Crossover from superconductivity fluctuation to vortex picture in the vortex state of high-Tc cuprate superconductors

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Abstract.

In this paper, we introduce our recent results on superconductivity fluctuation measurement of high-T\textsubscript{c} cuprate under finite magnetic field both for the hole-doped La\textsubscript{2-x}Sr\textsubscript{x}CuO\textsubscript{4} (LSCO) and the electron-doped La\textsubscript{2-x}Ce\textsubscript{x}CuO\textsubscript{4} (LCCO). Under finite magnetic fields, the scaling relation was valid only for weak fields, and for higher fields, aspects as vortices appeared. However, even at low temperatures, just above the first-order phase transition of the vortex lattice, vortex picture alone cannot describe the data satisfactory. Thus, we need a unified theory for the description of a large superconductivity fluctuation under finite magnetic fields for high-T\textsubscript{c} cuprates.

1. Introduction

High-temperature superconductivity of cuprates has been providing many new insights to condensed matter scientists continuously since its discovery in 1986\cite{1}. One of the most characteristic phenomena of the high-T\textsubscript{c} cuprates is a characteristic phenomenon called “resistive broadening” under finite magnetic fields\cite{2, 3}. The significance of the phenomena is that the conventional upper critical field, $B_{c2}$, only has the meaning in the mean-field sense. The true phase transition takes place at much lower fields, which is considered to be the first order vortex-solid-liquid transition\cite{3}. Thus, the vortex liquid state is the same as the normal state in the thermodynamical sense. However, just above the transition, the vortex picture is still appropriate. Therefore, it is very interesting how the vortex picture crosses over to the ordinary fluctuation picture with increasing temperature/magnetic field. We discuss this issue by measuring the complex impedance by the microwave broadband technique\cite{4, 5, 6, 7, 8} and analyzing the data in terms of the well established convenient model by Coffey and Clem\cite{9}.

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Figure 1. Scaled data of the extra complex conductivity of an underdoped LSCO (x=0.07) at several different magnetic fields. (a) phases and (b) amplitudes.

2. Experiments
Fluctuation in superconductivity and the response by vortex motion was investigated by measuring the ac complex conductivity in the so-called broadband technique[4, 8], where microwave frequency was swept in a continuous manner and the complex reflection from the samples placed at the end of the coaxial cable was measured. For this technique, thin films were used to make the analysis easy. Details of our techniques were described in refs.[5, 6, 7, 8]. Hole doped La$_{2-x}$Sr$_x$CuO$_4$ (LSCO) films were fabricated by the pulsed laser deposition (PLD) method[10], whereas electron doped La$_{2-x}$Ce$_x$CuO$_4$ (LCCO) films were fabricated by the molecular-beam-epitaxy (MBE) method[11].

3. Results and discussions
3.1. weak magnetic fields
Figure 1 shows the scaled data of the amplitude and the phase of the complex conductivity of an underdoped LSCO (x=0.07). Note that the conductivity by the normal fluid was already subtracted. For low fields (typically up to 0.1 T), ac conductivity data can be well scaled, suggesting that the data can be analyzed exactly by the same method as was made in zero magnetic field[5, 7]. As was shown in Fig. 2, for underdoped LSCO, it was found that the exponential divergence characteristic of the 2D-XY BKT feature was suppressed by introducing external magnetic flux[12, 13]. On the other hand, for all other samples (including electron doped LCCO), the scaling relation holds rather well even in finite magnetic fields (not shown in figures). Thus, the 3D-XY feature well established for the zero-field data still holds for weak fields without any modification of the scaling parameters, except for $T_c$. 


3.2. high magnetic fields

As was already shown in Fig. 1, the scaling relation did not hold for the data taken at higher magnetic fields (e.g. 1 T). For these data, we tried to analyze the data in terms of the following formula,

\[ \rho \equiv \rho_1 - i\rho_2 = \frac{\rho_{\text{vortex}}}{} \]

where \( \rho \equiv \rho_1 - i\rho_2 \), \( \rho_{\text{vortex}} \) are the complex resistivity, and the resistivity by the vortex motion, respectively, \( \mu_0 \), \( \omega \) are the permeability of vacuum, angular frequency, respectively, and \( \delta_{nf} = \sqrt{\frac{2\rho_0}{\mu_0}} \) is the normal fluid skin depth (\( \rho_0 \) is the resistivity in the normal state), and \( \lambda \equiv \sqrt{\frac{m}{n_s e^2}} \) is the London penetration depth (\( n_s \), \( m \) and \( e \) are the superfluid density, mass, and charge of superconducting electron). As for the vortex part, we used the expression derived by Coffey and Clem based on the mean-field treatment of the vortex motion[9],

\[ \rho_{\text{vortex}} = \left( \frac{B\phi_0}{\eta} \right) \left[ \frac{\varepsilon + (\omega \tau_p)^2 + i(1 - \varepsilon)\omega \tau_p}{1 + (\omega \tau_p)^2} \right], \]

where \( \eta \) and \( \tau_p^{-1} \) are the viscosity and the crossover frequency of the vortex, respectively, \( \varepsilon \) is the flux-creep factor, \( B \) and \( \Phi_0 \) are the magnetic field and the flux quantum, respectively. We regard \( \eta, \tau_p, \varepsilon, \) and \( \lambda \) as fitting parameters, and obtained them by fitting the measured \( \rho \) data to the above formula. Figure 3 shows the parameters obtained by these analyses. Most of these results show that the obtained parameters are reasonable, and the vortex picture holds rather well. However, the penetration depth decreases with increasing temperature, which is rather unusual. This suggests that the vortex picture alone is insufficient to explain the experimental data of ac conductivity under finite magnetic fields in this region. Thus, even at rather low temperatures just above the first order transition, the conventional picture of vortex motion collapsed. Unfortunately, we do not have any theoretical formula for these crossover regions, and a unified treatment of the large superconductivity fluctuation in cuprates is needed urgently.
4. Conclusion
In this paper, we introduced recent our results on complex conductivity measurement of high-$T_c$ cuprate both for the hole doped LSCO and the electron doped LCCO under finite magnetic fields. For weak fields the scaling relation was valid, whereas for higher fields, aspects as vortices appeared. However, even at low temperatures, just above the first order phase transition, vortex picture alone cannot describe the data satisfactory. Thus, we need a unified theory for the description of a large superconductivity fluctuation under finite magnetic fields for high-$T_c$ cuprates.

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