Direct Observation of Magnetic Metastability in Individual Iron Nanoparticles

Studying the magnetization of individual iron (Fe) nanoparticles by magnetic spectromicroscopy reveals that superparamagnetic (SPM) and ferromagnetic blocked (FM) nanoparticles can coexist in the investigated size range of 8-20 nm. Spontaneous transitions from the blocked state to the superparamagnetic state are observed in single particles and suggest that the enhanced magnetic energy barriers in the ferromagnetic particles are due to metastable, structurally excited states with unexpected life times.

Metastability is a well-known phenomenon in condensed matter, where energy barriers prevent a system to relax from a higher-energy state to the ground state. Since the barrier heights usually scale with the system size, the preparation of metastable, higher-energy states becomes possible at the nanoscale. Such states can be of profound interest when searching for materials with novel properties. For instance, much effort is currently undertaken to find magnetic nanostructures with properties that enable us to overcome the so-called “superparamagnetic limit,” which will occur when further reducing the magnetic bit size for future high-density magnetic data storage devices.

Researchers from the Paul Scherrer Institut, the University of Barcelona, the University of Ulm and the University of Konstanz used x-ray photoemission electron microscopy combined with x-ray magnetic circular dichroism at the Swiss Light Source to study the magnetic properties of individual iron nanoparticles on Si with sizes ranging from 20 down to 8 nm. They demonstrated that Fe nanoparticles can possess metastable magnetic properties that are significantly different from those derived from the properties of bulk Fe. Rather than all particles in the investigated size range exhibiting the expected superparamagnetism, a significant proportion of the Fe nanoparticles demonstrate FM behaviour. This FM proportion is characterized by uniaxial magnetization dynamics. The altered magnetic properties are attributed to metastable structurally excited states of the particles which can spontaneously relax to a lower-energy state that exhibits the anticipated SPM behavior. The coexistence of SPM and FM particles with the same size demonstrates that simple scaling of magnetic properties may not reflect the behavior of a nanoparticle ensemble—even when monodisperse, noninteracting samples are studied. The observed uniaxial magnetization dynamics in the FM particles indicates magnetic bistability—a property that is relevant for applications, such as magnetic data storage. Thus, searching for ways to stabilize nonequilibrium structures made from softmagnetic materials such as Fe might provide an interesting alternative to nanoparticles with ground state properties of hard-magnetic bulk alloys.

Read the full story

Reference

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Fig. (a),(b) Elemental and magnetic contrast images in the initial state before the magnetic field is applied. (c)–(f) Response of individual particles to a sequence of applied magnetic fields. The cycle starts with $H = 0$ mT at time $t_s$. The field cycle is indicated by black arrows. The full cycle is recorded over a time of about ten hours. The magnetic response of a particle is given by its field-dependent normalized XMCD contrast (circles). The red and the dashed lines serve as a guide to the eye. Three particles are denoted as “A,” “B,” and “C” in (a) and (b). Their magnetization curves are depicted in (c), (d), and (f). The insets in (c) and (d) show the normalized XMCD recorded as a function of orientation ($H = 0$ mT). The green line in (d) is a fit to the data. The magnetization curves in (e) and (f) demonstrate spontaneous transitions from (initially “white” and “black”) FM states to SPM behavior.