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Energy Gap Symmetry and Thermal Conductivity of $YBa_2Cu_3O_7$

Manabu Ikebe, Hiroyuki Fujishiro and Kiminari Nakasato

Faculty of Engineering, Iwate University, Morioka 020, Janan

The characteristic enhancement in the heat conduction below T_c is analyzed on sintered $YBa_2Cu_3O_7$ from viewpoints of both d-wave and s-wave coupling. Assuming the existence of a large energy gap Δ_0 ($\geq 1.5\Delta_{BCS}$), only d-wave coupling is consistent with experimental observation. It is found that the most reasonable explanation for the enhancement is provided by the weak-coupling phonon conduction model under d-wave energy gap.

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1. INTRODUCTION

The symmetry of the Cooper pair coupling in high T_c cuprates is one of the main topics of the current physical interest. The majority of recently accumulated experimental data seems to support anisotropic $d_{x^2-y^2}$ symmetry of the in-plane energy gap Δ rather than isotropic s-wave symmetry. However, the results of the tunneling spectroscopy are not so convergent and the conclusion on gap symmetry has not yet been settled. As for the magnitude of Δ, many recent reports on the tunneling spectroscopy have suggested the larger gap values of $2\Delta_0/k_BT_c \approx 5{\sim}9$[1,2] than the corresponding BCS value $2\Delta_{BCS}/k_BT_c=3.52$.

The thermal conductivity κ of superconductors has contributions from both electrons (κ_{es}) and phonons (κ_{phs}). With decreasing temperature, the electron contribution κ_{es} usually decreases, while the phonon contribution κ_{phs} increases. The mechanism which causes these variations is as follows: below T_c an increasing number of electrons condense into the Cooper pairs with zero entropy, which do not carry heat nor scatter phonons. The number density of normal electrons (=quasi-particles) $n_{qp}(T)$ is determined by the magnitude and distribution of the energy gap Δ, and then $n_{qp}(T)$ determines $\kappa_{es}(T)$[3,4] and

$\kappa_{phs}(T)$[5,6]. Thus the gap symmetry, or more precisely, the distribution of the gap Δ can be discussed by analyzing the temperature dependence of $\kappa(T)$ in the superconducting state. We measured $\kappa(T)$ of closely packed sintered $YBa_2Cu_3O_7$ crystals between 15K and 150K and tested the possibility to settle the gap symmetry in this system. The details of the experimental procedure have been presented elsewhere[7]. Merits of the use of a sintered crystal are that the electron component κ_e is small enough in comparison with the phonon component κ_{ph} at least in the normal state and that the homogeneity of the oxygen content can be more easily achieved than for single crystals.

2. EXPERIMENTAL RESULTS

Figure 1 represents the temperature dependence of the thermal conductivity $\kappa(T)$ and the electrical resistivity $\rho(T)$ of $YBa_2Cu_3O_7$, which shows a sharp superconducting transition at 92K. The ρ vs. T line follows a linear T dependence in the normal state. By extrapolating the linear T line to the 0K ordinate, the resistivity ratio $\rho(T_c)/\rho(0)$, which is necessary for the κ_e analyses in the next section, is estimated to be 9.8.

As can be seen in Fig. 1, $\kappa(T)$ very slightly increases with decreasing temperature down to T_c and then shows the characteristic enhancement below T_c. This type of enhancement directly connected to superconductivity has not been observed in the c-direction conductivity κ_c of single crystal cuprates.

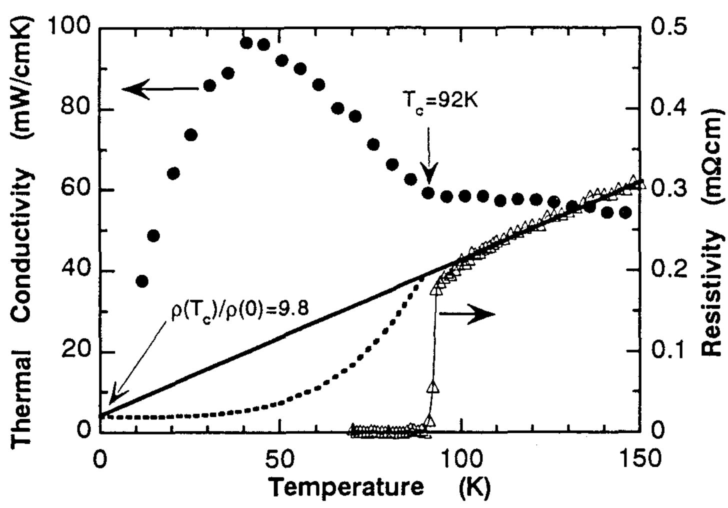

Fig. 1. $\rho(T)$ and $\kappa(T)$ vs. T of sintered $YBa_2Cu_3O_7$ crystal. By extrapolating $\rho(T)$ linearly to 0K, the resistivity ratio is estimated to be $\rho(T_c)/\rho(0)$=9.8. The broken line schematically represents hypothetical $\rho(T)\propto T^4$ curve with $\rho(T_c)/\rho(0)$=9.8 used for κ_e estimation (see text).

