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In search for molecules displaying ferromagnetic exchange: multiple-decker Ni$_{12}$ and Ni$_{16}$ complexes from the use of pyridine-2-amidoxime

Constantinos G. Efthymiou,$^{a,b}$ Luis Cunha-Silva,$^c$ Spyros P. Perlepes,$^b$ Euan K. Brechin,$^d$ Ross Inglis,$^{*,e}$ and Constantina Papatriantafyllopoulou$^*$

The use of pyridine-2-amidoxime (pyaoxH$_2$) in Ni chemistry has provided access to a dodecanuclear complex and a hexadecanuclear Ni cluster, namely $[\text{Ni}_{12} \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pyaox})_2 \{(\text{pya...}{/!

Electronic Supplementary Information (ESI) available: Tables with bond distances and angles, hydrogen bonding details, magnetism and heat capacity plots for 2 $10\text{H}_2$O 26MeOH. See DOI: 10.1039/x0xx00000x

ARTICLE

Introduction

It has been over 20 years since the discovery that the discrete [Mn$_{16}$]$^{8+}$[O$_2$(O$_2$CMe)$_6$($\text{H}_2$O)$_8$] molecule could possess an energy barrier to its spin vector reversal that was large enough to observe magnetic hysteresis, the classical property of a magnet.¹ This discovery constituted the commencement of a new era in transition metal cluster chemistry sparking off an intense interest in the synthesis and characterization of new coordination compounds that could behave like magnets at very low temperatures in the absence of an applied magnetic field. Such species are now known as single-molecule magnets (SMMs)² with their properties originating from intrinsic structural and electronic characteristics of their metal cores. The potential applications of SMMs range from high-density information storage, molecular spintronics, to qubits for quantum computation.³,⁵ Furthermore, several other quantum mechanical phenomena have been identified in SMMs, such as spin-phonon coupling,⁶ spin state entanglement,⁷ spin parity effects,⁷ both thermally assisted and pure quantum tunneling of the magnetization (QTM),⁸ and quantum phase interference.⁷b,⁹

Clusters containing Mn$^{III}$ ions have proven to be the most fruitful source of SMMs to date. This is not surprising considering that: 1) the first and most well-known SMM comes from Mn cluster chemistry, a fact that attracted intense research in this area, and 2) the d$^4$ Mn$^{II}$ ion displays significant anisotropy, an inherent requirement for the generation of new SMMs.⁵ However, SMMs are also known for 3d metal ions other than Mn, e.g. V$^{III}$, Fe$^{II}$, Fe$^{III}$, Ni$^{II}$, lanthanide ions, actinide ions, and combinations of 3d with 4d, 5d or 4f paramagnetic metal ions.²,¹⁰ Among them, Ni$^{II}$ has shown much promise in the synthesis of both SMMs and spin phonon traps,¹² due to its significant single-ion anisotropy and its paramagnetic nature when confined within a highly symmetric cage.

The isolation of new SMMs remains a hot research field, not only for a better understanding of the phenomenon but also for bringing these species closer to technological applications. In fact, the chances of identifying novel types of coordination clusters with improved or new magnetic properties will be increased by the development of new reaction systems with
suitable organic ligands or combinations of organic and inorganic ligands. The organic ligand often dictates the cluster symmetry, metal topology and number of metal ions that are present, which in turn affects the nature of the magnetic exchange interactions and the intermolecular interactions between the polynuclear molecules in the crystal. One fertile approach towards the synthesis of new polynuclear metal complexes with interesting magnetic properties is the use of oxime ligands, since oximates are good bridging groups fostering formation of coordination clusters. We and others have been investigating a number of oxime-based ligands, and one broad family of the latter have been the 2-pyridyl oximes (Scheme 1). The anions of 2-pyridyl oximes are versatile ligands for a variety of research objectives; the activation of 2-pyridyl oximes by 3d-metal centres towards further reaction is also becoming an exciting area of research. Such ligands have been key “players” in several areas of single-molecule and single-chain magnetism.

Restricting further discussion to nickel, our groups have been engaged in the use of 2-pyridyl oximate ligands for Ni\(^{II}\) cluster synthesis for many years. The first step of this approach included the synthesis and characterization of complexes of pao\(^{17}\), mpko\(^{18}\) and ppko\(^{17e,18c,d,19}\), i.e., complexes bearing anionic ligands in which R contains no additional donor site. In a second step, we have been studying Ni\(^{II}\) complexes with anionic ligands in which R contains a donor site, i.e., clusters of (py)ppko\(^{17a,20}\) and pyaoxH/pyaox\(^2\). In particular, the ligand pyaoxH (pyridine-2-oximido; IUPAC name: N-hydroxy-pyridine-2-carboxamidine) belongs to the class of amidoximes. Although the versatile chemistry of conventional oximes has been extensively studied over the years in both the organic chemistry and coordination chemistry literature, amidoximes, RC(NH\(_2\))=NOH, have so far received substantially less attention. The presence of the amino functionality is expected – due to its coordination capability, potential for deprotonation and hydrogen bonding effects – to alter the coordination behaviour of this ligand (and hence the identity of the resultant Ni\(^{II}\) complexes) in comparison with that of the pao, mpko, ppko, (py)ppko, etc., ligands.

