Monte Carlo Study of Pseudo-Gap Temperature T^* within JJA Model

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Abstract

We study pseudo-gap temperature T^* of high-T_c superconductors by a Monte Carlo simulation of anisotropic 3D Josephson Junction Array (JJA) model based on the Ginzburg-Landau theory. We investigate T^* both in the cases of zero external current and finite external current I in the JJA. It is found that, the external current I depresses only a little the pseudo-gap temperature T^*, while the superconducting critical temperature T_c is much affected by I.

Key words: Pseudo-gap temperature, High-T_c cuprate superconductor, Josephson Junction Array model, Ginzburg-Landau theory

Much attention has been focused on the pseudo gap of high-T_c cuprate superconductors. On the basis of the Josephson Junction Array (JJA) model for the high-T_c cuprate superconductors [1–4], we have investigated the pseudo-gap temperature T^* and the superconducting critical temperature T_c. In this paper, we report our result of the Monte Carlo simulation for the effect of the external current I on T^* and T_c.

We model the ceramic high-T_c materials as a JJA which consists of weakly coupled superconducting grains on an anisotropic 3D lattice (i.e., a stack of 2D-lattice layers) [1–4]. The grain at the lattice site i is characterized by the phase θ_i and the amplitude $|\phi_i|$ of the superconducting order parameter $\phi_i = |\phi_i| \exp(i\theta_i)$.

In previous papers [5,6], we performed the Monte Carlo simulation with a Hamiltonian in which only the phase θ_i was taken into account, and could investigate the effect of I on T_c only. In this paper, we investigate not only T_c but also T^* by considering both the phase θ_i and the amplitude $|\phi_i|$. Our effective Hamiltonian is given as

$$F_{\text{eff}} = F(\{\theta_i, |\phi_i|\}) - T\sum_i \ln(|\phi_i|) = F_0 + F_1 - T\sum_i \ln(|\phi_i|), \quad (1)$$

where

$$F_0 = -\sum_{i,j} |\phi_i|^2 \left[\cos(\theta_i - \theta_j) - 1\right] - \alpha {\sum_{i,k}}' |\phi_i|^2 \left[\cos(\theta_i - \theta_k) - 1\right] - \sum_{i,j} I \cdot [\theta_i - \theta_j], \quad (2)$$

$$F_1 = \frac{1}{2}\sum_{i,j}(|\phi_i| - |\phi_j|)^2 + \frac{\alpha}{2}{\sum_{i,k}}'(|\phi_i| - |\phi_k|)^2$$

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$$+\frac{A}{2}\sum_i\Big[-\big(1-T/T_0\big)|\phi_i|^2+\frac{1}{2}|\phi_i|^4\Big]. \qquad (3)$$

Here, $\sum_{i,j}$ means the summation over the neighboring intra sites in a 2D layer and $\sum'_{i,k}$ over the neighboring inter sites between the layers. The parameter α of the system anisotropy corresponds to Γ^2 of Ref. [7]; $\alpha \to 1$ (3D limit) and $\alpha \to 0$ (2D limit). The parameter A corresponds to $(a_\parallel/\xi_\parallel)^2$ and T_0 corresponds to $T'_{\rm MF}$ [7]. T is the temperature. The external current I is defined in Refs. [5,6].

We perform the Monte Carlo simulation on the 3D JJA system $\big[$Eqs. (1)–(3)$\big]$ with $A = 1$ and the anisotropy ratio $\alpha = 0.01$. The system size is $20 \times 20 \times 20$ with periodic boundary conditions. $T_{\rm c}$ is defined as the temperature at which the susceptibility $\chi = \sum_{i,j}\langle \cos\theta_i \cos\theta_j\rangle$ diverges [5,6]. The symbol $\langle\cdots\rangle$ represents the statistical average. T^* is defined as the temperature at which $\sum_i \langle|\phi_i|\rangle = 0$. In Table 1, we show the result obtained by the Monte Carlo Simulation. It is noticeable that, while the superconducting critical temperature $T_{\rm c}$ is much affected by I (namely, $\sim 50\%$ decrease of $T_{\rm c}$), the external current I depresses only a little the pseudo-gap temperature T^*. We have also performed the simulation with $\alpha = 0.001$ and 10^{-4}, and found that the results depended only a little on the anisotropy ratio α.

We hope that this result (i.e., the difference in the I sensitivity between T^* and $T_{\rm c}$) can be observed experimentally by applying the external current to the high-$T_{\rm c}$ cuprate superconductors and simultaneously measuring the pseudo-gap temperature and the superconducting critical temperature. Such observations are expected to be helpful to identify the origin of the pseudo gap in the high-$T_{\rm c}$ cuprates, i.e., to identify whether or not the separation between the pseudo-gap temperature and the superconducting critical one is described by the anisotropic 3D JJA- and XY(phase)-model scenarios [1–8] for the superconductivity in the high-$T_{\rm c}$ cuprates.

Table 1
The pseudo gap temperature T^* and the superconducting critical temperature $T_{\rm c}$ vs the external current I obtained by the Monte Carlo Simulation. The parameter $A = 1$. The anisotropy ratio $\alpha = 0.01$.

I	0	0.5	1.0
T^*	0.26	0.24	0.22
$T_{\rm c}$	0.09	0.09	0.05

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