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Quasiparticles in the vortex state of $La_{2-x}Sr_xCu_{1-y}Zn_yO_4$: a specific heat study

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Abstract

To explore the issue of quasiparticles in the d-wave vortex state, magnetic field dependence of the low-temperature specific heat (LTSH) of $La_{2-x}Sr_xCu_{1-y}Zn_yO_4$ is studied. This provides information about the quasiparticle electronic states in the vortex state of cuprates with the presence of impurities, and may test the present theoretical treatment of the extended quasiparticle states. The LTSH experimental results are compared with the most recent theoretical approach including impurity scattering. The approximate scaling behavior is also discussed.

Keywords: Impurity effects; $La_{2-x}Sr_xCuO_4$ substituted; Quasiparticle effects; Specific heat; Specific heat in magnetic fields

Recently, the issue of quasiparticle density of states in the vortex state of high-T_c cuprate superconductors has attracted much attention. Volovik has shown that, in the presence of magnetic fields, extended quasiparticle states near the order parameter nodes dominate at zero energy. These extended states lead to an electronic specific heat varying as $\Delta C \sim H^{1/2}$ [1]. In this context, the contribution from the cores is ignored in contrast to the case of conventional superconductors. In general, Volovik's predictions are in accordance with the experimental results on low-temperature specific heat (LTHS) $C(T,H)$ of optimally doped $YBa_2Cu_3O_{7-\delta}$ reported [2–4]. This scenario was further tested in different doping regimes in $La_{2-x}Sr_xCu_{1-y}Zn_yO_4$ (LSCO) [5]. Recently, calculations of the effects of impurities on LTSH of cuprate superconductors have been carried out [6,7]. The present work attempts to verify the very recent theory of the impurity effects on cuprate LTSH.

Polycrystalline $La_{1.84}Sr_{0.16}Cu_{1-y}Zn_yO_4$ with $y=$ 0, 0.01 and 0.02 were prepared as described elsewhere [5]. The powder X-ray-diffraction patterns of all samples showed a single T-phase with no detection of impurity phases. $T_c = 39$, 29 and 20 K for $y = 0$, 0.01 and 0.02, respectively, determined by midpoint of the resistivity drop. $C(T)$ was measured with a ^{3}He relaxation calorimeter. The details of $C(T)$ measurements were described in our earlier works [5].

The LTSH analyses have been made in the temperature range 2–7 K, since $C(T)$ of Zn-doped LSCO shows a large magnetic contribution below 2 K. The zero-field data were fit to $C(T,0) = \gamma(0)T + \beta T^3 + D/T^2$, where the T^3 term represents the phonon contribution and the third term is the hyperfine contribution. For the data in magnetic fields, the formula $C(T,H) = \gamma(H)T + \beta T^3 + nC_{\mathrm{Schottky}}(T,H)$ was used, where the third term is a two-level Schottky anomaly with Lande factor $g = 2$ [5]. It is found that $\gamma(0)$ increases significantly with increasing Zn doping, and quantitatively agrees with the calculations from d-wave pair-breaking scenario [8]. The magnetic field dependence of $\gamma(H)$ is compared with the theoretical prediction of the impurity effects on LTSH [6,7]:

$$\gamma(H) = \gamma(0)\left[1 + D\left(\frac{H}{H_{c2}}\right)\ln\left(\frac{H_{c2}}{H}\right)\right], \quad (1)$$

where $D \approx \Delta/32\Gamma$, Δ is the superconducting gap, and Γ is the impurity scattering rate.

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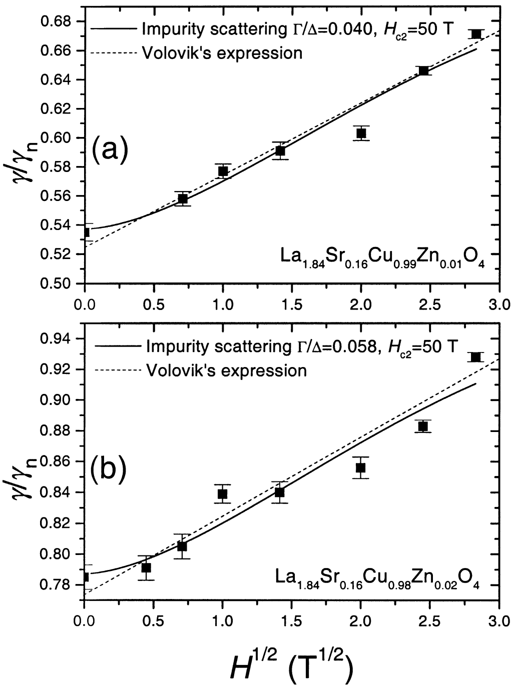

Fig. 1. Normalized $\gamma(H)$ versus $H^{1/2}$ for Zn-doped (a) $y = 0.01$ and (b) $y = 0.02$ samples. The solid lines are fits of Eq. (1), which includes the impurity scattering effects on $C(T, H)$. Dash lines represent $\gamma \sim H^{1/2}$. $\gamma_n \equiv 10\,\text{mJ/mol}\,\text{K}^2$ is the normal state γ of the samples [5].

Naively fitting $\gamma(H)$ by expression (1) results in a non-realistic large H_{c2}. To obtain a meaningful comparison between the data and the theory, H_{c2} is fixed to a reasonable value of 50 T [5]. The fits gave reasonable $\Gamma/\Delta = 0.040$ and 0.058 for $y = 0.01$ and 0.02, respectively [6,7], though a twofold increase in Γ/Δ is expected for $y = 0.02$. The fitting results are shown in Fig. 1. The solid lines represent the impurity scattering model. The dash straight lines represent Volovik's expression $\gamma \sim H^{1/2}$ presumably for clean d-wave superconductors. As one can see, Eq. (1) qualitatively describes $\gamma(H)$, as Volovik's expression does. However, it is hard to distinguish the impurity scattering model from Volovik's expression with the available data which are relatively scattered. Another aspect of the theory including impurity scattering is the breakdown of $C(T, H)$ scaling [6,7]. The analyses show no conclusive evidence, either. The accurate values of $\gamma(H)$ from fitting $C(T, H)$ are largely affected by the low-temperature magnetic contribution in $C(T)$.

The studies on LTSH of Ni-doped LSCO are under way. Hopefully, LTSH with smaller magnetic anomaly can be obtained to elucidate the issue of quasiparticles in the vortex state.

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