In 2008, our groups employed pyaoxH\(_2\) in Ni cluster chemistry and proved that it can be a fruitful method for the synthesis of high nuclearity species. Nevertheless, the use of pyaoxH\(_2\) for the synthesis of polynuclear Ni compounds remains limited. In particular, there have been so far reported only salts of the cations [Ni\(_2\)(pyaox)\(_2\)(pyaoxH)\(_2\)]\(^{2+}\) (L = imidazole, 1-methylimidazole, pyridine, 3-methylpyridine, 4-methylpyridine), [Ni\(_8\)(pyaox)\(_6\)(pyaoxH)\(_4\)]\(^{4+}\) (L’ = H\(_2\)O, imidazole), and [Ni\(_{12}\)(pyaox)\(_6\)(pyaoxH)\(_6\)(H\(_2\)O)\(_2\)(Ni\(_2\))]\(^{4+}\) and [Ni\(_{12}\)(pyaox)\(_6\)(pyaoxH)\(_6\)(H\(_2\)O)\(_2\)]\(^{4+}\). The cations have single-(Ni\(_8\)), double-(Ni\(_{16}\)) and triple- decker (Ni\(_{24}\)) structures, where each deck is composed of the same tetranuclear cationic unit [Ni\(_4\)(pyaox)\(_2\)(pyaoxH)\(_2\)]\(^{2+}\) (proved to be present in solution by ESI-MS spectrometry) and features two square planar and two octahedral Ni\(^{II}\) centres.

In this work, we expand the above mentioned family of multiple-decker Ni clusters by reporting the syntheses, crystal structures and magnetic and heat capacity properties of two such species, namely [Ni\(_{12}\)(pyaox)\(_6\)(pyaoxH)\(_6\)(MeOH)\(_2\)].Cl\(_2\).5MeOH (1:5MeOH) and [Ni\(_{16}\)(pyaox)\(_6\)(pyaoxH)\(_6\)(MeOH)\(_4\)][SO\(_4\)].10H\(_2\)O·26MeOH (2:10H\(_2\)O·26MeOH). The two clusters are high-spin featuring both the singly (pyaoxH) and doubly deprotonated (pyaox\(^2\)) forms of pyaoxH. 2:10H\(_2\)O·26MeOH is the first example of a metal cluster with a quadruple-decker topology, being also the highest nuclearity metal cluster, in general, containing any form of pyaoxH ligand and the highest nuclearity Ni\(^{II}\) cluster with any type of a 2-pyridyl oxime. In addition, its nuclearity is the highest that has been observed so far in metal clusters bearing 2-pyridyl oximes. The number of the decks in 1:5MeOH and 2:10H\(_2\)O·26MeOH, and hence the nuclearity of the products, depend on the nature of the inorganic anion that is present in the reaction system, providing elements of synthetic control towards new ferromagnetic species. Portions of this work have been previously communicated.

**Experimental section**

All manipulations were performed under aerobic conditions using materials (reagent grade) and solvents as received. The organic ligand pyaoxH was synthesized following the reported method. Elemental analyses (C, H, N) were performed by the University of Patras microanalysis service. IR spectra (4000–400 cm\(^{-1}\)) were recorded using a Perkin Elmer 16PC FT-IR spectrometer with samples prepared as KBr pellets. The magnetic susceptibility measurements were carried out on a Quantum Design SQUID magnetometer MPMS-XL 7 operating between 1.8 and 300 K for dc-applied fields ranging from 0 to 5 T. Microcrystalline samples were dispersed in Vaseline in order to avoid torquing of the crystalites. The sample mulls were contained in a calibrated gelatin capsule held at the center of a drinking straw that was fixed at the end of the sample rod. Alternating current (ac) susceptibility measurements were carried out under an oscillating ac field of 3.5 Oe and frequencies ranging from 0.1 to 1500 Hz. The heat capacity measurements were carried out for temperatures down to 0.3 K by using a Quantum Design 14T-PPMS, equipped with a \(^{3}\)He cryostat. The experiments were performed on thin pressed pellets (ca. 1 mg) of a polycrystalline sample, thermalized by ca. 0.2 mg of Apiezon N grease, whose contribution was subtracted by using a phenomenonlogogical expression.
Synthetic details
Preparation of the complex [Ni$_2$(pyaox)$_3$(pyaoxH)$_3$(MeOH)$_2$Cl$_2$]Cl$_2$·5MeOH (1·5MeOH). Solid NaOMe (0.054 g, 1.00 mmol) was added to a colourless solution of pyaoxH$_2$ (0.068 g, 0.50 mmol) in MeOH (15 mL); the solid soon dissolved. Solid NiCl$_2$·6H$_2$O (0.119 g, 0.50 mmol) was then added and the resulting slurry was stirred for 15 min at room temperature. The dark brown slurry was filtered and the solution was left to stand undisturbed in a closed flask for a period of 3–4 days. Dark brown crystals appeared which were collected by filtration, washed with H$_2$O (1 mL), cold EtOH (1 mL) and Et$_2$O (3 mL), and dried in air. Yield: 60%. The dried solid was analyzed satisfactorily as 1. Calcd (found): C 34.07 (33.84), H 2.86 (2.90), N 19.33 (19.21) %. IR (KBr, cm$^{-1}$): 3328, 1654, 1606, 1577, 1542, 1483, 1448, 1416, 1303, 1263, 1158, 1103, 1076, 1023, 992, 938, 782, 729, 702, 645, 517, 480, 405.

