3-D insulator loses a dimension to enter magnetic 'Flatland'

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In a scrambled Rubik's cube, colorful squares clash without order. As pieces click into place in the hands of a skilled puzzle solver, the individual characters of squares dissolve as solid faces of uniform color emerge.

In the same way, barium copper silicate-also known as "Han Purple," a vivid pigment used in ancient China-transforms from a nonmagnetic, disordered insulator into a magnetic, ordered condensate under conditions of extreme cold and high magnetic field. The components that "click into place" to form an entirely new phase are the electron orientations of atoms, or "spins," described by their quantum state as "up" or "down."

Now, scientists at Stanford, Los Alamos National Laboratory and the Institute for Solid State Physics (University of Tokyo) have discovered that at the abrupt lowest temperature transition at which the silicate enters a new state-called the quantum critical point-the three-dimensional material "loses" a dimension to form a Flatland, of sorts. Just as in the 1884 novella Flatland that posited a planar world, the spins strongly interact only in two dimensions. Effects from the third dimension are negligible. Their work appears in the June 1 issue of Nature.

First author Suchitra Sebastian of the Geballe Laboratory for Advanced Materials and of the Applied Physics Department conducted the experiments for her doctoral dissertation in collaboration with coauthors Ian Fisher, an assistant professor of applied physics at Stanford who was Sebastian's thesis adviser; scientist Neil Harrison, who was on Sebastian's thesis committee, and scientist Marcelo Jaime, postdoctoral fellow Peter Sharma and theorist Cristian Batista, all of the National High Magnetic Field Laboratory (NHMFL) at its Los Alamos National Laboratory campus; scientist Luis Balicas of the NHMFL's Florida State University campus; and Associate Professor Naoki Kawashima of the University of Tokyo.

"We have shown, for the first time, that the collective behavior in a bulk three-dimensional material can actually occur in just two dimensions," Fisher said. "Low dimensionality is a key ingredient in many exotic theories that purport to account for various poorly understood phenomena, including high-temperature superconductivity, but until now there were no clear examples of 'dimensional reduction' in real materials."

Said Harrison: "What these findings in barium copper silicate demonstrate is something very fundamental that may provide the key toward understanding the role of dimensionality in quantum critical phenomena. This may be a crucial step for understanding the required properties of new materials, including more exotic superconductors, perhaps even ones with superconductance at higher temperatures."

In the normal, or insulating, state of the silicate, a pair of "up" and "down" spins cancel out each other to produce no net order. But in the magnetic state, ordering occurs between neighboring electron pairs in all three dimensions. At magnetic fields above 23 tesla (800,000 times that of the Earth's magnetic field) and temperatures near absolute zero, the silicate enters a rare state, called a Bose-Einstein condensate, in which electron spins move as a collective whole.

From frustration to fruition

At a critical point, the ordered spins in the condensate appear to lose a dimension. Think of the silicate as stacked layers. Suddenly, the spins in one layer cannot influence those of neighboring layers. Magnetic waves travel only along flat planes rather than throughout the entirety of the three-dimensional material.

Batista proposed a theoretical explanation for this strange behavior: It may be due to an effect called "geometrical frustration." In the crystal structure of barium copper silicate, individual copper atoms in the silicate layers are not stacked directly above each other, but instead, are shifted over in each layer in zigzag fashion. Near the critical point, the quantum behavior of the spins in such a layered arrangement may "frustrate" one layer from influencing neighboring layers.

The experimental techniques Sebastian and researchers used to show this effect allowed them to tune high magnetic fields at the lowest experimentally accessible temperatures to precisely access the immediate vicinity of the quantum critical point and explore new physics. World-class facilities and technical support at the National High Magnetic Field Laboratory at Tallahassee, Fla., made this possible. Before this discovery, it had not been possible to experimentally achieve this level of proximity to the quantum critical point in Bose-Einstein condensates.

"Magnetic moments associated with the electron spin seem to play a crucial role in the behavior of high-temperature superconductor materials," Batista said. "Fluctuations of the magnetic moments affect the flow of current-carrying electrons in a nontrivial way, in particular near the quantum critical point, where these fluctuations become very large. By studying the quantum critical behavior of insulating materials (with no current-carrying electrons), we can isolate the magnetic properties and gain a better understanding of their possible behaviors."

The discovery of reduction in dimensions at the quantum critical point in the magnetic insulator barium copper silicate provides a clue to mysterious physical phenomena observed in other materials, such as superconductivity at high temperatures and the anomalous behavior of metallic magnets known as "heavy fermions."

"The holy grail for condensed matter physicists is to make the essential step of understanding the mechanisms that can produce high temperature superconductivity," Harrison said. "The observed dimensional reduction in the Bose-Einstein condensate of barium copper silicate provides a particularly vivid example of the role of dimensionality in condensate physics because it is free from other complications that cloud our understanding of superconducting materials."

While electron charge now transports information in electronic devices, electron spin may someday fulfill the same role in "spintronic" devices.

"Spin currents are capable of carrying far more information than a conventional charge current-which makes them the ideal vehicle for information transport in future applications such as quantum computing," Sebastian said.

Noted Fisher: "Our research group focuses on new materials with unconventional magnetic and electronic properties. Han Purple was first synthesized over 2500 years ago, but we have only recently discovered how exotic its magnetic behavior is. It makes you wonder what other materials are out there that we haven't yet even begun to explore."

Source: by Dawn Levy, Stanford University

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