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# The intricate determination of magnetic anisotropy in quasi-octahedral vanadium(III): a HF-EPR and magnetic study

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## ABSTRACT

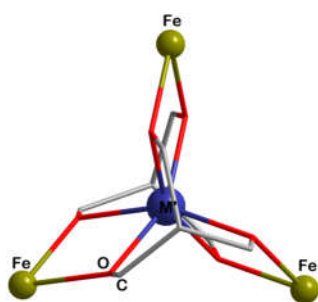
We report here the synthesis and a preliminary characterization of a the tetranuclear complex of formula  $[\text{Ga}_3\text{V}(\text{L}^{\text{Et}})_2(\text{dpm})_6]$ , (**Ga<sub>3</sub>VEt**), in which  $\text{H}_3\text{L}^{\text{Et}}$  = 2-Ethyl-2-(hydroxymethyl)-propane-1,3-diol and Hdpm = dipivaloylmethane, containing a single paramagnetic vanadium(III) center, from a structural, magnetic and spectroscopic point of view. Structural characterization by X-ray diffraction evidenced that this derivative is isostructural with the star-shaped Single Molecule Magnet  $\text{Fe}_3\text{V}(\text{L}^{\text{Et}})_2(\text{dpm})_6$ , **Fe<sub>3</sub>VEt**, and can thus be considered a model to analyze the magnetic anisotropy of vanadium(III) ion in that system. The observed results confirm the complexity in obtaining a rationalization of the magnetic behaviour of this metal ion, with magnetization data and High Field Electron Paramagnetic Resonance (HF-EPR) spectroscopy providing apparently conflicting results. Indeed, the former were rationalized assuming a rhombic distortion of the ligand field and a dominant easy-axis type anisotropy (equivalent to  $D \approx -14.1 \text{ cm}^{-1}$ ,  $E \approx 1.2 \text{ cm}^{-1}$ ), while a simple axial Spin Hamiltonian approach could explain HF-EPR data ( $|D| \approx 6.98 \text{ cm}^{-1}$ ).

## KEYWORDS

Electron Paramagnetic Resonance; Spin Hamiltonian; Single Molecule Magnets; Star-shaped clusters; Vanadium(III); Zero Field Splitting; Magnetic anisotropy

## 1. INTRODUCTION

The discovery in the early 90s of Single-Molecule Magnet (SMM) behavior, i.e., magnetic bistability at the molecular level in polynuclear transition metal complexes,[1] sparked intense research in the field of molecular magnetism, aiming at the possible use of these systems as magnetic memory units.[2] The cause of the slow relaxation of the magnetization in these systems was soon attributed to the existence of an anisotropy barrier that amounts to the total energy spanned by the ground spin state,  $S$ , of the systems.[3] For a system with an integer spin state and an easy axis of magnetization, this is equal to  $|D|S^2$ , where  $D$  is the parameter describing the zero-field splitting (i.e. magnetic anisotropy) of the  $S$  multiplet ( $D < 0$ ). When thermal energy is much lower than the height of the barrier, a system previously magnetized will retain its magnetization; on the contrary, on increasing temperature, thermal energy becomes large enough to allow fast relaxation of the magnetization, leading to a loss of the information stored in it. This prompted many groups to find ways to improve the magnetic anisotropy barrier rationally.[4,5] This is, however, by no means a simple task: in polynuclear clusters, it requires careful engineering of the anisotropic features of the constituent ions, the relative orientation of their magnetic anisotropy axis, and the exchange coupling among the centers.[6] In this context, one of the most accurately studied families is that of tetranuclear star-shaped complexes generally referred to as  $\text{Fe}_3\text{M}'$  ( $\text{M}' = \text{Fe}, \text{Cr}, \text{V}$ , see Scheme 1),[7–10] which also proved very successful in nanostructuration processes. [11–13]



**Scheme 1** General structure of star-shaped  $\text{Fe}_3\text{M}'$  SMMs, depicting the tripodal alkoxide ligands above and below the plane defined by the metal ions. The wireframe colors are grey for carbon and red for oxygen atoms. The alkyl or aryl group bound to the bridgehead carbon in each chelating alkoxide (Et, Me, Ph,  $\text{Bu}^t$  in different literature reports) is not shown.

For this family, some of us showed in the past that changing the central metal  $M'$  allows playing with both factors affecting the magnetic anisotropy barrier height. By changing  $M'$  from iron(III) to chromium(III) and vanadium(III), the global spin state increased from  $S=5$  to  $S=6$  to  $S=13/2$ . [8,9] At the same time, this modification affected the anisotropy parameter  $D$ , as a consequence of both the different single-ion contribution of the central site and the different ratio between single ion and global spin states. While the anisotropy in  $\text{Fe}_3\text{Cr}$  and  $\text{Fe}_3\text{Fe}$  could be rationalized entirely on the basis of single-ion and dipolar anisotropy as derived by the study of iron(III)- and chromium(III)-doped isostructural  $\text{Ga}_4$  diamagnetic clusters, [8] the situation remained unclear for  $\text{Fe}_3\text{V}$ . At that time,  $\text{Ga}_3\text{V}$  was not available, and we resorted to simple Ligand Field arguments to obtain a rough estimate of the single-ion anisotropy of vanadium(III), which is an orbitally degenerate ion in octahedral symmetry ( ${}^3T_{1g}$ ). As deeply discussed in a series of paper by the late Tregenna-Piggott, trigonal distortion may provide either an orbitally non-degenerate ground state, with hard-axis anisotropy, or an orbitally degenerate ground state, whose anisotropic properties cannot be directly mapped onto a Spin Hamiltonian in the absence of further rhombic distortions. [14–16] This complicates the analysis of the origin of the anisotropy in exchange coupled systems containing vanadium(III), [17] and in the case of  $\text{Fe}_3\text{V}$  a non-negligible contribution of anisotropic exchange was postulated. [9] The isostructural  $\text{Ga}_3\text{V}$  derivative has now been obtained, and we report here some preliminary results concerning its structural, High Field Electron Paramagnetic Resonance (HF-EPR), and magnetic properties, which evidence the complexity of the rationalization of this metal ion and suggest that our previous estimate might be wrong.

## 2. MATERIALS AND METHODS

### 2.1 General

Syntheses were carried out under  $\text{N}_2$  (99.999 %, Praxair) with the use of Schlenk and glove-box techniques. Solvents (Aldrich and Vetec) were dried by standard procedures [18] and distilled under  $\text{N}_2$  before use. Anhydrous vanadium(III) chloride, anhydrous gallium(III) chloride, dipivaloylmethane (Hdpm), and n-butyllithium (2.5 mol  $\text{L}^{-1}$  solution in hexanes) were purchased from Aldrich and used without additional purification. 2-Ethyl-2-(hydroxymethyl)-propane-1,3-diol ( $\text{H}_3\text{L}^{\text{Et}}$ , Aldrich) was recrystallized from a 3:1 toluene/tetrahydrofuran (thf) with nearly quantitative yield, as described previously [19].  $[\text{VCl}_3(\text{thf})_3]$  [20] and  $[\text{Ga}_2(\text{OMe})_2(\text{dpm})_4]$  [8] were prepared by published methods.

