Cold-atom lattice bends topological rules

In a periodically driven system, exotic phases can form that have no static counterparts.

The complex quantum interactions of electrons in solids give rise to a plethora of phenomena—most famously, high-temperature superconductivity—that challenge the ingenuity of theorists. Fortunately, experimenters have a path to gaining new understanding of those condensed-matter systems by engineering the same physics in an ultracold atomic gas. Atoms in a trap are easier to tune, control, and measure than electrons in a solid, and cold-atom researchers have built up a toolbox of techniques for mimicking electronic systems. Artificial magnetic fields, for example, can act on neutral atoms the same way real fields act on electrons (see the article by Victor Galitski, Gediminas Juzeliūnas, and Ian Spielman, PHYSICS TODAY, January 2019, page 38).

Now Monika Aidelsburger of Ludwig-Maximilians University Munich, her students Karen Wintersperger and Christoph Braun, and their colleagues are using those same tools to go beyond simulating condensed matter and into a new regime with no material counterpart.[1]

Their cold-atom experiment lies in the realm of topological physics, in which unusual behaviors at a system's edges relate to and are determined by properties of the bulk. (See the article by Arthur Ramirez and Brian Skinner on page 30 of this issue.) In particular, they're studying a class of systems with chiral edge modes: quantum states that carry particles around the system's perimeter, but only in one direction. Ordinarily, edge modes can be quantified by topological invariants called Chern numbers, which can be computed from measurements in the bulk. But the system Aidelsburger and colleagues have realized includes the so-called anomalous Floquet regime, in which edge modes are present but all the Chern numbers are zero.

Experiments on the anomalous Floquet regime should make it possible for experimenters to explore topological phenomena that are impossible to study in equilibrium—not because their manifestations in static solid materials are too complicated, but because they don't exist.

Driving test

The anomalous Floquet regime hinges on the unusual physics of periodically time-varying Hamiltonians—the same kind used to create time crystals (see the article by Norman Yao and Chetan Nayak, PHYSICS TODAY, September 2018, page 40). By convention, periodically driven systems are analyzed stroboscopically: Time is considered not as a continuous variable but in only discrete multiples of the driving period. That technique is blind to the so-called micromotion that occurs over the course of each driving cycle.

But the micromotion can lead to some interesting behavior. For example, consider the driving protocol from Aidelsburger and colleagues' experiment, shown in figure 1. The two-dimensional honeycomb lattice is simply the interference pattern of three lasers. By oscillating the lasers' intensities, the researchers can lower the energy barriers in each direction in turn to give atoms in the lattice a chance to hop from site to site along the red lines. In the conceptually simple limit—when the hopping probability approaches 1 along the red bonds and is zero along the gray ones—an atom in the bulk of the lattice travels counterclockwise around a single hexagon. After two driving periods, the atom is back to where it started, so in that stroboscopic view, the system is trivial: Particles localized in the bulk just stay where they are.

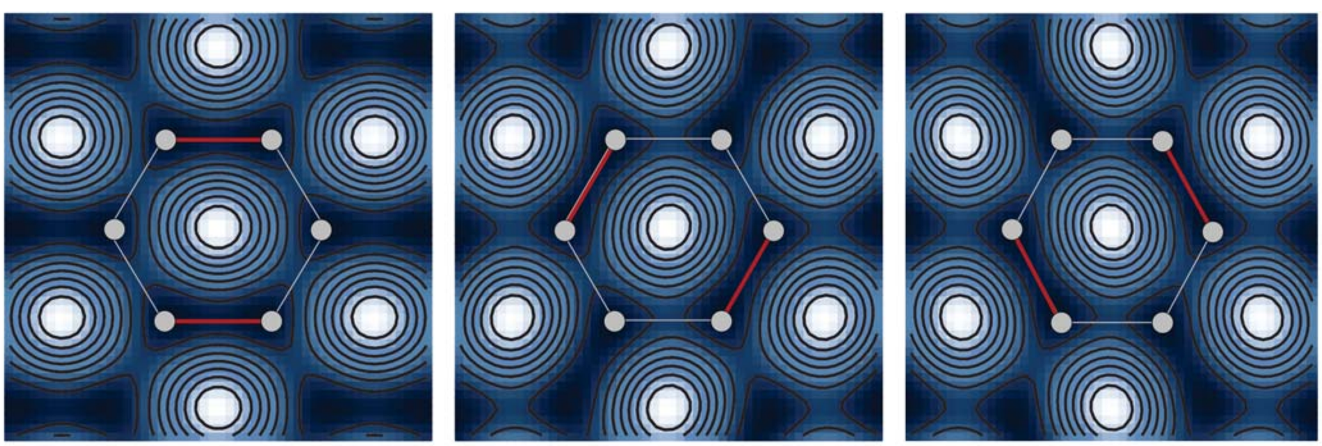

FIGURE 1. TOPOLOGICAL PHYSICS in a honeycomb optical lattice, created from three interfering lasers angled 120° from one another. Modulating the lasers' intensities periodically lowers the energy barriers along each set of parallel edges in turn, as shown by the red line segments. That protocol engenders qualitatively different behavior in the lattice bulk and at its edges. (Adapted from ref. 1.)

