2D Gapless Topological Superfluids Generated by Gauge Phases in a Rydberg Fermi Gas

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Abstract

We systematically investigate the ground state phase diagram and the finite temperature phase transitions for a Rydberg-dressed Fermi gas loaded in a bilayer optical lattice. The obtained ground state is a gapless topological superfluid with finite topological charges around the Weyl points, leading to a zero energy flat band at the edges. Finally, we calculate the finite temperature phase diagrams of this 2D gapless superfluid and observe two distinct critical temperatures, demonstrating the fruitful many-body effects on a paired topological superfluid.

Introduction

The development of experiment techniques in Cold Atom suggests the new possible realization Majorana fermions in Topological superfluid. In our work, we consider a 2D double layer system with a square optical lattice within the x-y plane, where a single-species Fermi gas are loaded with finite tunneling amplitudes between lattice sites in the same or opposite layers. In order to generate an effective interaction between these single-species Fermi gas, an off-resonant two-photon transition is introduced to weakly couple the electronic ground state to a Rydberg excited state via an intermediate state.

$$\hat{H} = -t\sum_{r,\sigma}\left[\hat{c}^\dagger_{r,\sigma}\hat{c}_{r+\hat{x},\sigma} + \hat{c}^\dagger_{r,\sigma}\hat{c}_{r+\hat{y},\sigma} + \text{ h.c. }\right] - t_z\sum_{r,\sigma}\hat{c}^\dagger_{r,\sigma}\hat{c}_{r,-\sigma} - \mu\sum_{r,\sigma}\hat{c}^\dagger_{r,\sigma}\hat{c}_{r,\sigma}$$
$$-\frac{1}{2}\sum_{r,r',\sigma}\{V_{\|}(r-r')\hat{c}^\dagger_{r,\sigma}\hat{c}^\dagger_{r',\sigma}\hat{c}_{r',\sigma}\hat{c}_{r,\sigma} - \frac{1}{2}\sum_{r,r',\sigma}V_{\perp}(r-r')\hat{c}^\dagger_{r,\sigma}\hat{c}^\dagger_{r',-\sigma}\hat{c}'_{r',-\sigma}\hat{c}_{r,\sigma}$$

We first calculate the energy within the meanfield approximation. The ground energy could be determined later through a variational approach.

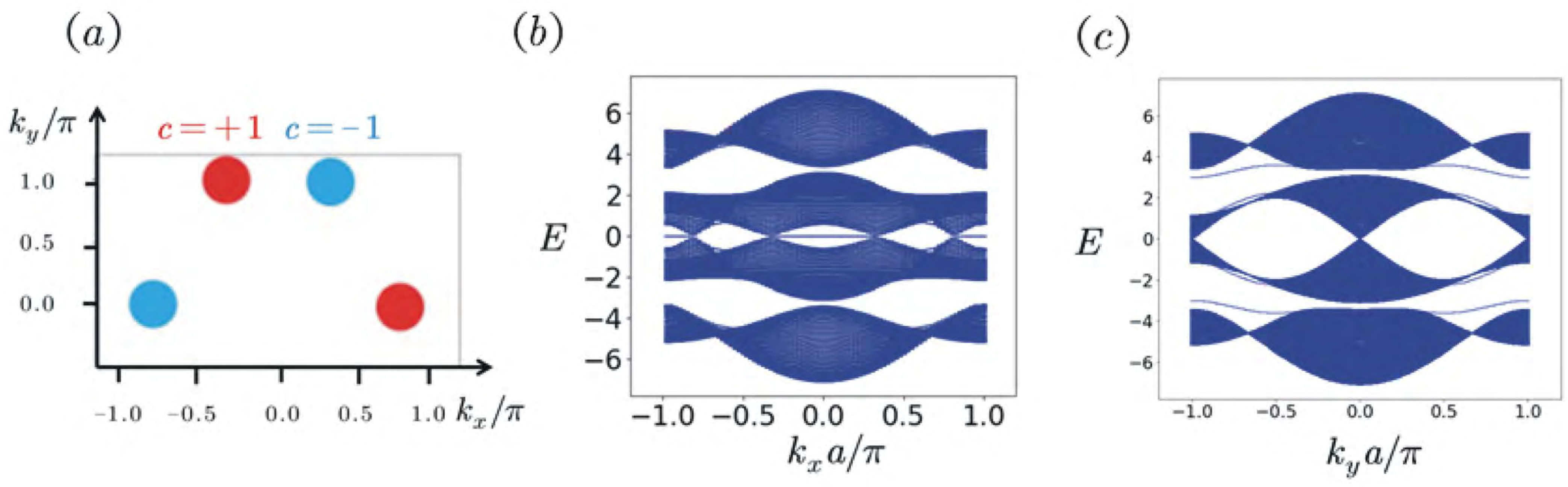

Fig. 2. (a) Topological charges for each Weyl point in the momentum space.
(b) (c) The energy spectra with semi-boundaries condition

