Mixing topology and spin

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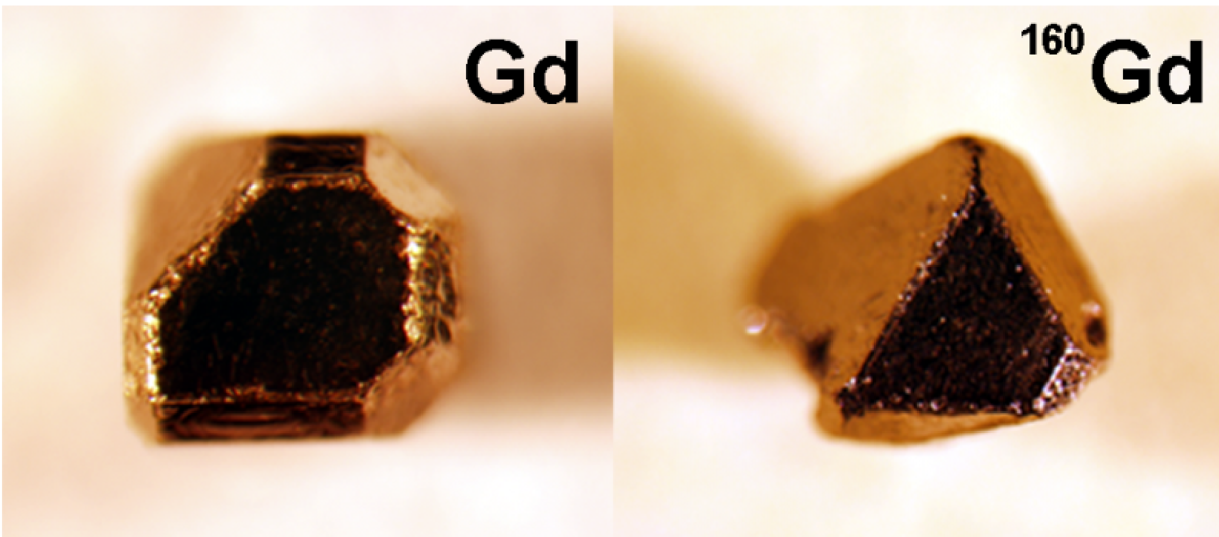


At left: A single crystal compound of gadolinium, platinum, and bismuth made with naturally occurring elements. At right, a single crystal of this material made with isotopically enriched gadolinium for neutron scattering experiments. Both crystals are approximately 1 mm in size. Credit: Massachusetts Institute of Technology

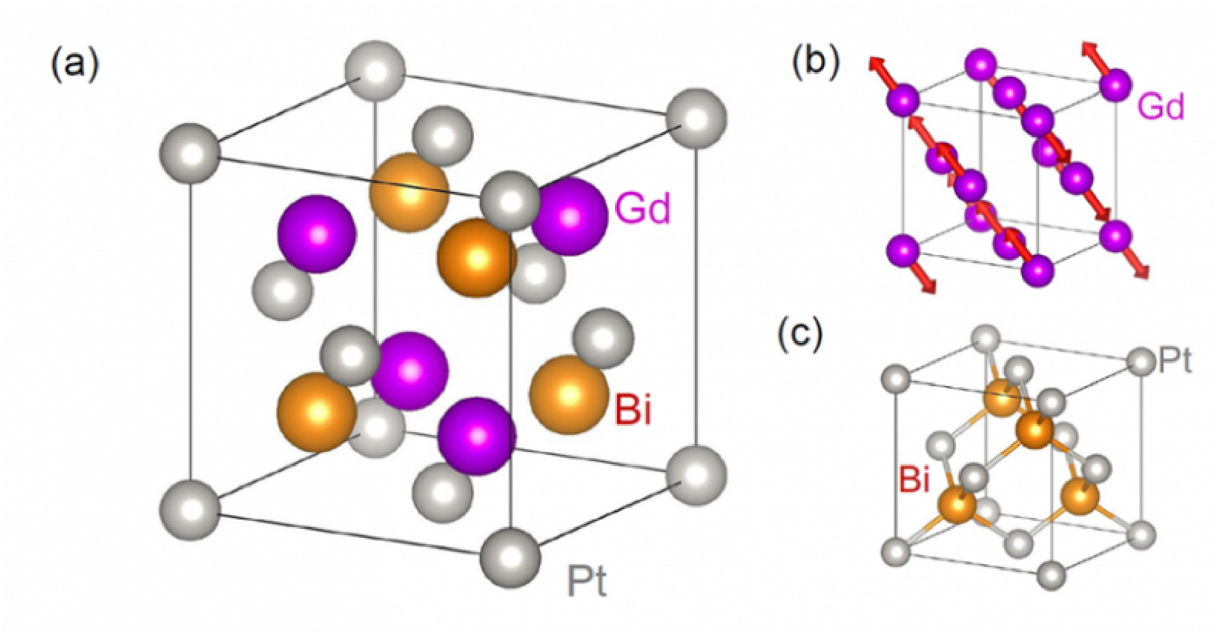
In the pursuit of material platforms for the next generation of electronics, scientists are studying new compounds such as topological insulators (TIs), which support protected electron states on the surfaces of crystals that silicon-based technologies cannot. Dramatic new physical phenomena are being realized by combining this field of TIs with the subfield of spin-based electronics known as spintronics. The success within spintronics of realizing important magnetic technologies such as the spin valve have increased the expectations that new results in TIs might have near-term applications. However, combining these two research threads has relied on "shoehorning" magnetism by forcing magnetic atoms to partially occupy elemental positions in TIs or by applying a conventional magnetic field. Realizing an integrated material that is both intrinsically magnetic and has a topological character has proven more challenging.