Particles that start at certain edge sites, however, don't just stay where they are. If an atom can't complete a trip around its hexagon without running into the lattice edge, it's instead carried clockwise along the lattice perimeter. Despite the system's trivial stroboscopic Hamiltonian, the intracycle micromotion gives it a chiral edge mode. Importantly, though, the researchers' interest in the system isn't limited to that simple example. The system's behavior depends on both the amplitude and frequency of the laser modulations, and its topological properties vary across that 2D phase diagram.

Figure 2 shows a schematic of the system's energetics. Two energy bands, analogous to a valence band and a conduction band, are shown in blue and gold, and edge modes correspond to connections between bands. Each band has its own Chern number, equal to the number of connections it makes to higher-energy bands minus the number it makes to lower-energy bands.

Ordinarily, if a system has any edge modes, the Chern numbers must be nonzero for at least the lowest- and highest-energy bands that participate in the modes. Furthermore, if one knows all the Chern numbers, one can deduce the system's entire edge-mode structure. But in a periodically driven system, that reasoning breaks down.

Because driven systems are perpetually out of equilibrium, and because energy can be pumped in or out during the driving cycle, their eigenstates no longer have absolute energies, only quasi-energies defined up to an integer multiple of $\hbar\omega$, where ω is the driving frequency. The quasi-energy spectrum is periodic, so the bands can connect in two ways, as shown by the red and orange lines in the figure. When both modes are present, both bands' Chern numbers are zero, just as if both modes were absent.

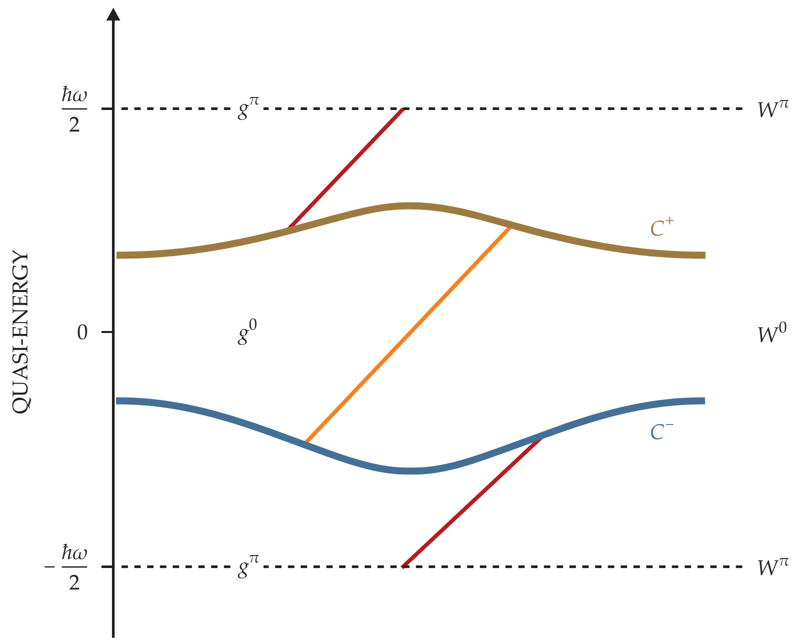

FIGURE 2. ABSOLUTE ENERGY DOESN'T EXIST in periodically driven systems; states have only a quasi-energy that's defined modulo $\hbar\omega$, where ω is the driving frequency. Two energy bands (blue and gold) can be connected by an edge mode across either the zero-energy gap g^0 (orange) or the quasi-energy gap g^π (red). The bands' Chern numbers C^+ and C^- are equal to the number of modes connecting to the band from above minus the number connecting from below. When both modes are present, C^+ and C^- are zero; they no longer define the system's topological state. Instead, the system is characterized by the winding numbers W^0 and W^π, equal to the number of modes traversing each gap. (Adapted from ref. 1.)

