An Aharonov-Bohm interferometer for determining Bloch band topology

L. Duca, T. Li, M. Reitter, I. Bloch, M. Schleier-Smith, U. Schneider, Science 347, 288 (2015)

Recommended with a commentary by Tin-Lun Ho

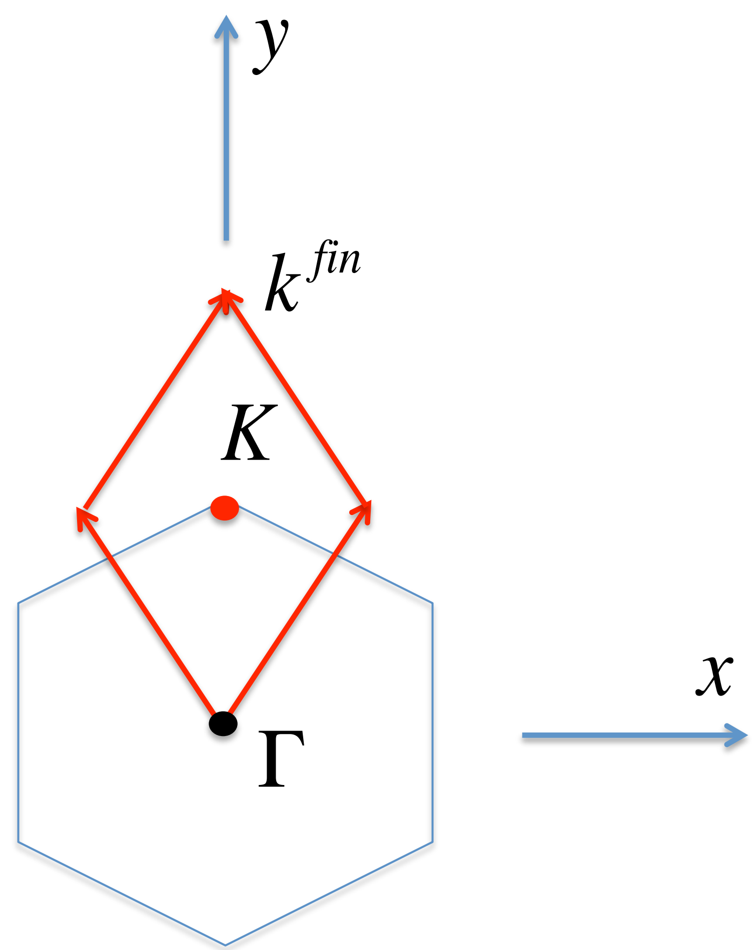
There has been a great surge of activities in the last few years in both the solid state and the cold atom communities to study topological matters. In solid state physics, there has been considerable efforts to manufacture materials with topological band structures. Such efforts are often very involved. There is also a parallel effort in cold atom experiments to realize tight binding Hamiltonians with topological bands using atoms in optical lattices. In the last two years, there has been rapid progress in this direction. We now have efficient ways in cold atom experiments to engineer complex nearest neighbor and next nearest neighbor hopping for a variety of lattices. This has led to the recent realization of the Hofstadter model and the Haldane model[1], paving ways for creating lattices with more complex topological band structures (including those containing the Wyle points), and for studying interaction effects in topological bands in a controlled manner.

In solid state experiments, the signature of the topological band is detected through the measurement of edge currents and the determination of surface energy spectrum using ARPES. In cold atom experiments, methods of detection are currently being developed. The experiment discussed here is a powerful way to probe the Berry curvature of the system with high precision. This method makes use of the fact that the Berry curvature acts like a magnetic field for particle motion in k-space. As a result, when a particle travels from one point to another point in k-space through different paths, there will be a phase difference between these paths proportional to the "magnetic flux" enclosed by these paths. For most cases, the Berry curvature is concentrated at isolated points in k-space which acts like a thin flux tube. The amplitude of interference between different paths in k-space on different sides of this flux tube is the analog of celebrated Aharonov-Bohm effect in real space.

This interference effect was demonstrated in the above experiment on a honeycomb lattice where Berry curvatures (with $\pm\pi$ flux) are concentrated at the Dirac points as shown in the figure. To create different interference paths around a Dirac point, (say, one that is on the y-axis), one starts with a Bose-Einstein condensate (BEC) in a particular hyperfine spin state $|\uparrow\rangle$ at **k**=0. It is then made into a superposition of two hyperfine states (denoted as $\left(|\uparrow\rangle+|\downarrow\rangle\right)/\sqrt{2}$) through an rf-transition. By applying a magnetic field gradient along x, the states $|\uparrow\rangle$ and $|\downarrow\rangle$ will move along –x and x direction. At the same time, both state states can be made to move along y by a linear frequency sweep of one of lattice beams that made up the optical lattice. By reversing the magnetic field gradient at some point while keeping the force along y, these states will later arrive at the same point $\mathbf{k}^{\rm fin}=(k_x=0,k^{fin})$ above the Dirac point at in the quantum state $\left(e^{i\varphi_1}|\uparrow\rangle+e^{i\varphi_2}|\downarrow\rangle\right)/\sqrt{2}$. By further applying a π/2 pulse to turn $|\uparrow\rangle$ and $|\downarrow\rangle$ into $|\uparrow\rangle+|\downarrow\rangle$ and $-|\uparrow\rangle+|\downarrow\rangle$, the number of $|\uparrow\rangle$ particle in the final state at $\mathbf{k}^{\rm fin}$ is $n_\uparrow \propto (1-\cos\varphi)$, where $\varphi=\varphi_1-\varphi_2$ is the Berry flux at the Dirac point. A measurement $n_\uparrow$ after the state arrives at $\mathbf{k}^{\text{fin}}$ will provide the information of the Berry flux enclosed by the paths.

In actuality, the BEC has at $\mathbf{k}$=0 has a momentum spread in k-space. However, in spite of this spread, the author were able to come up with clever methods to remove many systematic errors and to localize the curvature with a resolution of 10^{-6} of the Brillouin zone area! With such high resolution, one can in principle map out the Berry curvature over the entire Brillouin zone and determine the Chern number by integrating it up over the entire zone. The interference method discussed here illustrates the different approaches between solid state and cold atom experiment in studying topological matters. Rather than studying the transport properties, which are related to four-point correlation functions, many cold atoms experiments probe the single particle density matrix (which include density measurements after interference), which are two-point correlation functions. While cold atom experiments have great capability of creating different types of topological bands, they still face the challenge of reaching temperatures low enough to study strong correlation physics of fermions. There will surely progress in this direction in coming years. As of now, the studies on topological matter in cold atoms are flourishing.

[1] See my commentary JCCM_OCTOBER_2014_01 on Experimental realization of the topological Haldane model. Authors: G. Jotzu, M. Messer, R. Desbuquois, M. Lebrat, T. Uehlinger, D. Greif, and T. Esslinger, Nature 515, 237-240 (2014). arXiv:1406.7874v1.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