称号及び氏名	博士（工学）　東　陽一
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論　文　名	「Theoretical study for identifying unconventional superconductivity through vortex core bound states (渦芯束縛状態を通した非従来型超伝導の同定に対する理論的研究)」
論文審査委員	主査　魚住　孝幸
	副査　大同　寛明
	副査　岩住　俊明
	副査　石田　武和
	副査　加藤　勝

論文要旨

Superconductivity occurs with the quasiparticle(QP)states forming the Cooper pairs. The Cooper pair wave function may have the additional symmetry breaking other than U(1) gauge symmetry breaking. The additional symmetry breaking reflects remaining the internal degree of freedom of the Cooper pair such as the relative angular momentum, the total spin, the center of mass momentum and so on. Such superconductivity is called unconventional or exotic one. It is of great importance to identify the pairing state, namely the internal degree of freedom of the Cooper pair. It is because its identification gives the clue to the pairing mechanism and offers the future application of unconventional superconductors(SCs) to the new superconducting device such as the superconducting quantum interference device based on the d-dot composite, the Josephson junction and so forth.

The internal degree of freedom of the Cooper pair determines the characteristics of low energy excited states localized within quantized vortices in a type-II SC. The low energy excitations give the crucial contribution to thermodynamic and transport properties of SCs. Thus, in this dissertation, I theoretically investigate how the characteristics of unconventional superconductivity appear in the experimentally observable physical quantities through low energy excited states at a vortex core. In what follows, I give the brief summary and the main result with respect to each chapter.

In chapter 1, I introduce the fundamental concepts which form the bases to proceed the discussion. First of all, I give the physical picture of vortex bound states. Then, I explain anisotropic superconductivity and noncentrosymmetric one as examples of the superconductivity with the internal degree of freedom. Finally, I present the background and the motivation of the dissertation.

In chapter 2, I briefly summarize the mean-field theory of superconductivity and the derivation of the quasiclassical Eilenberger equation.

In chapter 3, we investigate the flux-flow resistivity(FFR)under rotating magnetic field in anisotropic SCs. It is known that a finite electric resistance appears in type-II SCs even in superconducting states under a uniform applied current if the flux pinning can be neglected. This electric resistance is called the flux-flow resistance. At low temperature, the energy dissipation is dominated by the relaxation of the low energy excitations at a vortex core. In the moderately clean system, which is realized in most SCs, the FFR is proportional to the impurity scattering rate within a core. Experimentally, the FFR is estimated by measuring the microwave surface impedance. First, on the basis of the quasiclassical theory and the Kramer-Pesch approximation, we analytically calculate the FFR from the impurity scattering rate inside a vortex core. Next, assuming the anisotropic superconducting pairing state (*d*-wave pair or line node *s*-wave one), we numerically calculate the in-plane field-angle dependence of the FFR. As a result of the calculations, we show that the field-angle dependence of the FFR is sensitive to the phase (sign change) of the superconducting order parameter. We should note that other field-angle dependent measurements such as field-angle resolved specific heat and thermal conductivity measurements can probe only the order parameter amplitude. In addition, we propose that measuring the microwave surface impedance under rotating magnetic field can be an experimental probe to identify the pairing symmetry including the phase structure of Cooper pairs.

In chapter 4, we focus on the impurity scattering effect on the LDOS around a vortex core in noncentrosymmetric SCs within the Born approximation. The noncentrosymmetric system is characterized by an anti-symmetric spin-orbit coupling. In this system, various interesting phenomena such as the parity mixing of the Cooper pair wave function and the characteristic spin structure on the Fermi surface affect the superconducting properties including the impurity effect. We point out that impurity effects around a vortex core in noncentrosymmetric SCs are different from that in the uniform system. Mentioning the bulk impurity effect, we show that the impurity effect in the vicinity of a vortex core is independent of the spin-orbit coupling (SOC) for an *s*-wave pairing, which is the same feature as that in the bulk. On the other hand, in an *s*+*p*-wave pairing, we find that the impurity effect can depend on the SOC. This means the interband impurity scattering occurs around a vortex core for the *s*+*p*-wave pairing state.

