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Low temperature specific heat of slightly overdoped $YBa_2Cu_3O_{7-\delta}$

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Abstract

Specific heat of a slightly overdoped $YBa_2Cu_3O_{7-\delta}$ single crystal has been measured at magnetic fields up to 12 T in low temperature region. By subtracting a spare linear term ($\gamma_0 T$), the phonon contribution ($\beta T^3 + \eta T^5$) and the Schottky anomaly (C_{Sch}), we obtain the field induced change of the specific heat coefficient $\Delta\gamma$ which behaves as the $A\sqrt{H}$ dependence (A is a constant) in zero-temperature limit and satisfies the Simon–Lee scaling law at finite temperatures, as expected by pure d-wave theory. The upper critical field $H_{c2}(0)$ is then determined according to the expression of $A = 0.74\gamma_n/\sqrt{H_{c2}(0)}$ in the framework of d-wave theory. This may be an alternative way to derive the $H_{c2}(0)$ value.

Keywords: Specific heat; YBCO; Upper critical field; Superconductivity

1. Introduction

One of the important issues related to high-temperature superconductors (HTSCs) is to determine their pairing symmetry, which is critical to clarify the microscopic mechanism of HTSCs. The low-temperature specific heat measurement is one of the most important experiments to investigate the pairing symmetry of the cuprate superconductors. According to the theoretical prediction for d-wave superconductors in the mixed state, the magnetic-field-induced density of states (DOS) in zero-temperature limit has the form of $C_{DOS} = \Delta\gamma(H)T = ATH^{1/2}$ with $A = 0.74\gamma_n/\sqrt{H_{c2}(0)}$ [1,2], which is quite different from $C_{DOS} = \Delta\gamma(H)T \propto TH$ for s-wave superconductors. Moler et al. [3,4] first demonstrated the existence of the $TH^{1/2}$ term in the specific heat measurement of $YBa_2Cu_3O_{7-\delta}$ (YBCO) single crystals, which was also testified by the work of Junod's group [5,6] and Wright et al. [7]. Later on, Simon and Lee [8] developed a scaling law of $C_{DOS}/T\sqrt{H} = f(T/\sqrt{H})$ with

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$T/\sqrt{H} \leqslant T_c/\sqrt{H_{c2}(0)}$ for d-wave superconductors. Though this scaling law has been proved by many groups [5–7,9–11], the validity of it in the whole doping regime remains unclear. Recently, Wen et al. [12] showed that in $La_{2-x}Sr_xCuO_4$ the C_{DOS} follows well the $\sqrt{H}$ dependence in zero temperature limit for all doping points but the applicability of the Simon–Lee scaling law at finite temperatures varies with the hole-doping concentration.

In this letter, we present the low-temperature specific heat of a slightly overdoped $YBa_2Cu_3O_{7-\delta}$ single crystal, and find that the magnetic-field-induced DOS follows the $\sqrt{H}$ dependence in zero-temperature limit and satisfies the Simon–Lee scaling law in the finite temperature and field regions. Moreover, $H_{c2}(0)$ is also obtained by using γ_n from Loram et al. [13] in the same system and the value of A from this work.

2. Experimental

The $YBa_2Cu_3O_{7-\delta}$ single crystal used in this work was prepared by top-seeded solution-growth, which is appropriate to grow big single crystals. In this way the T_c of YBCO single crystals can reach 93 K and the details about the sample preparation can be seen in Ref. [14]. After oxygenating the sample in flowing O_2 gas at 430 °C for 200 h, we checked it by DC magnetization in a superconducting quantum interference device (SQUID) by using the zero field cooling (ZFC) and the field cooling (FC) modes. As shown in Fig. 1 the oxygenated sample has a superconducting transition temperature (T_c) of about 88 K with the transition width of about 4 K. The single crystal for the specific heat measurement is cut into $2.36 \times 3.24 \times 0.66\ mm^3$ in dimensions with a mass of 27.03 mg.

We used the relaxation method [15] to measure the heat capacity based on an Oxford cryogenic system Maglab. The specific heat (C) of the sample is derived from the thermal time constant, $\tau = (C + C_{add})/\kappa_\omega$, here κ_ω is the thermal conductance between the chip and a thermal link, and C_{add} is the heat capacity of the addenda. The C_{add} value has been measured separately and subtracted from the total heat capacity. The field dependence of

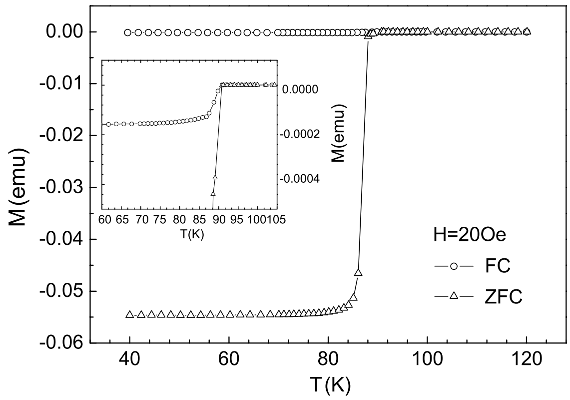

Fig. 1. Magnetization measurement of $YBa_2Cu_3O_{7-\delta}$ in a superconducting quantum interference device (SQUID) with the zero field cooling (ZFC) and the field cooling (FC) modes at the magnetic field of 20 Oe. The inset is an enlarged view nearby the transition from which we find that the width of the magnetic transition (ΔT) is about 4 K.

C_{add} has been checked and its change in 12 T is as the same order as the noise background here (20 nJ/K at 5 K and 40 nJ/K at 20 K). The more experimental details are described in elsewhere [12,16]. In this work, the applied magnetic field (H) was parallel to the c-axis of the sample during the measurement. In a settled field the sample was cooled to the lowest temperature (FC), and then the heat capacity data were acquired in the warming-up process.

3. Results and discussion

At low temperatures, specific heat $C(T,H)$ consists of four main contributions by neglecting the component of the nuclear moments [3–5,7,17], two of which are independent on H and the other two depend on H, but in different ways,

$$C(T,H) = C_{mag}(T,H) + C_{DOS}(T,H) + \gamma_0 T + C_{ph}(T), \quad (1)$$

where $\gamma_0 T$ represents a spare zero-field linear term which has been found in many systems of hole doped cuprates [3–5,7,18–20], and C_{ph} is due to the phonon contribution. In superconducting state, the origin of $\gamma_0 T$ is not entirely clear. The H-dependent terms in Eq. (1), i.e., $C_{mag}(T,H)$ and $C_{DOS}(T,H)$, are the contributions associated