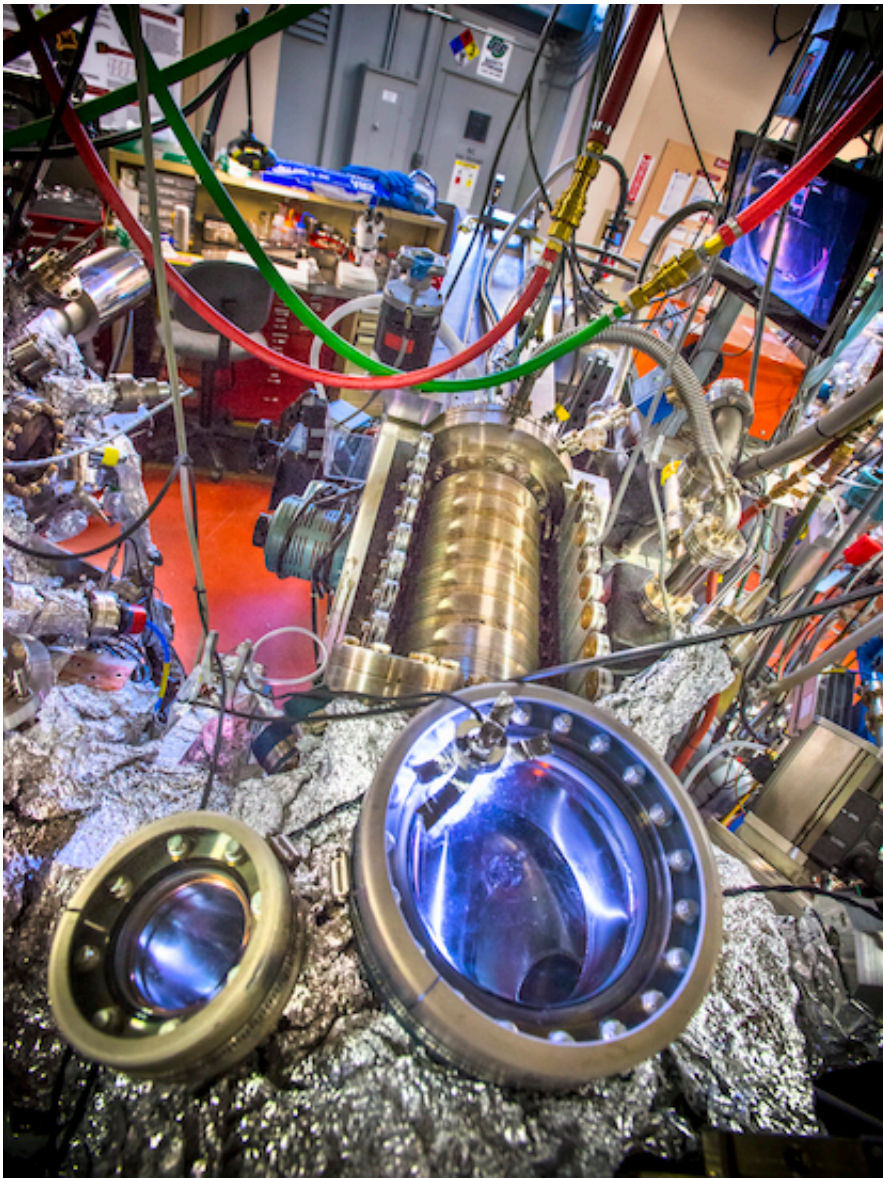


# How X-rays pushed topological matter research over the top

April 17 2017, by Glenn Roberts Jr.

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Beamline 10.0.1 at Berkeley Lab's Advanced Light Source is optimized for studies of topological properties in materials. Credit: Roy Kaltschmidt/Berkeley

## Lab

While using X-rays generated by the Advanced Light Source (ALS), a synchrotron facility at the Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab), to study a bismuth-containing thermoelectric material that can convert heat into electricity, physicist M. Zahid Hasan of Princeton University saw that something was interfering with the anticipated view of electrons' behavior inside the material.

Knowing how electrons move within this material was sought as a key to decipher how it worked, so this interference—which he and his team observed more than a decade ago during an experiment employing an X-ray-based technique dubbed ARPES (angle-resolved photoemission spectroscopy)—was a problem ... at first.

"Since 2004, I was involved with this research looking for a better understanding of bismuth-based thermoelectric materials, among other things," said Hasan.

