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Viewpoint

Reversal of expectations

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A microscopic study of magnetic nanoislands on a surface challenges the widely held view that all atoms in a relaxing nanoparticle flip their spins in unison.

Subject Areas: **Magnetism, Nanophysics, Spintronics**

A Viewpoint on:
Magnetization Reversal of Nanoscale Islands: How Size and Shape Affect the Arrhenius Prefactor
S. Krause, G. Herzog, T. Stapelfeldt, L. Berbil-Bautista, M. Bode, E. Y. Vedmedenko, and R. Wiesendanger
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Magnetic nanoparticles form the basis of today's magnetic recording technology, and are also of more fundamental interest because of their rich magnetic behavior, which strongly depends on their size and drastically differs from that of bulk magnets [1–3]. A key factor for successful application is the stability of a magnetic bit against thermal fluctuations, i.e., the probability that a cluster spontaneously reverses its net spin by switching between two energetically equivalent but opposite orientations [4]. A widely accepted view is that, for nanoscale particles, all atoms flip their spins in unison. The probability then depends just on the number of spins and on a parameter—the magnetic anisotropy—describing the preference for spins to orient themselves along certain crystallographic directions.

In a paper appearing in *Physical Review Letters*[5] experiments by Stefan Krause, Gabriela Herzog, Thim Stapelfeldt, Luis Berbil-Bautista (currently at Lawrence Berkeley National Laboratory, US), Matthias Bode (currently at Argonne National Laboratory, US), Elena Vedmedenko, and Roland Wiesendanger, performed at the Institute of Applied Physics in Hamburg, Germany, question this simple picture. They unveil the existence of a more complex relaxation mechanism, highly sensitive to the morphology of the cluster, which controls the magnetic switching of islands consisting of barely 30 iron atoms.

In bulk ferromagnets, domain walls separate regions with different magnetic polarization [6]. Pinning of these walls by defects gives rise to hysteresis and therefore to magnetic memory. Below a certain size ferromagnetic material does not contain domain walls, as they become too expensive energetically, and thus single-domain particles emerge. Such particles, however, still show hysteresis.

In trying to explain why the magnetic polarization of geological strata keeps a record of the earth's magnetic field, Louis Néel gave a first account of the hysteresis phenomenon in magnetic nanoparticles [7]. Each nanoparticle behaves as a giant magnetic moment, formed by the ferromagnetic alignment of all individual atomic spins. The magnetic anisotropy creates an energy barrier for the rotation of this giant moment between two preferred orientations, because the spins must then "travel" via undesired orientations. The thermally induced switching rate is determined by the activation energy, which increases with the volume of the nanoparticle, and by the attempt rate, i.e., the number of equivalent metastable "paths" that link the initial and final orientations and how often the spin tries to attain them [7, 8]. Within this model, making smaller stable magnetic bits requires increasing the magnetic anisotropy [4], which is why understanding and controlling this parameter at the nanoscale has been such an intense subject of research in recent years [1, 3, 9–12].

Does this simple picture hold for very small magnetic clusters deposited on a surface? The experiments the Hamburg group has carried out on single-layer iron nanoislands grown on a tungsten surface suggest it does not. Monitoring the magnetic switching of a single island made of a few atoms (30–150 atoms) is beyond the capabilities of even the most sensitive micro-SQUID magnetometers [1, 10]. In order to achieve this, Krause and co-workers have employed the tip of a scanning tunneling microscope, covered by a thin layer of chromium, as a local probe. A schematic of their experimental setup is shown in the upper panel of Fig. 1. Despite the fact that chromium is an antiferromagnetic material, with no net magnetization, the spins of electrons tunneling from the tip towards the surface receive some polarization from the chromium atom situated at the tip's apex [13]. This clever trick avoids the disturbing effects that the dipolar

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field created by a ferromagnetic tip might have on the nanoislands under study, a necessary precaution when the objects are made by only a few atoms. The differential conductivity depends then on the relative magnetic polarizations of the tunneling electrons and the iron nanoisland situated under the tip [14]. The thermally induced switching of the nanoisland between two opposite orientations gives rise to a "telegraphic noise" in the conductance. Video 1 shows a movie of this telegraphic noise [5]. By recording a histogram of the intervals between consecutive events, the authors extract the average relaxation rate. The technique can therefore detect the magnetic switching of a single island, simultaneously providing a direct map of its morphology, with the atomic resolution typical of a STM.