κ of polycrystals is an average of the in-plane conductivity κ_{ab} and the c-direction κ_c, which may be given by $\kappa=(2/3)\kappa_{ab}+(1/3)\kappa_c$ for the layered structure. Since many studies have reported $\kappa_{ab}>>\kappa_c$ ($\kappa_{ab}/\kappa_c \approx 5$), the observed κ in the present study may roughly correspond to $(2/3)\kappa_{ab}$ of the very anisotropic system. In the following section, we analyze this enhancement of $\kappa(T)$ based on the models of s-wave and d-wave energy gap symmetries.

3. DISCUSSION

3.1. Estimation of κ_e

Recently a variety of experimental results[8,9] on high T_c cuprates has suggested a possibility of drastic suppression of the quasi-particle scattering rate τ_{qp}^{-1} below T_c. Since the electronic thermal conductivity $\kappa_{es}(T)$ in the superconducting state is roughly proportional to the product $n_{qp}(T)\tau_{qp}$, the enhancement of κ_{es} below T_c is possible if the increase of τ_{qp} overcompensates the decrease of n_{qp}[10]. We estimate the electron component κ_{es} in the superconducting state by use of the formula derived by Kadanoff and Martin[4],

$$\frac{\kappa_{es}}{\kappa_{en}} = \frac{3}{4\pi^2}\int_0^{2\pi} d\phi \int_0^{\infty} d\varepsilon\, \varepsilon^2 \mathrm{sech}^2\{\tfrac{1}{2}[\varepsilon^2+(\beta\Delta)^2]^{1/2}\} \frac{[1+\alpha t^n]}{[\frac{\varepsilon}{\{\varepsilon^2+(\beta\Delta)^2\}^{1/2}} + \alpha t^n]}, \tag{1}$$

where α is the ratio of the temperature dependent resistance at T_c to the residual impurity resistance, ε is the electron energy relative to the chemical potential, β is the $1/k_BT$ and t is the reduced temperature T/T_c. The energy gap Δ is assumed to be $\Delta=\Delta_0$ for s-wave coupling and $\Delta=\Delta_0\cos2\phi$ for d-wave coupling with the azimuthal angle ϕ in the layer plane. We assumed that the electrical resistivity $\rho(T)$ obeys T^n (n=integer) dependence below T_c with the residual resistivity $\rho(T_c)/(\alpha+1)$ at 0K, *i.e.*,

$$\rho(T) = \rho(T_c)\left(\frac{1}{\alpha+1} + \frac{\alpha}{\alpha+1} t^n\right), \qquad \text{for } t \le 1, \tag{2}$$

where $\rho(T_c)$ is the resistivity value at T_c. From the estimated resistivity ratio $\rho(T_c)/\rho(0) = 9.8$, α value is determined to be 8.8. Yu *et al.*[10] proposed n=4 in their analyses of $\kappa(T)$ data of $YBa_2Cu_3O_7$. Since the tunneling spectroscopy experiments due to Nantoh *et al.*[2] have reported the maximum energy gap $\Delta_0 \approx 5k_BT_c$ for $YBa_2Cu_3O_7$, we calculated Eq.(1) for $\Delta_0=1.5\Delta_{BCS}$ and n=4 and 1. The results are shown for d-wave symmetry in Fig. 2(a) and for s-wave symmetry in Fig. 2(b). As can be seen, no clear enhancement of κ_e occurs below T_C even for n=4 and d-wave symmetry because of the estimated sizable residual resistivity of the present sample. Thus, if the estimated residual

