Tunneling, remanence, and frustration in dysprosium-based endohedral single-molecule magnets

Westerström, Rasmus; Dreiser, Jan; Piamonteze, Cinthia; Muntwiler, Matthias; Weyeneth, Stephen; Krämer, Karl; Liu, Shi-Xia; Decurtins, Silvio; Popov, Alexey; Yang, Shangfeng; Dunsch, Lothar; Greber, Thomas

DOI: https://doi.org/10.1103/PhysRevB.89.060406

Posted at the Zurich Open Repository and Archive, University of Zurich
ZORA URL: https://doi.org/10.5167/uzh-106639
Scientific Publication in Electronic Form

Originally published at:
Westerström, Rasmus; Dreiser, Jan; Piamonteze, Cinthia; Muntwiler, Matthias; Weyeneth, Stephen; Krämer, Karl; Liu, Shi-Xia; Decurtins, Silvio; Popov, Alexey; Yang, Shangfeng; Dunsch, Lothar; Greber, Thomas (2014). Tunneling, remanence, and frustration in dysprosium-based endohedral single-molecule magnets. Zürich: American Physical Society
DOI: https://doi.org/10.1103/PhysRevB.89.060406
A single molecule magnet (SMM) can maintain its magnetization direction over a long period of time [1, 2]. It consists in a low number of atoms that facilitates the understanding and control of the ground state, which is essential in future applications such as high-density information storage or quantum computing [3, 4]. The discovery of single molecule magnets containing one lanthanide ion triggered large interest in 4$f$ electron compounds [5, 6]. However, the remarkable double decker molecules with one magnetic 4$f$ ion have poor remanence: The zero field magnetization decays rapidly, also via the unavoidable tunneling between states with opposite magnetization. In this respect, dinuclear 4$f$ compounds appear to be more robust due to exchange coupling related stabilization of the magnetic moments, [7–11] and there are reports on trimuclear lanthanide ion complexes with [12] and without [13, 14] magnetic ground states.

Endohedral fullerenes [15] represent a new family in the class of lanthanide-based single molecules. They can contain clusters that are not found as free species in nature, and bear great potential when it comes to the production of molecular arrays on surfaces. Many of them are particularly stable, survive sublimation and may be easily imaged [16, 17] and manipulated with scanning probes [18, 19]. While the R=holmium or terbium based R$_3$N@C$_{80}$ showed non-collinear paramagnetism [20], it was recently found that the isotropic gadolinium R$_3$ species, shows ferromagnetically coupled collinear paramagnetic behavior [21]. The first endohfullerene which displayed hysteresis and qualified as a single molecule magnet was DySc$_2$N@C$_{80}$. The observed hysteresis is a result of a slow relaxation of the magnetization which is caused by a ligand field that splits the Hund ground state and causes barriers separating states with different magnetization. However, the symmetry constraints of an isolated Kramers ion with an odd number of electrons, as it is Dy$^{3+}$, did not apply [22].

Here we present results for the complete dysprosium-scandium endofullerene series Dy$_n$Sc$_{3−n}$N@C$_{80}$ ($n$ = 1, 2, 3) with one, two, or three 4$f$ moments inside a nanometer sized closed shell C$_{80}$ cage, see Fig. 1(a). This bottom up approach of building a magnet features the unique opportunity to study the effect of adding moments - one by one. The significantly different hysteresis curves demonstrate the decisive influence of the number of magnetic moments and their interactions. In zero field the magnetization of $n = 1$ decays via quantum tunneling, while ferromagnetic coupling of the individual dysprosium moments results in remanence for Dy$_2$ScN@C$_{80}$ and in a frustrated ground state for $n = 3$. The latter ground state turns out to be one of the simplest realizations of a frustrated, ferromagnetically coupled, system.
signal for the SQUID measurements the molecules were drop cast onto sample holders with a weak linear diamagnetic behavior made from kapton foil. This diamagnetic background has been subtracted from the data. For GdCl₃·6H₂O (Aldrich) our magnetometer shows at 6 K a Gd magnetic moment of 7.4±0.2 μB, which compares to 7μB as expected from the Gd³⁺ ⁸S₇/₂ ground state. To obtain the relaxation times at elevated temperatures, the ac susceptibility of 2 was measured for varying frequencies of the driving magnetic field.

