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COMMUNICATION

A High-Pressure Crystallographic and Magnetic Study of Na₅[Mn(L-tart)₂]·12H₂O (L-tart = L-tartrate)

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The crystal structure and magnetic properties of the compound Na₅[Mn(L-tart)₂]·12H₂O (1, L-tart = L-tartrate) have been investigated over the pressure range 0.34 – 3.49 GPa. The bulk modulus of 1 has been determined as 23.9(6) GPa, with a compression of the coordination spheres around the Na⁺ ions observed. 1 is therefore relatively incompressible, helping it to retain its magnetic anisotropy under pressure.

Recent years have seen an increased interest in high pressure crystallographic studies of coordination compounds. This is due to the wide array of structural features that can be modified by the application of hydrostatic pressure, and has been aided by technological developments. In addition, diamond anvil cells (DACs) allow access to a huge range of pressures, spanning atmospheres to tens of gigapascals, offering a much wider window over which to study the physical properties of materials, particularly when compared to variation of temperature. Hydrostatic pressure has been used to modulate non-covalent interactions, and bring about the polymerisation of discrete complexes.

For several years, we have been interested in the way in which pressure can affect high spin transition metal complexes, particularly those with pronounced Jahn-Teller axes. Recently, we demonstrated that the compound Na₅[Mn(L-tart)₂]·12H₂O (1, L-tart = L-tartrate) shows slow relaxation of magnetisation under an applied direct current (dc) field. As such, it forms part of a wider family of transition metal complexes that show single-molecule magnet (SMM) behaviour arising from a single transition metal ion in an appropriate ligand field. The presence in the crystal lattice of Na⁺ ions, Mn(III) ions, a flexible organic ligand in L-tartrate, and an extended network involving water molecules, make 1 an attractive candidate for high pressure crystallographic studies. Hydrated sodium salts have been shown to undergo substantial changes to their coordination environments on applying pressure, while pressure-induced flipping of the orientation of one of the Mn(III) Jahn-Teller axes in a Mn₁₂ SMM has been observed. Herein, we describe the effect on the crystal structure of 1 of hydrostatic pressure ranging from 0.34 to 3.49 GPa. The static and dynamic magnetic properties of 1 are also investigated as a function of pressure. The bulk modulus of 1 is derived, and it is found to be relatively incompressible when compared to other compounds of its type, with the effect of pressure largely being observed around the Na⁺ ions in the lattice. As a result, retains the axial anisotropy associated with the Mn(III) ion, and continues to display slow relaxation of the magnetisation under a direct current (dc) field, despite the pressure applied.

Figure 1. The structure of 1 at 0.34 GPa. Ellipsoids are shown at the 70 % probability level, and hydrogen atoms are omitted for clarity. The Jahn-Teller axis is shown with thicker bonds. The black arrow represents the largest component of the strain tensor (see text). Lower case letters represent the symmetry operations for duplicate atoms: \( a = (1-x, y, z), b = (1-x, y, 1-z), c = (1.5-x, 0.5+y, 1-z), d = (x, -1+y, z), e = (1-x, -1+y, 1-z), f = (-0.5+x, -0.5+y, z), g = (1.5-x, 0.5+y, 1-z) \).

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These [Mn(L-tart)2]5- complexes are linked through an extended network of Na+ ions and H2O molecules. The Na1 ion is octahedrally coordinated, with the oxygen atoms O11 and O12 equivalent counterparts from the second L-tartrate ligand.

The central Mn(III) ion lies on a two-fold rotation axis in a distorted octahedral geometry, in which three O-donor atoms are provided each by two fully deprotonated L-tartrate ligands, with an average bond length of 1.909(7) Å. The axial positions are filled by O12 of the carboxylate, with a bond length of 2.730(3) Å. Na2 is coordinated by three donor atoms the L-tart, O3, and O4. The water molecule containing O2 is terminal, and Na3 -O bond lengths range from 2.332(3) to 2.677(10) Å. Na3 is surrounded by three pairs of O-atom donors: two water molecules containing O4, in a cis- configuration; two carboxylato- O41 atoms in a trans- configuration, and finally two water molecules containing O6 in a trans- configuration. The Na3-O bond lengths range from 2.397(8) – 2.569(9) Å.