As expected, the switching rate increases with decreasing size. The surprising result is that the activation energy depends only on the cluster's length along the easy magnetization axis. Contrary to the simple model of rotation in unison [8], where mainly the number of atoms in the cluster matters, the magnetization reversal seems instead determined by the energy of a one-dimensional row of atomic spins. The ensuing picture, illustrated in the lower panel of Fig. 1, is that of a reversed domain nucleating at one of the ends of the island, which, by propagating towards the other end, reverses the overall magnetization. The changing magnetic configuration of the dot, obtained from Monte Carlo simulations, can be seen in Video 2. The strongly anisotropic dependence of the activation energy on the cluster's dimensions arises from the preference of domain walls to lie along certain crystallographic directions [15]. Within this model, the cluster's shape plays an additional important role, which is also observed experimentally. The attempt rate is largest for clusters that are elongated along the easy magnetization axis because many atoms might potentially act as effective nucleation centers of a reversed magnetic domain. In the case of clusters elongated along the propagation axis, by contrast, the ratio of failed attempts, that is, of walls that come back and get annihilated, increases.

Domain walls, it seems, dominate the magnetization process in spite of being absent from the initial and final states. Because of this result, the work reported by Krause *et al.*[5] opens some unexpected possibilities for the design of magnetic devices. By varying the cluster's shape and orientation, the switching can be made slower, as required for magnetic recording, or faster, as required for magnetic sensing, for example. In addition, domain walls become pinned at lattice defects, which might be artificially fabricated by a modification of the substrate. Although still at the laboratory level, the experimental setup represents a realization of a spintronic device able to read out the information stored in a single nanoscopic bit. From a practical point of view, the realization of these promises might not be straightforward, as the fabrication of large arrays of identical islands with a control over their sizes and shapes is still a challenging task. However, exploring the same idea with magnetic molecules, which are even smaller, perfectly monodisperse, and might exhibit magnetic memory, could provide an exciting alternative [16].

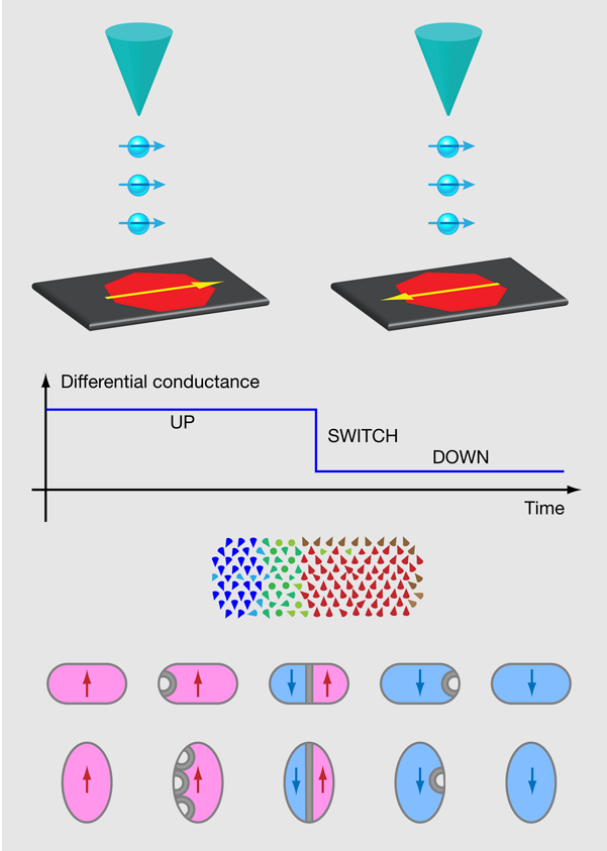

FIG. 1: (Top) Electrons tunnel between the tip of a STM microscope and a single-layer nanoisland of Fe atoms deposited on W. Because the tip polarizes the spins of these electrons, the differential conductance depends on the relative magnetic polarizations of the tip and the island: maximum when they are parallel (nanomagnet in "up" state), lower when they are antiparallel (nanomagnet in "down" state). (Bottom) During the magnetization reversal, the collinear alignment of atomic spins breaks down, as shown by the snapshot picture in the center, obtained from Monte Carlo simulations [5]. The nucleation of a reversed magnetic domain is followed by the propagation of a domain wall across the island. The probability of this process is determined by shape. For islands elongated along the propagation axis, domain walls are short and energetically more affordable, but they have a larger probability to turn back and annihilate. For islands elongated along the anisotropy axis, many atoms at the boundary can act as nucleation centers, but the activation energy increases, as does the length of the domain wall. (Illustration: Alan Stonebraker)

