

New Phenomena in Condensed Matter Physics: Topological Insulators and Twisted Bilayer Graphene

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Abstract. Phenomena include the Kosterlitz-Thouless phase transition, fractional quantum Hall effect, and high-temperature superconductivity have driven advances in condensed matter physics, offering a foundation for the investigation of superconductivity and the quantum Hall effect, as well as aiding in the comprehension of the behavior of strongly correlated electrons. The discovery of topological insulators and the preparation of graphene triggered important breakthroughs 20 years ago, leading to novel phenomena include topological superconductivity, the quantum anomalous Hall effect, corner graphene, and quantum spin liquids, which opened new directions in quantum materials research. Through the study of topological superconductors and flat band effects, this paper elucidates the role of topological energy band theory in describing Majorana fermions and their non-abelian statistical properties and reveals the phenomena of superconductivity and Mott's insulating state due to strong electronic interactions in magic-angle cornering graphene. The results show that the theory of topological energy bands and flat band effects can explain the strongly correlated electronic effects, providing theoretical support for understanding the phase transition from Mott insulating states to superconducting states and the Majorana zero mode in quantum computation. This paper emphasizes the importance of topological and two-dimensional materials in the study of strongly correlated electrons, providing guidance for future research.

Keywords: Topological insulators; Twisted bilayer graphene; Flat band; Quantum materials.

1. Introduction

Condensed matter physics is an important branch for studying the collective behavior of microscopic particles in macroscopic systems, and has traditionally made remarkable achievements in solid state physics, especially energy band theory and Landau phase transition theory, which have successfully explained the electronic structure and phase transitions in metals, semiconductors, and insulators. However, with the discovery of new phenomena, the traditional theories show limitations. Topological phenomena like the fractional quantum Hall effect transcend the Landau paradigm, and quantum states based on topological conservation cannot be explained by conventional phase transition theory. In addition, the BCS theory proposed in 1957, while explaining low-temperature superconductivity, fails to cover high-temperature superconductivity phenomena, which require more complex electronic interaction mechanisms. Quantum spin liquids, on the other hand, exhibit rich quantum correlation behavior different from that of conventional solid matter [1].

There are advances in quantum spin liquids and high-temperature superconductivity phenomena. Quantum spin liquid, proposed by PW Anderson in 1973, describes a state of matter without long-range magnetic order in the ground state, in which the spins remain quantum entangled in a "liquid" state. In recent years, the properties of quantum spin liquids have been experimentally verified in two-dimensional and topological materials, such as κ -(ET)₂Cu₂(CN)₃ and α -RuCl₃, where the dynamical features of no magnetic order and spin correlation have been confirmed by techniques such as neutron scattering. Quantum spin liquids are closely related to topological matter states and quantum computation, providing an important platform for studying Majorana fermions and non-abelian statistics [2].

The phenomenon of high-temperature superconductivity refers to the fact that certain materials exhibit superconductivity at relatively high critical temperatures, i.e., the material conducts electricity in a state of zero resistance and complete antimagnetism. In 1986, J. Georg Bednorz and K. Alexander

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