The effect of hydrostatic pressure on the structure of 1 was investigated at 10 further pressure points, reaching a maximum of 3.49 GPa. Selected crystallographic data are provided in Table 1. The structure remains in the monoclinic space group C2 over the full pressure range examined. All three unit cell lengths decrease with increasing pressure, with the b-axis being the most sensitive, displaying a decrease of 5.2 % between 0.34 and 3.49 GPa (Figure 2). There is a resultant reduction in the unit cell volume of 106.4(4) Å3. The pressure dependence of the volume of the unit cell was fitted to a third order Birch-Murnaghan equation of state:

\[
K_{PT} = K_0 \left( 1 + 2f_K \right)^{5/2} \left[ 1 + (3K' - 5)f_K + \frac{27}{2}(K' - 4)f_K^2 \right],
\]

where,

\[
f_K = \frac{1}{2} \left( \frac{V_0}{V_P} \right)^{2/3} - 1
\]

yielding a bulk modulus \(K_0\) of 23.9(6) GPa, with its pressure derivative \(K'\) equal to 4.2(5). The bulk modulus gives a measure of how incompressible a material is: diamond has \(K_0 =

### Table 1. Selected crystallographic data for compound 1. A full table for all of the datasets collected is given in the supporting information.

<table>
<thead>
<tr>
<th>Crystal System</th>
<th>Monoclinic</th>
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<tbody>
<tr>
<td>Space Group</td>
<td>C2</td>
</tr>
<tr>
<td>(a/\AA)</td>
<td>20.1905(14)</td>
</tr>
<tr>
<td>(b/\AA)</td>
<td>6.830(2)</td>
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<tr>
<td>(Z)</td>
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</tr>
<tr>
<td>(D_{calc}/g\ cm^{-3})</td>
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<tr>
<td>Reflections</td>
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<tr>
<td>Unique Reflections</td>
<td>1044</td>
</tr>
<tr>
<td>(R_{int})</td>
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</tr>
<tr>
<td>(R)</td>
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<tr>
<td>(wR)</td>
<td>0.064</td>
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<tr>
<td>(S)</td>
<td>0.99</td>
</tr>
<tr>
<td>Flack Parameter</td>
<td>0.06(6)</td>
</tr>
<tr>
<td>(\rho_{max}, \rho_{ave}/e\AA^{-3})</td>
<td>0.55, -0.58</td>
</tr>
</tbody>
</table>
440 GPa. Typically, $K_0$ is found to be lower than 30 GPa for molecular solids and in this class of material, 1 is relatively incompressible. As a comparison, the molecular complexes [bis(3-fluorosalicylaldoximato)nickel(II)] and Co$_3$(dpa)$_8$Br$_2$-CH$_2$Cl$_2$ were found to have $K_0 = 9.1(17)$ GPa$^9$ and 6.4(7) GPa$^9$, respectively. The bulk modulus found for the metal-organic framework [Zn$_2$(C$_3$H$_3$N$_2$)$_4$]$_n$ was 14 GPa$^{27}$ and the strongly hydrogen-bonded system L-alanine has $K_0 = 13.4(7)$ GPa$^{28}$. It is interesting that 1 is perhaps less compressible than could have been anticipated, given the conformational flexibility of the L-tartrate ligand.

1 displays a pronounced Jahn-Teller (JT) effect along the axis of the Mn$_1$-O$_{12}$,O$_{12a}$ bonds. Previous studies of molecular nanomagnets have shown that the application of pressure can lead to switching of the orientation of JT axes.$^{23}$ However, the geometry around the central Mn(III) ion in 1 was found to be largely unaffected by pressure. The variation in the Mn-O bond lengths as pressure is increased is shown in Fig. S1. The axial Mn$_1$-O$_{12}$ bond lengths decrease from 2.319(2) at 0.34 GPa to 2.283(4) at 3.49 GPa, and the average equatorial bond length changes from 1.909(7) to 1.884(14), at 0.34 GPa and 3.49 GPa, respectively. Therefore, the difference between the axial and average equatorial bond lengths is 0.410 and 0.399 Å for the lowest and highest pressures measured. The retention of the coordination environment around the Mn(III) ion is shown by the overlay of the structures at 0.34 and 3.49 GPa in Fig. 3. While there is almost full overlap of the Mn(III) ions, the six oxygen donor atoms, and the carbon atom backbone of the L-tartrate ligand at the starting and final pressures, more pronounced displacements are observed in the positions of the Na$^+$ ions, particularly Na$_1$. Calculation of the strain tensor,$^{29}$ which describes the magnitude of compression and its anisotropy, showed that its largest component lies along the $b$-axis, approximately in the equatorial plane of the Mn(III) ion, bisecting the O$_{31}$-Mn$_1$-O$_{31a}$ angle (Fig. 1). The application of pressure from 0.34 to 3.49 GPa leads to a very slight increase in the O$_{31}$-Mn$_1$-O$_{31a}$ (93.8(4) to 95.5(7)$^\circ$, at 0.34 and 3.49 GPa, respectively) and O$_{21}$-Mn$_1$-O$_{21a}$ angles (96.6(4) to 97.2(8)$^\circ$), accompanied by a decrease in the O$_{21}$-Mn$_1$-O$_{31}$ angles (85.4(2) to 84.1(3)$^\circ$).