In zero field the interaction between the magnetic moments may be described with a Hamiltonian reminiscent to Heisenberg and Lines [27, 28] of the form:

$$\mathcal{H} = \sum_{i \neq k} n J_{i,k} \mathbf{J}_i \cdot \mathbf{J}_k \quad (1)$$

where $J_{i,k}$ are the coupling constants and $\mathbf{J}_{i,k}$ the corresponding angular momentum operators on sites $i$ and $k$, respectively. For Ho and Tb trisicnic nitride endofullerenes it was proposed that the magnetic moments $\mu_i$, which are parallel to the expectation values $\langle \mathbf{J}_i \rangle$, remain aligned in the R³⁺ - N³⁻ ligand field [20]. Our findings on 1 [22] and ab-initio results [29] are in line with the picture where the $(\mathbf{J}_i)$ of every Dy³⁺, are uniaxial (anisotropic). This allows the reduction of the ground state problem to a non-collinear Ising model with $n$ pseudospins [14], which can take two orientations, parallel or antiparallel to the corresponding Dy-N axis. The $2^n$ solutions for such a Hamiltonian form $2^{n-1}$ doublets. They are labeled TRD since the two states are time reversal symmetric and have opposite magnetization but the same energy in zero field (see Fig. 1(c)). Importantly, the interaction $J_{i,k}$ between the different pseudospins lifts the degeneracy of the $2^{n-1}$ TRD’s and gives rise to excitation energies $U_n$. For 1 the solution is trivial since no interaction occurs. The tunneling rate between the two states in the single doublet determines the magnetization time. For 2 the two TR doublets are split by the interaction $J_{1,2}$. This causes remanence, because demagnetization involves the excitation into the second TRD, or simultaneous tunneling of the two magnetic moments. With the same $J_{i,k}$ between all ions in 3, which is given if the ions sit on an equilateral triangle, we find the four TRD’s to split in a group of three magnetic and one non-magnetic doublet. The fact that 3 shows paramagnetic behavior indicates a negative $J_{i,k}$, i.e. ferromagnetic coupling. This imposes a six fold degenerate ground state, where tunneling between these states enables demagnetization. The appearance of three TR doublets of anisotropic, ferromagnetically coupled pseudospins results in magnetic frustration. Localized ferromagnetism in two dimensions is also found in kagomé spin ice [30], while we deal here with a finite system of three pseudo-spins. Notably, this is analogous to the case of isotropic spins on an equilateral triangle, where frustration is caused by anti-ferromagnetic exchange interaction [31].

The pseudospin structures of the ground states for 1-3 are shown in Fig. 1(c). The level scheme of the $2^{n-1}$ TR doublets is reflected in the magnetization curves. The magnetic moment of a given molecule corresponds to the vectorial sum of the $n$ individual moments. In a magnetic field the TRD’s undergo Zeeman splitting, and since they are different for 1-3, distinct susceptibility, beyond scaling with $n$ is observed. In Fig. 1(d) the magnetizations at the temperature of 6 K are displayed as a function of the applied field. The curves for the three molecules are different, not only due to the number of Dy atoms per...
molecule, as can be seen in Fig. 1(e). The relative differences between the three molecules amount up to 10%, which allows the extraction of the different ground state parameters.

The magnetization curves are reminiscent to Brillouin functions, though, in the present case the Dy$^{3+}$ moments do not align along the magnetic field and the degeneracy of the $^6H_{15/2}$ ground state is partly lifted by the ligand field. Assuming randomly frozen, independent molecules, reduces the saturation magnetization to half the value of the maximum magnetization of free molecules, since only the projection on the field direction contributes. Together, with the given structure of the TRD’s we can extract the magnetic moments $\mu_n$ and the TRD splittings $U_2$ and $U_3$ (Fig. 1(c)) from comparison of simulated magnetization curves with the experiment. The solid lines in Fig. 1d represent the best fits of these simulations to the measured data.

The magnetic moment of 1 of $\mu_1=9.37\pm0.06 \mu_B$ agrees with a large $m_N$ ground state along the Dy-N axis. For 2 $\mu_2=8.75\pm0.13 \mu_B$, and the splitting $U_2$ between the two TRD’s gets $0.96\pm0.1$ meV. For 3 $\mu_3=9.46\pm0.05 \mu_B$, and value of $U_3$ of $0.3\pm0.2$ meV a weaker coupling than in 2.

Fig. 2(a) displays magnetization curves at 2 K taken with a field sweep rate of $0.8$ mT/s for 1-3. The observed hystereses demonstrate that the rate at which the magnetization relaxes to its equilibrium is slow compared to the measurement time, which is characteristic for single molecule magnets. The distinct shapes indicate on how strong the number of magnetic moments and their interaction influence the response to external magnetic field changes. For applications the remanence, i.e. the memory of magnetization history in zero-field is of particular interest. There is large "remanence" for 2, as compared to a sharp drop of the magnetization at low fields for 1, and a narrow hysteresis with vanishing zero-field magnetization for 3. It is a clear consequence of the magnetic interaction between the endohedral dysprosium ions in 2 and 3, which is partially mediated by the central N$^{3-}$ ion. For 1 the enhanced tunneling of magnetization in the absence of an applied field is seen in the abrupt jump of the magnetization when approaching the $\mu_0H = 0$ point. The narrow hysteresis of 3 makes it the softest single molecule magnet of the three. This is due to magnetic frustration of the ground state, which suppresses remanence. The Zeeman splitting between the lowest and the first excited state in 3 is smaller than in 1, which allows more efficient flipping of the magnetization, also in an applied field. So far frustration was not realized in trimuclear magnetic molecules as the relevant mechanism for zero field demagnetization [13, 14, 20]. In contrast to 1 and 3 the reversal of magnetization in 2 requires a simultaneous flip of both magnetic moments or the crossing of the barrier $U_2$, which consequently stabilizes the zero field magnetization. The barrier has contributions from the exchange energy and the dipolar coupling of the two moments $\mu_2$.