In chapter 5, we numerically investigate the vortex core structure in bilayer Rashba SCs by means of the self-consistent calculations using the quasiclassical theory. In multilayered systems, Yoshida *et* al. pointed out that the spatially inhomogeneous novel superconducting phases are stabilized under a high magnetic field, one of which is the pair-density wave (PDW) phase stabilized in a perpendicular field. We found that the structure of local density of states (LDOS) around a vortex core in the PDW state is quite different from that in the BCS state. The zero energy vortex bound state exists in the PDW state even if a high field, whereas it is absent in the BCS state due to the Zeeman split. Another signature of the BCS-PDW phase transition is the sudden decrease of the core size. These characteristics of the exotic superconducting phase means that the electronic structure of the vortex core changes drastically in the vicinity of BCS-PDW phase transition, which can be observed by scanning tunneling microscopy/spectroscopy at low temperature and in a high magnetic field. We also examine the origin of the contrasting behavior between these pairing states. The close examination of the SOC strength dependence of the zero-energy QP states and that of the energy spectra tells us that the prominent difference stems from (i) whether or not there is particle-hole symmetry in the mirror sector of the block-diagonalized Bogoliubov-de Gennes (BdG) Hamiltonian, and (ii) the change of the internal structure of the Cooper pair due to the SOC. We believe these features under a magnetic field can be a key to identify the exotic superconducting phase.

In chapter 6, we investigate the energy spectra and the wave functions of Bogoliubov QPs bound at a vortex and an edge in the PDW state in bilayer systems on the basis of the BdG theory. Around a vortex line with a rotational symmetry, the eigen wave functions are labeled by the angular quantum number. First, we show the excitation spectra, in which the branches of the edge modes appear inside the superconducting gap if the magnetic field exceeds the critical values, namely the system undergoes the phase transition into the topologically non-trivial phase. Then, we confirm the appearance of the zero energy vortex and edge QP bound states also from the spatial profiles of the zero energy eigen wave functions under the magnetic field above the critical values.

In chapter 7, we conclude our discussions on identifying unconventional superconductivity through vortex core bound states.

審査結果の要旨

本論文は，第２種超伝導である非従来型の超伝導体について，磁場を印加した場合に生じる渦糸内部のコア状態と呼ばれる準粒子の特性に着目し，超伝導電子対の対称性を同定する実験手法を理論研究の立場から提案するものである．従来型の等方的 s 波超伝導と異なり，同定が困難であると考えられていた非従来型に対する提案であり，超伝導機構の微視的解明や新規デバイスの開発につながり得る研究である．本論文では，３種類の非従来型超伝導を対象として以下の結果を得た．

(1) ２次元性のある系での d 波超伝導に対し，２次元面内に磁場を印加した場合について，フラックスフロー抵抗を準古典理論とクラマース＝ペッシュ近似を用いて計算した．この抵抗は渦糸コア内の準粒子が不純物に散乱されることで生じるが，準粒子が周りの超伝導電子対の対称性を反映するために，外部磁場の方向によって抵抗が変化することを明らかにし，その性質を利用した対称性の同定法を提案した．
(2) 空間反転対称性のない超伝導体では，反対称なスピン－軌道相互作用によって，パリティの異なる電子対が混合した超伝導の可能性が指摘されている．本論文では，渦糸コア内の準粒子の不純物散乱による影響が周りの電子対の対称性によって異なり，s 波超伝導とパリティの混合した s+p 波超伝導の場合ではスピン－軌道相互作用に対する依存性が異なることを明らかにした．この結果をもとに，走査型トンネル顕微鏡を用いた局所状態密度の観測による s+p 波超伝導の同定法を提案した．
(3) ２層構造の超伝導体では，必然的に空間反転対称性が破れているためにラシュバ型スピン－軌道相互作用が働くと考えられており，高磁場で電子対の波動関数の符号が層間で異なるペア密度波と呼ばれる超伝導が現れることが提案されている．本論文では，ペア密度波超伝導が実現している場合に渦糸コアの準粒子にゼロエネルギー束縛状態が現れることを明らかにした．これは s 波超伝導にも存在するゼロエネルギー状態が磁場印加で有限のエネルギーになるのと対照的である．この結果をもとに，走査型電子顕微鏡を用いた局所状態密度の観測によるペア密度波超伝導の同定法を提案した．

以上の研究成果は，非従来型超伝導体に対する重要な知見を与えるものであり，本分野の発展に貢献するところ大である．また，申請者が自立して研究活動を行うのに必要な能力と学識を有することを証したものである．