A more pronounced contraction in bond lengths is observed around each of the sodium ions in the lattice. At 3.59 GPa, the average Na-O bond lengths around Na$_1$, Na$_2$, and Na$_3$ are 2.358(13), 2.357(10), and 2.426(10) Å, representing a decrease of 0.100, 0.066, and 0.083 Å, when compared to the values at 0.34 GPa. The effect of this change is observed as a compression of the coordination octahedra around the three Na$^+$ cations (Fig. 2) for which the largest decrease in volume was observed in Na$_1$ (19.260 to 16.955 Å$^3$, as calculated using PLATON$^{30}$).

To verify whether the structural modifications induced by the application of pressure lead to changes in the magnetic properties of 1, both the direct current (dc) and alternating current (ac) susceptibilities were studied at four different applied pressures, ranging from 0 to 1.6 GPa. Consistent with our preceding work,$^{19}$ variable field magnetisation measurements performed at 2 and 5 K were not found to reach saturation at ambient pressure. Indeed, increasing the applied pressure to 0.5, 1.0, and 1.6 GPa appeared to have no effect on the $M$ v. $H$ curves (Fig. 4). Employing the program Phi,$^{31}$ the data were fitted according to the Hamiltonian:

\[
\mathcal{H} = D\left(\frac{S_z^2}{3} - \frac{1}{3}S(S+1)\right) + \mu_B g_S \cdot B
\]

yielding a value for the axial zero-field splitting (zfs) parameter $D$ of $-3.23$ cm$^{-1}$ at each pressure point investigated, in line with the ambient pressure value previously determined.
through high-field EPR spectroscopy. Thus, as was found for the octahedral environment of the Mn(III) ion in the crystal structures, the axial anisotropy of the Mn(III) ion in 1 appears insensitive to pressure to 1.6 GPa. The magnitude of the axial anisotropy is one of the determining factors in the size of the barrier to slow relaxation of the magnetisation, $U_e$. Correspondingly the barrier in 1, determined under an applied dc field of 2500 Oe, was also found to be invariant on applying pressure in the available ac frequency range (Fig. 5, S3 and Table S3).

Given the modifications induced in the crystal structure of 1 by the application of pressure, we propose that the $\text{Na}^+$ ions shield the central transition metal ion from the effects of compression. As a result, the principal effect of the hydrostatic pressure is to squeeze the coordination octahedra around the three $\text{Na}^+$ ions, rather than lead to any significant distortion around the Mn(III) ion. Accordingly, while pressure has been shown to alter the magnetic properties of other coordination complexes containing Mn(III), no such effect is found here. Soft ionic sites, such as the $\text{Na}^+$ ions in the lattice of 1, could therefore be envisaged to play a role in helping preserve important physical properties of other lattice entities – in this case the slow relaxation of the magnetisation of Mn(III) ions. Work is underway to investigate whether substitution of the $\text{Na}^+$ ions for other mono-cationic species would lead to more pronounced distortions in the coordination environment of the Mn(III) ion on the application of pressure.

**Experimental details**

Compound 1 was synthesised as reported previously. A crystal of 1 (0.20 × 0.15 × 0.10 mm³) was loaded into a Merrill-Bassett diamond anvil cell equipped with 600 mm culet-cut diamonds and conically-ground WC backing plates. The hydrostatic medium was Daphne oil, and the pressure was calibrated using a chip of ruby. High pressure single-crystal X-ray diffraction data were collected at room temperature on beamline I19 at Diamond Light Source ($\lambda = 0.4859$ Å). The data were integrated using the program SAINT while employing dynamic masks to account for regions shaded by the pressure cell and absorption corrections were carried out with SADABS. The structures were refined against $F^2$ using CRYSTALS. All non-H atoms were refined anisotropically. Bond angles and distances in the L-tart ligand were restrained geometrically calculated positions.

Magnetic measurements under pressure were carried out using a Quantum Design MPMS-XL5 SQUID Magnetometer. The sample, in the form of a crystalline powder, was loaded into the CuBe piston-cylinder-type high-pressure capsule cell. Daphne 7373 oil was used as a pressure-transmitting medium. A background measurement was performed using a complete, assembled cell with no sample contained in the cell. Alternating current (ac) susceptibility measurements were performed under an applied direct current (dc) field of 2500 Oe, with a drive field of 3 Oe.

**Acknowledgements**

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**Notes and references**


