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Theoretical Study on Novel Phenomena in Multi-Component Superconductors
（多成分超伝導体における新規現象の理論研究）

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論　文　の　要　旨

Superconductivity is a macroscopic quantum phenomenon with novel manifestations such as zero electrical resistance and expulsion of magnetic field at sufficient low temperatures. According to Bardeen-Cooper-Schrieffer (BCS) theory, electrons near the Fermi surface form Cooper pairs due to electron-phonon interactions and condense into the quantum state leaving an energy gap. In some materials, there are several Fermi surfaces originated from different electronic bands. Multiple superconducting gaps can arise from these Fermi surfaces, and these multi-component superconductors are the targets of this thesis.

Multi-component superconductivity was first discussed in transition metals with a two-band BCS model more than fifty years ago by Mattias and his co-workers. Kondo then pointed out that superconducting critical temperature should be increased by a Josephson-like interband coupling. The degree of freedom of relative phase in a two-component superconductor was first discussed by Leggett, and now known as the Leggett mode. The interest to multi-component superconductivity is recovered due to the discovery of superconductivity in MgB_2 with clear evidence for two superconducting gaps in 2001 and the discovery of iron-based superconductors with more than two superconducting gaps in 2008.

In superconductors with three or more components, time-reversal symmetry (TRS) may be broken

in the presence of repulsive interband couplings, resulting in a pair of degenerate states characterized by opposite chiralities. A hopeful candidate to host this TRS broken (TRSB) state is the iron-based superconductor with at most five gaps originating from the five Fe 3d orbitals. Repulsive interband couplings are suggested by some experiments.

In this thesis, we mainly focus on novel phenomena of the TRSB state. First, asymmetric critical current with respect to the current direction is revealed in a Josephson junction between a superconductor in the TRSB state and a single-component superconductor. Fractional flux plateaus are then found in the magnetization curve for a superconductor loop with two halves occupied by the degenerate states with opposite chiralities of the TRSB state. It is also discussed that magnetic field penetrates a constriction connecting two bulks occupied by TRSB states with opposite chiralities and the magnetic induction takes a ribbon-shaped distribution. Finally the magnetic response of two-component superconductors is investigated and a first-order phase transition associated with vortex penetration is discussed.

We first focus on the Josephson effect of the TRSB state. We consider a Josephson junction between a three-component TRSB superconductor with gap functions $\{\Delta_1,\Delta_2,\Delta_3\}$and a single-component superconductor with gap function Δ_0. By adopting Bogoliubov-de Gennes equations, we obtain Andreev spectra and the current-phase relation. It is interesting to find that critical currents are unequal in the two opposite directions. The asymmetry of critical current is a clear manifestation of the broken TRS. It is intriguing to notice that asymmetric critical currents have been observed in a hybrid junction between a single-band superconductor PbIn and an iron-based superconductor $BaFe_{2-x}Co_xAs_2$. Our theoretical work suggests that TRSB states probably have already been realized in iron-based superconductors.

Next, we consider a loop of a multi-component superconductor where the two halves are occupied by two TRSB states carrying on opposite chiralities, accompanied by two domain walls associated with inter-component phase kinks. The situation is interesting when the two domain walls accommodate different phase kinks, such as D_{12} and D_{23}, namely phase kink between component 1 and 2, and that between component 2 and 3, in domain wall I and II respectively. Presuming that the three bands are equivalent to each other with mutual Josephson-like inter-component repulsion, one sees by inspection that ϕ_2 rotates $4\pi/3$ anticlockwise over the two domain walls, while ϕ_1 and ϕ_3 rotate $-2\pi/3$. When the external magnetic field provides the additional phase rotation of $2\pi/3$ in all condensates, a state with 2π phase winding in ϕ_2 and 0 in both ϕ_1 and ϕ_3 is stabilized. This yields a state with magnetic flux $\Phi_0/3$ trapped in the superconductor loop. This state is stable in a certain range of external magnetic field, which leads to a fractional flux plateau in magnetization curve. The above discussion can be elucidated by the integration of magnetic flux over the superconducting loop using Ginzburg-Landau (GL) formalism for a thick enough loop. Although fractional flux plateaus individually take arbitrary values depending on material parameters and temperature, they form pairs related by the flux quantum Φ_0, which is a unique signature of TRSB state. This phenomenon is a clear evidence of TRSB superconductivity, and in a general point of view it provides a novel chance to explore relative phase difference, phase kink and soliton in ubiquitous multi-component superconductivity.