Preparation of the complex [Ni$_3$(pyaox)$_3$(pyaoxH)$_3$(MeOH)$_2$]SO$_4$·10H$_2$O·26MeOH (2·10H$_2$O·26MeOH). NET$_3$ (0.139 mL, 1.00 mmol) was added to a colourless solution of pyaoxH$_2$ (0.068 g, 0.50 mmol) in MeOH (20 mL). Solid NiSO$_4$·6H$_2$O (0.130 g, 0.50 mmol) was then added and the resulting solution was stirred under heating (45 °C) for 15 min. The dark brown solution was left to stand undisturbed in a closed flask for a period of 3–4 days. Dark brown crystals appeared which were collected by filtration, washed with cold EtOH (1 mL) and Et$_2$O (3 mL), and dried in air. Yield: 65%. The dried solid was analyzed satisfactorily as 2·8H$_2$O·22MeOH. Calcd (found): C 32.78 (32.52), H 4.69 (4.25), N 15.04 (15.17) %. IR (KBr, cm$^{-1}$): 1303, 1263, 1158, 1103, 1076, 1022, 981, 933, 777, 747, 700, 646, 617, 515, 468, 405.

Single-crystal X-ray crystallography
Suitable single-crystals of 1·5MeOH and 2·10H$_2$O·26MeOH were mounted on a Hampton Research Cryoloop using FOMBLIN Y perfluoropolyether vacuum oil (LVAC 25/6) purchased from Aldrich, with the help of a Stemi 2000 stereomicroscope equipped with Carl Zeiss lenses. Data were collected at 150(2) K on a Bruker X8 Kappa APEX II charge-coupled device (CCD) area-detect detector diffractometer (Mo Ka, graphite-monochromated radiation, λ = 0.71073 Å) controlled by the APEX2 software package, and equipped with an Oxford Cryosystems Series 700 cryostream monitored remotely using the software interface CryoP. Images were processed using the software package SAINT+. and data were corrected for absorption by the multi-scan semi-empirical method implemented in SADABS. The structures were solved by the direct methods of SHELXS-97, and refined by full-matrix least squares on F$^2$ using SHELXL-97.

All non-hydrogen atoms were directly located from difference Fourier maps and successfully refined with anisotropic displacement parameters. For both compounds, hydrogen atoms attached to carbon and to the hydroxido groups were located at their idealised positions and included in the structural model in subsequent refinement cycles in riding-motion approximation with $U_{iso} = 1.2$ (aromatic carbon) or 1.5 (–CH$_3$ and –OH groups) of $U_{eq}$ of the parent atom. Hydrogen atoms associated with the nitrogen included in the structures with the N–H and H···H distances restrained to 0.90(1) and 1.50(1) Å, respectively, and with Uiso = 1.5×Ueq(N).

For 2·10H$_2$O·26MeOH the hydrogen atoms belonging to the uncoordinated water molecules could not be directly located from difference Fourier maps and no attempt was made to place these in approximate calculated positions; they have been included in the empirical formula of the compound.

Beside the solvent molecules located in both the structures (5 MeOH in compound 1, as well as 10 H$_2$O and 26 MeOH in 2), considerable smeared-out electron densities were found in the empty spaces available in the two structures, which prevented a sensible location and refinement of other solvent molecules. Searches for the total potential solvent area using the software package PLATON revealed the presence of large voids housing the disordered molecules. The two data set were then treated using the SQUEEZE, and the reflection lists arising from this procedure were used for the final structural refinements.

Full details can be found in Table 1 and the cif files.

Results and discussion
Synthetic comments and IR spectra
Our groups have a strong interest in the employment of 2-pyridyl oxime ligands as a route to high nuclearity 3d transition metal clusters and 5MMS. As a part of this program we recently decided to explore pyaoxH$_2$ in Ni$^0$ cluster chemistry. Thus, a variety of

*Table 1 Crystallographic data for compounds 1·5MeOH and 2·10H$_2$O·26MeOH

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$^a$ Including solvent molecules. $^b$ Graphite monochromator. $^c$ R$_1$ = Σ||F$_o$| - |F$_c$||/Σ|F$_o$|; $^d$ wR$_2$ = Σ[|w(Fo$^2$ - Fc$^2$)]$^2$/Σ[w(Fo$^2$)]$^2$; $^e$ Uiso = 1.5×Ueq(N).
of experiments was performed studying how the different synthetic parameters affect the identity and/or crystallinity of the isolated product. In particular, treatment of NiCl₂·6H₂O with one equivalent of pyaoxH₂ and two equivalents of NaOMe in MeOH gave a dark brown solution from which the dodecanuclear cluster [Ni₁₂(pyaox)₈(pyaoxH)₈(MeOH)₂]Cl₄·5MeOH (1·5MeOH) was obtained in 60% yield. Its formation can be summarized by eqn (1):

\[
12\text{NiCl}_2\cdot 6\text{H}_2\text{O} + 12\text{pyaoxH}_2 + 18\text{NaOMe} \rightarrow [\text{Ni}_{12}(\text{pyaox})_8(\text{pyaoxH})_8(\text{MeOH})_2]\text{Cl}_4 + 18\text{NaCl} + 72\text{H}_2\text{O} + 16\text{MeOH} \quad (1)
\]

The methoxide ions act as proton acceptors to facilitate formation of pyaoxH₂ and pyaoxH ligands. The reaction procedure involved a slight excess of NaOMe over that required by eqn (1), and this might have proven beneficial in shifting a possible equilibrium to the right. The reaction mixtures which lead to 1 should be filtered before crystallization to remove NaCl which is insoluble in MeOH. The product also needs to be washed with a small amount of H₂O to ensure complete removal of NaCl.

