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Influence of fluctuations on thermal conductivity of high-T_c $YBa_2Cu_3O_{7-\delta}$ superconductor

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Abstract

To study a behavior of the thermal conductivity near T_c specific heat and thermal diffusivity of the $YBa_2Cu_3O_{7-\delta}$ high-T_c ceramics were simultaneously measured. Close to $T_c = 92.30$ K the thermal diffusivity and the thermal conductivity discovered minima and the specific heat – maximum. Quantitative analysis of the influence of thermodynamical fluctuations showed the same power laws with Gaussian exponent equal to 0.5 and existing of crossover from the 3D Gaussian to 3D *XY* critical behavior in the specific heat and thermal conductivity at the approach to T_c. To explain the minimum in thermal conductivity at T_c we propose a mechanism of scattering of phonons on the superconducting fluctuations.

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Keywords: Fluctuation effects; Coherence length; Critical phenomena; Specific heat at T_c; Thermal conductivity at T_c

1. Introduction

A large number of papers dealing with fluctuation effects in the electrical conductivity and the specific heat of "1–2–3" superconductors have been published. However, we know only a few publication [1,2] in which the authors interpret their results in terms of fluctuations of the electronic thermal conductivity, and at T_c they did not observe the extremum of thermal conductivity. The main reason, why so few studies have been made in this area, are the large temperature differences along the sample and relative errors, that are inherent in the standard static heat flow method and do not allow detailed studies of the anomalies in the thermal conductivity near T_c. Actually the temperature difference along the sample, used in this method, is ≈1–5 K and comparable with the width of the critical region. As a result, the temperature inhomogeneities in the volume of the sample lead to a smearing of the superconducting transition. Consequently, the true critical and Gaussian fluctuation regions might be hard to observe in the steady-state method because of thermal gradient on a sample, which does not allow yields data in close vicinity of the critical temperature. So, in this paper, to measure the specific heat and thermal conductivity, we used the original version of an a.c.-calorimetry [3]. One advantage of the method used here for determination of thermal conduction (as compared to a steady-state techniques) is that the temperature difference in the sample is small (5–10 mK), which is especially important in the studies of critical phenomena in the vicinity of phase transitions.

Corresponding to this situation regarding experimental investigations of the thermal conductivity are theoretical contradictions. One view is that the formation of the Cooper pairs leads to a decrease of the thermal conductivity near T_c [4]. Another view is that the formation of Cooper pairs leads to an increase of the thermal conductivity near T_c [5,6]. Varlamov and Livanov [6] showed that the fluctuation contribution to the electronic thermal conductivity may be some percent of the total thermal conductivity

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and must increase when approaching T_c from above. Notice that the theoretical calculations [4–6] explain only a regular behavior of the thermal conductivity and do not predict a critical extremum near T_c. It is possible that the observed minima of the thermal conductivity, $K(T)$, and thermal diffusivity, $\eta(T)$, are connected with scattering of heat carriers on critical fluctuations of the superconducting order parameter. This situation is similar to scattering of phonons on magnetic fluctuations in ferromagnetic substances near T_c, where minimum in the thermal conductivity [7–9] is observed, or the scattering of light on critical fluctuations in the liquid density when the size of fluctuation regions is comparable with the wave length of light [10].

In this paper, we report experimental results for the specific heat and thermal conductivity of the $YBa_2Cu_3O_{7-\delta}$. It is firstly found, to our knowledge, the influence of critical fluctuation of cooper's pairs on the phonon thermal conductivity of high-T_c superconductor near critical point with the critical exponents equals 0.5 for $\lg(\varepsilon) > -2.8$ and ≈ -0.013 at $\lg(\varepsilon) < -2.8$.

2. Experimental procedure

A sample of the high-T_c superconducting yttrium ceramic $YBa_2Cu_3O_{7-\delta}$ was prepared by a solid-state reaction from the appropriate starting components. The density of the sample which we studied was $\rho = 5.40$ g/cm^3, the size was $3 \times 3 \times 0.295$ mm^3, and the mass 14.3 mg.

