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Excitonic topological order in the moat-band physics

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In recent years, topological physics has become one of the major topics in condensed matter research. Various quantum topological phases are experimentally discovered and theoretically explored, including quantum Hall states [1–3] and topological insulators [4, 5]. The fractional quantum Hall (FQH) states are among the most celebrated examples, which attract a great deal of attention due to the interplay between correlation and topology. Topological orders exhibited in FQH systems are characterized by long-range quantum entanglements, emergent gauge fields, and fractional statistics [1–3]. Nevertheless, experimental realizations of novel topological orders in quantum materials remain an open challenge.

Two dimensional (2D) electron gases confined in semiconducting quantum wells serve as an ideal platform for studying exotic topological phases. The inverted electron and hole band structures can be tuned by varying the thickness of quantum wells and gate voltages. The quantum spin Hall insulator (QSHI), or, the time-reversal symmetry protected Z_2 topological insulator, is realized in the inverted HgTe/CdTe quantum wells [4, 5]. Time-reversal symmetry protects the Kramers pair of helical edge modes characterized by opposite chiralities. The helical edge modes remain gapless under disorders and weak interactions in the presence of time-reversal symmetry, but could be gapped out under strong interactions via spontaneous time-reversal symmetry breaking [6, 7].

The type-II semiconductor InAs/GaSb quantum wells is a new system for exploring the interplay between topology and correlation. A robust helical edge transport was observed [8], exhibiting the quantized longitudinal conductance $G_{xx} = \frac{2e^2}{h}$ when the sample length is smaller than the transport phase coherent length $\lambda = 4.4\mu$m. Such behavior even survives under a high in-plane magnetic field up to 12 Tesla, and the conductance increases in strong perpendicular magnetic fields. This seems beyond the scenario of time-reversal symmetry protection, since such a symmetry is broken by strong magnetic fields. Moreover, in shallowly inverted InAs/GaSb quantum wells the band hybridization gap is small, and then the correlation effect could play an important role. Considerable experimental and theoretical efforts have been carried out to explore the nature of the robust helical transport in InAs/GaSb quantum wells, which could be understood in terms of a topological excitonic insulator state [9, 10]. More experiments and theoretical studies are desired for further explorations.

In a recent work [11], Wang et. al. proposed a novel state of excitonic topological order (ETO) to understand the experimental findings in the InAs/GaSb quantum wells. The ETO state is a quantum analogue of bosonic FQH state, exhibiting non-trivial excitonic edge modes. In the experimental set-up, they studied transport properties by tuning charge carrier densities as well as the perpendicular magnetic fields in the shallowly inverted InAs/GaSb quantum wells (see Fig. 1). The metallic transport properties are observed as tuning the front-gate voltage below −3 Volt, or, above −2 Volt. The magneto-resistance behavior can be described by a two-carrier model of mobile electrons and holes. The electron and hole densities in the metallic regimes are imbalanced as indicated by the longitudinal and transverse magneto-resistance measurements. In contrast, when the front-gate voltage lies between −3 and −2 Volt, the bulk conductance exhibits an exponentially activated temperature dependence showing an insulating gap.

This experiment also shows a clear evolution from the helical-like edge transport to the chiral-like one in this insulating regime. At zero magnetic field, Hall conductance σ_{xy} is nearly zero while the longitudinal conductance σ_{xx} is finite due to the helical-like edge transport. By increasing the magnetic field, σ_{xy} increases while σ_{xx} decreases. When the magnetic field reaches 16 Tesla, σ_{xx} is kept nearly vanishing, while σ_{xy} shows approximately a quantized plateau of e^2/h, signalizing the appearance of the chiral-like edge transport. At an even higher magnetic field about 35 Tesla, the precision of the quantization of σ_{xy} is further improved. The authors of Ref. [11] propose that this exotic observation can be understood in terms of the ETO state, based on a moat-band like dispersion of excitons [12].