The determination of the crystal structure of 1 with single crystal x-ray crystallography revealed that the twelve metal ions have an unprecedented triple-decker topology with each “deck” containing two square planar and two octahedral Ni³⁺ atoms. The intriguing structural and magnetic features of 1 (vide infra) prompted us to further study this reaction system exploring the ability of pyaoxH₂ to deliver other novel polynuclear Ni³⁺ compounds. In the context of this investigation, we decided to employ different counterions possessing higher charge than Cl⁻ hoping that they could stabilize higher nuclearity clusters. Indeed, this turned out to be the case and the treatment of NiSO₄·6H₂O with one equivalent of pyaoxH₂ and two equivalents of NET₃ in MeOH gave a dark brown solution from which the higher nuclearity cluster [Ni₁₆(pyaox)₈(pyaoxH)₈(MeOH)₃][SO₄]₄ (2) was obtained in 65% yield. Its formation can be summarized by eqn (2):

\[
16\text{NiSO}_4\cdot 6\text{H}_2\text{O} + 16\text{pyaoxH}_2 + 24\text{NET}_3 + 4\text{MeOH} \rightarrow [\text{Ni}_{16}(\text{pyaox})_8(\text{pyaoxH})_8(\text{MeOH})_3][\text{SO}_4]_4 + 12(\text{NHEt}_3)_2\text{SO}_4 + 96\text{H}_2\text{O} \quad (2)
\]

The reaction mixture which leads to 2 should be heated for some minutes to facilitate the dissolution of NiSO₄·6H₂O (presumably by reaction with the organic ligand) in MeOH. We observed that reactions with small variations in the Ni³⁺:pyaoxH₂ ratio gave the same Ni₁₆ compound. The nature of the base and the crystallization method are not crucial for the identity of the product and affect only its crystallinity; we were able to isolate 2 (IR evidence) by using a plethora of bases such as NaOMe, NaOH, NH₃ etc.

The IR spectra of dried 1·5MeOH and 2·10H₂O·26MeOH exhibit a strong broad band at ~3330 cm⁻¹ assignable to the ν(OH) vibration of coordinated MeOH molecules, as well as solvent MeOH and H₂O molecules, and to the ν(NH) and ν(NH) vibrations of the pyaoxH/pyaox² ligands. The broadness and low frequency of these bands are both indicative of strong hydrogen bonding. There are medium intensity bands at 1566 and 1116 cm⁻¹ in the spectrum of the free pyaoxH₂ ligand, which are assigned to ν(C=N) and ν(N-O) vibrations, respectively. The 1116 cm⁻¹ band is shifted to a lower wavenumber (1103 cm⁻¹ in 1·5MeOH; 1100 cm⁻¹ in 2·10H₂O·26MeOH). This shift is attributed to the coordination of the oximate nitrogen. The band is strong in the spectrum of the Ni₁₆ cluster, because it also has a ν(ππ*) character from the ionic sulfates (T₇ symmetry). Somewhat to our surprise, the 1566 cm⁻¹ band is shifted to a higher wavenumber in the complexes (1577 cm⁻¹ in 1·5MeOH, 1580 cm⁻¹ in 2·10H₂O·26MeOH), overlapping with an aromatic stretch. This shift may be indicative of the oximate nitrogen coordination. Extensive studies on Schiff-base complexes (which also contain a C=N bond) have shown that a change in the s character of the nitrogen lone pair occurs upon coordination such that the s character of the nitrogen orbital, which is involved in the C=N bond, increases; this change in hybridization produces a greater C=N stretching force constant relative to the free neutral ligand. The in-plane deformation band of the 2-pyridyl ring of free pyaoxH₂ at 632 cm⁻¹ shifts upwards in 1·5MeOH (646 cm⁻¹) and 2·10H₂O·26MeOH (645 cm⁻¹), confirming the involvement of the ring-N atom in coordination.

**Description of structures**

Representations of the molecular structure and the structural core of compound 1·5MeOH are shown in Fig. 1. Selected interatomic distances and angles are listed in Table 2. Compounds 1·5MeOH...
and 2·10H₂O·26MeOH display related structures based on parallel Ni₄ layers, \( \text{[Ni}_6(\text{pyaox})_2(\text{pyaoxH})_2]^{lo}_x \) \( (x = 3, {1\text{SMeOH}}; \ x = 4, {2\text{10H}_2\text{O·26MeOH}}) \). Thus, only the structure of compound {1\text{SMeOH}} will be discussed in detail and compared to that of {2\text{10H}_2\text{O·26MeOH}}.

![Scheme 2](image)

The crystallographically established coordination modes of pyaoxH and pyaox² in complexes 1 and 2.