Elemental analyses were carried out by Medac Laboratories Ltd (Chobham, Surrey, UK). The equipment employed was a Thermal Scientific Flash EA 1112 Series Elemental Analyser (C and H contents) and a Varian Vista MPX ICP-OES spectrometer for Gallium and Vanadium contents. Infrared spectroscopy data presented as Supplementary Material (400–4000  $\text{cm}^{-1}$ , Figure S1) were recorded from KBr pellets on BIORAD FTS3500GX equipment with a spectral resolution of 2  $\text{cm}^{-1}$ .

## 2.2 Synthesis of $[\text{Ga}_3\text{V}(\text{L}^{\text{Et}})_2(\text{dpm})_6]$ ( $\text{Ga}_3\text{VET}$ )

The preparation was carried out by the procedure previously employed for  $\text{Fe}_3\text{CrEt}$ [19] and  $\text{Fe}_3\text{VET}$ [9]. A solution of  $\text{H}_3\text{L}^{\text{Et}}$  (230 mg, 1.51 mmol) in cold thf (30 mL, 0 °C) received the dropwise addition of n-butyllithium (4.50 mmol). The resulting white suspension was kept stirring at 0 °C for 5 h and was then filtered to give a quantitative yield of the tripodal lithium alkoxide  $\text{Li}_3\text{L}^{\text{Et}}$ . The white solid was dried under vacuum and immediately used as follows. Solid  $[\text{VCl}_3(\text{thf})_3]$  (280 mg, 0.749 mmol) was slowly extracted for 48 h into a boiling suspension of  $\text{Li}_3\text{L}^{\text{Et}}$  (221 mg, 1.45 mmol) in 1,2-dimethoxyethane (glyme, 120 mL). This produced a light-brown suspension that was added at room temperature to a white suspension of  $[\text{Ga}_2(\text{OMe})_2(\text{dpm})_4]$  (1.04 g, 1.11 mmol) in glyme (50 mL). The resulting mixture was heated under reflux for 5 h, cooled down to room temperature and then filtered, producing a greenish-brown solid mixed with a white contaminant (possibly LiCl and LiOMe). This solid was extracted with thf, and the light yellow extract was submitted to vapor diffusion of glyme over four weeks. From the crystallization chamber, brownish-green crystals ( $\text{Ga}_3\text{VET-1}$ ) were isolated by filtration and dried under vacuum. Total yield 0.23 g (ca. 19%). Elemental analysis contents calculated (%) for  $\text{C}_{78}\text{H}_{136}\text{O}_{18}\text{VGa}_3$ : C 57.76, H 8.45, Ga 12.90, V 3.14; found (%) for  $\text{Ga}_3\text{VET-1}$ : C 57.45, H 8.39, Ga 12.92, V 2.95.  $\text{Ga}_3\text{V}/\text{Ga}_4$  ratio (% m/m): 95.2/4.8.

An analogous procedure with the reaction time of 72 h in the extraction step gave crystals labeled as  $\text{Ga}_3\text{VET-2}$ , and an increase in total yield: 0.34 g (ca. 28%). Elemental analysis found (%) for  $\text{Ga}_3\text{VET-2}$ : C 57.48, H 8.49, Ga 13.09, V 2.92.  $\text{Ga}_3\text{V}:\text{Ga}_4$  ratio (% m/m): 93.5 : 6.5.

Samples of  $\text{Ga}_3\text{VET}$  can be handled in air in the solid state for several days without detectable change. Their structural, spectroscopic and magnetic characterization was performed in air.

## 2.3 Crystal structure analysis of $\text{Ga}_3\text{VET}$

*Crystal data:* C<sub>78</sub>H<sub>136</sub>Ga<sub>3</sub>O<sub>18</sub>V, M = 1621.96. Trigonal, space group *R*-3*c*:*h* (no. 167:h), *a* = *b* = 16.4261(4), *c* = 57.838(2) Å,  $\alpha = \beta = 90^\circ$ ,  $\gamma = 120^\circ$ , *V* = 13514.9(9) Å<sup>3</sup>. *Z* = 6, *D*<sub>calc</sub> = 1.196 g cm<sup>-3</sup>, *F*(000) = 5184, *T* = 273(2) K,  $\lambda(\text{Mo-K}\alpha) = 0.71073$  Å.

Crystals are greenish-brown rhombohedra. From a sample under oil, one, *ca* 0.46 x 0.40 x 0.23 mm, was mounted on a Micro-mount and fixed in the cool nitrogen stream on a Bruker D8 Venture diffractometer equipped with a Photon 100 CMOS detector, Mo-K $\alpha$  radiation, and graphite monochromator. Intensity data were measured at 273(2) K by thin-slice  $\omega$ - and  $\phi$ -scans. The total number of reflections recorded, to  $\theta_{\text{max}} = 25^\circ$ , was 146490 of which 2651 were unique [*R*(int) = 0.056]; 2186 were 'observed' with *I* > 2 $\sigma$ <sub>*i*</sub>.

Data were processed using the Bruker APEX2 software.[21] The structure was determined by direct methods in the SHELXS program[22] and refined by full-matrix least-squares methods, on *F*<sup>2</sup>'s, in SHELXL.[23] Scattering factors for neutral atoms were taken from the literature.[24] All computer programs used in these analyses were run through WinGX [25,26] at the Universidade Federal do Paraná and the University of East Anglia. Crystal data, data collection, and general structure refinement data are presented in Table S1.

#### **2.4 Notes on the structure**

Figure S2 presents the first coordination sphere of the central (vanadium) ion, while Figures S3 and S4 show different views of the tetranuclear structure, with the atom numbering scheme. The asymmetric unit of [V{(OCH<sub>2</sub>)<sub>3</sub>C*Et*}<sub>2</sub>{Ga(dpm)<sub>2</sub>}<sub>3</sub>] (Figure S5) contains two different metal centers in special positions: a Ga<sup>III</sup> ion that lies on a two-fold axis and a V<sup>III</sup> ion lying on several symmetry elements: one three-fold axis (parallel to *c*), three two-fold axes (one parallel to *b*, the second one parallel to *a*, and the third bisecting the angle between the first two), and three glide planes. The asymmetric unit (Figure S5) also contains a complete  $\beta$ -diketonate (dpm<sup>-</sup>) ligand coordinated to Ga<sup>III</sup>, and one-third of a tripodal alkoxide ligand (including one of the disordered orientations of its ethyl group) bridging the vanadium and gallium ions through the O3 donor atom.

A high degree of disorder affects the *tert*-butyl groups of the  $\beta$ -diketonate ligands. In the asymmetric unit, the disorder involving the carbon atoms attached to C4 (C1 to C3) was modeled with two orientations and occupancy factors of 0.56 and 0.44. In the minor component, the C100, C200, and C300 atoms were refined isotropically; these were the only non-hydrogen atoms refined in this way.

Disorder was also evident for C15 in the ethyl group of the tripodal alkoxide; this atom was refined with an occupancy factor of 0.33 as a consequence of the three-fold symmetry axis passing through C14 and C13. The distance restraint DFIX was applied to all disordered atoms mentioned above: C1, C2, C3, C15, C100, C200, and C300. All B alerts in the CheckCIF file refer to these disordered portions of the asymmetric unit.

