Researchers develop magnetic switch to turn on and off a strange quantum property

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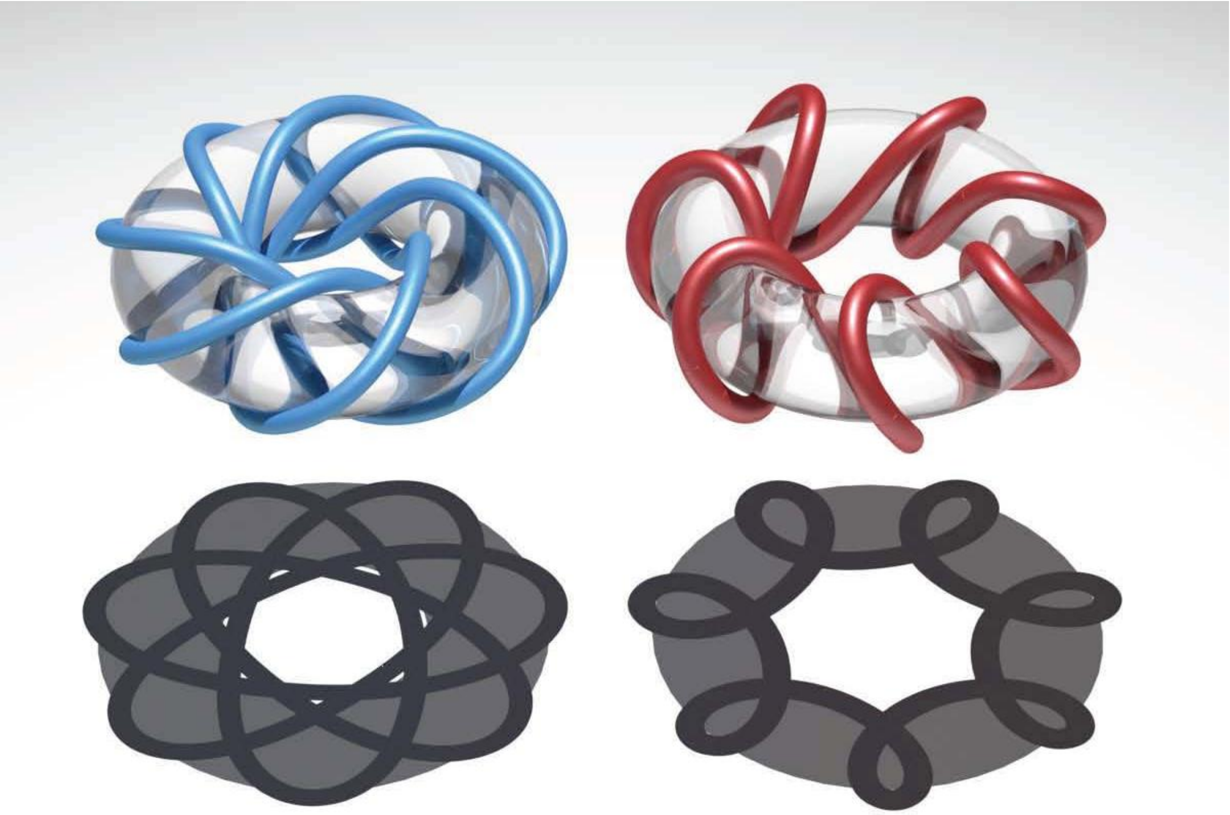


Three-dimensional renderings of electron trajectories in circular graphene resonators, and their projections on the horizontal plane. A weak magnetic field warps the classic type of atomic orbit (left) into the skipping type with outer loops (right). Because of the topological Berry phase inherent to electron's wavefunctions in graphene, the transition between them involves a sudden jump in the quantum-mechanical level energy. Credit: Christopher Gutiérrez, Jon