We then study vortex states on a domain wall at a constriction connecting two bulk superconductors with the two degenerate TRSB states. With GL approach we find that vortices in different components dissociate from each other, resulting in a ribbon-shaped distribution of magnetic induction at the domain wall.

We also explore the magnetic response of two-component superconductors in terms of GL theory. We find a novel vortex-lattice state with thermodynamic stability with the following characteristic features: (1) the vortex-lattice constant is finite even at the first penetration, (2) the superconducting order parameters do not recover to the bulk values in absence of external magnetic field and (3) the magnetic field is only partially screened, in area among vortices. At a threshold field H_{c1}, many vortices enter simultaneously to form such a lattice in the whole sample, yielding a discontinuous jump in magnetization and thus a first-order phase transition. As a sharp contrast, in single-component superconductors vortices penetrate into the sample at H_{c1} associated with a continuous phase transition corresponding to infinite separation among vortices. This phenomenon can be observed even when both components are categorized into type II in absence of inter-component coupling.

To summarize, we have explored several novel phenomena in multi-component superconductors, which cannot be seen in single-component superconductors. The present work highlights the unique properties of multi-component superconductors and provides deeper understandings on multi-component superconductivity.

審　査　の　要　旨

〔批評〕

本論文は、多成分超伝導成分間相互作用によって実現される時間反転対称性の破れた状態について理論的に調べたものである。先ず、著者は時間反転対称性の破れた状態にある多成分超伝導体と単成分超伝導体のジョセフソン接合系において、二つの電流方向でのジョセフソン臨界電流が異なることを、ボゴリュボフ-ドジャンアプローチによって明らかにした。磁場の印加がないにも関わらず、時間反転操作で結ばれる二つの状態で得られたこの結果は、多成分超伝導体の状態自身において時間反転対称性

が破られていることを反映している。著者は今までに鉄系超伝導体を含むジョセフソン接合系の実験でも、電流方向に依存した臨界ジョセフソン電流が報告されたことから、時間反転対称性の破れた超伝導状態が既に実現された可能性を指摘した。次に、時間反転対称性の破れた三成分超伝導体が持つ二つのカイラリティ状態が超伝導体ループの左半分と右半分に現れている状況を調べた。この場合、二つのドメインウォールがあり、その両側で三つの超伝導成分の中で二つの超伝導成分間の位相差が符号を変えるいわゆる位相キンクが生まれる。超伝導体ループを貫く磁束の調整によって、二つのドメインウォールに異なるキンクが現れる場合、磁束値が磁束量子の非整数倍になることを著者が突き止めた。さらに、超伝導体ループの磁化曲線に見られる非整数磁束プラトーが必ずペアになり、その磁束値の和或いは差が磁束量子の整数倍になることを明らかにした。これらの現象は多成分超伝導に見られる時間反転対称性の破れた状態のユニークな性質によるものであり、その存在検証に用いることができる。また、著者は二成分超伝導体においてマイスナー状態から量子磁束格子への熱力学一次相転移の可能性を見出し、単成分超伝導との差異について議論した。これらの結果は、多成分超伝導の持つ特異な物性現象の解明に寄与し、今後の実験研究の指針になりえるものである。

以上の理由から、本論文は博士論文として十分と判断された。

〔最終試験結果〕

平成28年2月16日、数理物質科学研究科学位論文審査委員会において審査委員の全員出席のもと、著者に論文について説明を求め、関連事項につき質疑応答を行った。その結果、審査委員全員によって、合格と判定された。

〔結論〕

上記の論文審査ならびに最終試験の結果に基づき、著者は博士(工学)の学位を受けるに十分な資格を有するものと認める。