Hydrogen atoms were included in idealized positions and were refined isotropically; their  $U_{iso}$  values were set to ride on the  $U_{eq}$  values of the parent carbon atoms.

No hydrogen bond or other intra/intermolecular interaction of considerable strength was found in the structure.

Replacement of the central vanadium atom by gallium was investigated, but no improvement was seen; the best refinement was reached with a **Ga<sub>3</sub>V** system.

## **2.5 Magnetic characterization**

The magnetization of the sample was measured by using a MPMS SQUID magnetometer (Quantum Design, Inc.). Microcrystalline powders were pressed in a pellet to avoid preferential orientation of the crystallites due to magnetic torque. Raw data were corrected for the sample holder contribution, measured in the same field and temperature range, and for the intrinsic diamagnetism of the sample, estimated using Pascal's constants.[27] Fits and simulations of magnetic data were obtained by using PHI.[28]

## **2.6 High Field Electron Paramagnetic Resonance (HF-EPR)**

HF-EPR measurements were performed on a home-built multi-frequency spectrometer operating in a double-pass configuration. A 110 GHz frequency source (Virginia Diodes Inc.) alone or with multipliers up to the 3<sup>rd</sup> harmonic), as well as 95 GHz and 115 GHz Gunn oscillators (Radiometer Physics GmbH) together with multipliers up to the 4<sup>th</sup> harmonic were used. The main magnetic field was supplied by a 16 T superconducting magnet associated with a Variable Temperature Insert (Cryogenic). A hot electron InSb bolometer (QMC Instruments) was used to measure the light transmitted through the sample. The spectrometer is designed to operate in the perpendicular mode, which means that the oscillating microwave field  $B_{mw}$  is perpendicular to the static  $B_{dc}$  and the selection rule for the transition is thus  $\Delta M_S = \pm 1$ . The measurements were done on the microcrystalline powder sample pressed into a pellet in order to limit torqueing effects (actually, the same pellet of ca. 12 mg which was used for SQUID measurements), in the 190-460 GHz

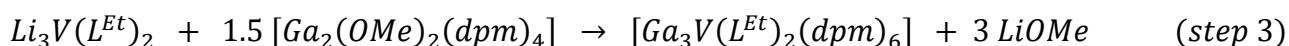
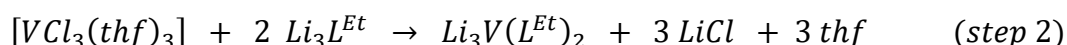
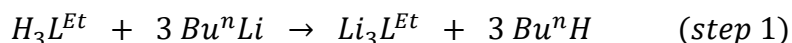
frequency range at 5 and 15 K. Spectral simulation and analysis were performed by using EasySpin.[29]

### 3. RESULTS

#### 3.1 Synthesis and structure

Previous works described several propeller-like complexes with the general formula  $[M_4(L^R)_2(dk)_6]$ , in which Hdk is a  $\beta$ -diketone and  $H_3L^R$  is a tripodal alcohol, containing different alkyl or aryl (R) groups in the tripodal ligand.[8,10,19,30] Synthetically speaking, the nature of the R group influences the solubility of the intermediate species in the three-step procedure (see below), and of the final complex, modifying the reaction yield. The choice of ethyl as the R group in the tripodal alkoxide was made in this case to allow comparison with the heterometallic  $M_3M'$  species available in the literature, and in particular with  $Fe_3V$ .

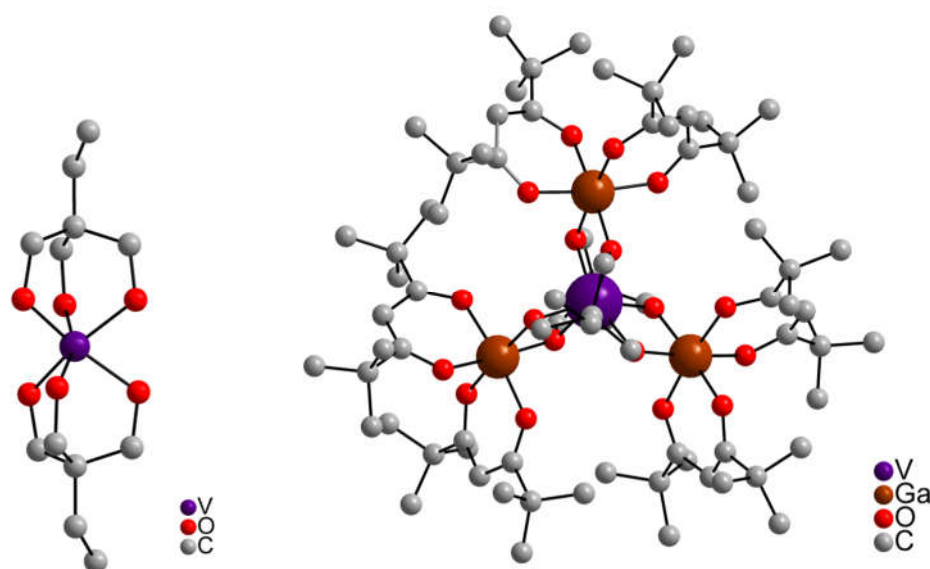
The complex  $[Ga_3V(L^{Et})_2(dpm)_6]$  ( $Ga_3V^{Et}$ ), in which  $H_3L^{Et} = 2$ -ethyl-2-(hydroxymethyl)-propane-1,3-diol and Hdpm = dipivaloylmethane, was prepared by the three-step route developed earlier for the isostructural  $Fe_3M'Et$  compounds in which  $M' = Cr^{III}$  and  $V^{III}$ : [9,19]



In agreement with our previous findings[9], step 2 was confirmed to be crucial to the success of the synthesis and isolation of a chemically pure heterometallic  $M_3M'$  species. This step leads to the formation of the central portion ("core", formulated as  $V(L^{Et})_2^{3-}$ , Figure 1 left) of the star-shaped compound, around which the propeller "blades",  $Ga(dpm)_2^+$ , assemble themselves in the last reaction step. We found that, for each tetra(hetero)nuclear compound, different reaction conditions had to be adjusted to maximize the global reaction yield, depending on the chemical nature of the central ion. As far as the preparation of  $Ga_3V^{Et}$  is concerned, longer and slower extraction of the vanadium(III) starting material into the boiling lithium alkoxide suspension in step 2 gives the best yields of the product, as described in the Experimental section.



The addition of the gallium(III) dimer  $[\text{Ga}_2(\text{OMe})_2(\text{dpm})_4]$  to the suspension of the “core” in dimethoxyethane (step 3), followed by heating under reflux, gives a greenish-(light)brown solution from which microcrystals of **Ga<sub>3</sub>VEt** and a white powder, probably a mixture of LiCl and LiOMe, are isolated by filtration. This impure product is then recrystallized by vapor diffusion of dimethoxyethane into a thf solution, producing beautiful greenish-(light)brown rhombohedra.