Wyrick, CNST/NIST

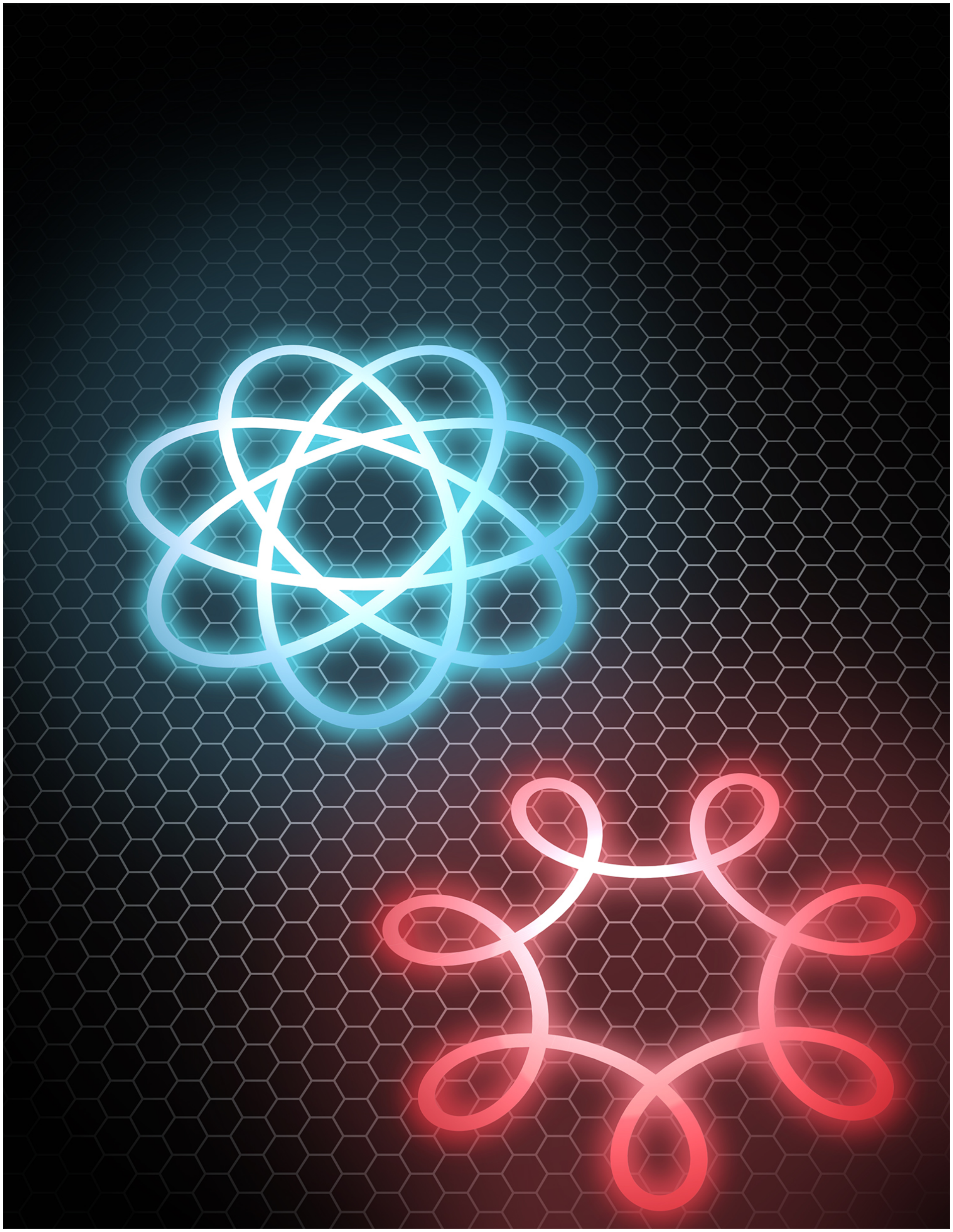
When a ballerina pirouettes, twirling a full revolution, she looks just as she did when she started. But for electrons and other subatomic particles, which follow the rules of quantum theory, that's not necessarily so. When an electron moves around a closed path, ending up where it began, its physical state may or may not be the same as when it left.

Now, there is a way to control the outcome, thanks to an international research group led by scientists at the National Institute of Standards and Technology (NIST). The team has developed the first switch that turns on and off this mysterious quantum behavior. The discovery promises to provide new insight into the fundamentals of quantum theory and may lead to new quantum electronic devices.

To study this quantum property, NIST physicist and fellow Joseph A. Stroscio and his colleagues studied electrons corralled in special orbits within a nanometer-sized region of graphene—an ultrastrong, single layer of tightly packed carbon atoms. The corralled electrons orbit the center of the graphene sample just as electrons orbit the center of an atom. The orbiting electrons ordinarily retain the same exact physical properties after traveling a complete circuit in the graphene. But when an applied magnetic field reaches a critical value, it acts as a switch, altering the shape of the orbits and causing the electrons to possess different physical properties after completing a full circuit.

