Large Enhancements of Magnetic Anisotropy in Oxide-Free Iron Nanoparticles

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Motivation—While the magnetism of isolated nanoparticles has been well understood for some time, a detailed understanding of the magnetism of nanoparticles interacting with a matrix material has been lacking. In particular, understanding the magnetic properties of nanoparticles with bound surfactants is critical for a variety of applications including such diverse areas as magnetic information storage and magnetic refrigeration.

Accomplishment—We are working with Fe nanoparticles as a model system to understand how the choice of surfactant modifies the magnetic properties of nanoparticles. Fe was chosen due to two important properties: it is both highly magnetic and extremely reactive. This allows us to easily measure the magnetic effects of chemical interactions of surfactants with the nanoparticle surface.

A recently developed synthesis that utilized beta-diketone based surfactants has been shown to produce oxide-free Fe nanoparticles with extremely high effective magnetic anisotropy. Measurements that demonstrate this are shown in Fig. 1. AC blocking temperature (the temperature where the particles direction of magnetization is able to reorient on the time scale of the experiment) measurements of 2.3 nm iron particles show a blocking temperature of approximately 20 K. Based on a calculation using the bulk anisotropy of iron, the expected blocking temperature is below 1K for particles of this size (see Fig. 2). The blocking temperatures of several sizes of particles are plotted in Fig. 2. These other sizes also exhibit the same high anisotropy, which is more than two orders of magnitude higher than the value for bulk iron.

There are a number of possible explanations for unusually high magnetic anisotropy in nanoparticles. One is surface anisotropy, where the lower coordination state of surface atoms causes excess anisotropy in the material. Another possibility is additional anisotropy caused by interparticle dipolar interactions. Both of these causes of excess anisotropy are, however, strongly size dependant. Surface anisotropy rapidly decreases with increased size due to the lower surface to volume ratio, while dipolar interactions increase greatly with increased size. Neither of these explanations are consistent with our observed constant anisotropy. It appears that the anisotropy is a material property induced by the unusual surfactant used. We are currently investigating this possibility and have observed unusual crystalline structure in these particles through X-ray diffraction. Developing an atomic level model of the structure of these particles is the subject of ongoing research.

Significance—Controlling the magnetic properties of nanoparticles has long been a goal of materials science. The technological benefits of exercising this control could be immense. For example, 2-5 nm magnetic particles could be used as bits for information storage if they were magnetically hard enough (have a high enough anisotropy). On the other hand, magnetic refrigeration requires lower anisotropy to maximize the magnetocaloric effect. Tuning the magnetic properties of the finite number of magnetic materials by varying surfactants could provide many new useful materials if it could be done in a controlled manner. This work is a step in that direction, as we have taken a famously soft magnetic material and made it a hard magnet.

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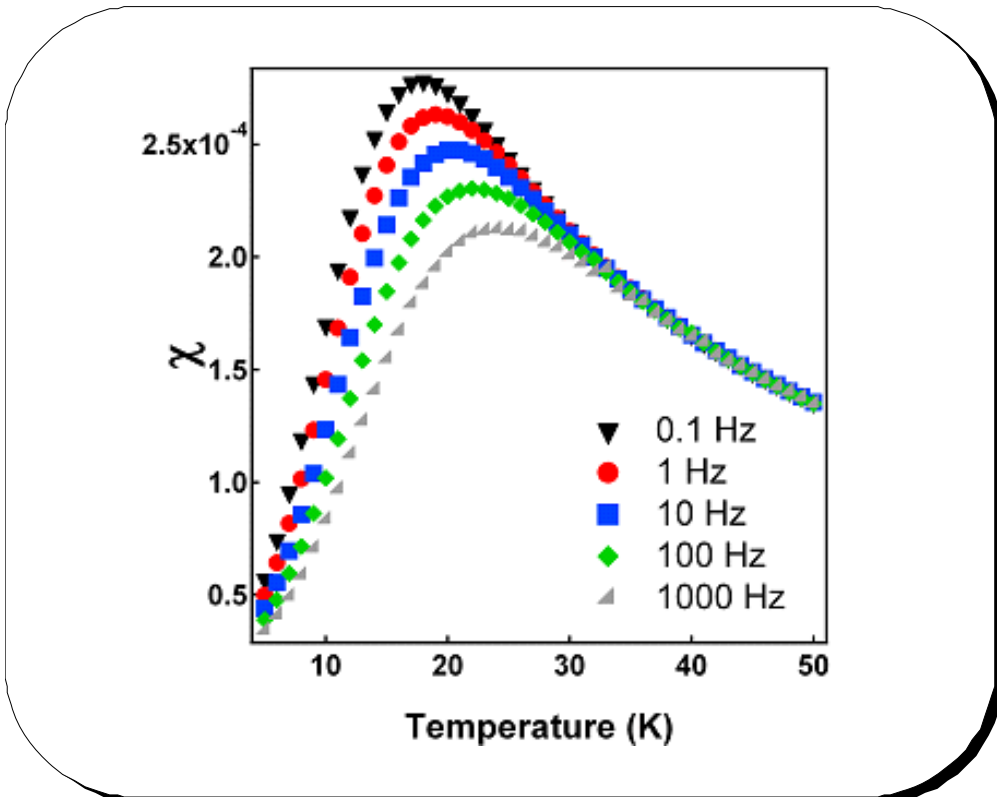

Figure 1. AC magnetic susceptibilities (χ) of a 2.3 nm diameter iron nanoparticle sample. These data are used to calculate an effective anisotropy for the nanoparticles.

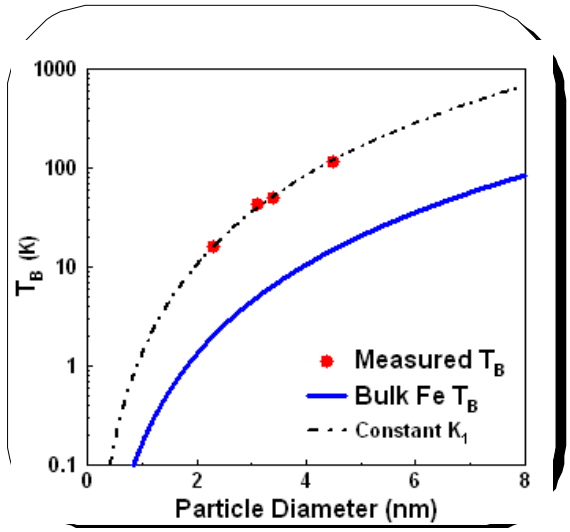

Figure 2. Plot of the measurement frequency (f) vs. $1/T_B$ for a 2.3 nm diameter iron nanoparticle sample. The data are fit with an Arrhenius function using the measured magnetic anisotropy for the nanoparticles and well-established literature values for bulk iron.