**Figure 1.** Left: Representation[31] of the  $\text{V}(\text{L}^{\text{Et}})_2^{3-}$  “core” in **Ga<sub>3</sub>VEt**. Only one of the three equivalent, disordered orientations of the ethyl group about the three-fold symmetry axis is shown. Right: General view[31] of the  $[\text{Ga}_3\text{V}(\text{L}^{\text{Et}})_2(\text{dpm})_2]$  (**Ga<sub>3</sub>VEt**) molecular structure down the three-fold symmetry axis. The disordered orientations of the ethyl group in the tripodal alkoxides and of the *tert*-butyl groups on the  $\beta$ -diketonate ( $\text{dpm}^-$ ) ligands were omitted for clarity. ORTEP-3[26] diagrams, with the atom numbering scheme, are presented in Figures S3 and S4.

Despite the well-formed appearance of the crystals, they produce weak X-ray diffraction patterns, even at low temperature, because of static and dynamic disorder in the ethyl group of the tripodal alkoxides and in the *tert*-butyl groups of the  $\beta$ -diketonate ( $\text{dpm}^-$ ) ligands. This disorder is common to several members of the star-shaped  $\text{M}_4$  family reported to date,[8,30,32] and, in the case of **Ga<sub>3</sub>VEt**, it hampered the obtainment of an accurate X-ray structural description of the molecule. After many attempts involving distinct synthesis and recrystallization conditions, we have been able to confirm that the tetranuclear molecules found in the crystals of **Ga<sub>3</sub>VEt** (Figures 1 right, S3 and S4) are isostructural, as expected, with the ‘star’ structures reported for **Fe<sub>3</sub>CrEt**[19] and **Fe<sub>3</sub>VEt**[9] in the same trigonal space group  $R\text{-}3c:h$ , and that the bond distances and angles in all three complexes are similar (Tables 1, S1-S3). The lower quality of the X-ray diffraction for **Ga<sub>3</sub>VEt**

compared to **Fe<sub>3</sub>CrEt**[19] and **Fe<sub>3</sub>VEt**[9] provides a higher uncertainty in the geometrical parameters. However, it allows us to establish the shape and symmetry of the molecule.

Further evidence in favor of the composition of the crystalline product came from elemental analysis (see Experimental) and spectroscopic data, as described below and in the Supplementary Material. Metal analysis results indicate *ca.* 95% chemically pure samples as far as the **Ga<sub>3</sub>V** formulation is concerned. This is particularly relevant considering that the modular synthesis described in steps 1-3 competes with the self-assembly of homometallic species (in this case, **Ga<sub>4</sub>Et**), as discussed earlier.[8,9,19] This success in the desired synthesis of the heterometallic **Ga<sub>3</sub>V** entity probably relates both to the chelate effect stabilizing the vanadium “core” assembled in step 2, and the similar labilities of vanadium(III) and gallium(III) towards ligand substitution reactions;[33–37] as a consequence, none of the homometallic Ga<sub>4</sub> or V<sub>4</sub> structures is particularly favored when compared to the heterometallic species. The loss of vanadium(III) from the “core” to give *ca.* 5% **Ga<sub>4</sub>** (see elemental analysis results) could come from the lower affinity of the softer V<sup>III</sup> ion (as compared to Ga<sup>III</sup>) towards the hard oxygen-donor atoms of the tripodal alkoxide[38,39].

Figures 1 right, S3, and S4 confirm the star-shaped, propeller-like molecular structure of a new component of the [M<sub>3</sub>M'(L<sup>Et</sup>)<sub>2</sub>(dpm)<sub>6</sub>] series. In addition, data presented in Tables 1, S2 and S3 give evidence in favor of the desired M = Ga<sup>III</sup> and M' = V<sup>III</sup> identities for the peripheral and central metal ions respectively, and reasserts that the synthetic route summarized in steps 1-3 is an efficient pathway to pure heterometallic M<sub>3</sub>M' species.

**Table 1.** Selected structural data for propeller-like complexes.<sup>(a)</sup> Temperatures of data collection are given in parentheses

Average bond lengths and non-bonding distances (Å)	Fe <sub>3</sub> M'Et (293K) (M' = V, Fe) [9]	Fe <sub>3</sub> CrEt (293K) [19]	Ga <sub>3</sub> VEt (273 K)
M <sub>central</sub> –O <sub>tripodal</sub>	1.977(2)	1.949(3)	1.999(8)
M <sub>peripheral</sub> –O <sub>tripodal</sub>	1.963(2)	1.963(3)	1.922(7)
M <sub>peripheral</sub> –O <sub>diketonate</sub> (average)	1.993(2)	1.991(4)	1.974(9)
M <sub>central</sub> ···C <sub>central</sub> <sup>(b)</sup>	3.029	2.986	3.004
M <sub>central</sub> ···M <sub>peripheral</sub>	3.075	3.023	3.036
M <sub>peripheral</sub> ···M <sub>peripheral</sub>	5.326	5.237	5.258
<b>Effective ionic radius (central ion) / Å</b> [40,41]	0.640 / 0.645 <sup>(c)</sup>	0.615	0.640
<b>Effective ionic radius (peripheral ion) / Å</b>	0.645	0.645	0.620
<b>Helical pitch angle<sup>(d)</sup> / °</b>	69.8	63.4	66.0
<b>Bond precision C–C<sup>(e)</sup> / Å</b>	0.0091	0.0117	0.0248

(a) Bond angles for the three complexes are compiled in Table S2, while Table S3 presents the complete listing of bond distances and angles for **Ga<sub>3</sub>VEt**.

(b) C<sub>central</sub> = Central (bridgehead) carbon atom in the tripodal alkoxide ligand, [RC(CH<sub>2</sub>O)<sub>3</sub>]<sup>3-</sup>.

(c) For V<sup>III</sup> and high-spin Fe<sup>III</sup> respectively. Crystals contained **Fe<sub>3</sub>VEt** and **Fe<sub>4</sub>Et** in 46:54 wt% proportion.[9]

(d) Dihedral angle between the planes defined by the M<sub>central</sub>(O)<sub>2</sub>M<sub>peripheral</sub> units and the four metal ions.

(e) From CheckCIF (<https://checkcif.iucr.org/>).

In Table 1 (last column) all M<sub>central</sub> and M<sub>peripheral</sub> bond distances to the O-donor atoms of the tripodal alkoxide and β-diketonate ligands support a larger ion (V<sup>III</sup>; effective atomic radius 0.640 Å) at the center of the molecular “core”, and a smaller cation (Ga<sup>III</sup>, effective atomic radius 0.620 Å) in the peripheral positions. This size ordering is the inverse of that observed for the Cr<sup>III</sup>/Fe<sup>III</sup> pairs in **Fe<sub>3</sub>CrEt**, [19] which is also in agreement with the ionic radii magnitudes. During structure refinement, attempts to replace the central vanadium(III) ion in **Ga<sub>3</sub>VEt** with gallium(III) to check for the possible formation of **Ga<sub>4</sub>Et** led to higher R-factors and significant change (increase or decrease) in the anisotropic thermal parameters, indicating the worsening of the structural model. This result supports the presence of vanadium in the molecular “core”.

Taking the small difference in temperature of data collection into consideration, data in Tables 1 and S2, together with unit cell volumes [13730.5(8) Å<sup>3</sup> for **Fe<sub>3</sub>CrEt**; 13740.4(5) Å<sup>3</sup> for **Fe<sub>3</sub>VEt** [9,19] and 13514.9(9) Å<sup>3</sup> for **Ga<sub>3</sub>VEt**], indicate no large differences in the molecular shape or global size on changing the nature of the central/peripheral metal ions across the fourth period of the periodic classification. These changes are well known to be crucial, however, for the easy- or hard-axis nature of the magnetic anisotropy in the entire molecular assembly, as well as to the height of the magnetization reversal barrier.[8,30] .

