SUPERCONDUCTIVITY IN THE STRIPE PHASE MAGNETIC PROPERTIES*

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One of unusual features of high-T_c superconductors, that we discuss in the present report, is related to inhomogeneous distribution of holes. It results in a stripe-phase which consists of antiferromagnetic domains separated by hole-rich domain walls. We study how the upper critical field is affected by this specific distribution of carriers. We consider a two-dimensional square lattice immersed in a perpendicular uniform magnetic field. In order to simulate the presence of a stripe-phase we carry out the calculations for a system with modulated hopping integral. Namely, the magnitude of the hopping integral is constant along the stripe, whereas it oscillates in the opposite direction.

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1. Introduction

Some of experimentally observed unusual properties of the high temperature superconductors (HTSC) are related to their magnetic properties. In particular, the measurements of the upper critical field (H_{c2}) reveal a qualitative differences with respect to classical superconducting systems. For optimal doped systems the extrapolated value of $H_{c2}(T \to 0)$ can be of the order of a few hundred Tesla. In contradistinction to conventional superconductors $H_{c2}(T)$ is characterized by positive curvature [1, 2]. Moreover, for overdoped compounds the critical field does not saturate even at genuinely low temperatures. These features cannot be explained within a conventional theory of H_{c2} [3]. From the theoretical point of view the positive curvature of $H_{c2}(T)$ occurs for instance in: Bose–Einstein condensation of charged bosons [4], Josephson tunneling between superconducting clusters [5], and

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in mean-field-type theory of H_{c2} with a strong spin-flip scattering [6]. However, none of these approaches has definitively been accepted. In particular, the purely bosonic approach [4] is not applicable in the overdoped regime, when HTSC exhibit a Fermi-liquid type of behavior [7].

Other unusual feature of high-T_c superconductors is related to the stripe phase. Within this scenario holes, which enter the copper-oxygen planes in the doping process, are not distributed uniformly. Instead, they form antiferromagnetic domains separated by hole-reach domain walls [8–14].

In the present report we investigate influence of the inhomogeneous distribution of carriers upon the upper critical field.

2. Model

We consider a square lattice immersed in a perpendicular, uniform magnetic field, described by the following Hamiltonian:

$$\hat{H} = \sum_{ij\sigma} t_{ij}\left(\boldsymbol{A}\right) c_{i\sigma}^{\dagger} c_{j\sigma} \; - \; V \sum_{i} \left(c_{i\uparrow}^{\dagger} c_{i\downarrow}^{\dagger} \Delta_i + c_{i\downarrow} c_{i\uparrow} \Delta_i^{\star} \right). \tag{1}$$

Operator $c_{i\sigma}^{\dagger}$ creates an electron with spin σ on site i, V stands for the magnitude of the pairing interaction, $\boldsymbol{A}$ is the vector potential corresponding to the external magnetic field $\boldsymbol{H}$, and $\Delta_i = \langle c_{i\downarrow} c_{i\uparrow} \rangle$ is the superconducting order parameter.

According to the Peierls substitution the original hopping integral t_{ij} is multiplied by a phase factor, which accounts for coupling of electrons to the magnetic field $t_{ij}\left(\boldsymbol{A}\right) = t_{ij}(0) \exp\left(\frac{ie}{\hbar c} \int_j^i \boldsymbol{A} \cdot d\boldsymbol{l} \right)$.

In order to simulate the presence of stripes we assume $t_{ij}(0)$ as a position-dependent quantity. We modulate the hopping in the direction perpendicular to the stripe and keep the hopping along the stripe constant. More precisely, we take $t_{ij}(0) = t$, when the bond between i and j is parallel to the stripe. t represents also the maximal value of the hopping integral in the perpendicular direction. Tuning the modulation depth, d, we can continuously drive the system between two limiting cases: separated stripes for $d \geq t$ and homogeneous two-dimensional lattice for $d = 0$. The site-dependent hopping integral is presented in Fig. 1.

To calculate H_{c2} one can apply the lattice version of the Gor'kov equations

$$\Delta_i = \frac{V(T)}{\beta} \sum_{j,\omega_n} \Delta_j G(i,j,\omega_n) G(i,j,-\omega_n). \tag{2}$$

Here, $G(i,j,\omega_n)$ is the one-electron Green's function in the presence of a uniform and static magnetic field and ω_n is the fermionic Matsubara frequency. For details we refer to Ref. [15].