Around 2007, after completing more X-ray experiments at the ALS and other synchrotrons, and after gaining some understanding of the theory related to his team's observations, it would become clear to Hasan that this obstruction was actually a discovery: One that would spark a revolution in materials research that continues today, and that could eventually lead to new generations of electronics and quantum technologies.

Topological matter research is now a flourishing field of research at the ALS, with several staff members devoted to supporting X-ray techniques that largely focus on its properties.

"Since 2005, something on the surface was annoying me quite a bit," said Hasan, a Princeton physics professor who in late 2016 became a visiting faculty member at Berkeley Lab's Materials Sciences Division and a Visiting Miller Professor at UC Berkeley. "I could not get rid of the surface states."

Back at Princeton, Hasan struck up a conversation with a fellow physics professor, Duncan Haldane, and he also spoke with Charles Kane, a physics professor at the neighboring University of Pennsylvania, for their collective theoretical insight about the surface effects he was seeing in some bismuth-containing materials. "At that point I was not aware of the theoretical predictions."

They discussed theoretical work, some of it dating back several decades, that had explored bizarre and resilient "topological" states in which electrons could move about the surface of a thin material with next to no resistance—like in a traditional superconductor but with a different mechanism.

The theoretical work provided little clue in how to find the effects in the materials exhibiting this phenomenon, though. So Hasan set out on a path that crossed into the fields of quantum theory, particle physics, and complex mathematics.

"I had to translate all of the abstract math into these experiments," he said. "It was like translating from a foreign language."

Flash forward to October 2016, and this time Haldane was describing his early theoretical work during a Nobel Prize press conference. Haldane shared the 2016 Nobel Prize in Physics with David Thouless of the University of Washington (a former postdoctoral researcher at Berkeley Lab), and J. Michael Kosterlitz of Brown University for their work in "theoretical discoveries of topological phase transitions and [topological](#)

[phases](#) of matter."

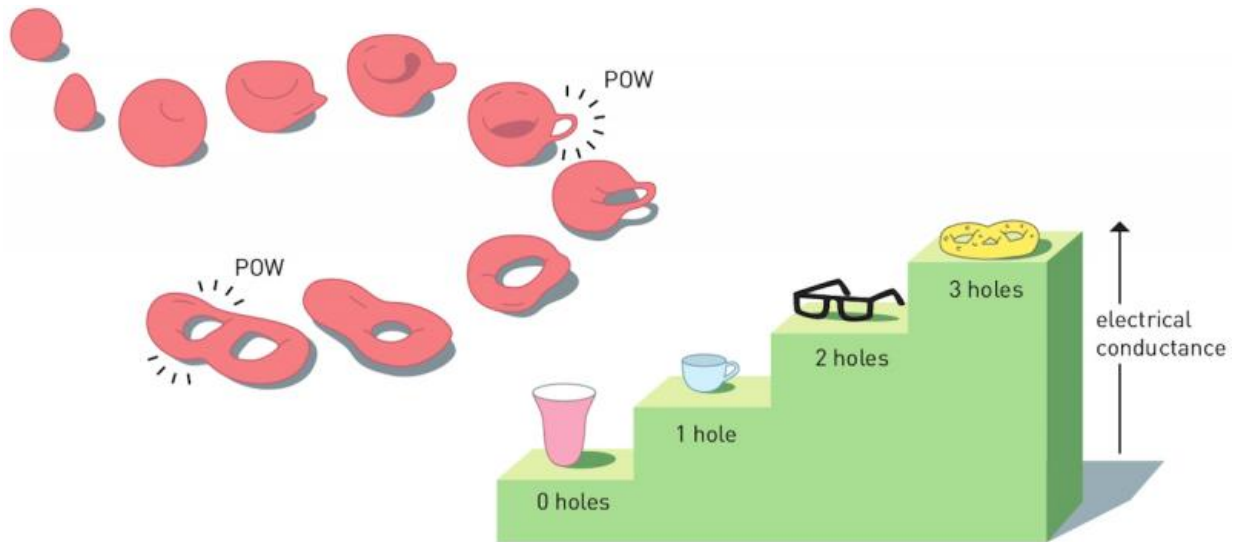
Haldane had said at the time of the Nobel Prize announcement, "I put in the first paper that this is unlikely to be anything anyone could make." His work, he said, was a "sleeper" that "sat around as an interesting toy model for a very long time—no one quite knew what to do with it."