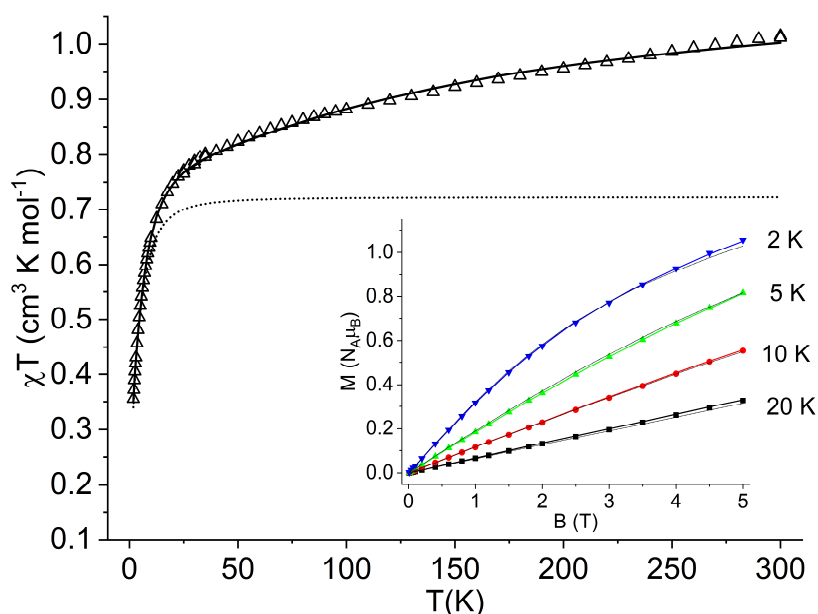
An interesting observation can be made at a more localized level: all bond angles involving the peripheral ions are significantly closer to the octahedral values in **Ga<sub>3</sub>VEt** than in **Fe<sub>3</sub>CrEt** or **Fe<sub>3</sub>VEt** (Table S2), leading to a more regular geometry for the peripheral units. This distinguishes **Ga<sub>3</sub>VEt** from the other two systems in which iron(III) ions are bound to the diketonate ligands. Additionally, the observation of the bond angles about the central atom in Table S2 shows an interesting similarity between the two ‘V-centered stars’, lending further support to the **Ga<sub>3</sub>VEt** formulation. Because of the constraints imposed by the several chelate rings, the O3–V<sub>central</sub>–O3 angles depart significantly from the octahedral figures (values of 76.7(4), 91.0(3), 104.8(5) and 160(4)<sup>o</sup> for **Ga<sub>3</sub>VEt**, Tables S2 and S3), resulting in the trigonally-distorted coordination sphere illustrated in Figure S2. The helical pitch angle, defined as the dihedral angle between the M<sub>4</sub> and the M<sub>central</sub>(O)<sub>2</sub>M<sub>peripheral</sub> planes, is larger in **Ga<sub>3</sub>VEt** than in **Fe<sub>3</sub>CrEt**; this is consistent with “propeller blades” that are more

tilted relative to the  $C_3$  axis, and a greater extent of structural distortion involving the central ion.[30] The pitch angles shown in Table 1 fit the trend to increasing values on going from Cr- to V- and then to Fe-centered stars,  $[M_3M'(L^R)_2(dpm)_6]$ , a trend that has been correlated with increasing axial zero-field splitting parameters  $|D|$  in this family of tetranuclear complexes.[19,30,42]

In the unit cell, the triangular molecules are arranged in pairs whose components are related by an inversion center (Figure S6). As a consequence of the high crystal symmetry, although each tetranuclear molecule is chiral ( $\Lambda$  or  $\Delta$  enantiomeric forms), the crystals themselves are non-chiral.[43,44] Additionally, each central  $V^{III}$  ion of the pair of molecules sits on four crystallographic proper rotation axes, one 3-fold (main) and three 2-fold (perpendicular to and related by the 3-fold symmetry axis) that, in turn, bisect the propeller blades. Symmetry requirements determine the 3-fold positional disorder of the ethyl groups in the tripodal ligands, and the resulting (disordered) arrangement has higher symmetry than the isolated molecules themselves.

### 3.2 Magnetic properties

The temperature dependence of the magnetic susceptibility of **Ga<sub>3</sub>VEt** is reported in the form of  $\chi T$  vs. T plot in Figure 2.



**Figure 2** Temperature dependence of  $\chi T$  and field dependence of M (inset plot) of **Ga<sub>3</sub>VEt** and best fits[28] obtained by using Ligand Field Hamiltonian (2) with parameters reported in the text

(continuous line). Dashed lines represent best fit[28] obtained by using Spin Hamiltonian (1) with parameters reported in the text.

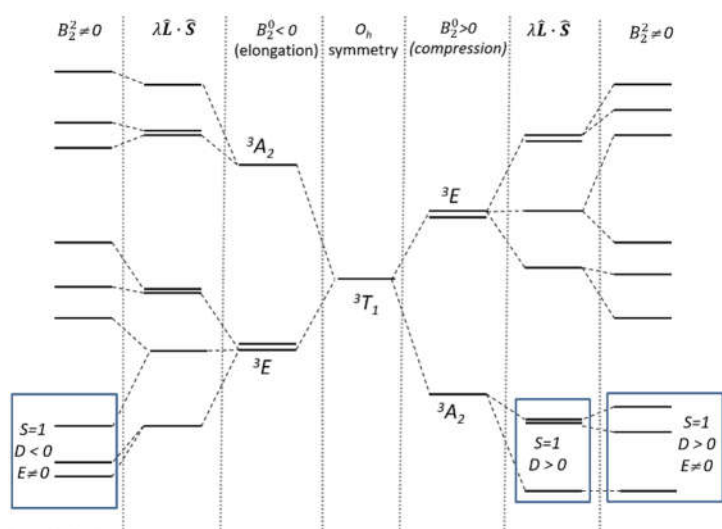
At room temperature, the observed  $\chi T$  value is  $1.04 \text{ cm}^3 \text{ K mol}^{-1}$ , in agreement with the expected value for  $S=1$  with  $g$  close to 2. However, on cooling the  $\chi T$  vs.  $T$  product steadily decreases to reach  $0.8 \text{ cm}^3 \text{ K mol}^{-1}$  at 40 K. Below this temperature, the  $\chi T$  value drops to  $0.35 \text{ cm}^3 \text{ K mol}^{-1}$  at 2 K. It is evident that such behavior cannot be rationalized on the basis of a simple  $S=1$  Spin Hamiltonian:

$$\hat{H} = g\beta\hat{\mathbf{S}} \cdot \vec{B} + D\hat{S}_z^2 + E(\hat{S}_x^2 - \hat{S}_y^2) \quad (1)$$

