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Quantum phenomena in topological materials

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In 1980, the integer quantum Hall effect in two-dimensional (2D) systems was discovered under high magnetic field [1], which opened a door to the novel phase of matter. The concept of topology was then introduced into condensed matter physics to distinguish the intriguing phenomenon of quantum Hall effect by non-zero Chern number (C) [2]. The topological scenario suggests a new type of phase where the phase transition does not need symmetry breaking. In 2005, Z_2 invariant was proposed to characterize the topological properties of time-reversal-invariant systems. In 2006, the HgTe quantum well was predicted to be a quantum spin Hall system with insulating bulk state and spin-orbit locking helical edge state, which was experimentally demonstrated in 2007 and called 2D topological insulator later on. Despite some debates on the evidence of the 2D topological insulator, the studies soon expanded to three-dimensional (3D) topological insulators. Further investigations also revealed topological semimetals and topological superconductors. The materials with topological nontrivial properties are collectively called topological materials.

Nowadays, many topological materials have become well-known and shown important quantum phenomena, such as Bi_2Te_3, Cd_3As_2, and $ZrTe_5$. In 2018, a new class of quantum oscillations was reported in high-quality $ZrTe_5$ crystals beyond the quantum limit under high magnetic field [3]. Different from the textbook works of Shubnikov-de Haas oscillations and Aharonov-Bohm effect, the observed resistance oscillations are periodic in logarithmic magnetic field (Figure 1(a)). Considering the Dirac relativistic quasi-particles and Coulomb interaction, two-body quasi-bound states with discrete scale invariance feature were proposed to explain the observation. Moreover, the investigation of these peculiar quasi-bound states in topological materials can broaden our understanding of supercritical atomic collapse. The log-periodic quantum oscillations represent rare discrete scale invariance in quantum matter and may open a new chapter in the 90-year history of quantum oscillations.

Actually, in many situations, symmetry protected topological properties are not robust enough, which might hinder the deep research and potential application of topological materials. However, when the correlation is brought into topological matter, topological protection could be very robust. A typical paradigm is the quantum anomalous Hall effect (QAHE) found in magnetic topological materials. In 1988, a honeycomb-net model was proposed to realize the quantum Hall effect without Landau levels [4], which can also be called QAHE or Chern insulator. 25 years later, QAHE was firstly observed at 30 mK in magnetically doped topological insulator films grown by molecular beam epitaxy [5]. The effect is topologically robust and does not depend on the size of the film, where the one-dimensional (1D) chiral edge state indeed forms the dissipationless channel. Two key obstacles to constructing an "information highway" by using QAHE are how to increase working temperature and how to realize multiple dissipationless chiral edge states. Recent research on intrinsic magnetic topological material $MnBi_2Te_4$ has seen the possibility to overcome these obstacles. $MnBi_2Te_4$ with layered septuple-layers (SL) structure was an intrinsic antiferromagnetic topological insulator but became a ferromagnetic Weyl semimetal under a magnetic field.

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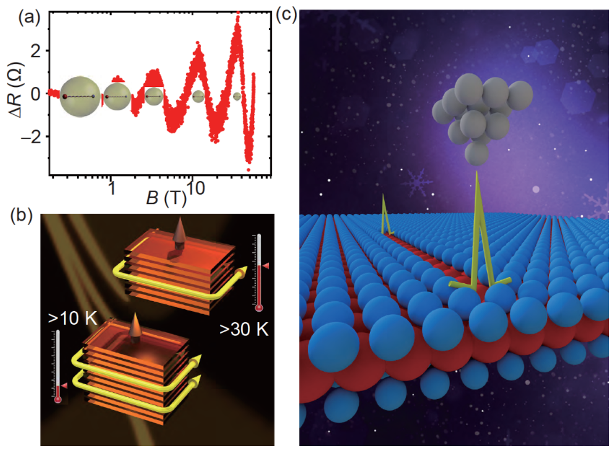

Figure 1 (Color online) (a) Log-periodic quantum oscillations and the schematic of two-body quasi-bound states. The experimental data (red points) are adapted from ref. [3]. (b) A schematic of high-Chern-number quantum Hall effect without Landau levels above 10 K and high-temperature Chern insulator state above 30 K in 10-SL and 7-SL $MnBi_2Te_4$ devices, respectively. (c) A schematic of Majorana zero-energy bound states simultaneously appearing at both ends of a 1D atomic line defect in monolayer high-temperature superconducting $FeTe_{0.5}Se_{0.5}$ films.

With the thickness increasing from 7 SL to 10 SL, the $MnBi_2Te_4$ devices were observed to change from a Chern insulator with one chiral edge state (C=1) to a Chern insulator with two chiral edge states (C=2) under moderate magnetic fields [6]. For C=2 devices, the observed quantum Hall effect without Landau levels displayed quantization behavior above 13 K. For C=1 devices, the working temperature was at least 30 K, much higher than that previously reported. The high-temperature and high-Chern-number (C>1) Chern insulators found in $MnBi_2Te_4$ devices (Figure 1(b)) may encourage the studies aiming at QAHE working above 77 K, thus leading to the innovation in quantum information technology.

The topological superconductor is another correlated topological system, where the bulk state shows a superconducting gap and the surface (or edge) state can host Majorana quasi-particles, the analogue of Majorana fermions in condensed matter. Majorana fermions are identical to their own antiparticles and named after Ettore Majorana. Theoretically, Majorana zero energy bound states (or Majorana zero modes) exist at the ends of the 1D topological superconductor, which would obey non-Abelian statistics and thus could be used in topological fault-tolerant (i.e. non-sensitive to the environment) quantum computation. Such prospect stimulated a boom of studies on topological superconductivity and Majorana bound states. Among them, the interface between the topological insulator and s-wave superconductor was predicted to be an effective chiral p-wave topological superconductor, where the vortex core as 1D platform might host the Majorana bound state. Indeed, the spin-dependent zero bias conductance peak as a signature of Majorana bound state was experimentally detected by scanning tunneling microscopy in the superconductor-topological insulator heterostructure [7]. Furthermore, the observation of unconventional superconductivity on the surface of non-superconducting topological semimetals induced by non-superconducting tips indicated that the topological superconductivity might be induced even on the metal-topological semimetal interface [8]. These heterostructures normally showed low superconducting critical temperature T_c and strong quasiparticle poisoning, which caused difficult conditions for observing and manipulating Majorana bound states. Recently, the iron-based superconductor bulk $FeTe_{0.55}Se_{0.45}$ with T_c~15 K was proved to show the superconducting topological surface state, where zero bias conductance peaks were detected at vortex cores, suggesting potential Majorana bound states in a more stable and simple system [9]. Nevertheless, for constructing applicable topological quantum bits, a better platform with an even higher T_c and without any magnetic field was still highly desired. Recently, one-unit-cell-thick $FeTe_{0.5}Se_{0.5}$ films grown on $SrTiO_3$ substrate were reported to show high T_c superconductivity ~60 K. Very interestingly, the signature of Majorana bound states was detected simultaneously at both ends of the 1D atomic line defect in monolayer $FeTe_{0.5}Se_{0.5}$ films when applying no magnetic field [10], which offered a high T_c topological system for potential application in feasible topological quantum computers, see Figure 1(c).

In summary, many novel quantum behaviors have been detected in topological materials, such as QAHE, Majorana bound states, and log-periodic quantum oscillations, making topological matter a very active field in both physics and materials science. In the future, QAHE working above liquid nitrogen temperature, manipulation on Majorana bound states, and more quantum characteristics can be expected in this field. The related potential applications in quantum technology may revolutionarily change our world.

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