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Magnetic Memory from Site Isolated Dy(III) on Silica Materials

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ABSTRACT: Achieving magnetic remanence at single isolated metal sites dispersed at the surface of a solid matrix has been envisioned as a key step toward information storage and processing in the smallest unit of matter. Here, we show that isolated Dy(III) sites distributed at the surface of silica nanoparticles, prepared with a simple and scalable two-step process, show magnetic remanence and display a hysteresis loop open at liquid 4He temperature, in contrast to the properties of the SMMs and the surface are produced separately and then assembled together. In other words, the properties of magnetic entities at the surface differ from the properties in the bulk or of individual molecular entities. Most of the SMMs are based on transition metals or f-elements and result from the combination of two key parameters: a large spin and a significant magnetic anisotropy. This anisotropy is a property of the metal center used, and its magnitude can be significantly modulated by its coordination sphere. Hence, heterogenization, which often changes the coordination sphere of the metal center, can significantly alter the required magnetic properties.

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As illustrated recently, single-atom deposition directly onto the surface is the ultimate size limit. The magnetic remanence for single atoms of Ho on MgO/Ag(100) persists up to 30 K (Figure 1C). This strategy showed unprecedented magnetic properties of lanthanide ions when isolated on silica matrices. Toward this goal, we have developed a strategy for producing single atoms of Ho on MgO/Ag(100) persists up to 30 K (Figure 1C). This strategy showed unprecedented magnetic properties of lanthanide ions when isolated on silica matrices.

**Figure 1.** Immobilization strategies of single-molecule and single-atom magnets. (A) Immobilization of single-molecule magnets by grafting (a), through surface decoration with organic ligands (b), or by physisorption on the surface (c). (B) Immobilization on carbon nanotubes by supramolecular interaction (a) or encapsulation (b). (C) Immobilization of single-molecule magnets by supramolecular interaction (a) or encapsulation (b). (D) Our strategy for immobilization of ions on metal oxide surfaces, based on a grafting step (a) and a thermolytic step (b).
Figure 2. (A) Grafting of 1 on SiO$_2$-700 to form 1/SiO$_2$ followed by a thermal annealing under high vacuum yielded Dy@SiO$_2$ (color code: carbon (gray), silicon (orange), oxygen (red), and dysprosium (blue)). (B) FTIR transmission spectra of SiO$_2$-700, 1/SiO$_2$, and Dy@SiO$_2$. Grafting of 1 (1.05 equiv/silanol or ca. 0.26 mmol g$^{-1}$) on SiO$_2$-700 leads to the disappearance of most isolated silanols while a broad band appears at 3650 cm$^{-1}$, consistent with the presence of unreacted silanols interacting with organic ligands. (C) Dy L$_{III}$-edge XANES of 1, 1/SiO$_2$, and Dy@SiO$_2$. (D) $k^3$ weighted EXAFS fits in $k$-space (top) and $R$-space (bottom) of 1. The fit of 1 includes five O atoms in the first coordination sphere: three at 2.11 Å, and one each at 2.39 and 2.53 Å. (E) $k^3$ weighted EXAFS fits in $k$-space (top) and $R$-space (bottom) of 1/SiO$_2$. Aside from a shortening of the Dy–O paths of the $\kappa^\ast$ neutral silanol at 2.26 and 2.40 Å compared to the molecular structure, the structure of 1/SiO$_2$ is similar to 1 (Figures S4 and S5, Table S3). (F) $k^3$ weighted EXAFS fits in $k$-space (top) and $R$-space (bottom) of Dy@SiO$_2$. The best fit was obtained by including five O ligands, three with short (2.20 Å) and two with longer (2.42 Å) Dy–O distances (Figures S4 and S6, Table S3).