### Table 2

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*Symmetry transformations used to generate equivalent atoms: x-1, y, z+1

**Complex 1·5MeOH** crystallizes in the triclinic space group \( P\bar{1} \). Its structure consists of \( \text{[Ni}_6(\text{pyaox})_2(\text{pyaoxH})_2Cl_2(\text{MeOH})_2]^{lo}_x \) cations, \( \text{Cl}^- \) counterions and MeOH lattice molecules. The centrosymmetric cation of 1·5MeOH is composed of six distorted octahedral \( \text{Ni}_1, \text{Ni}_2, \text{Ni}_3 \) and symmetry equivalents) and six square planar \( \text{Ni}_4, \text{Ni}_5, \text{Ni}_6 \) and symmetry equivalents) \( \text{Ni}_4 \) atoms, which are held together through two \( \eta^1\cdot\eta^1\cdot\eta^1\cdot\mu_4 \) and four \( \eta^1\cdot\eta^1\cdot\eta^1\cdot\mu_2 \) pyaoxH ligands, as well as two \( \eta^1\cdot\eta^1\cdot\eta^1\cdot\mu_4 \) and four \( \eta^1\cdot\eta^1\cdot\eta^1\cdot\mu_2 \) pyaox² groups (Scheme 2). The coordination sphere of the Ni atoms is composed by two terminal chlorido ligands on Ni2 and Ni2', and two terminal MeOH molecules on Ni3 and Ni3'. The twelve metal ions in 1·5MeOH are arranged into three layers, which are stacked one above the other forming an unusual, for 3d-metal cluster chemistry, triple-decker topology. Each “deck” contains two square planar and two octahedral Ni⁶ atoms, whereas the linkage of the central deck with each of the outer decks is achieved through two bridging oxygen atoms from two \( \eta^1\cdot\eta^1\cdot\eta^1\cdot\mu_4 \) pyaoxH ligands and two bridging oximate nitrogen atoms from two \( \eta^1\cdot\eta^1\cdot\eta^1\cdot\mu_2 \) pyaox² groups. The four Ni⁶ atoms of the two outer layers are arranged in an almost planar topology with the largest deviation from the plane being 0.14 Å for Ni3 and Ni6, whereas the metal ions in the central layer are perfectly coplanar. The distance between two adjacent decks is ~2.70 Å. The chromophores in 1·5MeOH are \( \text{Ni}(1,1')\{\text{Np}_2\{\text{Nap}_2\{\text{Oap}_3\}}\{\text{Cl}_2\}, \text{Ni}(2,2')\{\text{Np}_2\{\text{Nap}_2\{\text{Oap}_2}\}}\{\text{Oap}_2\}\{\text{Oap}_2\}, \text{Ni}(3,3')\{\text{Np}_2\{\text{Nap}_2\{\text{Oap}_2}\}}\{\text{Oap}_2\} \) and \( \text{Ni}(4,4',5,5',6,6')\{\text{Np}_2\{\text{Nap}_2\{\text{Oap}_2}\}}\{\text{Oap}_2\}{\text{Oap}_2}\}, \) where the abbreviations “py”, “ox” and “am” are for the 2-pyridyl, oximate and deprotonated
amino donor atoms, respectively. The strong ligand field, deprotonated amino donor atoms are coordinated only to the square planar Ni\(^{II}\) atoms and may be considered responsible for their geometry. The average Ni(4,5,6)-N\textsuperscript{ao} \(O\textsubscript{ao} \) bond distances are 1.893, 1.850 and 1.827 \(\AA\), respectively, while the average Ni(1,2,3)-N\textsuperscript{ao} \(O\textsubscript{ao} \) bond lengths are 2.052, 2.140 and 2.062 \(\AA\), respectively. The longer bonds involving Ni(1,2,3) compared to those involving Ni(4,5,6) are a consequence of the higher coordination number of Ni1, Ni2 and Ni3.

The \(\eta^1: \eta^2: \eta^2: \mu_2\) coordination mode of pyaox\(^2\) found in 1\(5\)MeOH is extremely rare in the coordination chemistry of pyridine-2-amidoxime.\(^{25}\) In fact, this can be rationalised by considering the C-N\textsubscript{ox} bond lengths; the C-N\textsubscript{ox} and C-N\textsubscript{am} distances for the \(\eta^1: \eta^2: \eta^2: \mu_2\) pyaox\(^2\) ligands (average values: 1.345 and 1.322 \(\AA\)) are longer and shorter, respectively, than those for the \(\eta^1: \eta^2: \eta^2: \mu_3\) pyaox\(^2\) ligands (1.318 and 1.336 \(\AA\)), indicating a decreased double bond character for the C-N\textsubscript{ox} bond and an increased double bond character for the C-N\textsubscript{am} bond in the former.

The crystal structure of 1\(5\)MeOH is stabilized by strong intramolecular hydrogen bonds between the O atoms of the terminally ligated MeOH molecules (O1Me, which act as donors, and the terminal chlorido ligands, which act as acceptors [O1Me – Cl \(= 3.199 \) (2) \(\AA\), H1M – Cl \(= 2.256(2) \) \(\AA\), O1M – H1M – Cl \(= 167.19(2)\)\(^{\circ}\)]. In addition, there is a network of intermolecular H bonds that involve: 1) the Cl counterions (acceptors) and the NH\(^2\) groups (donors) of the organic ligands [N\textsuperscript{N3} – Cl \(= 3.245(2) \) \(\AA\), H3B – Cl \(= 2.36(1) \) \(\AA\), N3 – H3B – Cl \(= 166.93\)\(^{\circ}\), N9 – Cl \(= 3.282(2) \) \(\AA\), H9B – Cl \(= 2.421(2) \) \(\AA\), N9 – H9B – Cl \(= 159.83\)\(^{\circ}\)] resulting in the formation of 1D chains, and 2) the coordinated chlorido ligands (acceptor) and the MeOH lattice molecules (donors) [O3M – Cl \(= 3.237(2) \) \(\AA\), H9M – Cl \(= 2.422(2) \) \(\AA\), O3M – H9M – Cl \(= 163.49\)\(^{\circ}\)].

