Anisotropy of upper critical field for high temperature superconductors

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Abstract

The anisotropy of high T_c superconductors arises both from the coupling constant and the Fermi surface in the Ginzburg-Landau framework. The anisotropy of the former is expressed by $d_{x^2-y^2}$ symmetry. The shapes of the Fermi surface of high T_c superconductors are various and depend on materials and doping ratio. In this paper, we study the anisotropy of the upper critical field H_{c2} in the ab plane with $d_{x^2-y^2}$ symmetry and with typical shapes of the Fermi surface.

Key words: anisotropic upper critical field; anisotropic Fermi surface; pairing symmetry

1. Introduction

The upper critical field H_{c2} of some high temperature superconductors shows interesting behavior with fourfold symmetry, when the magnetic field is applied in the ab plane. For example, the angular dependence of $Ca_{0.5}La_{1.25}Ba_{1.25}Cu_3O_x$ [1] is different by $\pi/4$ from that of $La_{1.86}Sr_{0.14}CuO_4$ [2] and $Pb_2Sr_2Ca_{0.38}Cu_3O_8$ [3].

To explain these results, we studied both the effects of anisotropic coupling constant of the pairing state and anisotropic Fermi surface, assuming a simple Fermi surface [4]. In this paper, we present the results of H_{c2}, using more realistic Fermi surface.

2. Formulation

The detailed derivation of the fourfold symmetry for the upper critical field in the ab plane is given in [4] and expressed near the transition temperature T_c as

$$\Delta h \equiv \frac{\Delta H_{c2}}{\overline{H_{c2}}} = \frac{B_4 \cos 4\theta}{A_2}\delta, \tag{1}$$

where $\delta = \ln(T/T_c)$, θ is the angle between the magnetic field and the principal crystal axes in the ab plane and

$$A_{2n} = \frac{2(-1)^n}{(2\pi k_B T)^{2n}}\left(1 - \frac{1}{2^{2n+1}}\right)\zeta(2n+1)\ . \tag{2}$$

Here, $\zeta(z)$ is the Riemann's zeta function.

The quantitiy which expresses the magnitude of anisotropic part is given by

$$B_4 = \frac{1}{64 p_{0X}^2 < V_x^2 >} - \frac{3A_4 < V_x^4 - 3V_x^2 V_y^2 >}{16 A_2 < V_x^2 >^2}\ . \tag{3}$$

To obtain the explicit values of B_4, we assume a following expression for the energy dispersion:

$$\varepsilon(\mathbf{p}) = \sum_n C_n \varepsilon_n(\mathbf{p}_\perp) + \frac{p_z^2}{2m} \equiv \varepsilon_{ab}(\mathbf{p}_\perp) + \varepsilon_z(\mathbf{p}_z)\ , \tag{4}$$

where

$$\varepsilon_1(\mathbf{p}_\perp) = 2 - \cos ap_x - \cos ap_y\ , \tag{5a}$$

$$\varepsilon_2(\mathbf{p}_\perp) = 1 - \cos ap_x \cos ap_y \tag{5b}$$

and

$$\varepsilon_3(\mathbf{p}_\perp) = 2 - \cos 2ap_x - \cos 2ap_y\ , \tag{5c}$$

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where a is the lattice constant in the ab plane. These are first three functions with square symmetry in the momentum space.

The velocity $\mathbf{V}$ in (3) is obtained by

$$\mathbf{V} = \frac{\partial \varepsilon(\mathbf{p})}{\partial \mathbf{p}} \ . \tag{6}$$

These quantities $\mathbf{p}$ and $\mathbf{V}$ are defined with respect to the crystalline axes.

The function which expresses the anisotropy of the pairing state enters in the average $< \cdots >$ at the Fermi surface as

$$< B >= \frac{1}{N(0)} \int d\Omega(\mathbf{p}_F)\phi^2(\hat{\mathbf{p}})N(\mathbf{p}_F)B(\mathbf{p}_F) \ , \tag{7a}$$

$$N(0) = \int d\Omega(\mathbf{p}_F)\phi^2(\hat{\mathbf{p}})N(\mathbf{p}_F) \ , \tag{7b}$$

where we consider the $d_{x^2-y^2}$ pairing state:

$$\phi(\hat{\mathbf{p}}) = \sqrt{2}\cos 2\psi \ . \tag{8}$$

3. Numerical Results and Conclusions

For numerical calculation of the equation (1) for Δh, we need an explicit expression of the energy dispersion and we use a set of parameters $C_n = (0.05, 0.01, 0.015)$ eV in (4). In Fig. 1, we show the equilateral energy surface in the ab plane. These shapes resemble the results of the doping dependence of the Fermi surface, taken from the ARPES spectra for $La_{2-x}Sr_xCuO_4$ [5].

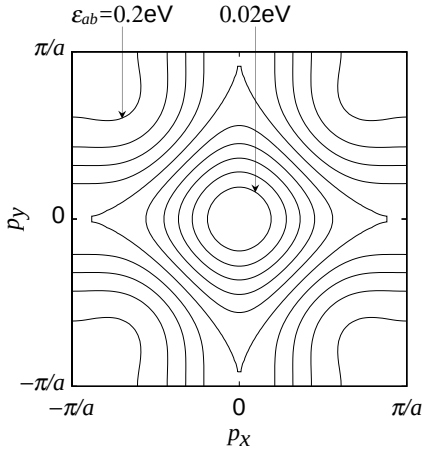

Fig. 1. Equilateral enery surfaces for the energy dispersion (4) whose parameter values are given in the text. The enegy difference between two adjacent curves is $\Delta\varepsilon = 0.02$ eV.

In Fig. 2, we present the Fermi energy ε_{ab} dependence of Δh for the temperature $T = 35, 36$ and 37K for $T_{c2} = 37.5$K. The divergence of Δh at $\varepsilon_{ab} = 0.12$ eV is due to that of the density of states at $\mathbf{p}_\perp = (\pi/a, 0)$ and its equivalent points.

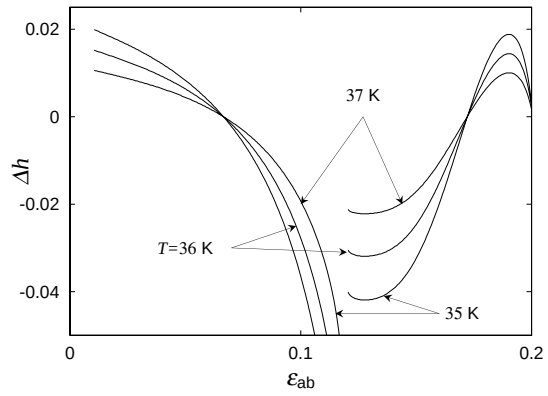

Fig. 2. The relative magnitude of anisotropy Δh as a function of ε_F for $T = 35, 36$ and 37K with $T_c = 37.5$K with the same parameter set of Δh Fig. 1.

The sign change of Δh depending on ε_{ab} corresponds to the reverse of the maximum-minimum position of the upper critical field with respect to the angle θ found in the observations. The magnitude of Δh is, however, small and doping dependence is not clear in this study. To solve these ploblems, it is necessary to have informations of C_n on doping dependence, which is obtained from microscopic theory.

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