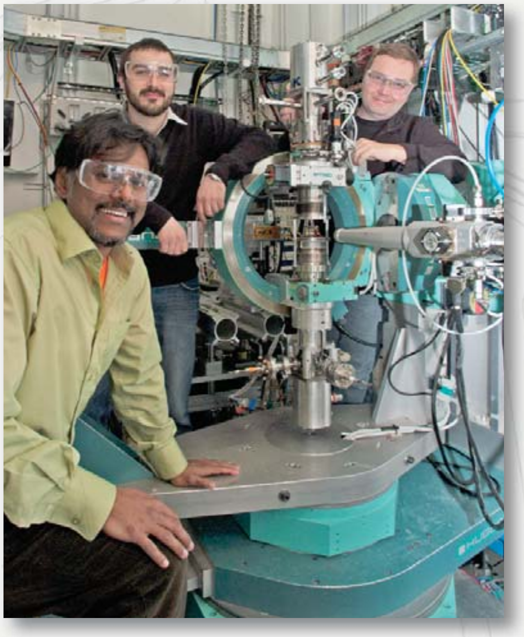
The Advanced Photon Source

Probing Spin Liquids with a Pulsed-Magnet System

Unexplored experimental vistas could be opened by a new pulsed-magnet system developed by an international team of scientists. This system generates magnetic fields as high as 30 T for synchrotron x-ray scattering experiments. The researchers completed the first practical work using the system at the X-ray Science Division (XSD) 4-ID-D beamline at the Advanced Photon Source, studying magnetoelastic effects in the rare-earth pyrochlore terbium titanate ($Tb_2Ti_2O_7$). The study produced unique insights into the $Tb_2Ti_2O_7$ system, and is the first step in developing this new capability at the APS to address high-field science at the frontiers of contemporary condensed matter physics.



Co-authors and collaborators (l. to r.) Zahirul Islam , Jacob Ruff, and Jonathan Lang with the pulsed-magnet system in the XSD 4-ID-D station.

Terbium titanate is a member of a materials class called "frustrated magnets" because tetrahedral coordination of magnetic moments of Tb ions in the lattice structure prevents them from settling into a predictably ordered magnetic ground state. Such materials may exhibit magnetostrictive effects (a property that causes them to change their shape or dimensions when subjected to a magnetic field) and other exotic ferromagnetic and antiferromagnetic properties, which may be relevant to electronic transducers and switching applications.

Terbium titanate remains in a highly disordered spin-liquid ground state even at the lowest measurable temperature, while exhibiting magneto-striction exceeding that in commercial compounds such as Terfenol-D. Attempts to explain the material's behavior theoretically have been inconclusive, awaiting experimental data on its lattice properties in the spin-liquid state. The problem in general for magnetoelastic effects, and in particular for systems that don't order, hasn't been well studied using structural probes such as x-rays.

The new pulsed-magnet system at the APS [1] has proven to be an ideal tool for direct structural observation of the $Tb_2Ti_2O_7$ compound at low temperatures using single-crystal x-ray diffraction and extreme magnetic fields on the 4-ID-D beamline. Prior to the work in question, there was much incidental evidence that the orientation of the magnetic moments was strongly coupled to the actual positions of the atoms inside the crystal lattice. The APS pulsed magnet allowed the experimenters to carefully constrain and measure that directly with x-rays. By applying high magnetic fields they could watch the lattice shift and bend and twist around.

Pulsed-magnet experiments provide some unique advantages for materials science work. Materials often display exotic phases under extreme conditions, which are fundamental to understanding their functionality, and the pulsed magnet can generate this type of extreme condition in a contact-free way. Because the pulsed field is generated fast for a short duration, one may also combine it with the natural timing structure and high brilliance of synchrotron radiation for precision studies of structural relaxations and metastable phenomena on a micro-second level.

The researchers subjected $Tb_2Ti_2O_7$ crystals to pulsed magnetic fields of up to 30T and temperatures as low as 4.4K, measuring the transverse magnetostriction in different conditions and observing the deformations of the crystal lattice via diffraction studies. They found anisotropic magnetoelastic effects that have not been previously observed or predicted in the rare-earth titanates. At high temperatures, the $Tb_2Ti_2O_7$ system behaves much like a conventional paramagnet, but crosses over to display a collective response in the spin-liquid regime. Under moderate magnetic fields, some cubic pyrochlore symmetry is restored, but this gives way to a structural phase transition when the magnetic field is increased. The results indicate a very large coupling between spin and lattice degrees of freedom in the spin-liquid state of $Tb_2Ti_2O_7$. Most likely, the reason it doesn't order at low temperature is that any ordered state would have internal magnetic fields and would have to distort or bend the lattice around.

The split-pair coil used in the APS dual-cryostat pulsed-magnet system was designed and fabricated by Hiroyuki Nojiri and Yasuhiro Matsuda at the Institute for Materials Research at Tohoku University. The experimental team plans two complementary instruments that will allow different experimental orientations of the x-ray beam and magnetic fields, permitting researchers to design experiments utilizing various x-ray techniques.

While the pulsed magnets are not the answer to every problem requiring magnetic fields, it is the only practical approach that will be available in the foreseeable future for studying many materials at a synchrotron in high magnetic fields. The current work not only provides unique insights into the $Tb_2Ti_2O_7$ system, but serves as the first major step in developing this exciting new capability at the APS to address high-field science at the frontiers of contemporary condensed matter physics. — *Mark Wolverton*

[1] Zahirul Islam, Jacob P.C. Ruff, Hiroyuki Nojiri, Yashuhiro H. Matsuda, Kathryn A. Ross, Bruce D. Gaulin, Zhe Qu, and Jonathan C. Lang, "A portable high-field pulsed-magnet system for single-crystal X-ray scattering studies," Rev. Sci. Instrum. 80, 113902 (2009).

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Call for APS General-User Proposals

The Advanced Photon Source is open to experimenters who can benefit from the facility's high-brightness hard x-ray beams.
General-user proposals for beam time during Run 2011-3 are due by Friday, July 8, 2011.
Information on access to beam time at the APS is at http://www.aps.anl.gov/Users/apply_for_beamtime.html or contact Dr. Dennis Mills, DMM@aps.anl.gov, 630/252-5680.

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