Indeed, this model is unable to reproduce the linear increase of  $\chi T$  in the high-temperature range. This behaviour is indicative of a partially quenched orbital contribution to the magnetic moment of **Ga<sub>3</sub>VEt** which, together with spin-orbit coupling (SOC) results in close-lying excited states. The latter are effective in inducing a sizeable temperature independent paramagnetism (TIP) contribution and thus a linear behaviour of  $\chi T$ . [45] On the contrary, the experimental data can be rationalized by considering a non-negligible. Indeed, in pure octahedral symmetry, vanadium(III) is a  ${}^3T_{1g}$  state (having two electrons in the  $t_{2g}$  d orbital set); this can be split by the combined action of SOC and geometrical distortion of the ligand field from purely octahedral symmetry. This can be described using the following Hamiltonian:

$$\hat{H} = \sigma\lambda\hat{\mathbf{L}} \cdot \hat{\mathbf{S}} + \sigma^2 B_2^0 (3\hat{L}_z^2 - \hat{L}^2) + \sigma^2 B_2^2 (\hat{L}_x^2 - \hat{L}_y^2) + \mu_B (\sigma\hat{\mathbf{L}} + g_e\hat{\mathbf{S}}) \cdot \vec{B} \quad (2)$$

where  $\sigma$  is the combined orbital reduction factor and  $\lambda$  is the SOC constant, while  $B_2^0$  and  $B_2^2$  are the axial and rhombic distortion parameters of the ligand field. As largely discussed in the literature [15,46] and anticipated in the Introduction, when  $B_2^0$  is positive, the  $T_{1g}$  orbital state is split in such a way that a singlet orbital ground state is lying lowest, and the ensuing SOC provides an essentially isolated Zero-field-split triplet state (see Figure 3). The situation is different when  $B_2^0$  is negative, since this provides an  $E$  orbital ground state; while this cannot be mapped on a Spin Hamiltonian, it can be further split by rhombic distortion, providing two orbital singlet states, close in energy, each of them with rhombic anisotropy. It is evident, however, that the rhombic distortion is only possible in cases where the point symmetry of the vanadium(III) ion is lower than axial.



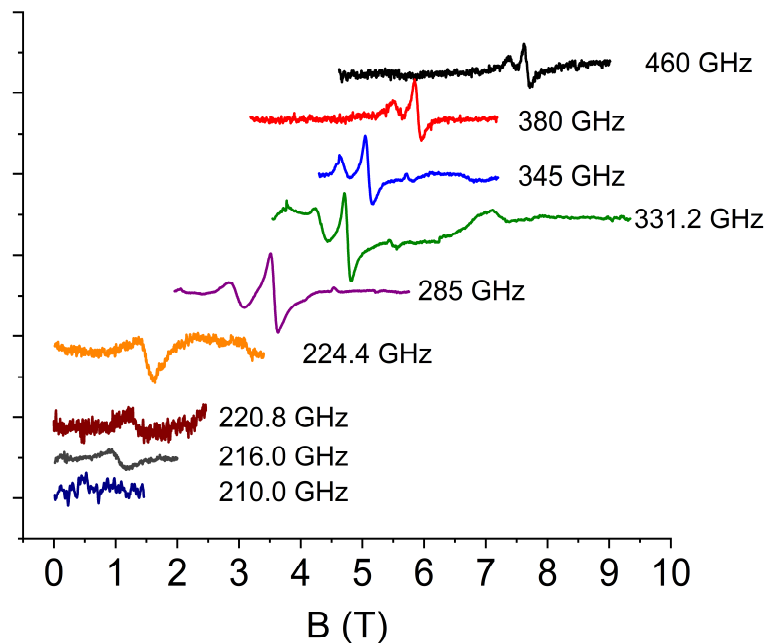
**Figure 3** Scheme of the energy pattern expected for vanadium(III) in distorted octahedral symmetry after application of different perturbations of Hamiltonian (2). Adapted from ref. [9]

Magnetic data, including isothermal magnetization curves, were fitted using (2), as implemented in PHI.[28] The best-fit parameters, which provide a perfect simultaneous reproduction of both M vs. H and  $\chi T$  vs. T curves, were:  $B_2^0 = -439 \pm 1 \text{ cm}^{-1}$ ,  $B_2^2 = 148.4 \pm 0.3 \text{ cm}^{-1}$  and  $\sigma = -0.734 \pm 0.003$  with  $\lambda$  fixed to  $75 \text{ cm}^{-1}$ . With these values, there is a ground singlet with two close-lying states at  $1.67$  and  $14.97 \text{ cm}^{-1}$ ; further excited states are at  $173.9$ ,  $188.2$ ,  $195.8 \text{ cm}^{-1}$ , and at  $812$ ,  $813$ ,  $817 \text{ cm}^{-1}$ . It is clear that the levels are now grouped in a set of pseudo triplets, for which the ground one has essentially easy-axis type, with an effective zero-field splitting of *ca.*  $-14.1 \text{ cm}^{-1}$ . Accordingly, Hamiltonian (1) could only be employed to model the low temperature magnetic properties, i.e. the isothermal magnetization curves, providing as best fit values  $D = -14.1 \pm 0.3 \text{ cm}^{-1}$ ,  $E = 1.21 \pm 0.02 \text{ cm}^{-1}$ ,  $g = 1.72 \pm 0.01$ . While the latter value may appear quite low, it is very close to the value derived from HF-EPR of  $\text{Fe}_3\text{VET}$ . [9] However, this approach is clearly not reproducing the thermal behavior of the magnetic susceptibility above  $50 \text{ K}$  (see dotted line in Figure 3), which is much influenced by the presence of low lying excited states.

### 3.3 HF-EPR spectroscopy

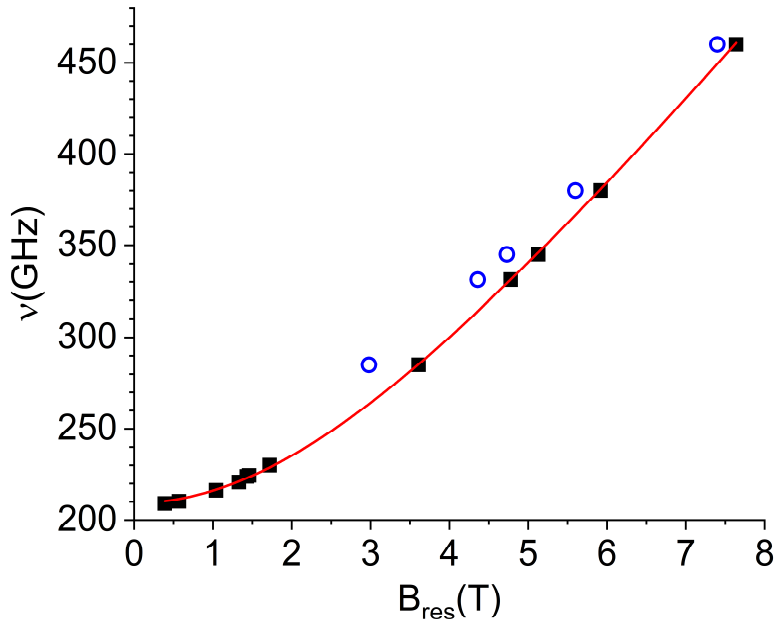
HF-EPR spectra, measured at frequencies between  $190$  and  $460 \text{ GHz}$  and at  $5 \text{ K}$  are reported in Figure 4. They clearly show a main transition that moves toward zero field on decreasing frequency. No spectrum is observed below  $210 \text{ GHz}$ , indicating a quite large Zero Field Splitting. A second weaker transition is observed at a somewhat lower field and disappears for frequencies lower than  $285 \text{ GHz}$ . No other identifiable transitions are observed in the investigated field range. Measuring at  $5 \text{ K}$  in

this frequency range allows getting a high polarization of the spin system with mostly only the lowest energy level populated (the energy of a frequency of 210 GHz corresponds to the one of a  $\sim 11$  K temperature). Furthermore, the intensity of both transitions decreases when increasing the temperature to 15 K, indicating that they are issued from the lowest energy level.



