Time-reversal symmetry breaking surface states in $t-J$ model

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Recently a phenomenological Ginzburg-Landau (GL) theory has been proposed to describe the occurrence of a locally time-reversal symmetry ($\mathcal{T}$) breaking state near a Josephson junction between unconventional superconductors. In this paper we derive this type of GL free energy microscopically from the $t-J$ model within a slave-boson mean-field approximation. The resulting GL free energy is shown to satisfy the conditions to have a $\mathcal{T}$-violating surface state. The existence of this junction state may explain some of the recent experiments on High-T_c superconductors.

KEYWORDS: unconventional superconductivity, broken time reversal symmetry

§1. Introduction

The symmetry of the superconducting state in high-temperature superconductors (HTSC) has been a subject of intensive study as an important clue to clarify the mechanism of their superconductivity. The Josephson effect allows us to investigate directly the phase properties of a superconducting order parameter (OP), and thus it is a powerful experimental probe for this study. Many experiments demonstrate that the superconducting OP in these systems has a predominantly $d_{x^2-y^2}$-wave character, i.e. the OP changes sign under 90°-rotation in the CuO_2 plane[1,2].

In d-wave superconductors interface properties can be qualitatively different from those of conventional superconductors because of the nontrivial angular dependence of their pair wave functions. We have shown that a locally time-reversal symmetry ($\mathcal{T}$) breaking state can occur near an Josephson junctions between d-wave superconductors and, in general, unconventional superconductors[3,4,5,6]. This $\mathcal{T}$-violating state exists only near the surface and decays exponentially toward the bulk. It has important consequences on Josephson effects. The arguments which led to this conclusion were based on a phenomenological Ginzburg-Landau (GL) theory including several assumptions.[3,4,5,6,10,11]

In this paper we derive the GL free energy from the $t-J$ model within a slave-boson mean-field approximation, and demonstrate that it is possible to have a $\mathcal{T}$-violating surface state. The reason we consider the $t-J$ model is the following. Mean-field (MF) theories of the $t-J$ model based on a slave-boson method predict a superconducting state with a $d_{x^2-y^2}$-symmetry,[12,13] and they may explain the magnetic[14,15] as well as the transport[16] properties of HTSC if the gauge fields representing the fluctuations around the MF solutions are properly taken into account. Thus, it is interesting to study whether the $t-J$ model leads to a $\mathcal{T}$-violating state, in particular, at the Josephson junction.

§2. Mean Field theory and GL expansion of free energy

We consider the $t-J$ model on a square lattice with the Hamiltonian

$$\begin{aligned} H = & -t \sum_{<i,j>\sigma} (\tilde{c}^\dagger_{i,\sigma}\tilde{c}_{j,\sigma} + h.c.) \\ & + \; J\sum_{<i,j>} \vec{S}_i \cdot \vec{S}_j \end{aligned} \tag{2.1}$$

where the summation is taken over nearest-neighbor bonds $\langle i,j\rangle$, and $\tilde{c}_{i\sigma} \equiv c_{i\sigma}(1-n_{i,-\sigma})$. We use the slave-boson method to enforce the condition of no double occupancy by introducing spinons ($f_{i\sigma}$; fermion) and holons (b_i; boson) ($\tilde{c}_{i\sigma} = b^\dagger_i f_{i\sigma}$). Then the Hamiltonian is decoupled with the following order parameters (OP)[12,13]: (1) the bond OP, $\langle b^\dagger_j b_i\rangle \equiv \chi_B$ and $\langle f^\dagger_{j\sigma} f_{i\sigma}\rangle \equiv \chi_F$ which we assume to be homogeneous for all nearest-neighbor bonds; (2) the OP for the Bose condensation of holons, $\langle b_j b_i\rangle$[7]; (3) the singlet RVB OP, $\langle f^\dagger_{i\uparrow} f^\dagger_{j\downarrow} - f^\dagger_{i\downarrow} f^\dagger_{j\uparrow}\rangle \equiv \Delta^*_{ij}$. The superconducting OP is given by the product of the last two, $\langle b_j b_i\rangle\Delta^*_{ij}$. In a slave-boson mean field theory there are four kinds of ordered states in all of which the bond OP are finite: (a) the uniform RVB state where only the bond OPs are finite; b) the spin gap state where the singlet RVB OP is also finite[8]; In this state there is a (pseudo-) gap in the spin, but not in the charge excitations. Hence the name spin gap state; c) the superconducting state where all three OP's listed above are finite; d) the Fermi liquid state[9]. A schematic phase diagram is shown in Fig.1.

In this paper we consider only the optimally and over doped case where $T_{BE} \geq T_{RVB}$, and so the critical temperature for superconductivity, T_c, is given by T_{RVB}. (In other words we do not treat the case where the onset of superconductivity is given by the Bose condensation of holons.) In this case we can take $\chi_B = \delta$, since we always consider the case $T \leq T_{BE}$. Since the superexchange interaction exists only for nearest-neighbor bonds, the $d_{x^2-y^2}$- and the extended s-wave are natural candidates for the symmetry of the superconducting OP. The for-