The researchers report their findings in the May 26, 2017, issue of *Science*.

The newly developed quantum switch relies on a geometric property called the Berry phase, named after English physicist Sir Michael Berry who developed the theory of this quantum phenomenon in 1983. The Berry phase is associated with the wave function of a particle, which in quantum theory describes a particle's physical state. The wave function—think of an ocean wave—has both an amplitude (the height of the wave) and a phase—the location of a peak or trough relative to the start of the wave cycle.



These images show the orbital paths of electrons trapped within a circular region within graphene. In the classical orbit (top image), an electron that travels in a complete circuit has the same physical state as when it started on the path. However, when an applied magnetic field reaches a critical value, (bottom image), an electron completing a circuit has a different physical state its original one. The change is called a Berry phase and the magnetic field acts as a switch to turn on the Berry phase. The result is that the electron is raised to a higher energy level. Credit: Christopher Gutiérrez, Daniel Walkup/NIST

When an electron makes a complete circuit around a closed loop so that it returns to its initial location, the phase of its wave function may shift instead of returning to its original value. This phase shift, the Berry phase, is a kind of memory of a quantum system's travel and does not depend on time, only on the geometry of the system—the shape of the path. Moreover, the shift has observable consequences in a wide range of quantum systems.

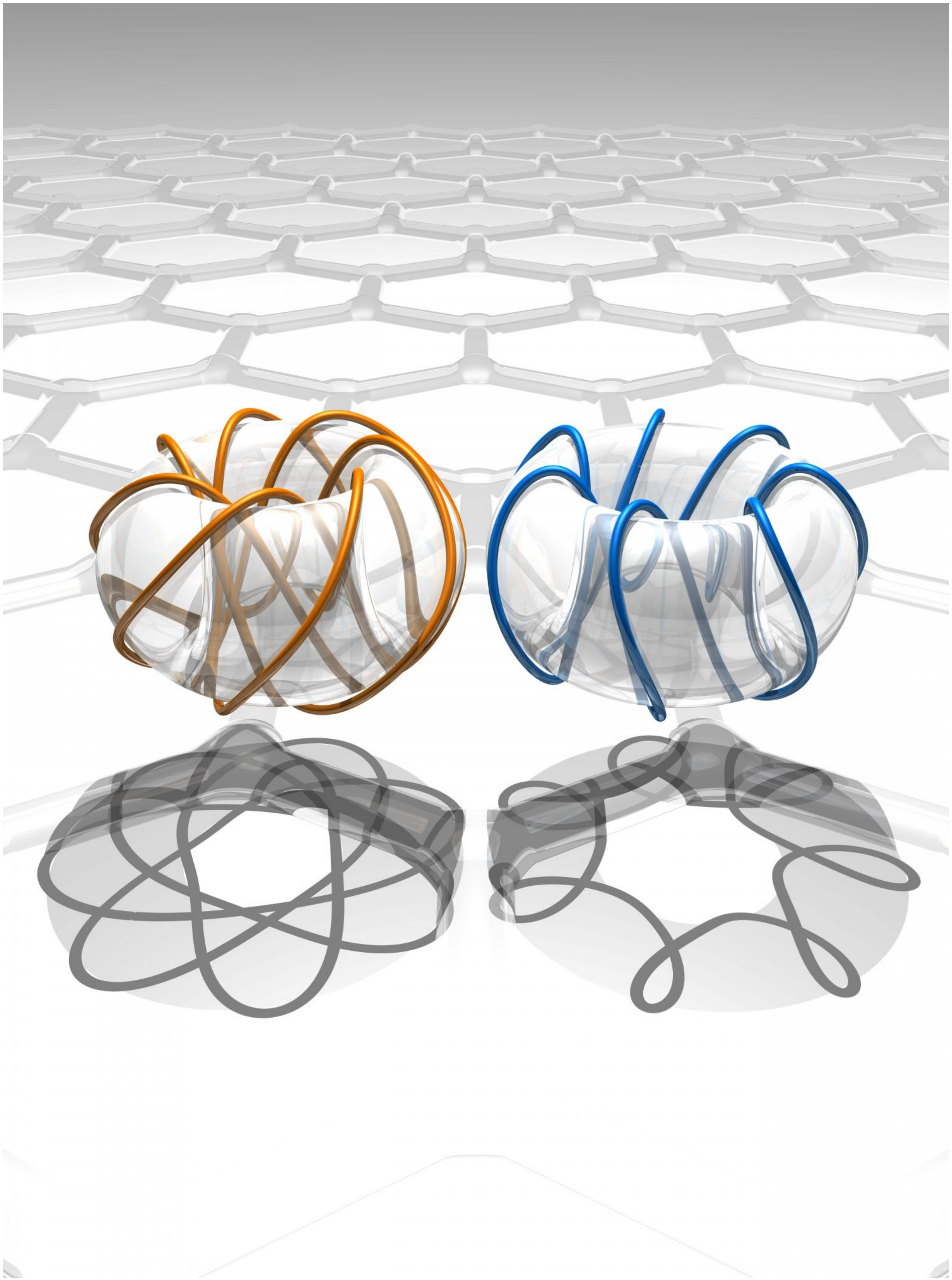
Although the Berry phase is a purely quantum phenomenon, it has an analog in non-quantum systems. Consider the motion of a Foucault pendulum, which was used to demonstrate Earth's rotation in the 19th century. The suspended pendulum simply swings back and forth in the same vertical plane, but appears to slowly rotate during each swing—a kind of phase shift—due to the rotation of Earth beneath it.

