}$Cu hyperfine structure, hence the Cu ions are not magnetically dilute. At the $g_1$ region, where the hyperfine interaction would be at its largest for tetragonal Cu(II), the (Lorentzian) linewidth (ca. 4 mT) is much narrower than the expected spread of the hyperfine multiplet (50-60 mT for $A_{11} = 0.015-0.02$ cm$^{-1}$): this is characteristic of an exchange narrowing regime where the intermolecular interactions in the lattice are...
comparable to the hyperfine interaction. Hence, care should be taken in interpreting the bulk magnetic properties of $6$ from the Hamiltonian (1) alone; it is also possible that the EPR $g$-values are characteristic of the lattice rather than the true molecular values.

**Conclusions**

The use of 2-pyridinemethanol in heterometallic 3d cluster chemistry has led to the isolation of a large family of complexes of general formula $[M^{	ext{III}}_2M^{	ext{II}}_2(\text{hmp})_2]^+$ where $M^{	ext{III}} = \text{Cr, Al and M}^{	ext{II}} = \text{Mn, Fe, Co, Ni, Cu, Zn}$. These complexes all conform to the Anderson structure type describing a centred hexagon, in which the two $M^{	ext{III}}$ ions are disordered around the outer wheel. The only exceptions are observed for $M^{	ext{III}} = \text{Cr and M}^{	ext{II}} = \text{Cu}$ where the same structure type forms but with the $M^{	ext{III}}$ localised in the 1,4-positions, and for $M^{	ext{III}} = \text{Al and M}^{	ext{II}} = \text{Cu}$ where a structurally related, but larger tridecanuclear $[M^{	ext{III}}_8M^{	ext{II}}_4(\text{hmp})_2]^+$ species is formed. The Anderson type structures display all competing magnetic exchange interactions as one might expect from planar complexes containing triangular building blocks, while the $Cu^{	ext{II}}$ ions $[M^{	ext{III}}_4\text{Cu}_2(\text{hmp})_2]^2+$ are very weakly antiferromagnetically coupled through either/both the intramolecular 3-atom Cu-O-Al-O-Cu moieties and dipolar, intermolecular interactions.

The modular assembly of large heterometallic cages is extremely rare, interestingly the only other known example is a family of Cr-based wheels which also show positional disorder at the metal sites. Building larger molecular cages based on the Anderson core in ‘2D’ such that they resemble larger and larger fragments of the kagomé lattice is of fundamental interest to chemists and physicists studying the unusual physical phenomena resulting from spin frustration. The $[M_3]$ structure type reported here is commonly observed in Al and Ga chemistry, but previous examples in 3d chemistry are limited to just Ni and Co.

**Conflicts of interest**

There are no conflicts of interest to declare.

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**Notes and references**