Representations of the molecular structure and the structural core of compound 2\(10\)H\textsubscript{2}O-26MeOH are shown in Fig. 2. Selected interatomic distances and angles are listed in Table S1 in the ESI.

Complex 2\(10\)H\textsubscript{2}O-26MeOH crystallizes in the triclinic space group \(\overline{P}1\). Its structure consists of [Ni\textsubscript{12}(pyaox)(pyaoxH)(MeOH)]\(^{4+}\) cations, SO\textsubscript{4}\(^2-\) counterions, and MeOH and H\textsubscript{2}O lattice molecules. Similarly to 1\(5\)MeOH, the Ni\(^{II}\) atoms in 2\(10\)H\textsubscript{2}O-26MeOH are stacked in four layers, which form an unprecedented quadruple-decker topology. In particular, the inner decks in 2\(10\)H\textsubscript{2}O-26MeOH are identical with the central deck of 1\(5\)MeOH; thus, figuratively speaking, an internal deck has been added to the Ni\textsubscript{12} cation of the latter to form a Ni\textsubscript{16} cluster (2\(10\)H\textsubscript{2}O-26MeOH). In addition, the external decks in 2\(10\)H\textsubscript{2}O-26MeOH are similar to the corresponding decks in 1\(5\)MeOH, with their only difference being the replacement of the chlorido ligands in the latter by terminal MeOH molecules in the former. The octahedral metal centres are Ni1, Ni2, Ni3 and Ni4 (and their symmetry equivalents) and the square planar ones are Ni5, Ni6, Ni7 and Ni8 (and their symmetry equivalents). The presence of many lattice molecules and counterions in the crystal structure of 2\(10\)H\textsubscript{2}O-26MeOH results in the formation of a network of strong intermolecular hydrogen bonding interactions. Details of these interactions are listed in Table S2 in the ESI. As it was the case for 1\(5\)MeOH, the cations of 2\(10\)H\textsubscript{2}O-26MeOH, are in close proximity with the shortest metal–metal separation between the adjacent Ni\textsubscript{16} units being 4.671 (2) \(\AA\) (Ni1–Ni7).

1\(5\)MeOH and 2\(10\)H\textsubscript{2}O-26MeOH are new additions in the small family of high nuclearity, high spin Ni compounds with multiple-decker metal topology.\(^{23,24}\) In particular, 2\(10\)H\textsubscript{2}O-26MeOH is the first structurally characterized complex of any metal displaying a quadruple-decker configuration. Compound 1\(5\)MeOH can be described as a “trimmer-of-tetramers”, while 2\(10\)H\textsubscript{2}O-26MeOH as a “tetrامر-of tetramers”, where the tetramer in both cases is the structural unit (Ni\textsubscript{16}(pyaox)(pyaoxH)\(^2\))\(^{4+}\), which has been previously observed in a discrete tetranuclear cluster.\(^{25,24}\) The number of the decks, and hence the nuclearity and spin, of 1\(5\)MeOH and 2\(10\)H\textsubscript{2}O-26MeOH is affected by the nature (charge, shape) of the inorganic anion that is present in the reaction system providing elements of synthetic control towards new high nuclearity Ni\(^{II}\) clusters. Both compounds contain the singly and doubly deprotonated pyridine-2-amidoxime ligand, with 2\(10\)H\textsubscript{2}O-26MeOH being 1) the highest nuclearity metal cluster bearing this ligand, 2) one of the few highest nuclearity hexadecanuclear metal clusters with any 2-pyridyl oxime, in general,\(^{31,26}\) 3) the highest nuclearity Ni\(^{II}\) cluster with 2-pyridyl oximes. Furthermore, complex 2\(10\)H\textsubscript{2}O-26MeOH joins only a very small family of Ni\textsubscript{16} clusters with O- or/N-ligation.\(^{40}\)

**Magnetic susceptibility studies**

In order to probe the magnetic properties of the clusters, direct current (dc) magnetic susceptibility measurements were performed on polycrystalline samples of compounds 1 and 2 in the temperature range 2–300 K, with an applied magnetic field of 0.1 T.
χ_MT versus $T$ plots is indicative of dominant ferromagnetic interactions between the paramagnetic ions within the cations of 1 and 2. The low temperature decrease of the χ_MT value is attributed to intermolecular antiferromagnetic interactions and/or zero-field splitting. The former is consistent with the crystal structure of the two compounds (vide supra).

