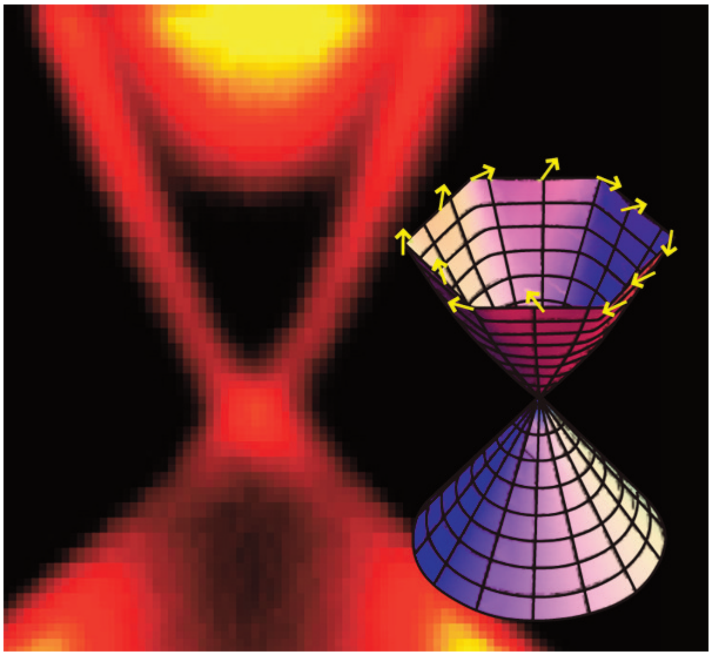
ALS SCIENCE HIGHLIGHT

PUBLISHED BY THE ADVANCED LIGHT SOURCE COMMUNICATIONS GROUP

# ALS Reveals New State of Matter

Publications about this work: D. Hsieh et al., *Nature* **452**, 970 (2008); D. Hsieh et al., *Science* **323**, 919 (2009); Y. Xia et al., *Nat. Phys.* **5**, 398 (2009); Y.L. Chen et al., *Science* **325**, 178 (2009); D. Hsieh et al., *Nature* **460**, 1101 (2009); P. Roushan et al., *Nature* **460**, 1106 (2009); and D. Hsieh et al., *Phys. Rev. Lett.* **103**, 146401 (2009).

ALS user groups from Princeton and Stanford have been making waves this past year with several high-profile papers and extensive news coverage of their work on a new state of matter embodied by "topological insulators," materials that conduct electricity only on their surfaces. First identified at the ALS in 2007 by a Princeton team led by M. Zahid Hasan, topological insulators have been the subject of intense interest, based on unusual quantum properties that manifest themselves macroscopically. The discovery of a "second generation" of topological insulators that robustly retain these properties well above room temperature has spurred a rising tide of theoretical proposals for potential applications in nanoscale spintronic devices and fault-tolerant quantum computers. In addition, it's also been suggested that topological insulators may serve as a test bed for studies of never-before-seen particles predicted by high-energy physics.



**Band structure of the topological insulator, bismuth selenide ($Bi_2Se_3$). The red areas represent surface states. The vertical space between the yellow areas is the bulk band gap (about 0.3 eV). Because the surface states cross the band gap, this "insulator" conducts electricity on its surface. Inset: Three-dimensional schematic of the cone-shaped surface band structure. The spin states (yellow arrows) indicate that electrons on the surface won't backscatter from disorder and impurities. (Image courtesy of David Hsieh, Yuqi Xia, and Andrew Wray, Princeton University).**

The research from Princeton and Stanford (Yulin Chen and others from Z.-X. Shen's group) used angle-resolved photoemission spectroscopy (ARPES) to identify new classes of topological insulator materials and to establish key traits of their unique electronic environment. The Princeton group worked at ALS Beamlines 12.0.1 and 10.0.1 as well as Stanford Synchrotron Radiation Lightsource (SSRL) Beamline 5-4, while the Stanford group worked at ALS Beamline 10.0.1 and SSRL Beamline 5-4. Their results have reinforced the importance of synchrotron light sources as an indispensable tool in exploring matter in the twenty-first century.

