First-ever direct observation of chiral currents in quantum Hall atomic simulation

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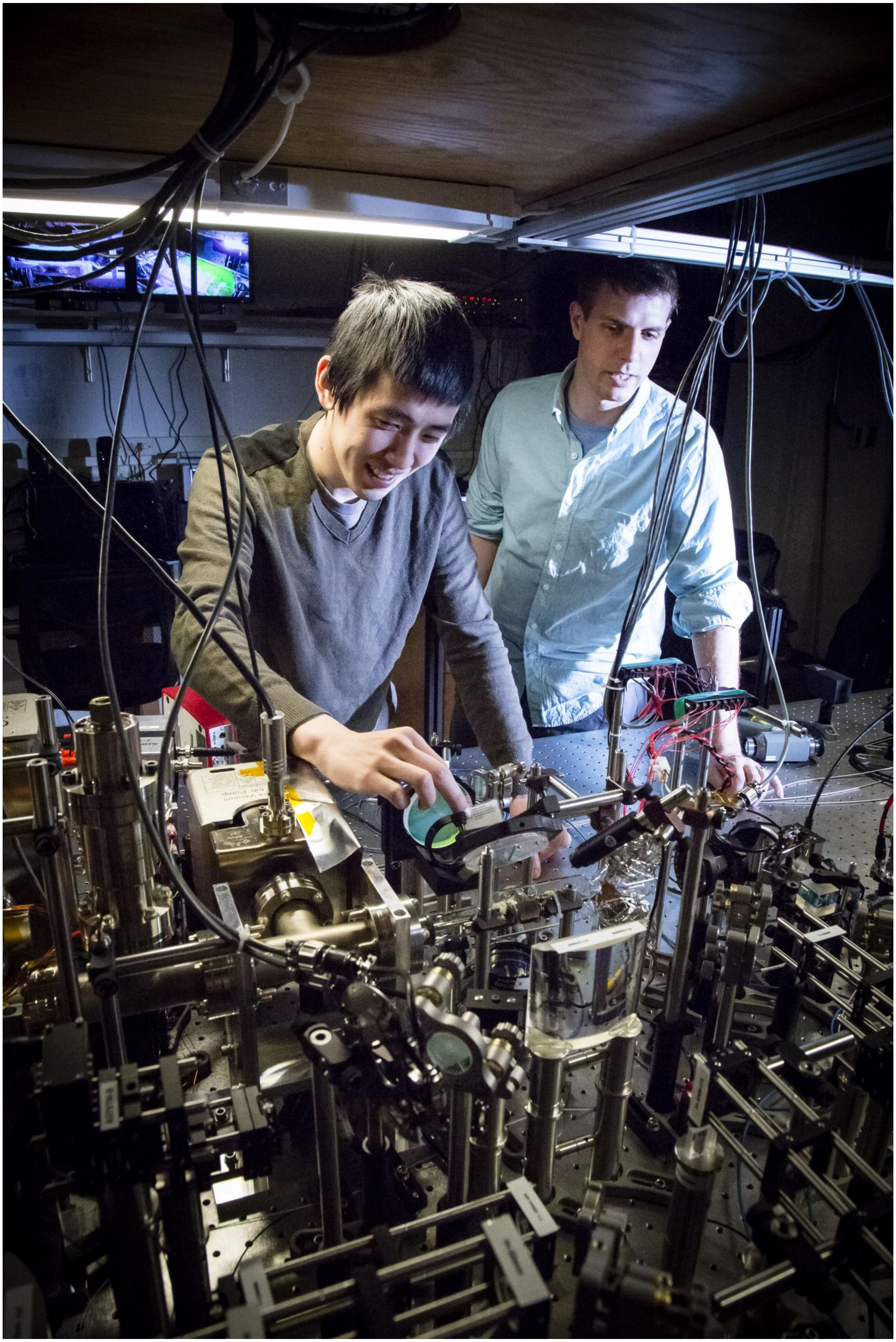


Graduate student Fangzhao Alex An working with Physics Professor Bryce Gadway in Loomis Laboratory at Illinois. Credit: L. Brian Stauffer, University of Illinois

Using an atomic quantum simulator, scientists at the University of Illinois at Urbana-Champaign have achieved the first-ever direct observation of chiral currents in the model topological insulator, the 2-D integer quantum Hall system.

