UPPER CRITICAL FIELD IN A STRIPE–PHASE*

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We study the problem of the upper critical field (H_{c2}) for tight-binding electrons in a phase with stripes. Carrying out calculations for finite systems we analyze the influence of the external field in the commensurable and incommensurable case on an equal footing. The upper critical field is discussed for anisotropic intersite pairing as a function of the width of stripe. We show that the upper critical field increases with a decrease of the width of stripe. This effect is of particular importance close to the superconducting transition temperature.

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1. Introduction

Despite enormous efforts the mechanism, which is responsible for the formation of high-temperature superconductivity, remains an open problem. Moreover, neither theoretical nor experimental results allow for a complete and unique description of the normal-state. Above the superconducting transition temperature one finds two major phases: underdoped, and overdoped. The natural question which arises concerns the distribution of holes which enter the copper-oxygen planes in the doping process. There is a convincing argumentation speaking in favor of spatially inhomogeneous distribution of holes. It results in a stripe-phase which consists of antiferromagnetic domains separated by hole-reach domain walls [1–7]. In the present paper we investigate influence of the spatial distribution of carriers upon the upper

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critical field, H_{c2}, for anisotropic superconductivity. Within a simple mean-field approach we demonstrate that inhomogeneous distribution of holes affects the structure of Landau levels and leads to a serious modification of the upper critical field.

In order to simulate the presence of a stripe-phase we investigate a two-dimensional rectangular-shape clusters that consist of $N_{||}$ lattice sites along the domain wall and $N_{\perp}$ sites in the perpendicular direction, with $N_{\perp} \ll N_{||}$. Since the length of a stripe is assumed to be infinite we make use of periodic boundary conditions in the parallel direction. The antiferromagnetic domains between stripes are insulating and thus we take fixed boundary conditions in the perpendicular direction.

2. The model

In order to determine H_{c2} for anisotropic superconductivity we consider the nearest-neighbor pairing and introduce a uniform magnetic field, which is perpendicular to the cluster. The Hamiltonian reads

$$\begin{aligned} \hat{H} \;=\; & \sum_{\langle i,j\rangle\sigma} t_{ij}\left(\boldsymbol{A}\right) c^{\dagger}_{i\sigma} c_{j\sigma} + g\mu_B H_z \sum_i \left(c^{\dagger}_{i\uparrow} c_{i\uparrow} - c^{\dagger}_{i\downarrow} c_{i\downarrow} \right) \\ & - V \sum_{\langle i,j\rangle} \left(c^{\dagger}_{i\uparrow} c^{\dagger}_{j\downarrow} \Delta_{ij} + c_{i\downarrow} c_{j\uparrow} \Delta^{\star}_{ij} \right) . \end{aligned} \tag{1}$$

Here, $c^{\dagger}_{i\sigma}$ ($c_{i\sigma}$) creates (annihilates) an electron with spin σ on site i; g and μ_{B} are the gyromagnetic ratio and the Bohr magneton, respectively. V stands for the magnitude of the nearest-neighbor attraction and $\boldsymbol{A}$ is the vector potential corresponding to the external magnetic field $\boldsymbol{H}$. We introduce anisotropic superconducting order parameter

$$\Delta_{ij} = \langle c_{i\downarrow} c_{j\uparrow} - c_{i\uparrow} c_{j\downarrow} \rangle, \tag{2}$$

which, in general, can be site-dependent. According to the Peierls substitution [8] the original hopping integral t_{ij} is multiplied by a phase factor, which accounts for coupling of electrons to the magnetic field

$$t_{ij}\left(\boldsymbol{A}\right) = t \exp\left(\frac{ie}{\hbar c} \int_{\boldsymbol{R}_j}^{\boldsymbol{R}_i} \boldsymbol{A} \cdot d\boldsymbol{l} \right) . \tag{3}$$

In order to evaluate the upper critical field we make use of an unitary transformation that diagonalizes the kinetic part of the Hamiltonian. Then, in the new basis, equations of motion for the Green function allow one to obtain the upper critical field. The details of this approach can be found in Refs. [9,10].