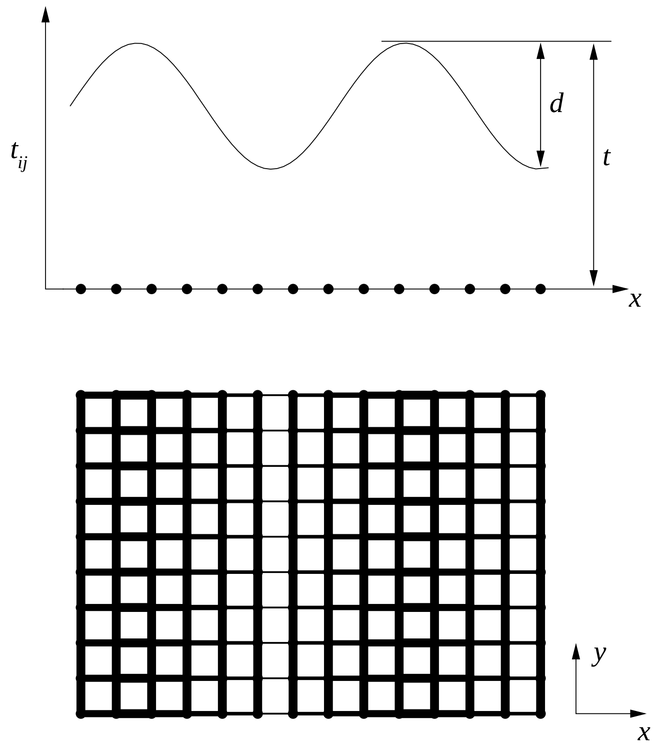

Fig. 1. Modulation of $t_{ij}(0)$. The upper panel shows the hopping integral in the direction perpendicular to the stripe. In the lower panel the thickness of lines is proportional to the magnitude of $t_{ij}(0)$.

3. Results and discussion

Figure 2 shows the temperature dependence of H_{c2} determined for different values of the modulations depth.

Small-to-medium modulation hardly affects the shape of $H_{c2}(T)$. However, for $d/t \geq 0.9$ stripes become almost separated and one can see a substantial modification of the critical field. This modification is of particular importance for weak magnetic fields, when the radii of the Landau orbits exceed the width of the stripe. Here, one can observe a dramatic change of the slope, $\mathrm{d}H_{c2}/\mathrm{d}T$, calculated at $T = T_c$. This effect has a nice physical interpretation: the geometry of the stripe does not allow for a formation of rotationally invariant Landau orbits. Therefore, the diamagnetic pair-breaking is strongly reduced and superconductivity is hardly affected by a weak magnetic field. For stronger fields the radii of the Landau orbits decrease, and this effect becomes less important.

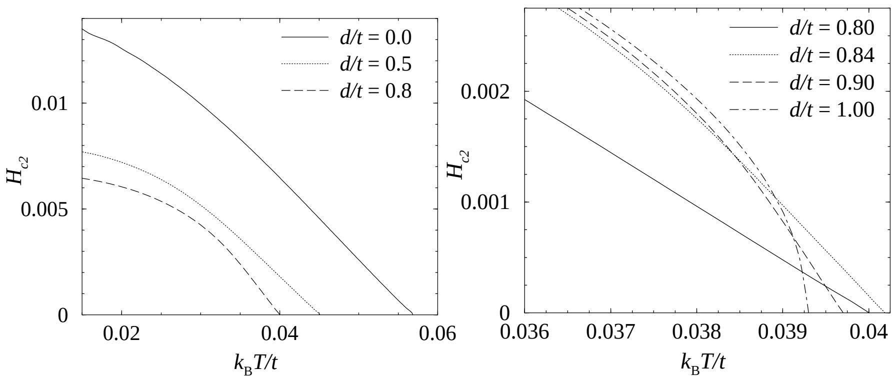

Fig. 2. $H_{c2}(T)$ calculated for $V = 1.2t$ and different values of the modulation depth d. Left plot shows results for modulation depth up to $d/t = 0.8$, whereas right plot shows results for $1 \geq d/t \geq 0.8t$.

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