Measurements of specific heat and thermal diffusivity were carried out on the experimental apparatus detail described in Refs. [3,11], while the thermal conductivity is determine as their product according to the formula $\kappa = (d/\mu)C_p\eta$, where d is the sample density and μ the molar mass. The error in the measurements of thermal diffusivity is approximately 0.3%. The relative error in measurements of the heat capacity is about 0.05% and those of the thermal diffusivity and thermal conductivity are 1%. We improved experimental conditions in comparison with the $(YBa_2Cu_3O_{7-\delta})_{0.9}Ag_{0.1}$ measurements [12], have using: double precision variables in computer program; longtime device operation before measurements, for 6 h; slower measurement speed, no more 0.05 K/min. The average temperature of the microcalorimeter was measured by millivoltmeter "SHCH300" using a copper-constantan thermocouple with a wire diameter of 100 μm.

The temperature oscillations were detected by lock-in nanovoltmeter "Unipan 232B" using a chromel-constantan thermocouple made by spot welding from wires from Omega Engineering Inc., USA, 25 μm in diameter which were flattened to a thickness of 5 μm. Temperature oscillations were excited in the sample with a frequency of 2 Hz by the light beam of an incandescent lamp, which was modulated by a quartz-stabilized mechanical chopper. The frequency of the light-flux chopping is set in the following way. Home-made lock-in motor controller [13] performs the division of frequency coming from the "SPEAKER" output of an IBM PC. Then the divided frequency signal is fed to synchronous motor home-made from a Sankyo servomotor taken out from crushed 5.25′ floppy disk driver. The stator of the motor has 12 coils and the rotation frequency of the rotor is 12 times lower than the frequency of the current flowing through the stator winding. A chopper provided with the required number of windows is fixed at the rotor shaft. Computer control of the measurements was performed with the HEAT-MASTER program compiled in Microsoft Quick-BASIC [14].

3. Results and discussion

Fig. 1 shows temperature dependencies of the specific heat, C_P, and the thermal diffusivity, η, in the $YBa_2Cu_3O_{7-\delta}$, as well as thermal conductivity, κ, determined from their conjunction. As seen in the Figure there are anomalies C_P, η and κ near 92.30 K, induced by superconducting phase transition. Specific heat jump, calculated by extrapolation of the experimental data using balance entropy below and above the transition, is $\Delta C_P = 4.6$ J/mol K. The width of the specific heat transition, ΔT, is less 1 K. Width, ΔT, and height, ΔC_P, of the specific heat peak confirm the high superconducting properties of the $YBa_2Cu_3O_{7-\delta}$ sample. Using BCS, $\Delta C_p/\gamma T_c = 1.43$, Zommerfeld coefficient $\gamma = 34.9$ mJ/mol K^2 was calculated.

At the viewpoint of Junod et al. [15] an objective and extrapolation-independent measure of the specific heat anomaly at T_c is difference between maximum value of C_p/T just below T_c and the minimum value of T_c just above T_c. This difference is 4% for our ceramic $YBa_2Cu_3O_{7-\delta}$. It is more than for single crystals $YBa_2Cu_3O_{7-\delta}$ [15].

Popular opinion about that a single crystal in all respects being more good than polycrystalline are a mistakes, though in particular as consequences to revealing their critical behavior and possibility approaching to T_c as near as. Indeed, even for the best single crystalline and ceramic, residual inhomogeneity prevents a verification of the critical behavior. In the result of this, we come across finite-size scaling which lead to smearing specific heat peak over three decades in reduced temperature.

By comparing anomalies of the specific heat of the $YBa_2Cu_3O_{7-\delta}$ in various magnetic field and oxygen deficit index δ near T_c it is evident that effect of inhomogeneity in T_c distribution is akin to influence of magnetic field. So, temperature dependence of the specific heat for ceramic $YBa_2Cu_3O_{7-\delta}$ shown in Fig. 1 is surprisingly well similar to temperature dependence of the specific heat for single crystal under applied magnetic field within from 1 to 2 T depicted in Fig. 1c in Ref. [16].

As regards to the Gaussian fluctuation behavior as our data show it may be verified using ceramic sample too, if to exclude from analyzing points below the short vertical mark in Fig. 1, corresponded to "shoulder-like" rounding.

In this paper, we shall not make up one's mind that is a origin of "shoulder-like" rounding the specific heat anomaly in Fig. 1. Possibly, it can be attributed to fine-granular structure and/or Jozephson boundaries between crystal-