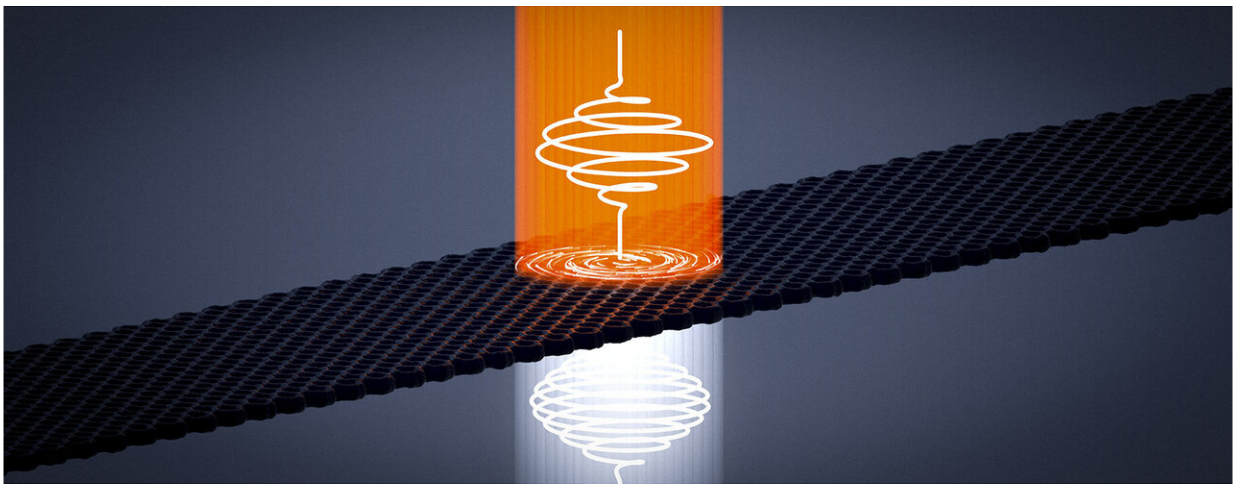
A new hands-off probe uses light to explore electron behavior in a topological insulator

February 2 2021, by Glennda Chui



Researchers at SLAC National Accelerator Laboratory and Stanford University discovered that focusing intense, circularly polarized laser light on a topological insulator generates harmonics that can be used to probe electron behavior in the material's topological surface, a sort of electron superhighway where electrons flow with no loss. The technique should be applicable to a wide range of quantum materials. Credit: Greg Stewart, SLAC National Accelerator Laboratory

Topological insulators are one of the most puzzling quantum materials—a class of materials whose electrons cooperate in surprising ways to produce unexpected properties. The edges of a TI are electron superhighways where electrons flow with no loss, ignoring any impurities or other obstacles in their path, while the bulk of the material blocks electron flow.

Scientists have studied these puzzling materials since their discovery just over a decade ago with an eye to harnessing them for things like quantum computing and information processing.

Now researchers at the Department of Energy's SLAC National Accelerator Laboratory and Stanford University have invented a new, hands-off way to probe the fastest and most ephemeral phenomena within a TI and clearly distinguish what its electrons are doing on the superhighway edges from what they're doing everywhere else.

The technique takes advantage of a phenomenon called high harmonic generation, or HHG, which shifts laser light to higher energies and higher frequencies—much like pressing a guitar string produces a higher note—by shining it through a material. By varying the polarization of laser light going into a TI and analyzing the shifted light coming out, researchers got strong and separate signals that told them what was happening in each of the material's two contrasting domains.