In order to fit the χ_MT data for 1-5MeOH, we modeled the Ni_6 magnetic core with the 2J-model described in Fig. 4, left, (the octahedral Ni_6 atoms define two triangles related by an inversion center) employing the isotropic spin-Hamiltonian (1):

$$H = -2J_1(\hat{S}_1 \cdot \hat{S}_3 + \hat{S}_3 \cdot \hat{S}_4 + \hat{S}_4 \cdot \hat{S}_5 + \hat{S}_5 \cdot \hat{S}_6 + \hat{S}_6 \cdot \hat{S}_1) - 2J_2(\hat{S}_3 \cdot \hat{S}_4 + \hat{S}_4 \cdot \hat{S}_5 + \hat{S}_5 \cdot \hat{S}_6 + \hat{S}_6 \cdot \hat{S}_3 + \hat{S}_3 \cdot \hat{S}_1 + \hat{S}_1 \cdot \hat{S}_2 \cdot \hat{S}_2 \cdot \hat{S}_3 \cdot \hat{S}_4 \cdot \hat{S}_4 \cdot \hat{S}_5 \cdot \hat{S}_5 \cdot \hat{S}_6 \cdot \hat{S}_6 \cdot \hat{S}_1 + \sum_i \mu_B g_i \hat{S}_i \cdot \vec{H})$$

(1)

where $J_1$ is the isotropic exchange interaction parameter, $i$ is the index for each Ni^{II} ion in the Ni_6 core, $\mu_B$ is the Bohr magneton, $g_i = \mu_B / 2.10$, the g-factor of the Ni^{III} ions, $B$ is the applied magnetic field and $\hat{S}$ is a spin operator. The data was numerically fitted using the simplex algorithm, with intermolecular interactions being taken into account in the frame of mean-field theory, by use of the Curie-Weiss temperature, $\theta$. The fit affords the parameters $J_1 = +5.14$ cm$^{-1}$, $J_2 = +3.01$ cm$^{-1}$ and $\theta = -5.73$ K. This results in an $S = 6$ ground state with the nearest excited states being $S = 5$, lying 8.38 cm$^{-1}$ higher in energy, and $S = 4$, lying at 17.11 cm$^{-1}$. A plot of energy versus total spin state is given in Fig. S1, left, in the ESI. Similarly, the 2J-model described in Fig. 4, right, was used in order to fit the data for the Ni_6 magnetic core of 2-10H_2O-26MeOH using the isotropic spin-Hamiltonian (2):

$$H = -2J_1(\hat{S}_3 \cdot \hat{S}_3 + \hat{S}_3 \cdot \hat{S}_4 + \hat{S}_4 \cdot \hat{S}_5 + \hat{S}_5 \cdot \hat{S}_6 + \hat{S}_6 \cdot \hat{S}_3 + \hat{S}_3 \cdot \hat{S}_1 + \hat{S}_1 \cdot \hat{S}_2 \cdot \hat{S}_5 \cdot \hat{S}_5 \cdot \hat{S}_5 \cdot \hat{S}_6 \cdot \hat{S}_6 \cdot \hat{S}_1 + \sum_i \mu_B g_i \hat{S}_i \cdot \vec{H})$$

(2)

The fit afforded the parameters $J_1 = +5.45$ cm$^{-1}$, $J_2 = +2.00$ cm$^{-1}$ and $\theta = -3.43$ K. This results in an $S = 8$ ground state with the nearest excited states being $S = 7$ (3.95 cm$^{-1}$) and $S = 6$ (8.07 cm$^{-1}$) lying relatively close in energy, Fig. S1, right. We have also collected the alternating current (ac) magnetic susceptibility in zero applied dc field for both complexes, which revealed no frequency dependence (Fig. S2 in the ESI).

Fig. S3 in the ESI shows the dc-field magnetization data $M(H)$ collected in the range 0–7 T at three temperatures between 2.3 and 20 K for 1 and 2. In both cases, $M(H)$ initially rises quickly at the lowest temperatures, as expected for ferromagnetic exchange, and then keeps increasing slowly even at the highest applied fields, without reaching saturation. In accordance with the susceptibility data, this behaviour is attributed to intermolecular antiferromagnetic interactions, likely combined with some degree of magnetic anisotropy. For comparison, the calculated Brillouin curves were also plotted assuming uncorrelated molecules with $S = 6$ (1) and $S = 8$ (2) for the representative temperatures. For both compounds, it is observed that the experimental data tend to lie below the calculated curve, suggesting the influence either from antiferromagnetic intermolecular correlations or from low-lying excited spin states. The latter is more evident in 2 with respect to 1, as it is revealed from the larger deviation of the calculated curve and experimental data, which indicates that 2 does not display a well-defined ground state spin value. Keeping stable the values of $S$ and $g$, detectable improvements are obtained only by adding a uniaxial magnetic anisotropy term $D$ to values exceeding any physical meaning in the case of 1. Since this applies also at the lowest investigated temperatures, in which the influence of excited states should be negligible, we conclude, in agreement with the susceptibility data, that antiferromagnetic interactions between cations are important for the two complexes.

It has recently been reported that the dominant factor which affects the magnetic properties of the oximato Ni^{II} compounds is the length of the bridging N-O bond. In particular, DFT calculations on an oximato bridged Ni^{II} compound revealed that N-O distances larger than 1.394 Å result in ferromagnetic interactions, while shorter ones propagate antiferromagnetic interactions. This observation has been explained by considering that with the decrease of the N-O bond, the spin population on the N and O atoms increases, thus enhancing the antiferromagnetic coupling between Ni^{II} ions. In compounds 1-5MeOH and 2-10H_2O-26MeOH, the N-O distances are in the range of 1.401-1.425 Å, and thus the experimentally obtained ferromagnetic interactions are in excellent agreement with the previously reported theoretical calculations.