In Fig. 2(b) the Hilbert space of the time reversal doublets $(n, \pm d)$ for the three molecules (see Fig. 1(c)) are shown. $\pm d$ are the indices of the two states in the given TRD’s. The $2^n$ states are connected by a network of single tunneling transitions that correspond to the flipping of one magnetic moment. For 1 and 3 all ground state TRD’s are connected by single-tunneling transitions at the ground state energy, which is an intrinsic demagnetization mechanism that suppresses remanence. For 2 there is no single-tunneling path connecting the ground state TRD, and a single-tunneling event costs the energy $U_2$.

The $U_2$ barrier is also reflected in the temperature dependence of the zero field magnetization decay times. Below 5 K a double exponential was fitted to the decay data (Fig. 3(a)), as done for the case of DySc$_2$N@C$_{80}$, where this behavior was ascribed to different hyperfine interaction of different Dy isotopes [22]. The resulting decay times for the slower process, $\tau_A$, are displayed on a logarithmic scale versus the reciprocal temperature in Fig. 3(b). A 100 s blocking temperature of about 5.5 K is determined, which is amongst the highest temperatures reported for single molecule magnets [8, 9]. Higher temperatures were accessed using ac magnetic susceptibility measurements and the corresponding relaxation times are displayed as open symbols in Fig. 3(b). Clearly, the relaxation times show two temperature regimes, indicating distinct relaxation mechanisms. Down to 2 K the zero-field relaxation times do not show a temperature independent region, as observed for a single pseudospin flip tunneling regime in 1 [22], because this relaxation mechanism is suppressed in the ground state of 2 by the barrier $U_2$.

Fitting the lifetimes $\tau_A$ to:

$$\tau_A = \frac{\tau_1 \cdot \tau_2}{\tau_1 + \tau_2}$$

leads with $\tau_t = \tau_{2,t}^0 \exp(U_{2,t}^{\text{eff}}/k_B T)$ to the solid curve in Fig. 3b. The effective energy barriers for magnetization reversal get $U_{2,1}^{\text{eff}} = 0.73 \pm 0.04$ meV and $U_{2,2}^{\text{eff}} = 4.3 \pm 0.1$ meV with pre-exponential factors $\tau_{2,1}^0 = 56.5 \pm 9.8$ s and $\tau_{2,2}^0 = 12.0 \pm 1.3$ ms, respectively. The lower barrier $U_{2,1}^{\text{eff}}$ corresponds to the energy gap between the two TR doublets of 2 (Fig. 1(c)). The higher barrier $U_{2,2}^{\text{eff}}$ is similar to the one found in a Co$_2$Dy$_2$ compound [10], and must be related to relaxation via higher lying excited states. It is however much smaller than the theoretical result in Ref. [29] and Ref. [10], respectively. As in 1 [22] the prefactors $\tau_{2,t}^0$ in 2 are, compared to other Dy based single molecule magnets [5, 10], remarkably large. This is taken as an indication that the phase spaces for tunneling and excitations leading to decay of the magnetization are particularly small, which must be due to the peculiar protection of the magnetic moments in the closed shell C$_{80}$ cage.
In summary, the three dysprosium based endofullerenes Dy₃Sr₃−ₙ,N@C₈₀ (n = 1, 2, 3) are identified as single molecule magnets with three different ground states. The present pseudospin model for the ground states is expected to be generally valid for uniaxially anisotropic R₃N@C₈₀ endofullerenes. The distinct hysteresis curves reflect on how dramatic changes can be caused by stoichiometry and interaction in single molecule magnets. The observed large remanence in 2 is due to an energy barrier for flips of individual 4f moments. For the trimuclear nitrogen-cluster Dy₃N@C₈₀ the ferromagnetic coupling results in a frustrated ground state that suppresses remanence regardless of the exchange and dipolar barrier. These findings demonstrate the crucial role of magnetic frustration for the suppression of magnetization blocking in single molecule magnets.

The project is supported by the Swiss National Science Foundation (SNF project 200021 129861 and 147143), the Swedish research council (350-2012-295) and the Deutsche Forschungsgemeinschaft (DFG project PO 1602/1-1). We acknowledge discussions with one of the authors of Ref. [29].

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