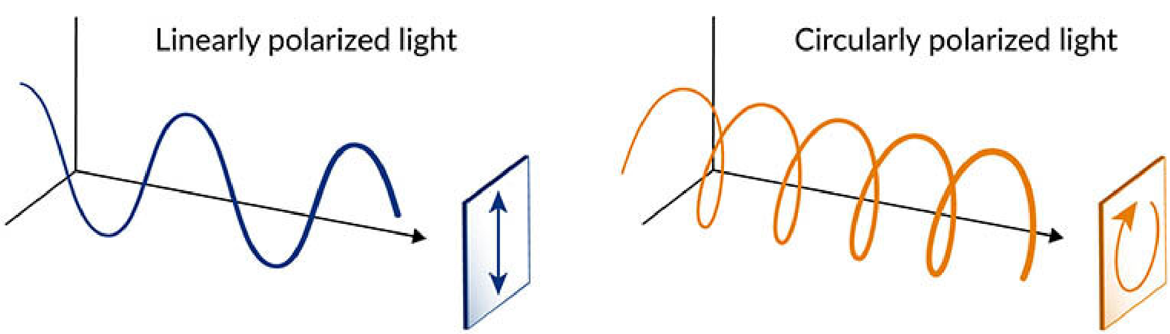
"What we found out is that the light coming out gives us information about the properties of the superhighway surfaces," said Shambhu Ghimire, a principal investigator with the Stanford PULSE Institute at SLAC, where the work was carried out. "This signal is quite remarkable, and its dependence on the polarization of the laser light is dramatically different from what we see in conventional materials. We think we have a potentially novel approach for initiating and probing quantum behaviors that are supposed to be present in a broad range of quantum materials."

The research team reported the results in *Physical Review A* today.

Light in, light out

Starting in 2010, a series of experiments led by Ghimire and PULSE Director David Reis showed HHG can be produced in ways that were previously thought unlikely or even impossible: by beaming laser light into a crystal, a frozen argon gas or an atomically thin semiconductor material. Another study described how to use HHG to generate attosecond laser pulses, which can be used to observe and control the movements of electrons, by shining a laser through ordinary glass.

In 2018, Denitsa Baykusheva, a Swiss National Science Foundation Fellow with a background in HHG research, joined the PULSE group as a postdoctoral researcher. Her goal was to study the potential for generating HHG in topological insulators—the first such study in a quantum material. "We wanted to see what happens to the intense laser pulse used to generate HHG," she said. "No one had actually focused such a strong laser light on these materials before."



Laser light is usually linearly polarized, meaning that its waves oscillate in only one direction - up and down, in the example at left. But it can also be circularly polarized, at right, so its waves spiral like a corkscrew around the direction the light is traveling. A new study from SLAC National Accelerator Laboratory and Stanford University predicts that this circularly polarized light can be used to explore quantum materials in ways that were not possible before. Credit: Greg Stewart/SLAC National Accelerator Laboratory

But midway through those experiments, the COVID-19 pandemic hit and the lab shut down in March 2020 for all but essential research. So the team had to think of other ways to make progress, Baykusheva said.

"In a new area of research like this one, theory and experiment have to go hand in hand," she explained. "Theory is essential for explaining experimental results and also predicting the most promising avenues for future experiments. So we all turned ourselves into theorists"—first working with pen and paper and then writing code and doing calculations to feed into computer models.

An illuminating result

To their surprise, the results predicted that circularly polarized laser light, whose waves spiral around the beam like a corkscrew, could be used to trigger HHG in topological insulators.

"One of the interesting things we observed is that circularly polarized laser light is very efficient at generating harmonics from the superhighway surfaces of the topological insulator, but not from the rest of it," Baykusheva said. "This is something very unique and specific to this type of material. It can be used to get information about electrons that travel the superhighways and those that don't, and it can also be used to explore other types of materials that can't be probed with linearly polarized light."

The results lay out a recipe for continuing to explore HHG in quantum materials, said Reis, who is a co-author of the study.

"It's remarkable that a technique that generates strong and potentially disruptive fields, which takes electrons in the material and jostles them around and uses them to probe the properties of the material itself, can give you such a clear and robust signal about the material's topological states," he said.

"The fact that we can see anything at all is amazing, not to mention the fact that we could potentially use that same light to change the material's topological properties."

Experiments at SLAC have resumed on a limited basis, Reis added, and the results of the theoretical work have given the team new confidence that they know exactly what they are looking for.

More information: Denitsa Baykusheva et al, Strong-field physics in three-dimensional topological insulators, *Physical Review A*, DOI: 10.1103/PhysRevA.103.023101

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