Topological Insulators (TIs) are arguably the most promising class of materials discovered in recent years, with many potential applications theorized. That's because TIs exhibit a special quality: the surface of the material conducts electricity, while the bulk acts as an insulator. Over the last decade, scientists have extensively probed the microscopic properties of TIs, to better understand the fundamental physics that govern their peculiar behavior.

Atomic quantum simulation has proven an important tool for probing the characteristics of TIs, because it allows researchers greater control and greater possibilities for exploring regimes not currently accessible in real materials. Finely tuned laser beams are used to trap ultracold rubidium atoms (about a billion times colder than room temperature) in a lattice structure that precisely simulates the structure of ideal materials.

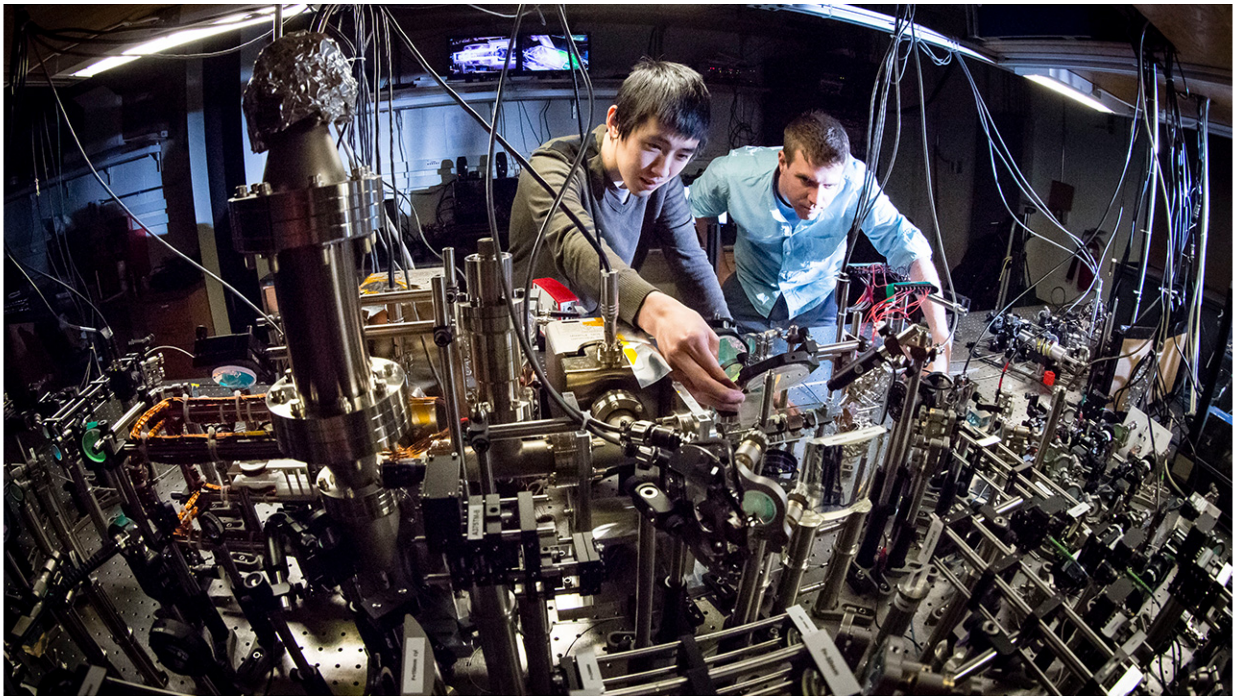
Alex An, a physics graduate student working under Assistant Professor Bryce Gadway at Illinois, is lead author of the study, "Direct observation of chiral currents and magnetic reflection in atomic flux lattices," recently published in *Science Advances*.

The 2-D integer quantum Hall system in real materials is characterized by a magnetic field that causes electrons to make closed trajectories—such as a simple closed square orbit around four sites of a two-dimensional square lattice—in order to acquire a phase shift known as an Aharonov-Bohm phase. The magnitude of this phase shift depends on the strength of the magnetic field enclosed by the trajectory.

An explains, "Both in the electronic system and in our simulated system, magnetic fields give rise to nontrivial topology: while particles in the bulk of the system undergo orbits around four-site cells, the edge particles cannot undergo full orbits and instead flow cyclically around the edge of the entire system, generating chiral currents. These microscopic phenomena lead to a macroscopic quantized conductance, which has been measured in materials like graphene and in 2D electron gases based on semiconductor heterostructures."

