BASIC RESEARCH

ALS SCIENCE HIGHLIGHT

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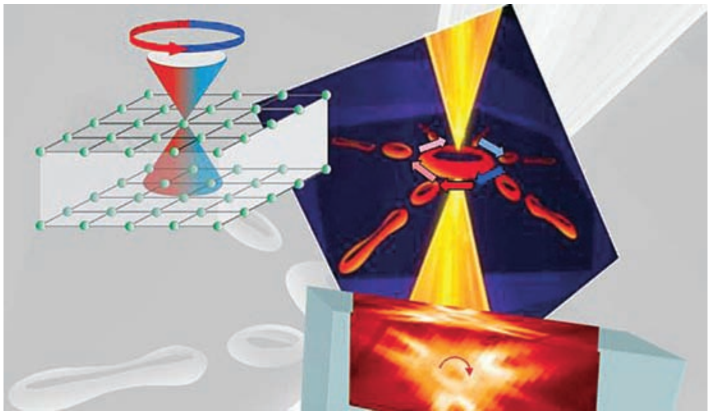
Observation of a Macroscopically Quantum-Entangled Insulator

It has recently been proposed that insulators with large band gaps and strong spin–orbit coupling can host a new phase of quantum matter called a topological insulator that is characterized by entangled wavefunctions. The proposal has now been realized by an international collaboration led by researchers from Princeton University who studied the electronic structure of insulating alloys of bismuth and antimony by means of angle-resolved photoemission spectroscopy (ARPES) and spin-resolved ARPES. Their results constitute the first direct experimental evidence of a topological insulator in nature that is fully quantum entangled. In the future, a detailed study of topological order and quantum entanglement using their method can potentially pave the way for fault-tolerant (topological) quantum computing.



A new type of quantum matter called a topological insulator contains only half an electron pair (represented by just one cone in schematic crystal structure at top left), which is observed in the form of a single ring (red) in the center of the electron map (top right) with electron spin in only one direction. This highly unusual observation shows that if an electron is tagged "red" and then undergoes a full 360-degree revolution about the ring, it does not recover its initial face as an ordinary everyday object would, but instead acquires a different color "blue" (represented by the changing color of the arrows around the ring). This new quantum effect can be the basis for the realization of a rare quantum phase that had been a long-sought key ingredient for developing quantum computers that can correct themselves.

Quantum entanglement can occur in quantum mechanical systems of two or more objects in which the quantum states of the constituent objects are linked together, thus leading to nonclassical correlations between observable physical properties of the system. Entanglement is a required feature of quantum computing schemes. The wavefunction coherence required for entanglement is difficult to maintain for macroscopic objects, so entanglement is usually observed in systems comprising atoms or smaller particles. However, the recently proposed topological insulators are described by a quantum entanglement of its wavefunction, dubbed topological order, which survives over the macroscopic dimensions of the crystal. The topological order sets these insulators apart from "ordinary" quantum phases of matter such as superconductors, magnets, or superfluids.

Topologically ordered phases of matter are extremely rare and are experimentally challenging to identify. The only previously known example was the Nobel Prize–winning discovery of the quantum Hall effect insulator in the 1980s in a two-dimensional electron system under a large external magnetic field at very low temperatures. While these systems are characterized by robust conducting states localized along the one-dimensional edges of the sample, two-dimensional topological insulators are predicted to exhibit similar edge states even in the absence of a magnetic field because spin–orbit coupling can simulate its effect. Three-dimensional topological insulators are an entirely new state of matter with no charge quantum Hall analogue. Their topological order or quantum entanglement is predicted to give rise to conducting two-dimensional surface states that

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U.S. DEPARTMENT OF ENERGY

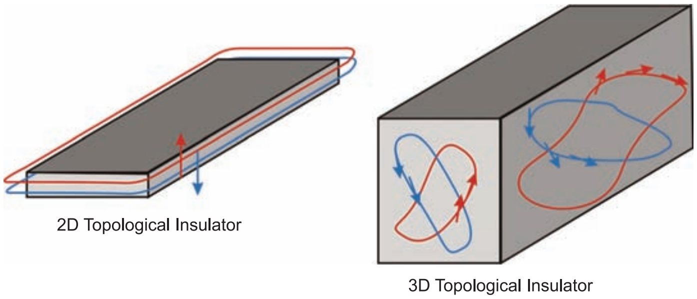
BERKELEY LAB

ALS ADVANCED LIGHT SOURCE

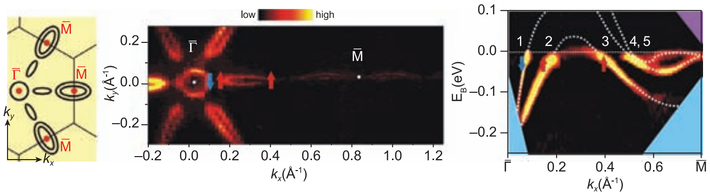
A New Form of Macroscopic Quantum Weirdness

