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Research Highlight

Three-dimensional quantum Hall effect in acoustic crystals

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At low temperatures, when a semiconductor hosts a two-dimensional electron gas (2DEG) and is subjected to a strong magnetic field, the Hall resistance exhibits quantization to integer multiples of h/e^2 with remarkable precision (h is Planck's constant and e is the elementary charge). The phenomenon, soon recognized as the quantum Hall effect (QHE), emerged as a groundbreaking discovery in condensed matter physics [1,2], stimulating exploration into new research avenues. This discovery paved the way for the investigation of topological states of matter, leading to unforeseen theoretical insights and practical applications. Subsequently, much research has been devoted to deepen the understanding of the QHE in various settings, yet, chiefly in 2D. But it was not until 1987 where Halperin [3] added another dimension by predicting the QHE in 3D. His intriguing finding, however, came with quite some hurdles that had to be overcome. In order to realize such a 3D QHE, high mobility, low charge carrier density in the bulk, and high levels of crystalline purity should be considered. A breakthrough was finally made with the first experimental realization of the 3D QHE in bulk zirconium pentatelluride ($ZrTe_5$) [4].

Exploring the symmetrical properties of metamaterials represents a frontier topic in wave physics. Particularly, the emergence of topological metamaterials has sparked considerable interest due to their potential for guiding waves while maintaining resilience against obstacles. These materials possess surface states that are topologically protected, ensuring the persistence of certain characteristics even in the presence of material imperfections or defects. Originally conceived to uncover acoustic and optical analogues to unusual electronic surface conducting properties, this pursuit has evolved into established avenues of research [5,6]. The analogy of the QHE in the domain of acoustics is not straightforward. This is primarily because sound does not interact with a magnetic field, which is crucial for generating discrete Landau levels and related phenomena in a 2D electron gas. However, in 2019, a 2D acoustic QHE was demonstrated, facilitated by the use of an array of resonators biased with angular momentum and featuring broken Lorentz reciprocity [7]. Achieving a 3D acoustic QHE presents significant challenges, particularly in enforcing time-reversal symmetry breaking for sound, beyond the conventional 2D settings.

Recently, in a time-reversal symmetric system, on the basis of a pseudo-magnetic field, the first 3D acoustic QHE has been reported [8]. Using an A-A stacked hexagonal lattice, the authors in Ref. [8] constructed an acoustic analogue Weyl semimetal (Fig. 1a). The most fascinating feature of a Weyl semimetal is that it contains band touching points in the bulk called Weyl points, which usually appear in pairs, each with opposite topological charges, connected through a surface Fermi arc [9]. When an external magnetic field is applied, the Fermi arc can form discrete plateaus, which are similar to the Landau levels in association with the 2D QHE. Interestingly, the gapped surface Landau plateaus hosts 1D hinge states as opposed to the usual surface states [10].

To induce a pseudo-magnetic field (PMF) for sound waves, the authors in Ref. [8] introduced a structural gradient using different on-site energy distributions along an armchair direction in the hexagonal plane (Fig. 1a). The idea of creating such a structural gradient to generate a PMF for sound waves has been previously reported to have similar effects on electrons to the magnetic field [11]. When the on-site energy gradient is imposed, the Weyl points residing at the $\bar{k}_{\pm}$ points shift their positions along the positive/negative k_z direction to a different level (Fig. 1b). Consequently, this shift enforces a movement of the bulk Weyl points and Fermi arc trajectories, which forms the chiral Landau level (left panel of Fig. 1c) and Landau plateaus for the arc surface states on the opposite side surfaces (right panel of Fig. 1c). Subsequently, 1D hinge states appear in the gaps between the surface Landau plateaus, which is the indicator of the 3D QHE in the acoustic Weyl semimetal (Fig. 1d).

In summary, this intriguing study demonstrated a feasible approach capitalizing on Weyl semimetals to enable the first observation of the 3D acoustic QHE, interesting also for explorations in photonics and cold atomic systems. The results provide an ideal and tunable platform to explore quantum and classical Hall physics, which can potentially trigger new directions for acoustic devices.

Conflict of interest

The authors declare that they have no conflict of interest.