**Figure 4** HF-EPR spectra of a polycrystalline powder sample of **Ga<sub>3</sub>VEt**, measured at variable frequencies and 5 K.

By plotting the resonance field of the main transition as a function of frequency, a behavior that is linear at high fields and parabolic at low fields is observed (Figure 5). This, together with the lineshape, clearly identifies the transition as a perpendicular one, while the resonant field points to a formally forbidden one.



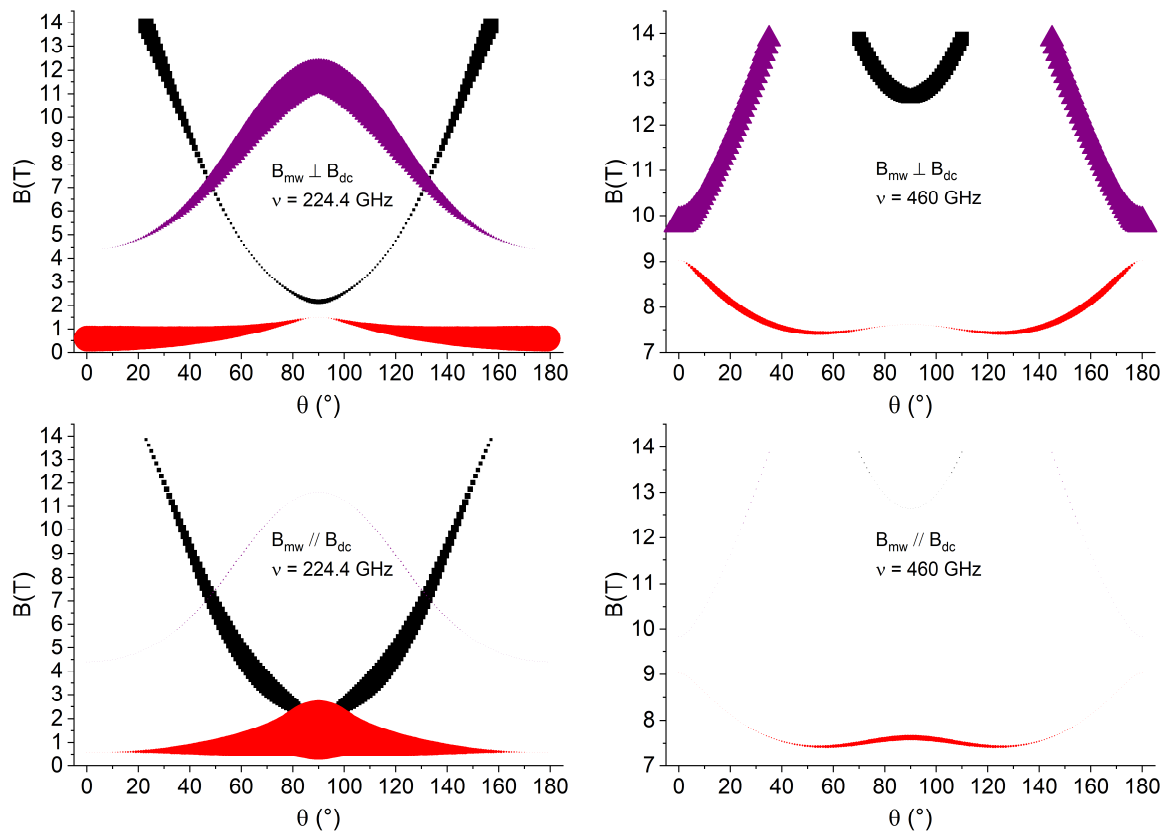
**Figure 5** Frequency dependence of the observed HF-EPR resonant fields of **Ga<sub>3</sub>VEt** and best fit to the main transition field using expression (3). Black squares are resonant fields of the main transition, empty circles represent the resonant fields of the second transition, observed only for  $D/h\nu < \frac{3}{4}$ . See text for details.

If we assume a Spin Hamiltonian description of our system, the observed transition is the one between the levels labeled as  $m_s=|0\rangle$  and  $m_s=|1\rangle$  in zero field ( $|\pm 1\rangle$  in applied field, thus formally forbidden). We can fit this dependence by using the following relation: [47]

$$\Delta E = \sqrt{(4g_{x,y}^2\beta^2H^2 + D^2)} \quad (3)$$

This provides a nice agreement with the experimental data using the following best-fit parameters:  $D = 209.35 \text{ GHz}(6.98 \text{ cm}^{-1})$ ,  $g = 1.9196$ . It is well known [48],[49] that if  $D/h\nu < \frac{3}{4}$  the forbidden transition at half field can provide two signals in a powder spectrum, one corresponding to a canonical orientation of the field, the other one to an off-axis resonant field.





**Figure 6** Angular dependence of the HF EPR resonance fields of **Ga<sub>3</sub>VEt** at two frequencies in the *zx* plane, using Spin Hamiltonian (1) and parameters obtained by best fit of (3). Size of the symbols are proportional to the transition probability.

We then plot in Figure 6 the angular dependence of the resonant fields for two of the experimentally used frequencies, calculated on the basis of Spin Hamiltonian (1) and the *D* value obtained by the fit to Eq. (3). This clearly points to the presence of one canonical maximum and one minimum are observed at 224.4 GHz, while one minimum (non-canonical,  $\theta = 55.5^\circ$ ) and two (canonical) maxima are observed at 460 GHz. It is however worth noting that the  $\theta = 90^\circ$  transition has zero probability for perpendicular polarization of the microwave radiation (i.e., the experimental setup we used, selecting  $\Delta M_S = \pm 1$  transitions), whereas its probability is highest for parallel polarization (i.e. with oscillating  $\mathbf{B}_{mw}$  parallel to  $\mathbf{B}_{dc}$ , selecting  $\Delta M_S = 0$  transitions). On the contrary, the  $\theta = 0^\circ$  transition has zero probability in parallel polarization and maximum probability for perpendicular polarization (see Figure 6). By considering the lineshape of the observed transitions and their resonance fields, the observed spectrum should then be assigned to the parallel polarization, which also results in zero probability for the “allowed” transitions. With this approach,

reasonable simulations could be obtained for the experimental spectra at different frequencies (see Figure S7). Unfortunately, due to the low sensitivity of the observed “forbidden” transition to the sign of  $D$ , no conclusion can be reached on this point. Finally, it is worth noting that assuming the same model used to rationalize magnetic data did not lead to reasonable reproduction of the experimental spectra.