The results of Krause and co-workers open a few fundamental questions as well. They suggest that the switching of single-layer nanomagnets is fundamentally different from that of nanoparticles of the same size. Understanding why will probably require further studies, performed on magnetic elements with varying magnetic anisotropy and exchange couplings, as these parameters control the

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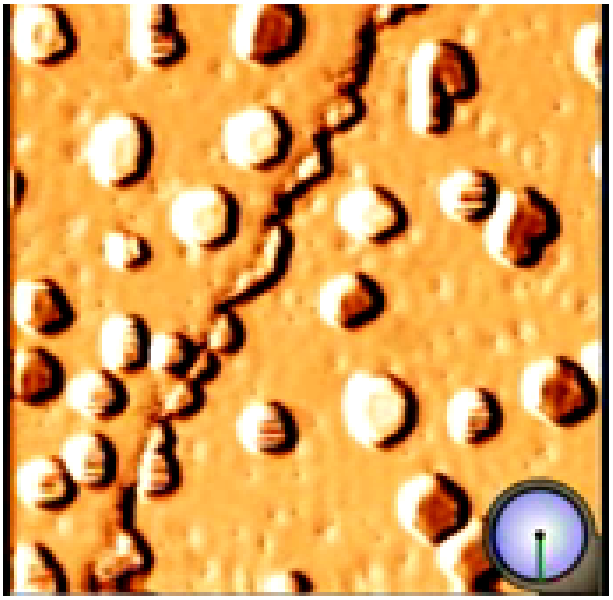
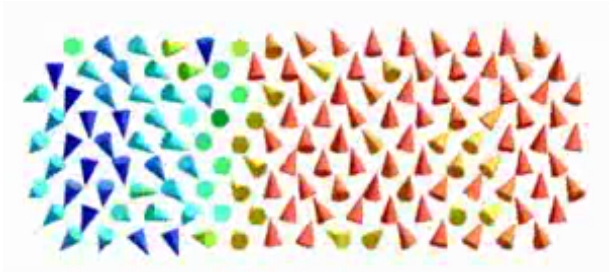


VIDEO 1: Spin-polarized scanning tunneling microcsopy images of switching nanoislands. Video available at: `http://physics.aps.org/articles/v/#video`.



VIDEO 2: The magnetic configuration within a nanoisland during reversal, as calculated with Monte Carlo simulations. Video available at: `http://physics.aps.org/articles/v/#video`.

structure, nucleation, and propagation of domain walls. From the point of view of theory, these results highlight the need for a more realistic description, which must include the influence of the substrate. Already important in nanometer-sized particles [1, 10, 11], the interaction with the supporting material becomes crucial for clusters made by just a single layer of atoms. In the case of iron atoms on tungsten, for instance, this interaction modifies Fe-Fe nearest neighbor distances and exchange interactions, in this way favoring the formation of domain walls and defining preferential orientations for them. The dominant mechanism probably results from a subtle balance between several factors, depending on the nature of the magnetic ions and the substrate, as well as on the cluster's morphology. In nanomagnetism, not only size matters after all.

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About the Author

Fernando Luis

Fernando Luis received his Ph.D. from the University of Zaragoza, Spain, in 1997, with a thesis on the phenomenon of spin quantum tunneling. He performed his post-doctoral research work first at the Kamerlingh Onnes Laboratory of the University of Leiden, The Netherlands, between 1998 and 2000, and then at the Institute of Materials Science of Aragón (ICMA), Spain, from 2000 until 2003. Since 2003, he has held a permanent appointment with the Spanish Council of Research (CSIC) at the ICMA. His research activity focuses mainly on the study of magnetic nanoparticles and molecular clusters, with a special interest on phenomena, like quantum tunneling, quantum coherence, dipolar magnetism, and quantum phase transitions, which occur near the absolute zero.

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