Magnetic analyses of 1/SiO$_2$ and Dy@SiO$_2$ provide room temperature $\chi_M T$ of 13.5 and 12.4 cm$^3$ K mol$^{-1}$ respectively, in agreement with the expected value of 14.2 cm$^3$ K mol$^{-1}$ for the $^9$H$_{15/2}$ multiplet ground state of Dy(III) ions (Figures S7 and S8). The $\chi_M T$ values decrease on cooling with the thermal depopulation of $M_1$ states to reach 11 and 10.4 cm$^3$ K mol$^{-1}$ at 2 K. The saturation magnetizations at 2 K (4.6 and 4.5 N\(\beta\) for 1/SiO$_2$ and Dy@SiO$_2$ respectively) are consistent with the stabilization of the $m_f = \pm 15/2$ Kramers doublet state well isolated from the first excited Kramers doublet (Figures S7 and S8). Ac susceptibility measurements performed in zero external dc field for 1/SiO$_2$ and Dy@SiO$_2$ show that the magnetic moments of Dy(III) ions relax independently below 16 K at the nanoparticle surface, which is not the case for the molecular precursor 1. Plots of the in phase ($\chi'_M$) and out of phase ($\chi''_M$) ac magnetic susceptibilities in zero dc field as a function of frequency in the 2–18 K range (Figures 3A and S9) illustrate the slowdown of the magnetic relaxation and confirm that Dy(III) ions behave as magnets. These results indicate that the oxide surface can be viewed as the ligand that dictates the electronic properties of the Dy(III) ions. Dy@SiO$_2$ relaxes more slowly than 1/SiO$_2$ at all temperatures and is therefore a more persistent magnet in zero field. At 2 K the relaxation time determined using an extended Debye model (Figure S10, Tables S4 and S5) is 100 times slower in Dy@SiO$_2$ than in 1/SiO$_2$. The high frequency limit ($\chi'_M$) corresponding to the nonrelaxing fraction of the magnetic susceptibility was fixed at zero to minimize free parameters. $\tau$ obeys the Arrhenius law above 9 K with an activation energy of $65(\pm 3)$ K (Table S4, Figure S11, see Materials and Methods for details) for center. Taking into account such additional ligands is necessary for a good fit of the EXAFS spectra of Dy@SiO$_2$. In contrast, the EXAFS results show no Dy–Dy scattering paths, consistent with site isolation and with the coordination of the Dy(III) sites in Dy@SiO$_2$ solely to the surface (Figure 2F and Table S3). Overall, EXAFS shows that Dy in Dy@SiO$_2$ is bound to only 5 oxygen atoms and is therefore coordinatively unsaturated. The oxygen ligands arise from the surface and should therefore impose a very asymmetric environment. In fact, 1,10-phenanthroline, a bidendate ligand, coordinates to Dy as evidenced by a shift of the aromatic ring (C$=$C) frequency in the 2–18 K range (Figures 3A and S9) illustrate the slowdown of the magnetic relaxation and confirm that Dy(III) ions behave as magnets. These results indicate that the oxide surface can be viewed as the ligand that dictates the electronic properties of the Dy(III) ions. Dy@SiO$_2$ relaxes more slowly than 1/SiO$_2$ at all temperatures and is therefore a more persistent magnet in zero field. At 2 K the relaxation time determined using an extended Debye model (Figure S10, Tables S4 and S5) is 100 times slower in Dy@SiO$_2$ than in 1/SiO$_2$. The high frequency limit ($\chi'_M$) corresponding to the nonrelaxing fraction of the magnetic susceptibility was fixed at zero to minimize free parameters. $\tau$ obeys the Arrhenius law above 9 K with an activation energy of $65(\pm 3)$ K (Table S4, Figure S11, see Materials and Methods for details) for
Dy@SiO$_2$ while the activation energy (16(±1) K, Table S5 and Figure S11) is much lower in 1/SiO$_2$. At low temperature, the average relaxation time reaches a maximum at 1 s (Figure 3A) in Dy@SiO$_2$. Saturation of the relaxation time, which is commonly observed in Dy(III)-based SMMs,$^{25}$ prevents the storage of information at zero field. However, in the present case, a non-negligible fraction of Dy centers relaxes at time scale longer than 100 s due to the relatively large distribution of the relaxation times (Figure 3A, Table S4), which produces a hysteresis loop open at zero field between 2 and 5 K (Figures 3B and S12) in sweeping the field at 16 Oe s$^{-1}$. The same hysteresis loop closes when the sweep rate is decreased down to 0.6 Oe s$^{-1}$ and remains slightly opened at intermediate rate of 2.5 Oe s$^{-1}$ (Figure S13a). It must be mentioned that the loops close at high field (Figure S13b). The relaxation time in Dy@SiO$_2$ is almost unaffected by an external dc field (Figure S14). On the contrary, the application of a moderate field on 1/SiO$_2$ slows down the relaxation time by a factor 100 (Figure S15) at 2 K, which causes the opening of a butterfly like hysteresis (Figure S16). This difference might originate from the higher number of vibration/rotation modes resulting from the presence of organic ligands in 1/SiO$_2$ with respect to its fully inorganic and more rigid counterpart Dy@SiO$_2$.

In contrast to traditional SMM heterogenization strategies where the magnetic properties of the molecular precursor are transferred to the surface, the magnetic memory properties of Dy@SiO$_2$ appear only after grafting and thermal decomposition in our approach. This behavior most likely arises from the formation of highly constrained surface species and geometries that could not be obtained with molecular materials, thus illustrating the potential of the thermolytic precursor approach. Furthermore, thermolysis produces a non-centrosymmetric environment in Dy@SiO$_2$, with low coordinated Dy(III) exposed at the material surface as shown by EXAFS and 1,10-phenanthroline probe experiment (vide supra).

The strategy used here enabled the simple generation of fully inorganic isolated Dy(III) ions on a silica matrix, which is thermally stable up to at least 400 °C and behaves as isolated SMMs at liquid $^4$He temperatures. The magnetic remanence of Dy sites in Dy@SiO$_2$ depends solely on the site isolation on silica and is not found in the corresponding molecular entities, likely resulting from the unusual coordination environment of surface sites and the absence of ancillary organic ligand. The synthetic approach developed here is easily amenable to large scale production and is transferable to any type of oxide surfaces including layers of ferromagnetic oxides or oxide layers on wafers. It thus opens new avenues to generate and manipulate lanthanide nanomagnets for data storage at the nanoscale and quantum information processing.

**ASSOCIATED CONTENT**

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acscentsci.7b00035.

- Synthesis and characterization, IR, solution NMR, XRD data, XAS, and SQUID details (PDF)

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**Author Contributions**

O.M., B.L.G., O.C., and C.C. designed and supervised the project. F.A., G.L., and V.M. developed the synthesis and the characterization of the Dy samples and the preparation of the samples for magnetic measurements. W.W.L. recorded the EXAFS data, and the analysis was performed by G.S. and W.W.L. O.C. performed the magnetic measurements. F.A., G.S., B.L.G., J.D., W.W.L., F.P., O.C., V.M., and C.C. wrote the article.

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Notes
The authors declare no competing financial interest.

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ABBREVIATIONS
SMM, single-molecule magnet; STM, scanning tunneling microscope; EXAFS, extended X-ray absorption fine structure; XANES, X-ray absorption near edge structure

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(34) The discrepancy between these data is likely due to the low amount of magnetic centers in the samples measured (ca. 0.3 mg per sample).