The estimation of charge carrier densities in the insulating regime was performed based on the two-carrier model in Ref. [11], which shows the population imbalance between electron and hole densities except at the

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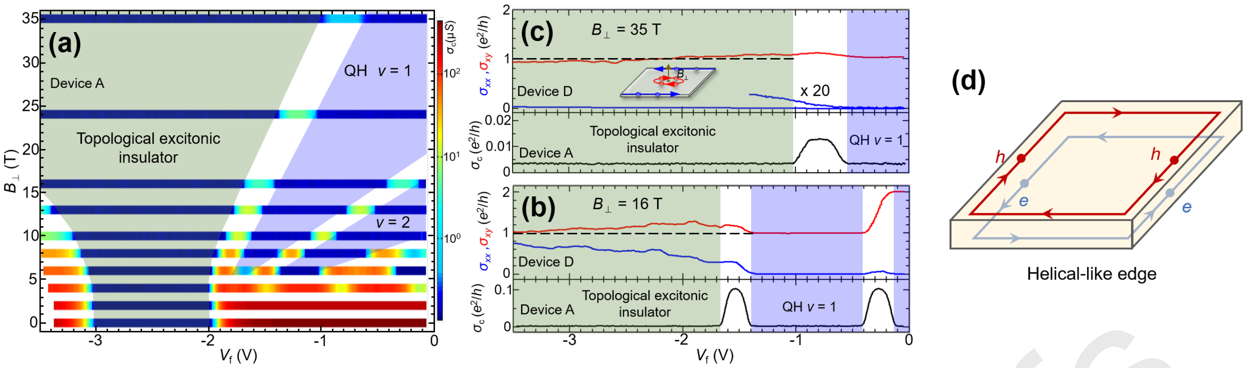

Figure 1: (Color online) The transition from the helical-like transport to the chiral-like one as varying magnetic fields and gate voltage in InAs/GaSb quantum wells. (a) Front-gate voltage V_f tuned topological excitonic insulator and quantum Hall (QH) states under magnetic field $B_\perp$. (b) and (c) Transitions from QH state ($\nu = 1$) to chiral-like ETO tuned by V_f at $B_\perp$ = 16T and 35T. The chiral-like transport behavior is characterized by nearly quantized Hall plateau ($\sigma_{xy} \simeq e^2/h$), which differs from the perfect quantized Hall plateau in the QH state. Figures are reproduced from Refs.[11]. (d) A sketch of the helical-like edge motion in a ETO state. The helical-like edge modes contain a pair of electron and hole channels. Electrons and holes move in the same direction while their charge currents are in opposite directions.

charge-neutrality point. The charge-neutrality point is reached by fine-tuning the gate voltage, while the excitonic insulating phase exists for a wide parameter regime. Moreover, potential fluctuations from disorder could also induce local population imbalance between electron and hole densities even near the charge-neutrality point. If the electron density n_e and hole one n_h are imbalanced, their Fermi wavevectors should differ by $Q = \sqrt{2\pi|n_e - n_h|}$, which suggests that electron-hole pairs carry a finite magnitude of momentum Q. In the mean-field level, a Fulde–Ferrell–Larkin–Ovchinnikov (FFLO) like excitonic insulating phase with the Bardeen-Cooper–Schrieffer type electron-hole pairing is stabilized in the weak coupling limit. The bosonic excitons tend to condensate at wavevectors in specific directions. However, the mean-field solution ignores the directional fluctuations of the condensation wavevectors, which could destabilize the Bose-Einstein condensation (BEC) of excitons [12]. An effective interacting model of excitons was constructed whose energy minima lie along a ring with the magnitude of Q in momentum space, exhibiting a moat-band dispersion. Such a model reflects the frustration effect of the exciton formation due to the population imbalance between electrons and holes [11, 13].

The 2D bosonic systems with moat-band dispersion have been attracting considerable attention, owing to exotic phenomena emerging from strong frustrations [12, 14]. The ring of the lowest single-particle energy states leads to heavy degeneracies, which can be viewed as a Bose surface. The Bose surface can exist in spin-orbit coupled boson systems, which could give rise to Landau-level like degeneracy, and skyrmion-like spin texture of BEC exhibiting spontaneous time-reversal symmetry breaking in a harmonic trapping potential [14]. 2D bosons with Bose surfaces could support the exotic Bose liquid states [15], which may be relevant to the strange metal phase in strongly correlated systems. The interplay between correlation and frustration could destabilize the FFLO states, or, BECs with non-zero condensation wavevectors [12, 13]. Consequently, novel ETOs could appear for excitons with a moat-like dispersion, which are energetically more favorable at low exciton densities [11].