Winding roads

The theory of anomalous Floquet systems was first described[2] in 2010, and by

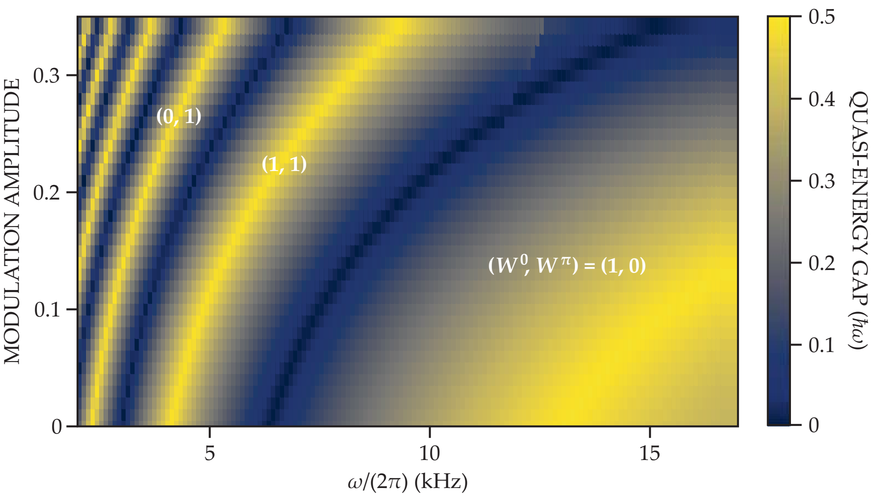

FIGURE 3. MAPPING THE PHASE DIAGRAM of the driven atomic system. Interferometric measurements probe the smaller of the two energy gaps—g^0 and g^π in figure 2—as a function of the modulation amplitude and frequency ω. When one of the gaps is zero, the bands touch and an edge mode can appear or disappear. The dark blue lines therefore mark the boundaries between topological phases. The anomalous Floquet regime, in which both winding numbers W^0 and W^π equal 1, is the second yellow region from the right. (Adapted from ref. 1.)

2017 the anomalous regime had been realized experimentally in arrays of photonic waveguides.[3] But only now, with Aidelsburger and colleagues' cold-atom experiment, is it possible to readily tune and characterize such a system. Because the topology is no longer fully defined by the Chern numbers, one must turn to a different set of topological invariants, the winding numbers W^0 and W^π, which are equal to the number of edge modes traversing each gap. And Aidelsburger and colleagues have figured out a way to measure them.

They start with a technique called Stückelberg interferometry: They prepare an atomic wavepacket that lies partly in each energy band, let it propagate for a time, and probe how it interferes with itself. That measurement gives the smaller of the quasi-energy gaps g^0 and g^π, and when mapped for all values of the modulation amplitude and frequency, the measurements yield the phase diagram shown in figure 3.

Edge modes can appear or disappear—and Chern and winding numbers can change—only when an energy gap is zero and the bands touch. The dark blue lines in the figure therefore represent boundaries between topological phases with different numbers of edge modes. The interferometry measurements by themselves, though, don't indicate which of the energy gaps closed or whether the associated winding number increased or decreased.

To fill in that information, the researchers first noted that the high-frequency limit is equivalent to a static system: The quasi-energy spectrum is wide, the gap g^π is large, and the winding number W^π must equal zero. As the frequency is decreased, the gap g^π is the first to close, then g^0, and so on. Finally, by measuring the Hall deflection on either side of each phase transition (see the article by Joseph Avron, Daniel Osadchy, and Ruedi Seiler, PHYSICS TODAY, August 2003, page 38), they deduced the transition's topological charge—that is, whether crossing the phase boundary causes the number of edge modes to increase or decrease by one. By tracking those changes across the phase diagram, they deduced both winding numbers for each phase, and they demonstrated that the anomalous Floquet regime is the second phase from the right.

Into the unknown

Everything the experimenters have found was already anticipated by theory. But that's because their experiment focused on the system in its simplest, most theoretically tractable form: noninteracting atoms in a perfectly uniform lattice. Adding more complicating factors, such as lattice defects or interactions, quickly takes the system beyond theorists' abilities to reliably model it and into uncharted experimental territory.

Especially interesting is the effect of disorder. One of the hallmarks of topological properties is that they don't change when the system is slightly deformed, and theory tentatively predicts that the anomalous Floquet phase, because its Chern numbers are all zero, should be especially robust. By projecting an optical speckle pattern onto their lattice to alter the trap depths and barrier heights, Aidelsburger and colleagues will investigate just how much disorder they can introduce without disrupting the phase's topology.

The experiments so far have focused on measuring the band structure of the periodically driven lattice, irrespective of how those bands are filled by atoms. Another important goal, then, is to figure out how to completely fill one of the system's energy bands—a different and more difficult task than completely filling the lattice—and leave the other band empty.[4] If the researchers can stabilize the system in such a state, they will have realized a new phase of matter, an anomalous Floquet insulator.

Strikingly, Aidelsburger and colleagues managed to completely characterize their system's edge modes without ever looking at the edge modes themselves. In fact, they can't study the edge modes directly because the system lacks well-defined edges—like most optical lattices, the optical intensity fades away gradually in all directions. So one more item on their to-do list is to engineer a new optical potential with a sharp interface between the lattice and the vacuum. With it, they hope to get a reassuring glimpse of chiral edge transport in action.

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References

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