Specific heat measurements

Fig. 5 shows the collected specific heat $C(T,H)$ data of 1 as a function of temperature for several applied fields. No particular feature is detected except for a very broad anomaly around 2 K at zero applied field, whose magnetic nature is proven by the fact that it quickly moves towards higher temperatures as the field $H$ is increased. As typical for molecule-based materials, the contribution to the total $C$ arising from lattice vibrations dominates as $T$ increases above that of liquid helium.

Fig. 5 Specific heat $C$ for 1 normalised to the gas constant $R$ vs. $T$ in the
indicated temperature and field ranges. Inset: Magnetic contribution \( C_m \) as obtained by subtracting the lattice contribution (dashed line) to \( C \).

The lattice contribution can be described by the Debye model (dashed line in Fig. 5), which simplifies to \( C(R) = a \, R^3 \) dependence (\( R \) is the gas constant) at the lowest temperatures, where \( a = 3.9 \times 10^{-3} \, \text{K}^{-1} \). The magnetic contribution \( C_m \) (see inset in Fig. 5) is then obtained by subtracting the lattice contribution to the total \( C \). This analysis reveals a bump centered at \( k \approx 9 \, \text{K} \), that we associate with a Schottky-like anomaly, i.e., crystal-field splitting of the \( S = 6 \) multiplet. By decreasing the temperature, magnetic fluctuations within the 2D layers show up in the anomaly centered at \( k \approx 2 \, \text{K} \). To properly associate these features with the magnetic contribution, we estimate the zero-field magnetic entropy \( S_{\text{m}}(T) = \int C_m(T) \, dT \), shown in Fig. S4 in the ESI. This tends at high-\( T \) to the value of 2.8 \( R \), which is in fair agreement with the magnetic entropy expected, \( R \ln(2S+1) = 2.56 \, R \) (provided the spin value is \( S = 6 \)) and consistent with the magnetization data. Since the lattice contribution is sensibly larger than \( C_m \), the latter is affected by an important uncertainty. This inhibits us from providing anything other than a qualitative analysis of the experimental data.

Specific heat data have been also collected for 2 and these are shown in Fig. S5 in the ESI as a function of temperature for several applied magnetic fields. As it is the case for 1, the specific heat at high temperatures is dominated by a non-magnetic contribution, which is due to the thermal vibrations of the lattice. Furthermore, there is a clear magnetic contribution, which extends over a broad temperature range, i.e., from the lowest accessed \( T \) to well inside the range mainly determined by the lattice contribution to the specific heat. The fact that 2 does not display a well-defined ground state spin value (\( S = 8 \), vide supra) prevents to determine reliably the magnetic contribution by subtracting the lattice specific heat from the total measured signal, as in the case of the Ni12 complex. As a result, a valuable analysis of the specific heat data is not feasible for 2.

Conclusions

The employment of pyaoxH2 in Ni11 chemistry has provided access to the new multiple-decker Ni complexes \([\text{Ni}_{11}(\mathrm{pyaox})_4(\mathrm{pyaoxH})_2(\mathrm{MeOH})_2Cl_2]4\,\text{Cl}\,5\,\text{MeOH}\) (1·5MeOH) and \([\text{Ni}_{11}(\mathrm{pyaox})(\mathrm{pyaoxH})_3(\mathrm{MeOH})_2][\mathrm{SO}_4]_{2+}\,\text{H}_2O\,26\,\text{MeOH}\) (2·10H2O·26MeOH) comprising stacked Ni8 layers, \([\text{Ni}_{11}(\mathrm{pyaox})(\mathrm{pyaoxH})_3]^{24}\,\text{H}_2\,\text{O}\,\text{H}_2\,\text{O}\) (\( x = 3 \), 1·5MeOH; \( x = 4 \), 2·10H2O·26MeOH), with each layer containing two square planar and two octahedral Ni8 centres.

Compound 1·5MeOH is a new addition to the small family of Ni8 clusters with a triple-decker topology.\(^{23,24}\) Compound 2·10H2O·26MeOH displays a quadruple-decker configuration, which has never been observed before in metal cluster chemistry. In addition, 2·10H2O·26MeOH is the highest nuclearity metal cluster bearing pyaoxH2 and joins only a very small family of Ni16 clusters with O- or/and N-ligation. It also belongs to the very small family of the hexadecanuclear homometallic or/and heterometallic clusters, which display the highest nuclearity that has been observed so far for compounds containing 2-pyridyl oximes, being the only Ni11 cluster in this category.\(^{17,25}\)

Dc and ac magnetic susceptibility and heat capacity measurements were performed on 1 and 2, which revealed that both display ferromagnetic exchange interactions resulting in a spin ground state of \( S = 6 \) for 1 and \( S = 8 \) for 2. Interactionic interactions, as revealed by single crystal X-ray crystallography, affect the magnetic properties preventing an in-depth analysis of the heat capacity measurements.

The number of decks in 1 and 2 is affected by the use of different inorganic anions with the bulkier and of higher charge anion (SO42- vs. Cl-) being able to stabilize the higher nuclearity cluster. This could lead to the development of a rational method towards the increase of the nuclearity and the spin of ferromagnetic species. Based on this, we believe that we have seen just the tip of the iceberg in the Ni11/pyaoxH2 compounds with multiple decker topology. We have every reason to believe that higher nuclearity such species (e.g., Ni12o, Ni14, ... ) are waiting to be discovered. Further studies towards this direction are currently in progress including the employment of higher charge counterions (e.g., PO43-). These studies will be reported in due course.

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Notes and references

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