Since the mid-1980s, experiments have shown that several types of quantum systems have a Berry phase associated with them. But until the current study, no one had constructed a switch that could turn the Berry phase on and off at will. The switch developed by the team, controlled by a tiny change in an applied magnetic field, gives electrons a sudden and large increase in energy.

Several members of the current research team—based at the Massachusetts Institute of Technology and Harvard

University—developed the theory for the Berry phase switch.

To study the Berry phase and create the switch, NIST team member Fereshte Ghahari built a high-quality graphene device to study the energy levels and the Berry phase of electrons corralled within the graphene.



Three-dimensional renderings of electron trajectories in circular graphene resonators, and their projections on the honeycomb lattice (shadows). A weak magnetic field warps the classic type of atomic orbit (left) into the skipping type with outer loops (right). Because of the topological Berry phase inherent to electron’s wavefunctions in graphene, the transition between them involves a sudden jump in the quantum-mechanical level energy. Credit: Christopher Gutiérrez, Jon Wyrick, CNST/NIST

First, the team confined the electrons to occupy certain orbits and energy levels. To keep the electrons penned in, team member Daniel Walkup created a quantum version of an electric fence by using ionized impurities in the insulating layer beneath the graphene. This enabled a scanning tunneling microscope at NIST's nanotechnology user facility, the Center for Nanoscale Science and Technology, to probe the quantum energy levels and Berry phase of the confined electrons.

The team then applied a weak magnetic field directed into the graphene sheet. For electrons moving in the clockwise direction, the magnetic field created tighter, more compact orbits. But for electrons moving in counterclockwise orbits, the magnetic field had the opposite effect, pulling the electrons into wider orbits. At a critical magnetic field strength, the field acted as a Berry phase switch. It twisted the counterclockwise orbits of the electrons, causing the charged particles to execute clockwise pirouettes near the boundary of the electric fence.

Ordinarily, these pirouettes would have little consequence. However, says team member Christopher Gutiérrez, "the electrons in graphene possess a special Berry phase, which switches on when these magneticallyinduced pirouettes are triggered."

When the Berry phase is switched on, orbiting electrons abruptly jump to a higher energy level. The quantum switch provides a rich scientific tool box that will help scientists exploit ideas for new quantum devices, which have no analog in conventional semiconductor systems, says Stroscio.

More information: F. Ghahari, D. Walkup, C. Gutiérrez, J.F. Rodriguez-Nieva, Y. Zhao, J. Wyrick, F.D. Natterer, W.G. Cullen, K. Watanabe, T. Taniguchi, L.S. Levitov, N.B. Zhitenev, J.A. Stroscio. An on/off Berry phase switch in circular graphene resonators. *Science*. May 26. science.sciencemag.org/cgi/doi … 1126/science.aal0212

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