#### 4. DISCUSSION

The results reported in the previous sections deserve some comments. It is first to be noted that the analysis of magnetic and HF-EPR data provides conflicting indications: for the first set of techniques, the results can only be rationalized by assuming vanadium(III) in **Ga<sub>3</sub>VEt** has easy-axis type anisotropy, and its global behavior cannot be traced back to a simple spin triplet, but rather to a <sup>3</sup>E ligand field state partially split by rhombic distortion. The presence of a rhombic term in the Hamiltonian is not at odd with the observed trigonal crystallographic symmetry. Indeed, the latter is only a consequence of the statistical disorder of the ethyl pendant on the tris-alkoxo ligand, while the molecular symmetry of **Ga<sub>3</sub>VEt** is not axial. The results obtained by the magnetic characterization provides a magnitude of single ion anisotropy for V<sup>III</sup> in the star-shaped compound which would allow rationalizing the global anisotropy of **Fe<sub>3</sub>VEt** without invoking any anisotropic exchange, at variance with what we reported in ref. [9]. Indeed, in the strong exchange approximation, the Zero Field Splitting tensor of **Fe<sub>3</sub>VEt** is related to the microscopic anisotropic parameters (single-ion anisotropy tensor and spin-spin interactions) through:

$$\mathbf{D}_{Fe3V} = d_{Fe}(\mathbf{D}_{Fe(1)} + \mathbf{D}_{Fe(2)} + \mathbf{D}_{Fe(3)}) + d_V \mathbf{D}_V + d_{Fe-Fe} \sum_{i,j=1}^{3(j>i)} \mathbf{D}_{Fe(i)-Fe(j)} + d_{Fe-V} \sum_{i=1}^3 \mathbf{D}_{Fe(i)-V} \quad (4)$$

Where  $d_i$ 's and  $d_{ij}$ 's are the projection coefficients on the global anisotropy of spin state S of the single ion anisotropies ( $\mathbf{D}_{Fe(i)}$ ,  $\mathbf{D}_V$ ) and of the spin-spin interaction ( $\mathbf{D}_{Fe(i)-Fe(i)}$ ,  $\mathbf{D}_{Fe(i)-V}$ ), respectively, which can be calculated recursively[50] (see Table 2). A similar relation hold for the  $\mathbf{g}$  tensors:

$$\mathbf{g}_{Fe3V} = c_{Fe}(\mathbf{g}_{Fe(1)} + \mathbf{g}_{Fe(2)} + \mathbf{g}_{Fe(3)}) + c_V \mathbf{g}_V \quad (5)$$

It is now firmly established that peripheral Fe<sup>III</sup> ions in star-shaped complexes have hard axis anisotropy with substantial rhombicity ( $D_{Fe} \approx +0.7 \text{ cm}^{-1}$ ,  $E_{Fe} \approx 0.08 \text{ cm}^{-1}$ ). Furthermore, different HF-

EPR and magnetometry studies pointed out that the easy axis direction of the anisotropy tensor of Fe<sup>III</sup> is approximately perpendicular to the plane of the star and that the local intermediate axis is oriented along the Fe–M direction (which is often a symmetry imposed direction[8,51–53]). If one substitutes the values and orientations expected for Fe<sup>III</sup>, the dipolar contribution calculated in the point dipole approximation and  $D_V = -14.1 \text{ cm}^{-1}$ , which models the splitting in the low energy region for vanadium(III), the estimated anisotropy for the ground  $S=13/2$  state of **Fe<sub>3</sub>VEt** from Equation (4) is  $-0.290 \text{ cm}^{-1}$ , in good agreement with the experimentally determined value in ref. [9] ( $D(\text{Fe}_3\text{VEt}) = -0.314 \text{ cm}^{-1}$ ). It is further to be noted that the experimentally determined[9]  $g$  value for **Fe<sub>3</sub>VEt** requires  $g_V=1.7$  which is exactly the value one obtains by modeling the low temperature magnetic data of **Ga<sub>3</sub>VEt** with a ground pseudo triplet (see above) .

**Table 2** Projection coefficients and calculated dipolar contribution to the anisotropy of the ground state in **Fe<sub>3</sub>VEt**.

$d_{Fe}$	$d_V$	$d_{Fe-Fe}$	$d_{Fe-V}$	$c_{Fe}$	$c_V$
$\frac{17}{140}$	$\frac{1}{120}$	$\frac{17}{112}$	$-\frac{17}{360}$	$\frac{17}{45}$	$-\frac{2}{15}$

On the other hand, HF-EPR data can be rationalized assuming a standard spin triplet Spin Hamiltonian, resulting from a positive value of the trigonal distortion of the ligand field, and thus in an orbital singlet ground state. This would confirm our previous hypothesis, based essentially on literature data,[15,46,54] of positive zero-field splitting for vanadium(III) in the **Fe<sub>3</sub>VEt** cluster. It is however to be noted that appropriate simulation of the HF-EPR spectra required to assume, as discussed, parallel polarization of the microwave radiation. This is not the experimental setup used, thus raising further issues about these data. Similar problems with the radiation polarization were recently reported for an experimental study of a Ho-based polyoxometalate (POM) Single-Molecule Magnet.[55]

## 5. CONCLUSIONS

We have reported a preliminary characterization of a **Ga<sub>3</sub>VEt** cluster both from a structural, magnetic and spectroscopic point of view. The observed results do not allow to obtain a firm conclusion as to the anisotropy of central vanadium(III) in **Ga<sub>3</sub>VEt** and, thus, in the isostructural

SMM **Fe<sub>3</sub>VEt**. Indeed, while the magnetic measurements point to an easy axis type anisotropy with a relevant rhombicity, HF-EPR spectra can only be interpreted on the assumption of an easy plane type anisotropy, of smaller magnitude but with some rhombicity. Also, given the small amount of sample available for HF-EPR measurements, some weak signals, associated to allowed transitions and giving more stringent constraints on the anisotropy parameters, may have been missed. This confirms the difficulties in getting a reliable characterization of V(III) containing complexes. Despite that we have succeeded in stabilizing it with tripodal ligand and in exploiting its anisotropy in **Fe<sub>3</sub>VEt** with a triplication of  $T_B$  compared to the archetypal  $Fe_4$  SMM, a rational design of optimized SMMs based on this metal ion is still challenging. In perspective, it might be useful to extend the HF-EPR study to higher fields and frequencies using a larger amount of sample to obtain more sound conclusions. This would allow to obtain clearer indication as to the contribution of the anisotropic exchange to the anisotropy of this system. In this perspective, the potential use of single crystal techniques, such as cantilever torque magnetometry, which proved very powerful in the investigation of the lanthanide-based variant of tetranuclear star shaped SMM,[56] might also prove useful.

## **AUTHOR CONTRIBUTIONS**

LS and RS designed the study. All authors performed the experiments. LS and JFS wrote the manuscript with input from all authors.

## **ELECTRONIC SUPPLEMENTARY MATERIAL**

Crystallographic data for **Ga<sub>3</sub>VEt** have been deposited with the Cambridge Crystallographic Data Centre (CCDC, <https://www.ccdc.cam.ac.uk>). Deposition number: 2008356. Online Resource contains crystal and structure refinement data, further crystallographic figures, infrared spectroscopy characterization and further analysis of HF-EPR data.

## **CONFLICTS OF INTEREST**

The authors declare that there is no conflict of interest.

## **ACKNOWLEDGMENTS**

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