3. Discussion

In order to visualize the role of magnetic field in the normal-state we have calculated the resulting current distribution:

Figures 1 and 2 show results obtained for a square cluster with $N_\perp = N_{||}$, which can simulate a homogeneous phase, and for $N_\perp \ll N_{||}$ that is relevant to the stripe-phase. In the stripe-phase the geometry of the system does not allow for a formation of standard Landau orbits. Then, one can expect that the diamagnetic pair-breaking mechanism is reduced and superconductivity can survive in the presence of much stronger magnetic field than in the case of a homogeneous phase.

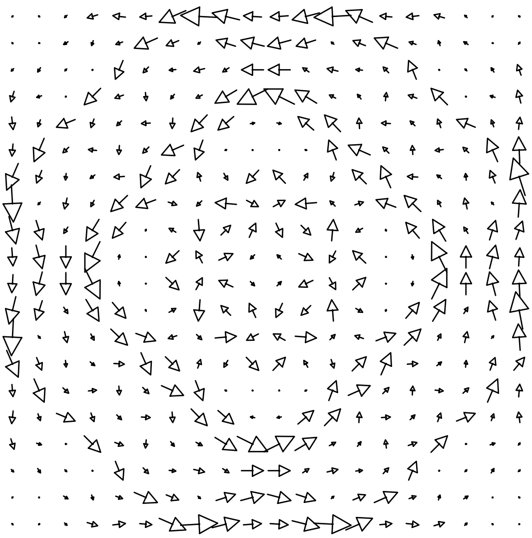

Fig. 1. Current distribution originating from external magnetic field calculated for a 20×20 cluster with fixed boundary conditions. $ea^2H_z/(\hbar c) = 0.1$ was used.

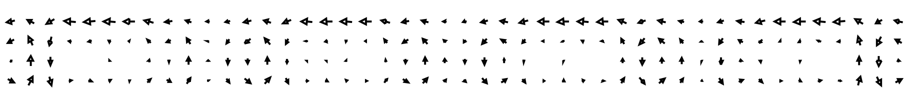

Fig. 2. The same as above, but for 100×5 cluster.

This observation can be confirmed by the calculation of the upper critical field for clusters of different geometry (see Fig. 3).

Transition form the stripe to homogeneous phase has been simulated by changing the ratio $N_\perp/N_{||}$. Dependently on the geometry of cluster we have adjusted the magnitude of the pairing potential to obtain the same $T_{\rm c}$ in

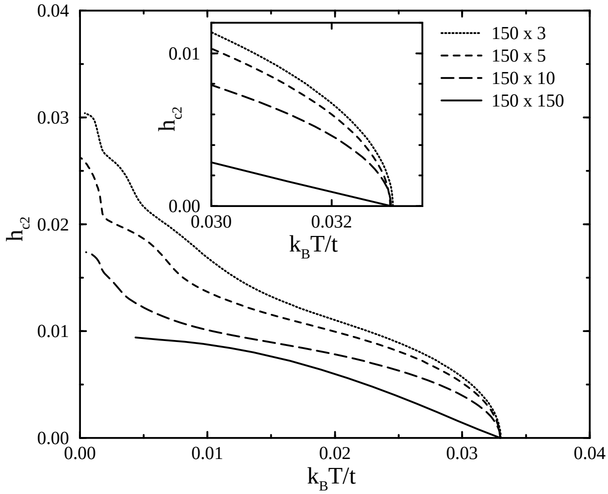

Fig. 3. Comparison of the upper critical field for a homogeneous system (continuous line) and systems with stripes of different width (3, 5 and 10 lattice sites).

the absence of magnetic field. One can see, that the upper critical field increases when the width of the cluster decreases. This effect is of particular importance for weak magnetic fields and leads to a dramatic change of the slope, $dH_{\rm c2}/dT$, calculated at $T=T_{\rm c}$. These results can, to some extend, account for the temperature dependence of the upper critical field observed in the copper–oxide superconductors. One should keep in mind that even in overdoped and underdoped samples the measurements of the upper critical field are restricted to temperatures close to $T_{\rm c}$ [11, 12]. In this region even very strong magnetic fields hardly affect the superconducting transition temperature, leading to a large slope of $H_{\rm c2}(T)$.

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