Experimental realization of the topological Haldane model

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Recommendation and Commentary by Tin-Lun Ho

In the last decade, there have been intense efforts to realize various types of topological band structures in solid-state systems. These efforts are very involved, as one needs to find materials with the right band structure and the right spin-orbit coupling. In the last few years, there have also been increasing efforts to realize topological band structures in quantum gases using bosons and fermions in optical lattices. Quantum gases are attractive platforms as there is considerable flexibility in engineering lattices, hopping matrix elements, and interaction strengths in these systems. There is fast progress in these efforts. Two years ago, Esslinger's group at ETH had created a deformed honeycomb lattice and had demonstrated how the Dirac points moved around in k-space as the lattice was deformed [1]. I had reported this work in a Commentary on Feb 27, 2012. Recently, the same group has realized in the same type of lattice the Haldane model – an important model that underlies the theory of topological insulators.

In 1988, Haldane [2] showed that quantum Hall phenomena could arise entirely from band structure effects without the presence of a real magnetic field. However, his model contains complex matrix elements (hence broken time reversal symmetry) that are difficult to realize in real materials. In fact, Haldane remarked in his paper "the particular model presented here is unlikely to be directly physically realizable". The flexibility in cold atom experiments, however, successfully meets this challenge. In a recent experiment with fermionic atoms in a honeycomb lattice, the ETH group has engineered complex hopping by simply shaking the lattice in a proper way.

A shaking lattice with displacement $\mathbf{a}(t)$ will lead to a time dependent potential $V(\mathbf{r},t) = V(\mathbf{r} - \mathbf{a}(t))$. In the co-moving frame of the lattice, the shaking will generate a perturbation $\mathbf{p}.(d\mathbf{a}/dt)$. Depending on the frequency and the nature of the shaking, (i.e. where $\mathbf{a}$ is linear or circular), this oscillation can couple and even invert different energy bands. This is similar to NMR, where a transverse magnetic field can couple and invert Zeeman energy levels. By applying an elliptical shaking on a honeycomb lattice, which breaks time reversal symmetry, the system has a time averaged Hamiltonian with complex nearest neighbor and next nearest neighbor hopping matrix elements, exactly what needed for the Haldane Hamiltonian. Moreover, by varying the strength and the phase of these matrix elements (by changing $\mathbf{a}(t)$), a topological band can emerge. Using the method in their previous experiment [1] to study the motion of the atom cloud in the Brillioun Zone, the ETH group was able to map out the phase diagram of the topological phase and had verified the prediction of Haldane [2].

A major challenge in simulating solid-state physics using cold fermions in optical lattices is the heating due to spontaneous emission. Such heating effects are particularly severe in the experiments that use Raman processes to create synthetic gauge fields. Despite the success of the NIST group a few years back to create scalar gauge field [3] and spin-orbit coupling [4] with Raman processes, (see my Commentary on March 2001), cooling alkali fermions to quantum degeneracy remains difficult. Remarkably, the ETH experiment [1] shows that heating effect can be quite small for small shaking amplitudes.

In the current ETH experiment, the fermions on each lattice site (in the xy plane) are confined in a tube along z. As of now, experimental groups have not yet constructed 2D a tight-binding system with at most one atom per site. In the future, if tight confinement along z can be achieved with little heating, one can then perform systematic studies of many properties of the Haldane model, and explore in detail the role of interaction, which are hard to do in solid-state experiments.

The ETH experiment is an exciting development in the effort of performing quantum simulation with cold atoms. Not only does it create the Haldane model, but also show that the "shaking" method is an efficient way to create synthetic gauge fields and topological bands with little heating. It also leads to other exciting possibilities. At present, it is possible to creating optical lattices that only trap atoms in specific spin states – the so-called spin dependent optical lattice. The "shaking" of these lattices will enable one to create an even greater variety of spin-orbit coupling. The study of topological matters with ultra-cold atoms is really heating up.

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