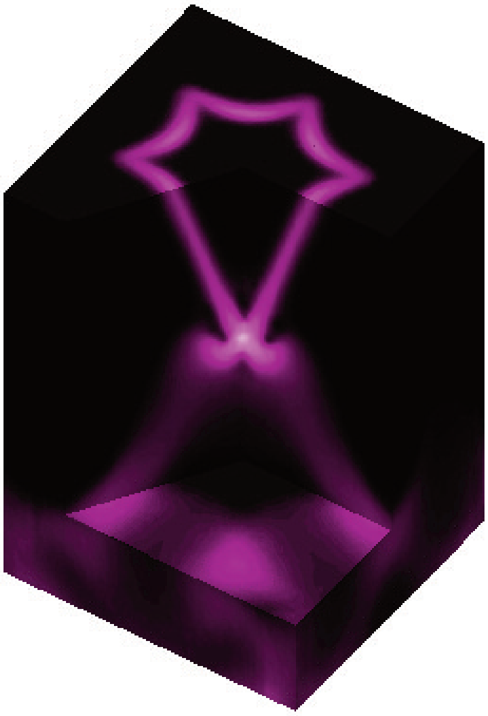
The experimental results show that electrons in topological insulators are constrained by a very different set of rules than are electrons in normal matter. Macroscopic topological insulators are referred to as insulators because electrical conductivity is very weak deep inside the bulk of the crystal; however, a skin of highly conducting states becomes available as electrons draw close to the crystal surface, making the physical system of a topological insulator crystal analogous to a hollow metallic box. The photoemission measurements confirmed that these surface states are described in momentum space by an odd number of Dirac cones, which signify electrons that behave as if they have no mass. In addition, the spin-sensitive measurements showed that the surface conduction states are spin polarized: electrons with a given spin will all move in the same direction along the surface and retain their quantum phase.

The researchers combined atomic-scale scanning tunneling microscopy and spin-resolved photoemission measurements to show that the nature of spin polarization in topological insulators removes the ability of electrons to backscatter (no "Uturns" for electrons) and largely protects them from all scattering that would be caused by impurities and defects in a normal conducting material. Scattering from defects is a source of electrical resistance, wavefunction decoherence, and electron localization, all of which are obstacles to device engineering with normal materials on the nanometer scale. This opens the door to many advances in spintronics and quantum computing.

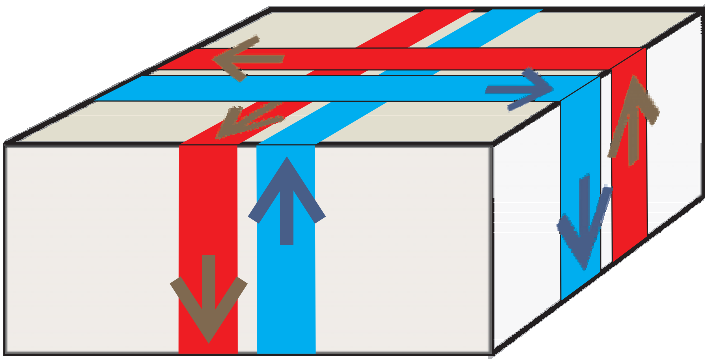
The Princeton collaboration originally identified a bismuth antimony alloy ($Bi_{1-x}Sb_x$) to be the first known three-dimensional topological insulator in 2007 and hypothesized that a closely related class of bismuth-based material, the bismuth selenide ($Bi_2Se_3$) class, should also display similar topological behavior but with a larger bulk insulating gap, simpler Dirac electron kinetics, and possibly much higher operating temperatures. Investigations by Princeton, Stanford, and several other groups throughout 2009 have confirmed that a significant class of materials with the chemical formula $M_2X_3$ (M = Sb, Bi; X = Se, Te) can achieve topological behavior (in most cases), and the bulk band gap in $Bi_2Se_3$ in particular was seen in photoemission experiments to be the largest (around 300 meV), setting an energy scale record that renders the topological insulator state stable up to the crystalline melting point (~710 °C, or 1310 °F).

Beyond their potential for practical applications, topological insulators may also provide a way to study fundamental particle physics—a "tabletop universe" of sorts. Some researchers believe that the conditions inside this new state of matter can be manipulated (for example, by bringing it into contact with a superconductor or adding an electromagnetic field) in ways that cause electrons to simulate the quantum properties of theorized but elusive particles. Examples of such exotic particles include axions (a possible constituent of dark matter), magnetic monopoles (poles of north and south magnetism isolated from each other), and Majorana particles (fermions that function as their own antiparticles).

The successful collaborative application of diverse experimental techniques confirms that the spectroscopic tools for identifying and investigating the physics of still more topological insulator materials are developing rapidly. Taken collectively, the latest results have already uncovered an exciting macroscopic quantum environment, in which new physical rules create a new realm of phenomenological possibilities.



**Three-dimensional image of the surface band structure of bismuth telluride ($Bi_2Te_3$). The V-shaped pure surface state is nearly isotropic in the momentum plane, forming a Dirac cone in momentum space. (Image courtesy of Yulin Chen and Z.-X. Shen, Stanford University.)**



**Schematic of the two-dimensional surface states in a three-dimensional topological insulator. The red and blue strips represent surface currents with opposite spin character.**