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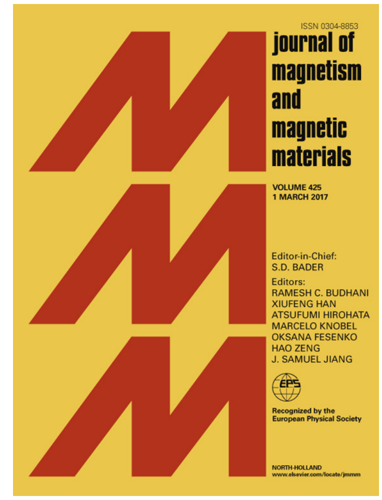

The nontrivial ground state topology in the coexistence phase of chiral *d*-wave superconductivity and 120-degree magnetic order on a triangular lattice

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The nontrivial ground state topology in the coexistence phase of chiral *d*-wave superconductivity and 120-degree magnetic order on a triangular lattice

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Abstract

The Z_2 topological invariant is defined in the chiral *d*-wave superconductor having a triangular lattice in the presence of the 120-degree magnetic ordering. Analyzing the Z_2 invariant, we determine the conditions of implementing topological phases in the model with regard to superconducting pairings between the nearest and next nearest neighbors. It is often supposed in such a system that the pairing parameter between the nearest neighbors should be equal to zero due to the intersite Coulomb interaction. We show that taking into account even weak pairings in the first coordination sphere leads to the disappearance of the gapless excitations of the bulk spectrum in the wide region of the parameter space. Thus, topological invariants can be defined in this region. In solving the problem of open edges it is shown that the zero energy modes are realized basically in the topologically nontrivial phases. Such zero modes are topologically protected Majorana modes. A connection between the Z_2 invariant and the integer topological invariant of the ground state of the 2D lattice is established in the presence of the electron-hole symmetry and noncollinear magnetic ordering.

Keywords: Majorana zero modes, topological invariant, chiral superconductivity, noncollinear magnetic order, triangular lattice
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1. Introduction

Recently, much attention has been paid to topological superconductors supporting Majorana zero modes. In pioneering works [1, 2], such quasiparticles were predicted in the *p*-wave and effective *p*-wave superconductors. However, this type of superconductivity is still rather exotic for real materials. For the systems with *s*-wave pairing several mechanisms have been proposed for the formation of the Majorana zero modes. One of the mechanisms is characterized by the proximity-induced triplet $p_x + ip_y$ pairings on the surface layer of a topological insulator in the *s*-wave superconductor / topological insulator hybrid structures [3]. Another mechanism is connected with the combined influence of strong spin-orbit interaction, proximity-induced superconductivity, and magnetic field [4, 5, 6]. In this case the Majorana zero modes arise when the external (or exchange) magnetic field is greater than some critical field.

At present, a new mechanism of the formation of the Majorana edge states in topological spin-singlet superconductors due to the presence of the long-range magnetic order is often considered [7, 8, 9, 10]. The symmetry of the superconducting state is considered to be chiral $d_{x^2-y^2} + id_{xy}$ supporting the non-trivial topology and edge states [11]. It should be noted that the time-reversal symmetry is broken in such a state. It is widely believed that the chiral *d*-wave superconductivity may be realized in materials with a triangular lattice (for example, Na_xCoO_2 [8]) and hexagonal lattice (graphene [10]).

For the topological classification of the systems with many degrees of freedom as well as in the systems with strong electron correlations the topological invariant N_3 expressed in terms of the Green functions was derived [12, 13]. Using this invariant the quantum topological phase transitions were studied in liquid helium ^{3}He-B [14], semiconducting nanowires [15], and quantum Hall systems. It should be noticed that the N_3 topological invariant is introduced for the gapped ground state in the systems with 2 + 1-dimensions [13].

The non-zero values of N_3 indicate the non-trivial topology and the possibility of the edge state formation. For 1D systems with the particle-hole symmetry the well-known Z_2 invariant (Majorana number) was proposed [2]. This invariant expressed in terms of the Pfaffian of the Bogoliubov Hamiltonian in the Majorana representation allows one to study the conditions supporting the Majorana zero modes in the systems with the gapped bulk excitation spectrum. Later, the connection between N_3 and Z_2 numbers was established for the noncentrosymmetric superconductors with the broken time-reversal symmetry [15]. The main result is that the Majorana zero modes is expected to appear in the states with the odd N_3 invariant.

On a triangular lattice the appearance of the Majorana zero modes was demonstrated in Ref. [8] for the coexistence phase of $d_{x^2-y^2} + id_{xy}$-wave superconductivity and non-collinear stripe magnetic ordering. The superconducting pairings between the nearest neighbors were assumed to be suppressed by the intersite Coulomb interaction. Therefore, the pairing interaction between the next nearest neighbors was considered.

Recently, by solving self-consistent integral equations for the

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