One of the strangest consequences of quantum mechanics is the possibility of seemingly instantaneous communication between subatomic particles over long distances. When they are "entangled," pairs or groups of particles become linked so that any changes made to one will cause the others to respond faster than the speed of light. Can quantum entanglement of this type also occur at a macroscopic scale (i.e., one we can see)? One place scientists have been looking for it to occur is in materials that do not conduct electricity well. Dubbed a topological insulator, this theorized state of matter would have unusual properties. Not only would it be interesting as an exotic new state of matter, it could also have application to quantum computers because its information-processing properties would be insensitive to the presence of impurities, making quantum operations naturally fault-tolerant.

By using an advanced form of x-ray spectroscopy at three different synchrotron light sources to study the properties of the entangled electrons in a proposed topological insulator material made from bismuth and antimony, an international collaboration led by scientists from Princeton University has now confirmed that the material is fully quantum entangled, making this the first example of a three-dimensional topological insulator in nature. In addition, the groups' work is applicable to other materials because it defined a general method for identifying and characterizing other topological insulator states of matter.



Left: Schematic of the one-dimensional edge states in a two-dimensional topological insulator. The red and blue curves represent the edge currents with opposite spin character. Right: Schematic of the two-dimensional surface states in a three-dimensional topological insulator.



Surface of a quantum-entangled insulator: Left: Schematic representation of the surface-state (SS) Fermi surface of a three-dimensional topological insulator near the high-symmetry Kramers' points $\overline{\Gamma}$ and $\overline{M}$ of the hexagonal Brillouin zone. The x and y components of the two-dimensional momentum are represented by k_x and k_y. Center: ARPES-determined Fermi surface of a SS in insulating Bi$_{1-x}$Sb$_x$ showing spin-polarization directions (red and blue arrows). Right: ARPES energy–momentum dispersion of the surface states showing that the Fermi surface enclosing is actually is formed from two bands, so that that the Kramers' points are enclosed an odd number of times (bands 1, 4, and 5 in the figure; the Fermi surface loop due to bands 2 and 3 does not enclose Kramers' points). The shaded areas (blue, violet) denote the bulk bands while the dashed white lines are guides to the eye for surface-state dispersions.

have unusual spin-selective energy–momentum dispersion relations.

With these conducting surface states as a key signature of the sought-for topological insulator, the collaboration studied the electronic structure of insulating alloys of bismuth and antimony (Bi$_{1-x}$Sb$_x$) by means of ARPES at ALS Beamline 12.0.1 and Stanford Synchrotron Radiation Lightsource (SSRL) Beamline 5-4, and by spin-resolved ARPES at the COPHEE beamline of the Swiss Light Source (SLS). An important feature of the electronic structure of conductors is the Fermi surface, a map in momentum space of the maximum electron energy in the ground state. By systematically tuning the incident photon energy, the researchers isolated the signal from surface states for further investigation of the surface-state Fermi surface.

Among their findings, they observed a notable property characteristic of the surface states of a three-dimensional topological insulator; namely, that its Fermi surface supports a geometrical quantum entanglement phase, which occurs when the spin-polarized Fermi surface encloses certain high-symmetry points (Kramers' points $\overline{\Gamma}$ and $\overline{M}$) of the surface Brillouin zone (a kind of unit cell in momentum space) an odd number of times. In this way, they were able to confirm that these insulating alloys exhibited a three-dimensional topological insulating phase. In addition, the observed spin texture in the Bi$_{1-x}$Sb$_x$ alloys is consistent with a magnetic-monopole image field beneath the surface, as predicted in theory.

The work also demonstrates a general measurement approach for identifying and characterizing topological insulator materials for future research that can be utilized to discover, observe, and study other forms of topological order and quantum entanglement in nature.