What helped bring that "toy model" to life were later theories by Kane and collaborators, and innovative ARPES studies at the ALS and other synchrotrons that directly probed exotic topological states in some materials.

Synchrotrons like the ALS have dozens of beamlines that produce focused X-rays and other types of light beams for a variety of experiments that explore the properties of exotic materials and other samples at tiny scales, and ARPES provides a window into materials' electron properties.

The Nobel Committee, in its [supporting materials](#) for the prize, had cited early experiments by Hasan's team at the ALS on materials exhibiting topological insulator phases. A topological insulator acts like an electrical conductor on the surface and an insulator (with no electrical flow) inside.

Zahid Hussain, division deputy at the ALS said, "Hasan is an exceptional scientist with a deep understanding of both theory and experiment. He is the reason this became experimentally visible. One experiment did that."



In mathematics, topology is focused on properties that change step-wise, like the number of holes in the objects in the above image. Pioneering theories on topological phenomena in materials were key to the 2016 Nobel Prize in Physics, and were ultimately realized in X-ray experiments at Berkeley Lab's Advanced Light Source and other similar light sources. Topology explains why electrical conductivity changes in thin-layer materials. Credit: Johan Jarnestad/The Royal Swedish Academy of Sciences

Hasan's work provided an early demonstration of a 3-D [topological insulator](#), for example.

In these materials, the electron motion is relatively robust, and is immune to many types of impurities and deformities. Researchers have found examples of topological properties in materials even at room temperature.

This is a critical advantage over so-called high-temperature superconductors, which must be chilled to extreme temperatures in order to achieve a nearly resistance-free flow of electrons.



With [topological materials](#), the electrons exhibit unique patterns in a property known as electron spin that is analogous to a compass needle pointing up or down, and this property can change based on the electron's path and position in a material.

One potential future application for the spin properties of electrons in topological materials is spintronics, an emerging field that seeks to control the spin on demand to transmit and store information, much like the zeroes and ones in traditional computer memory.

Spin could also be harnessed as the information carriers in quantum computers, which could conceivably carry out exponentially more calculations of a certain type in a shorter time than conventional supercomputers.

Jonathan Denlinger, a staff scientist in the Scientific Support Group at the ALS, said the breakthrough studies on materials with topological behavior led to a rapid shift in focus on materials' surface properties. Researchers had historically been more interested in electrons within the "bulk," or inside of materials.

Hasan's group used three ALS beamlines—[MERLIN](#), [12.0.1](#), and [10.0.1](#)—in pioneering ARPES studies of topological matter. Hasan was a co-leader on the proposal that led to the construction of MERLIN in the early 2000s.

Denlinger, and fellow ALS staff scientists Alexei Fedorov and Sung-Kwan Mo, work at these ALS beamlines, which specialize in ARPES and a related variant called spin-resolved photoelectron spectroscopy. The techniques can provide detailed information about how electrons travel in materials and also about the electrons' spin orientation.

ARPES beamlines at the ALS remain in high demand for topological

matter research. Fedorov said, "These days, almost every proposal submitted to our beamline in one way or another deals with topological matter."

The quest for discoveries of new topological matter at the ALS will also be boosted by a beamline known as MAESTRO (Microscopic and Electronic Structure Observatory) that opened to users last year and will help visualize exotic ordered structures formed in some topological materials.

"ALS-U, a planned upgrade of the ALS, should improve and enhance topological matter studies using the ALS," Mo said. "It will allow us to focus down to a very small spot," which could reveal more detail in the electron behavior of topological matter.

Improved X-ray performance could help identify some topological materials that were previously overlooked, and to better distinguish and classify their properties, Hasan said.

Hasan's early work in topological matter, including topological insulators, led him to the detection of a previously theorized massless particle known as the Weyl fermion in topological semimetals, and he is now devising a related experiment that he hopes will mimic the period of the early universe in which particles began to take on mass.

Denlinger, Fedorov, and Mo are gearing up for more studies of topological matter, and are reaching out to possible collaborators across Berkeley Lab and the global scientific community.

Nanoscale materials show a lot of promise for topological materials applications, and thermoelectrics—those same [materials](#) that can transfer heat to electricity and vice versa, and that led to the first realization of topological matter in X-ray experiments—should see performance gains

in the short term thanks to the feverish pace of R&D in the field, Fedorov noted.

Hasan, too, said he is excited about progress in the field. "We are in the middle of a topological revolution in physics, for sure," he said.

Provided by Lawrence Berkeley National Laboratory

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