For this study, the team developed a new atomic-quantum-simulation technique that allowed the scientists to directly observe the chiral currents for the first time ever. The scientists employed about a dozen lasers to trap and cool rubidium atoms to nano-Kelvin temperatures. Next they configured the ultracold atoms in a periodic lattice, in precise analogy to electrons in the periodic crystal structure of a real material. Then, using their new technique, the scientists manipulated the synthetic magnetic field to observe the emergent behavior of the electrons.

"While other researchers working in atomic-molecular-optical physics create this lattice in real space, we instead link atomic momentum states to create a lattice not in a real, physical dimension, but in a 'synthetic' dimension, or momentum space," An differentiates. "We link these states using a pair of laser beams that can impart photon momentum to the atoms in discrete bunches."



Graduate student Fangzhao Alex An working with Physics Professor Bryce Gadway in Loomis Laboratory at Illinois. Credit: L. Brian Stauffer, University of Illinois

An goes on to explain how this new approach offers greater control over the lattice parameters at the individual site level, allowing the scientists to engineer phases onto the atoms as they travel between the lattice sites.

"With the addition of a second pair of laser beams, we create a fully synthetic, 2-D lattice of momentum states," he continues, "Because of our site-resolved control over the lattice, we can apply different synthetic magnetic fluxes to each four-site cell. So where previous studies have constructed two-dimensional systems with one real-space dimension and one synthetic dimension, our fully synthetic approach allows us to do a few unique things.

"First, we have the ability to create homogenous as well as inhomogenous flux patterns—the latter is not currently attainable in real-space systems. Secondly, we demonstrate the ability to rapidly and easily tune the flux of a homogeneous field across the full range of flux values—this has now been achieved in a real-space setup, at about the same time as our work. And finally, our new technique enables direct site-resolved observation of chiral currents. Direct observation of the underlying chiral currents has not been possible in real materials."

In the homogenous flux study, the team observed the chiral currents of a homogeneous artificial magnetic field for the entire range of applied flux values (-π to π). A positive flux caused the surface atoms to flow clockwise around the system, and a negative flux induced an opposite, counter-clockwise flow. The engineered system enabled the team to tune quickly and easily the applied flux across the full range of flux values, beyond the range of conventional materials and with more versatility than real-space atomic systems.

Then, in the inhomogeneous flux study, the team engineered a sharp dislocation in the artificial magnetic field by combining this topologically nontrivial system with a topologically trivial region of zero flux. They observed that atomic population reflected off of the boundary between these two regions, with maximum reflection at the largest difference in flux. A more traditional sense of reflection, like a ball bouncing off of a wall, requires a shift in the potential energy landscape. However, this magnetic reflection occurs solely due to the difference in topology. This phenomenon would be very difficult to study with other atomic systems, and would be essentially impossible to study in real electronic materials. "For a real electronic material, engineering such a step-like increase of magnetic flux would require a jump of magnetic field strengths by 104 Tesla over just a few angstroms - a crazy situation that we're however able to simulate using a controlled atomic system," says Gadway.

An stresses that, while TIs hold tremendous implications for future applications in technology, this is fundamental research, and these findings won't immediately go into a pocket-sized device like a smartphone.

"We hope to shed more light on similar phenomena in real materials by studying them in our atomic system," shares An. "The integer quantum Hall effect that we study in this work is marked by macroscopic phenomena like quantized conductance which have been studied in real materials, but the underlying, microscopic chiral edge states that give rise to these phenomena have been out of reach of real materials—but not out of reach of our system! Similarly, we hope to gain more insight into the underlying workings of more complex systems, fueled by a fundamental desire to understand and as a way to eventually construct real materials that display the same properties."

In future studies, the team plans to engineer systems having similar two-dimensional geometries, with more complex topological features.

"One of these systems consists of two coupled topological wires like those featured in our previous work on the Su-Schrieffer-Heeger model. The group of Smitha Vishveshwara has predicted that by adding specific disorder to this system, we may be able to probe the elusive Hofstadter butterfly spectrum. We also hope to study a new type of 'multipole insulator' system recently proposed by Wladimir Benalcazar, Taylor Hughes, and collaborators. This system would be characterized by topological corner modes carrying fractional quantized charge."

More information: Fangzhao Alex An et al, Direct observation of chiral currents and magnetic reflection in atomic flux lattices, *Science Advances* (2017). DOI: 10.1126/sciadv.1602685