学 位 論 文 内 容 の 要 旨

博士の専攻分野の名称　　博士（工学）　　氏名　姜　治宇

学 位 論 文 題 名

Dual Symmetry Classification and $\mathbb{Z}_2$ Point-gap Topology in Non-Hermitian Systems
(非エルミート系における双対対称性分類と $\mathbb{Z}_2$ ポイントギャップ・トポロジカル相)

In recent years, the study of non-Hermitian systems has gained significant attention due to their potential for novel physical phenomena. These systems play a crucial role in exploring topological phases and finding practical applications in open quantum systems affected by gain and loss. Because the energy spectrum appears in the complex energy plane, non-Hermitian systems exhibit richer topological phases compared to their Hermitian counterparts. These non-Hermitian systems obtain two distinct types of energy gaps: line gaps and point gaps. Especially, the point gap, a distinctive feature of non-Hermitian systems, gives rise to unique phenomena, e.g., the non-Hermitian skin effect, wherein all eigenstates localize near open boundaries. Notably, there are two kinds of point gaps, namely, $\mathbb{Z}$ point gaps and $\mathbb{Z}_2$ point gaps, depending on the symmetry class for non-Hermitian Hamiltonians. While the $\mathbb{Z}_2$ topology has been extensively studied in Hermitian systems, theoretically and experimentally towards practical applications such as quantum spin Hall insulators and Majorana fermions, there has been limited theoretical exploration and no experimental investigation of $\mathbb{Z}_2$ point-gap topology in non-Hermitian systems. Despite these challenges, it is a topic worthy of further study. In this thesis, we focus primarily on the theory, applications, and experimental realization of $\mathbb{Z}_2$ point-gap topology.

In the first part of our research, we propose an extension of the symmetry classification on non-Hermitian systems. We show that non-Hermitian systems can always be classified in two distinct ways; based on the symmetry relations for non-Hermitian Hamiltonians and those for non-unitary time-evolution operators. This is based on the fact that there is no strict difference in mathematical definition between non-Hermitian Hamiltonians and non-unitary time-evolution operators. We call the proposed method “*dual symmetry classification*”. This classification approach enables non-Hermitian systems to exhibit more non-trivial topological phases than those considered in the previous classification methods.

In addition, we apply the dual symmetry classification to a time-evolution operator defined for non-unitary quantum walks which provides a novel arena for studying non-Hermitian physics even within the quantum realm. By treating the time-evolution operator as the non-Hermitian Hamiltonian, we successfully define a non-unitary quantum walk with spinful time-reversal symmetry and confirmed that the non-unitary quantum walk exhibits $\mathbb{Z}_2$ point gaps and $\mathbb{Z}_2$ non-Hermitian skin effect.

In the second part of our research, we highlight the advantages of leveraging non-Hermitian perspectives to explore Hermitian topological systems. As an application, we use $\mathbb{Z}_2$ point-gap topology to provide a systematic understanding of why the $\mathbb{Z}_2$ topological phase remains robust against stacking in the presence of chiral symmetry. We show that this robustness originates from level repulsion of the corresponding non-Hermitian Hamiltonian derived through a Hermitization procedure. Considering the spectrum of the non-Hermitian Hamiltonian, we can clearly understand the emergence of the robust $\mathbb{Z}_2$ topological invariant by counting if the energy winding around a reference point on the energy complex plain is even or odd. Our analysis relies on a novel correspondence through Hermitization, showing that the reference point E_p on the energy complex plain of the non-Hermitian system is mapped to the chemical potential μ of the Hermitian system with chiral symmetry. This relationship implies that the energy region for non-trivial $\mathbb{Z}_2$ point-gap topology aligns precisely with the range of μ where the $\mathbb{Z}_2$ topological phase of the Hermitian system is non-trivial, and zero-energy states appear.

We further substantiate our theoretical findings by studying a class DIII Hermitian superconductor with $\mathbb{Z}_2$ topology and its corresponding non-Hermitian system in symmetry class AII†, which exhibits $\mathbb{Z}_2$ point-gap topology. In the non-Hermitian system, when two layers are stacked, the four-fold degeneracy of the spectrum reduces to a two-fold degeneracy due to level repulsion between Kramers pairs. Crucially, the $\mathbb{Z}_2$ point-gap topology persists, ensuring the robustness of the corresponding DIII Hermitian superconductor against stacking within the range of μ corresponding to E_p, and the system continues to exhibit zero-energy states.

Through this series of research, we have expanded the symmetry classification methods for non-Hermitian systems, revealed the unique topological and dynamical properties of $\mathbb{Z}_2$ point-gap topology, and demonstrated the advantages of adopting a non-Hermitian perspective to investigate Hermitian topological systems. These discoveries provide a theoretical foundation for novel topological phenomena in non-Hermitian systems, accelerating the development of non-Hermitian topological phases and even Hermitian topological phases. Looking ahead, we hope that these theoretical results will be experimentally validated and applied in real physical systems, further deepening our understanding of non-Hermitian topological phases.