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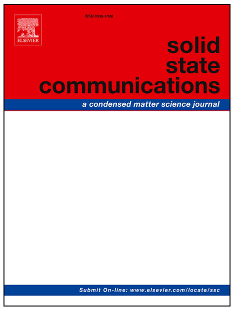

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Nontrivial superconductivity in two-dimensional superconductors with both magnetic field and spin-orbit coupling

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Abstract

Symmetry broken in a superconducting (SC) system is believed to affect the superconductivity, especially in the case of both time-reversal and inversion symmetry breaking. Accordingly, a two-dimensional (2D) SC system coexistence with both magnetic field and spin-orbit coupling (SOC) is investigated in the framework of mean-field theory. We find that SOC will introduce a mixture of spin-singlet and triplet pairings independent of magnetic field. However, SOC effects on each pairings are dependent on the presence of magnetic field both for its magnitude and direction. For both magnetic field out and in the plane, there seems to be some critical magnetic fields, below and above which SOC and magnetic fields shows different effects on the two pairings. Moreover, these critical magnetic fields are determined and enhanced by SOC. The composite effects of magnetic field and SOC on SC pairings might be helpful for understanding pairing mechanism in nontrivial 2D superconductors.

Keywords: A. 2D superconductors, D. Rashba spin-orbit coupling, D. Magnetic field, D. Superconductivity

1. introduction

Symmetry breaking in a superconducting (SC) system may affect the properties of SC states[1, 2, 3, 4]. Generally, application of a magnetic field will break the time-reversal symmetry which is essential for spin-singlet pairing, and destroy the spin-singlet SC state due to Zeeman effect and orbital effect[5, 6]. Ferromagnetic spin fluctuations will also involve time-reversal symmetry breaking and then favors spin-triplet pairing[7, 8, 9]. According to Anderson's theory, the inversion symmetry breaking of a SC system will affect the spin-triplet pairing[10]. The lack of inversion symmetry is believed to introduce spin-orbit coupling (SOC) interaction[11], which might lift the spin degeneracy and result in the mixture of spin-singlet and spin-triplet pairings[12, 13]. In particular, combination of time-reversal (applied magnetic field or spontaneous magnetization) and inversion symmetry breaking (SOC) may lead to new classes of SC states[8, 14].

Experimentally, noncentrosymmetic superconductors (NCSCs) like $CePt_3Si$, UIr are found to establish coexistence of magnetism, SOC and superconductivity [15, 16]. Two-dimensional (2D) SC systems exhibiting both time-reversal and inversion symmetry breaking are found in the 2D layer: interface between $LaAlO_3$ and $SrTiO_3$[17], Pb films [18], Bi/Ni bilayer films[19] and a monolayer of Pb covering magnetic Co−Si islands grown on Si(111)[20]. Theoretically, it is believed that the SC states in the above mentioned superconductors are a mixture of spin-singlet and spin-triplet ones due to the presence of SOC[11, 12, 21, 22]. Moreover, Fujimoto proposed a weakly NCSCs model with an out-of-plane magnetic field and found that the competition between magnetic field and SOC may result in anisotropic Pauli depairing effect in momentum space even in an isotropic s-wave state[23]. Loder *et al.* characterized the possible SC ground states in the entire regime of SOC and in-plane magnetic field strength within a microscopic model, which showing a transition between an intra-band pairing regime with dominant SOC and an inter-band regime with dominant Zeeman coupling[1]. Steinbok *et al.* investigated the effect of magnetic fluctuations in superconductors with strong SOC, and showed that they drive a phase transition between two SC states: a conventional phase with zero center-of-mass momentum of Cooper pairs, and an exotic phase with nonzero pair momentum[24]. Furthermore, both magnetic field and spin-orbit coupling are important key ingredients for the existence of nontrivial topological SC phases[25, 26, 27, 28]. It is also suggested that superconductors with strong spin-orbit coupling may go through a topological phase transition by tuning a magnetic field[25]. In 2D superconductors with a sizable SOC and an out-of-plane Zeeman field, which considering a strictly s-wave pair potential, the s-wave SC pair can never be zero by the application of a Zeeman field[26]. While, the effect of the interplay between magnetic field and SOC on the mixed parity of spin singlet-triplet pairings is still an open question in the SC systems with both time reversal and inversion symmetry breaking.

In this paper, we introduce a simple model to describe a 2D SC system in the presence of both magnetic field and Rashba

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