Integrating correlation

Recently a team of researchers based in the group of Joseph G. Checkelsky, assistant professor of physics at MIT, and collaborators at the NIST Center for Neutron Research (NCNR), Carnegie Mellon University, and the Beijing Institute of Technology have experimentally demonstrated a "hybrid material" solution to this problem. They studied a compound of three elements, gadolinium, platinum and bismuth, known together as a ternary compound. In their compound, gadolinium supplies the magnetic order while the platinum-bismuth components support a topological electronic structure. These two components acting in concert make a correlated material that is more than the sum of its parts, showing quantum mechanical corrections to electrical properties at an unprecedented scale. Their results were reported July 18 in *Nature Physics*.

Proving this delicate interplay between the constituent elements of this compound required studying it from different perspectives. With experimental efforts led by research scientist Takehito Suzuki, the MIT group (including physics graduate student Aravind Devarakonda and physics undergraduate Yu-Ting Liu) synthesized single crystals and studied their electronic and magnetic properties. The team found these crystals at the same time were exotic magnets and exhibited signatures of electronic topology. The latter was observed through the so-called Berry phase corrections to electronic behavior, where they saw the largest such response reported to date in this type of magnet, which is known as an antiferromagnet.

The Berry phase reflects the quantum mechanical nature of the charge-carrying electrons in metals and is influenced by magnetic order. They identified an antiferromagnetic transition temperature of 9.2 kelvins (-443 degrees Fahrenheit). At or below this temperature, magnetic moments of the gadolinium atoms align in an alternating pattern of spin up and spin down. Interestingly, for temperatures significantly higher than this they could observe remnants of this magnetic order in both magnetic and electronic properties, a possible hallmark of the underlying frustrated geometry of the crystal lattice.



A: Crystal structure of a gadolinium (Gd), platinum (Pt), and bismuth (Bi) compound that is composed of [B] a magnetic gadolinium-face-centered cubic sublattice and [C] a platinum-bismouth zinc-blende sublattice. An MIT-led study found that these crystals at the same time were exotic magnets and exhibited signatures of electronic topology. Credit: Massachusetts Institute of Technology

Viewed from many angles

While these experiments were enticing, the team wanted to be sure that what they were observing originated from the topological properties that would connect this material to potentially ground-breaking types of future electronic devices. Experimentally, this involved work at national facilities including the NCNR, where Suzuki worked with Robin Chisnell PhD '14 and NIST Fellow Jeffrey W. Lynn. Using a triple axis spectrometer (BT-7), they studied the scattering of neutrons from carefully aligned single crystals in the low temperature antiferromagnetic phase including in different magnetic field conditions. These experiments provided the ability to map the behavior of the magnetic gadolinium spins to precisely know their orientation and response to temperature and magnetic field. In order to do these experiments, naturally occurring gadolinium could not be used due to its overwhelming neutron scattering cross-section, and the researchers used instead a costly isotope known as gadolinium -160.

In general, growing single crystals of these compounds is challenging because of their high melting temperature; the growth process known as a "flux method" requires high-temperature centrifuging to remove the crystals from a bath of liquid bismuth. "It's a bit like growing rock candy sugar crystals, except that we use liquid bismuth instead of water," says Checkelsky. The process is well-known to solid state chemists, but can have a high failure rate. The team was able to obtain enough of the isotope for just two growth runs, both of which turned out to be successful. The subsequent experiments at NCNR were able to provide critical information about the gadolinium moments that shaped the team's understanding of their results.

The team also made use of the National High Magnetic Field Laboratory (NHMFL) based in Tallahassee, Florida. There, the MIT team brought the crystals to measure their response to extreme magnetic conditions involving magnetic fields in excess of 30 T (among the largest DC fields available in the world). The extreme conditions available at the NHMFL also allowed the group to broadly map the electronic and magnetic properties of the crystals to complete the picture of the magnetic order. In particular, they were able to observe a previously unreported phase transition for the gadolinium spins near 25 T that appeared to finally "break" the antiferromagnetic state.

The final aspect of the collaborative effort was with professors Di Xiao of Carnegie Mellon University and Wanxiang Feng of Beijing Institute of Technology, who provided first principles electronic structure calculations based on the experimental data taken at MIT, NCNR, and the NHMFL to determine the underlying electronic character of this new materials system.

"The authors combine high-quality crystal growth, transport measurements, neutron spectroscopy, and theoretical calculations to establish the magnetic ordering and its profound effect on electrical properties in a topological material," says Liang Fu, assistant professor of physics at MIT, who was not involved in this research. "This seminal work reveals surprising quantum phenomena arising from the interplay between electron topology and correlation. This type of correlated topological phenomena is long sought after, but has been difficult to find in real materials. By identifying the right material, Joe Checkelsky's group and collaborators have found a new, promising platform for fundamental research and potential spintronics applications."

New "hybrid" approach

Checkelsky notes that the experiments reported in *Nature Physics* provide proof that such a "hybrid approach" to designing new electronic platforms can pay dividends despite the challenge it presents directly to theoretical predictions. "The approach to realize TIs in which the correlated behavior of the underlying electrons plays an important role has stood as a challenge to the TI community. Part of this is due to the increased complexity of correlated electronic systems that increases the difficulty for theoretical predictions to guide experimental work," he says. The results have a wide variety of potential implications, ranging from new approaches to exotic antiferromagnetic materials to new topological phases known as Weyl semimetals. The present experiment demonstrates that forging ahead with experimental work can be successful in then feeding back into theory to make significant progress at the crossroads of complex materials and topological phases.

More information: T. Suzuki et al. Large anomalous Hall effect in a half-Heusler antiferromagnet, *Nature Physics* (2016). DOI: 10.1038/nphys3831

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