Nanomagnets bend the rules

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Nanocomposite materials seem to flout conventions of physics. In the latest example of surprising behavior, reported* by scientists at the National Institute of Standards and Technology (NIST) and Brookhaven National Laboratory, a class of nanostructured materials that are key components of computer memories and other important technologies undergo a previously unrecognized shift in the rate at which magnetization changes at low temperatures.

The team suggests that the apparent anomaly described as an "upturn" in magnetization may be due to the quantum mechanical process known as Bose-Einstein condensation. They maintain that, in nanostructured magnets, energy waves called magnons coalesce into a common ground state and, in effect, become one. This collective identity, the researchers say, results in magnetic behavior seemingly at odds with a long-standing theory.

The new finding could prompt a reassessment of test methods used to predict technologically important properties of "ferromagnetic" materials. The results also could point the way to marked improvements in the performance of microwave devices. Magnets are integral to these devices, used in a variety of communication and defense technologies.

Ferromagnets, including iron, cobalt, nickel and many tailor-made materials, become magnetic when exposed to an external magnetic field. As the strength of the external field increases, the materials become more magnetic, an atomic-level, temperature-influenced process called magnetic saturation. When the external field is removed, ferromagnets undergo an internal restructuring and the acquired magnetization decays, or fades, very slowly at a rate that increases with temperature.

Determined through accelerated testing methods, the temperature dependence of magnetic saturation and the rate of magnetization decay are key concerns in the design of permanent magnets, hard disks and other magnetic data storage systems.

The curious "upturn" in magnetic saturation is consistent with another magnetic anomaly reported in 1987 by NIST materials scientist Lawrence Bennett and colleagues. In an analysis of magnetic decay in a nickel-copper alloy, the team found a then-inexplicable peak in the decay rate within a range of low temperatures.

"Two very different experiments, almost 20 years apart, gave us similar results," explains Bennett. "These phenomena appear to be confined entirely to nanostructured materials."

Bennett is a co-author of the new report, along with Edward Della Torre, a NIST materials researcher and engineering professor at George Washington University, and Richard Watson, a theorist at Brookhaven National Laboratory.

In ferromagnetic materials immersed in a magnetic field, magnetization increases as the temperature drops. Cooling permits electrons, whirling like tops as they rotate about and among atoms that make up the materials, to line up their spins with the external field. As more heat energy is lost, more electrons align their spins in a very tidy arrangement. The strength of magnetization rises as this long-range ordering extends inside the material.

In so-called single-crystal ferromagnets, with their lattice-like atomic arrangement, the alignment of spins proceeds almost systematically. In fact, this seemingly straightforward relationship between temperature and magnetization had been reduced to a formula (known as Bloch's temperature law) more than seven decades ago.

The more structurally disordered multilayered cobalt-platinum ferromagnet initially evaluated by the researchers did not conform with the textbooks, however. As the temperature was lowered, the magnetization started increasing faster than expected, beginning at 14 degrees above the coldest possible temperature, called absolute zero. And the rate remained unexpectedly high down to 2 degrees above absolute zero.

The researchers attribute this apparent law-defying behavior to the banding together of variously dispersed magnons into a kind of quantum confederation. The shared identity technically termed a Bose Einstein condensate has a countervailing influence on normally unruly magnons.

Magnons typically are isolated wave patterns that are out of magnetic alignment with the rest of a sample, an indication that spinning electrons are breaking ranks. In effect, magnons could be classified as "anti magnetic." Bose-Einstein condensation results in a collective behavior that appears to counter this tendency among magnons, leading to the observed upturn in magnetization.

Rather than rewriting a long-accepted law of physics, this new understanding can be used to extend Bloch's law into the nanostructural regime, explains Della Torre. After inserting a term that accounts for energy change in a system, the team used the law to predict the high rate of saturation magnetization observed in several types of ferromagnetic nanocomposites.

"Now," says Bennett, "the challenge is to determine how the size, shape and other features of nanostructured materials are related to the Bose-Einstein condensation temperature."

*E. Della Torre, L.H. Bennett, and R.E. Watson,"Extension of the Bloch $T^{3/2}$ Law to Magnetic Nanostructrures: Bose-Einstein Condensation," Physical Review Letters, April 15, 2005.

Source: National Institute of Standards and Technology (NIST)

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