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Earth-crushing pressure? This electron spin doesn't care

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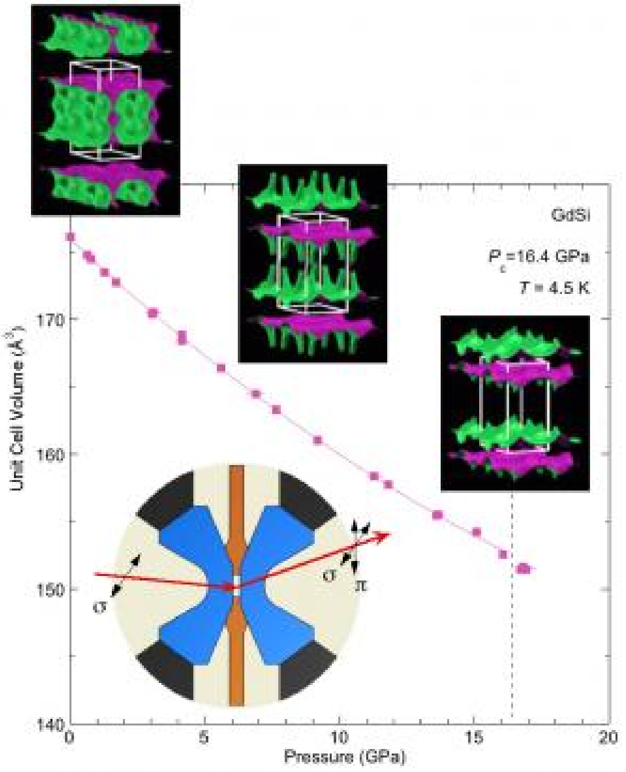

X-rays from a synchrotron-based source are so brilliant that it is now possible to perform magnetic diffraction in a specially-designed, high-pressure diamond anvil cell at pressures above 15 GPa (circular inset). A sample's magnetic nature is reflected in the modified polarization of the x-rays in both transverse directions. When applied to GdSi, the researchers were able to directly trace its antiferromagnetism over a large volume reduction of up to 1/7th of the original size (main figure). The magnetism was found to remain constant, while the pressure's effect is reflected in the gradual change in the material's band structure. The Fermi surface, which supports the formation of itinerant antiferromagnetism at ambient pressure, grows increasingly one dimensional (to a sheet shape) under pressure (three inset panels). However, as long as it survives, magnetism does as well.

(Phys.org) —To fully understand something, it is often instructive to view it at its extremes. How do materials behave when their bits are forced much closer together than is comfortable? How do electrons accommodate proximity? What normal behaviors break down?

The highest pressure a nuclear submarine can safely experience is around 850 lbs per sq in. (psi), or nearly 6 million Pascals (Pa). Pressure washers spew out water at roughly five times this pressure, or 30 million Pa. Three-hundred miles below the surface of the Earth, in a part of the mantle called the transition zone, minerals are squeezed at an immense 15-billion Pa—enough to turn carbon into diamonds.

This is the kind of intense environment that researchers working at the X-ray Science Division 4-ID-D x-ray beamline at the U.S. Department of Energy's (DOE's) Advanced Photon Source (APS) at the DOE's Argonne National Laboratory applied to GdSi, a compound of gadolinium (Gd) and silicon (Si).

While a diamond anvil cell bore down on the crystalline fleck, x-rays penetrated within, bouncing off of, ejecting, and energizing the material's component parts, and relaying back to the researchers information about the locations and states of its atoms and electrons.

Despite shrinking by one-seventh of its volume, the team discovered that GdSi's magnetism remained robust. This behavior was surprising. High pressure will often quench a magnet. But here, the electrons responded to the harsh conditions by forming a resilient superstructure —ideal behavior for digital memory that needs to withstand abuse.

Some computer memory is based on a concept called "giant magnetoresistance." These devices consist of thin, alternating layers of magnetic and non-magnetic material. The materials interact such that changes in magnetic attraction and repulsion of one layer affect the electrical resistance in the next. Small magnetic fluctuations can create large electronic variations. In this way, digital information can be stored: electric signals change the characteristics of the magnetic material. When the user wants that information back, the magnetic material changes electron flow in the adjacent non-magnetic layer, and the digital information is read back out.

One of the challenges with memory storage is stability. Sometimes the thin layers of material do not match up, and this causes great internal stress. Heat adds another layer of instability. If these stresses change the magnetic material, information is lost. A material like GdSi, which retains its magnetism despite great stress, could make for very stable memory storage.

But what causes this behavior? It can be traced, in part, to a cooperative interaction between mobile electrons and localized spins. With high-sensitivity x-ray diffraction, the researchers examined both the atomic structure and the magnetic state of the GdSi crystal as it was squeezed from all sides (see the figure). Until recently, such direct magnetic tracking was nearly impossible and in fact, this is the first successful use of x-ray magnetic diffraction at such high pressures.

Previously, researchers had to rely on more indirect methods. Now, utilizing the high-brightness x-rays from the APS, a DOE Office of Science user facility, they could "watch" how the magnetic states evolved and compare their observations with theoretical calculations. Previous work had shown that these interactions should stabilize GdSi's magnetism, but now the researchers were able to prove that these effects remained under high pressure.

With experimentally sourced lattice information, the researchers in this study, from Argonne; The University of Chicago; DOE's Los Alamos National Laboratory; the National Science Foundation; the University of Tennessee, Knoxville; and DOE's Oak Ridge National Laboratory then calculated the structure of GdSi's electronic energy bands—the ranges of energy that an electron within the material may assume. These energy bands depend on many factors, including the location of atomic species, as well as the long-range atomic patterns.

The researchers found that through the entire pressure range one dominant band flattened yet still persisted. This continuity likely benefited from the material's stable atomic structure—Gd atoms in hexagonal sheets, layered to form tubes surrounding paired Si atoms, a linear arrangement that translated into robust electronic bands. Each is connected: the lattice created a stable electron band, which together with stable local spins helped to maintain the material's robust magnetism despite immense pressure.

The interplay between electron spin, charge, and atomic arrangement is complex and not always fully understood. GdSi clearly has potential as a material well-suited to computer memory and magnetic sensors but beyond this, the ability to observe how a material's magnetic properties change under extreme conditions should promote more discoveries. Researchers now have a new window into the complex lives of electrons under stress.

More information: Yejun Feng, et al. "Hidden one-dimensional spin modulation in a three-dimensional metal," *Nat. Commun*. 5, 4218 (2014). DOI: 10.1038/ncomms5218

Provided by Argonne National Laboratory

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