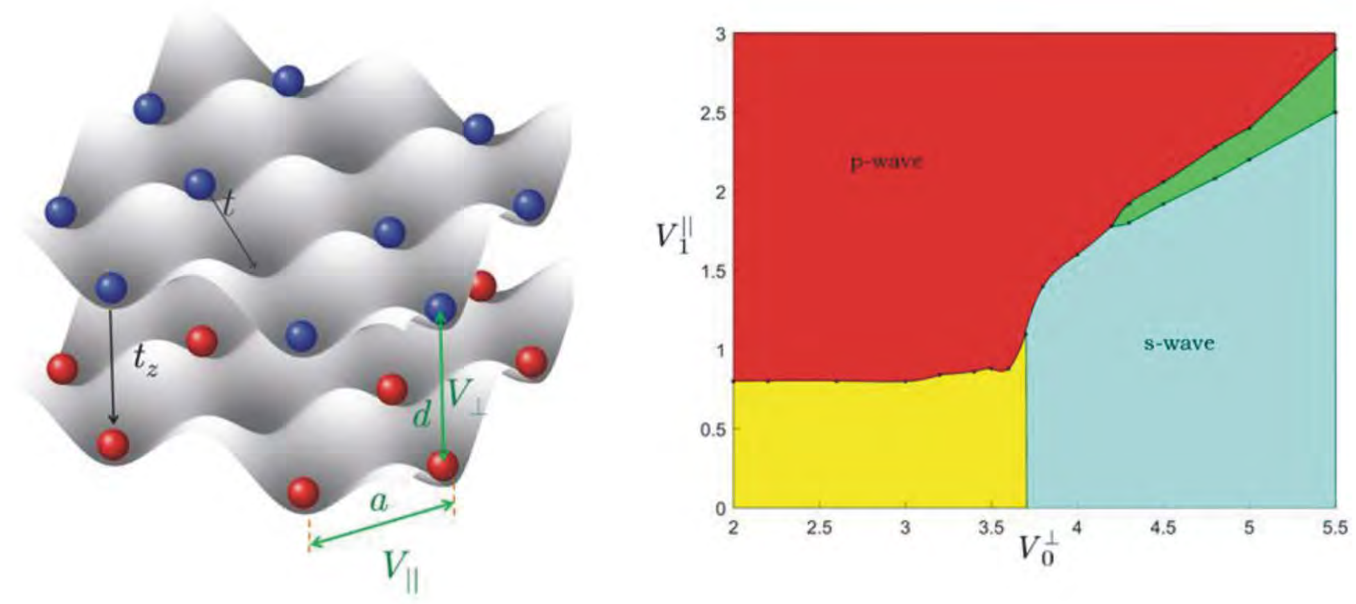

Fig. 1. Geometric of bilayer system and Quantum phase diagram in terms of interacting. The coexistence state of s-wave and p-wave pairing in green regime.

Result

We show the quantum phase diagram in terms of interacting for the gauge phases $(\alpha,\phi)=(\pi,\pi)$. In a stronger interaction regime, we find the possibility to have a co-existing s-waves and p-waves superfluid , which was not investigated before. The coexisting regime providing an important meaning to the investigation of topological superfluidity: the traditional chiral p-wave superfluids could be coupled and paired together, making a possible new topological superfluid.

In Fig.2.(b) (c). We could find that their band structures are very different due to the phase locking between the inter-layer pairing and the intra-layer pairing order parameters. The points of positive charge and negative charge appear alternatively at these gapless (Weyl) points as show in Fig.2.(a). The breakdown of rotational symmetry C_4 makes the projection of total charge to be zero on the k_y axis, but non-zero on the k_x axis. It explains why a zero mode appears in the edge state when the boundary is open in the direction y in Fig.2 (b).

Conclusions

We show that the ground state energy of a Rydber-dressed Fermi gas in a bilayer system can be a good system to realize the gapless topological superfuid, which could be tuned by the relative gauge phases between the s- and p-wave pairing.