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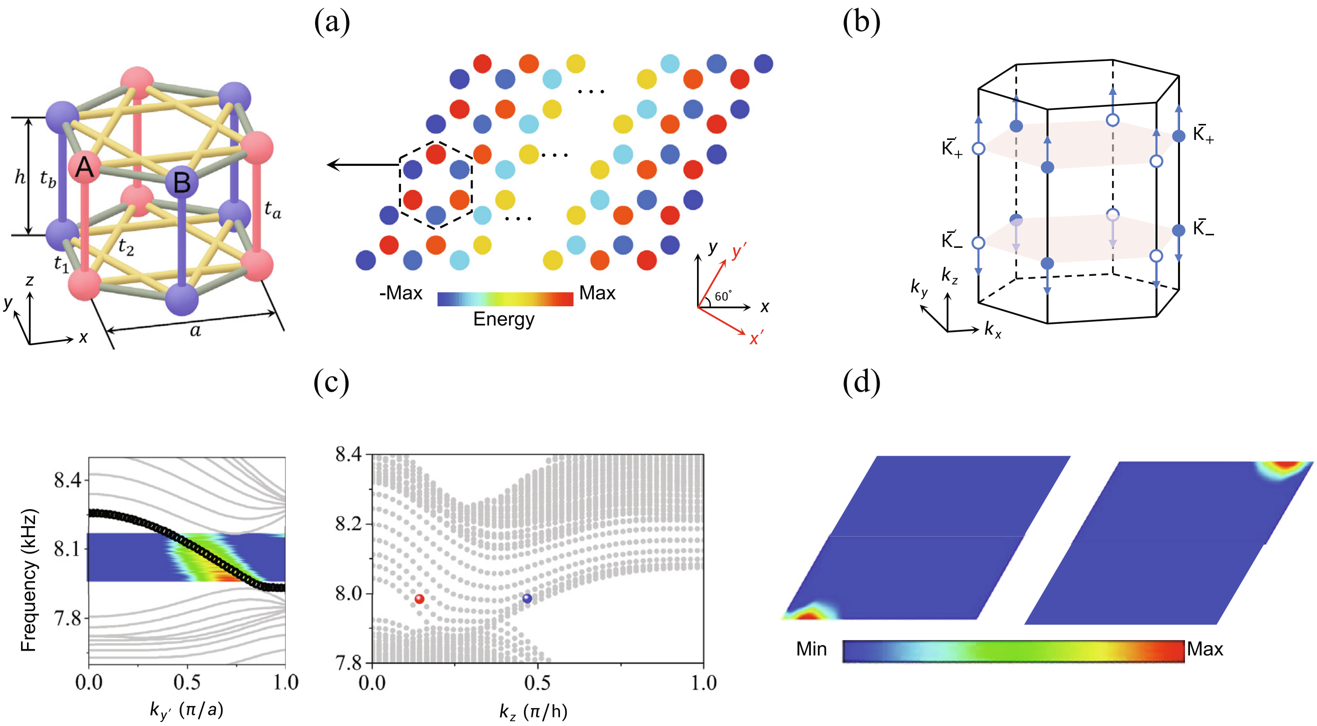

Fig. 1. (a) Schematics of the A-A stacked hexagonal lattice and inhomogeneous configuration with a gradient on-site energy along the x' direction indicated by the color. (b) First Brillouin zone and the distribution of the Weyl points denoted by the hollow and solid circles. The arrows show their shifts along the directions ± k_z by changing the on-site energies. (c) Left panel: Measured projected state dispersion along the $k_{y'}$ direction for k_z = 0.34π/h. The color maps represent the experimental results. Right panel: Simulated projected dispersion of a rhombus phononic crystal structure along the k_z direction. (d) Measured acoustic pressure field distributions of the edge states at the excitation frequency around 7.98 kHz for k_zh/π = 0.20 (left panel) and 0.44 (right panel), corresponding to the red and blue dots in (c), respectively.

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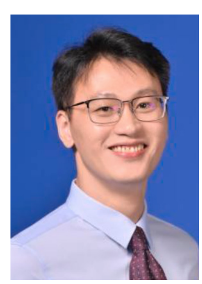

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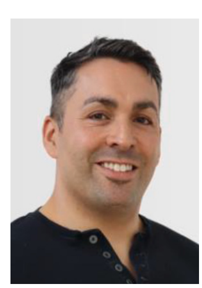

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