The theoretical framework of the FQH effect can be generalized to ETO due to the close connection between them. The FQH states arise from the interplay between topology and correlation, which do not exhibit any symmetry breaking and go beyond the Landau paradigm of phase transitions [1]. In the composite particle approach, each electron is attached with an odd or even number of flux quanta. Taking into account all the phase contributions arising from the particle-particle and particle-flux exchanges, it can be concluded that a composite particle is bosonic/fermionic if the attached flux quanta are odd/even, respectively. Physically, it can be viewed as adopting a Jastrow factor in the correlated many-body wavefunction characterized by an integer quantized vortex. This intuitive picture can be implemented via the statistical Chern-Simons transformation, and the Chern-Simons flux density is proportional to the particle density [2, 3].

Following the same reasoning, the ETO could be thought as a bosonic FQH state, effectively in the same class of Laughlin state of $m = 2$, where m is relative orbital angular momentum between every two bosons. This is a prototype of bosonic topological order. Such a state can also be described by a Slater determinate state of composite fermions, which are obtained by the Chern-Simons transformation, i.e., attaching one flux quantum to each exciton [11, 13]. The composite fermions with moat-band dispersion undergo the Landau level quantization under the Chern-Simons field, whose flux density is proportional to the exciton density n. The fermionic nature of composite particles, which arises from the vortex-like Jastrow factor, reduces the probability of two particles approaching each other, suppressing their interaction energy. On the other hand, the flux attachment increases the kinetic energy. Nevertheless, thanks to the divergence of low-energy density of states associated with the moat band, the kinetic energy scales as $\sim n^2(\log n)^2$ at the low density. In contrast, a BEC-type wavefunction optimizes the kinetic energy but pays the price that the interaction energy scales linearly with n. Hence, the correlated ETO-type many-body wavefunction is energetically more favorable than the uncorrelated simple BEC wavefunction at low densities.

The ETO state spontaneously breaks time-reversal symmetry even without an external magnetic field, exhibiting chiral excitonic edge modes. They can be viewed as a pair of correlated electron and hole edge channel modes, which are spatially separated in two layers, as depicted in Fig. 1(d). Electrons and holes feel the opposite Chern-Simons fields, such that their cyclotron motions are in the same direction and exhibit nearly quantized helical-like edge conductance [8, 11]. On the other hand, the Hall conductance σ_{xy} is nearly vanishing since the contributions from electrons and holes cancel each other. After applying the external magnetic fields, the helical-like transport evolves to the chiral-like one, which can also be understood based on the above two-channel picture [11]. The external magnetic field affects the cyclotron motions of electrons and holes in the opposite way. Combining the Chern-Simons field and the external magnetic field together, the edge channels of electrons and holes could be separated if the magnetic field exceeds a critical value, then only the outer chiral channel contributes to the edge transport exhibiting nearly quantized value $\sigma_{xy} \simeq \frac{e^2}{h}$. Nevertheless, the quantization is not perfect due to the residue scattering between the two channels.

The work by Wang et. al. [11] shows that the InAs/GaSb quantum wells serves as a new platform for exploring novel quantum states of correlated excitons. They have observed the transition from the helical-like transport to the chiral-like one as varying the external magnetic field. This phenomenon could be explained by the state of ETO, which is an analogy of the bosonic fractional quantum Hall state. Such an exotic state could be driven by frustrations arising from the moat-like dispersion of excitons. This work provides possible evidence for the ETO state and inspires new directions for studying novel topological orders. In order to establish the stability of the ETO state regarding to its competition with other possible states like BECs, further analytic and numerical studies are useful. A few questions arise naturally. If the external magnetic fields drive the edge modes from the helical-like nature to the chiral-like one, are bulk topological properties affected or not? Should the magnetic field be further increased, would both electrons and holes ultimately exhibit edge modes with the same chirality? Moreover, the ETO states should exhibit anyonic excitations with fractional statistics, and more spectral and transport experiments are desired to reveal these exotic properties. These advances would greatly extend our knowledge in exploring exotic correlated states in quantum materials.

Conflicts of interest

The authors declare that they have no conflict of interest.

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