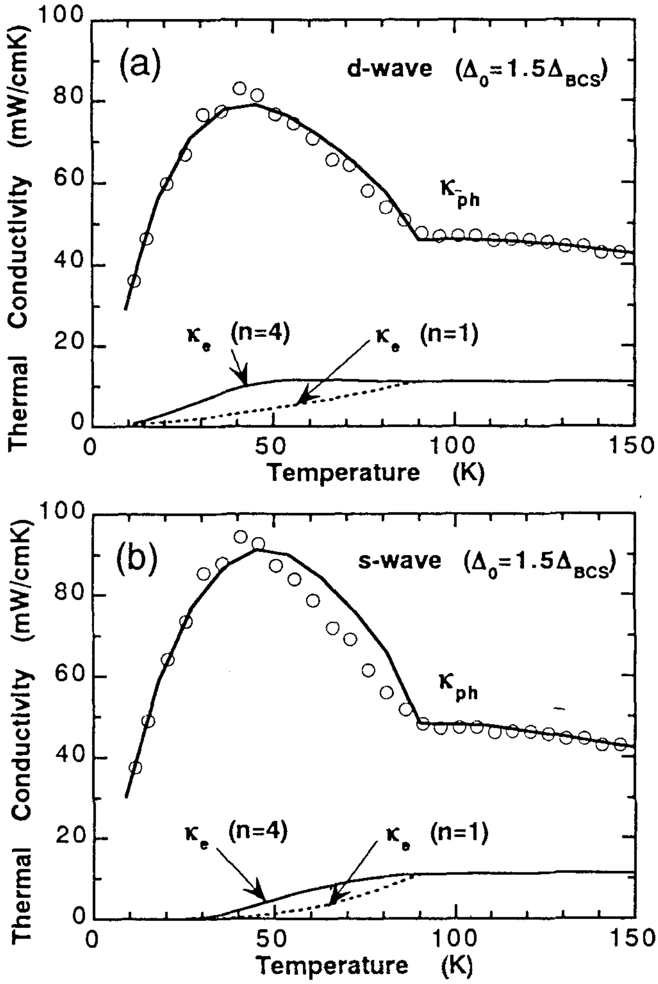

Fig. 2. The fitting curves for κ_{phs} based on TW-BRT[3,5] theory (a) for d-wave symmetry and (b) for s-wave symmetry. With Δ_0=1.5Δ_{BCS}, the weak coupling model under d-wave symmetry gives good fitting, while s-wave coupling cannot reproduce the peak position of κ_{ph}. In the present fittings for κ_{ph} the electronic component κ_e(T) with n=4 is used. Even if we adopt κ_e(T) with n=1, d-wave model again gives a far better fitting than s-wave model.

resistivity of this magnitude ($\rho(0)=\rho(T_c)/9.8$) really exists in the sample, the observed enhancement of κ cannot be attributed to the electronic component κ_e.

3.2. Analyses of κ_{ph}

By solving the Boltzman equation on the basis of the relaxation time approximation, the phonon thermal conductivity is given by[5]

$$\kappa_{ph} = \frac{3dNR}{2\pi M} v^2 \left(\frac{T}{\Theta_D}\right)^3 \int_0^{2\pi} d\phi \int_0^{\Theta_D/T} \frac{x^4 e^x}{(e^x-1)^2} \tau_{ph}\, dx , \tag{3}$$

where x is the reduced phonon frequency, N(=13) is the number of atoms composing $YBa_2Cu_3O_7$, R is the gas constant, Θ_D is the Debye temperature, d is the mass density and M is the molar weight. The phonon scattering rate τ_{phs}^{-1} in the superconducting state is given by the sum of various scattering centers in the crystal;

$$\tau_{phs}(x)^{-1}=\tau_b^{-1}+S(Tx)^2+P(Tx)^4+E(Tx)g(x,\ y)+UT^3x^2\exp(-\Theta_D/bT). \tag{4}$$

Here, parameters τ_b^{-1}, S, P, E and U represent the strength of the phonon scattering due to grain boundaries, sheet-like faults, point defects, conduction electrons and other phonons (Umklapp process), respectively, and b is a constant which controls the cut-off frequency of Umklapp process. The function $g(x,\ y)=\tau_{phn}^e/\tau_{phs}^e$ is the phonon scattering ratio due to electrons in the normal and superconducting state, which depends on the energy gap through the parameter y $(=\Delta/k_BT_c)$[3]. As shown in Fig. 2(a), the best fitting curve for $\Delta_0=1.5\Delta_{BCS}$ was obtained for d-wave coupling with the parameter values summarized in Table I. If we assume isotropic s-wave coupling with $\Delta_0=1.5\Delta_{BCS}$ the peak position of the calculated κ_{phs} shift to a higher temperature as shown in Fig. 2(b) and agreement with experiment cannot be achieved irrespective of the choice of the parameter values. It is noteworthy that the strong coupling model is incompatible with the present observation of $\kappa(T)$ because then the peak position of κ shift toward even higher temperatures as pointed out by Tewordt and Wölkhausen[6].

Finally, we make a rough estimation of the electron-phonon coupling parameter λ which is given by[5],

$$\lambda = \frac{2a\langle t\rangle E}{\pi v}, \tag{5}$$

Table I. Fitting parameters for the weak coupling of d-wave symmetry with $\Delta_0=1.5\Delta_{BCS}$.

$\tau_b^{-1}(s^{-1})$	$S(K^{-2}s^{-1})$	$P(K^{-4}s^{-1})$	$E(K^{-1}s^{-1})$	$U(K^{-3}s^{-1})$	$\Theta_D(K)$
5.2×10^8	3.0×10^6	1.1×10^3	8.5×10^8	3.4×10^3	400

where a is an average lattice constant, $<t>$ the effective hopping matrix element of electrons and v is the sound velocity. If we take a=4Å, $<t>$=5000K[5] and v=4700m/s (=measured value by us), then λ is estimated to be ~0.25.

4. SUMMARY

i) The electronic component κ_e of the thermal conductivity does not explain the observed enhancement below T_c because of the existence of the sizable residual resistivity in the present $YBa_2Cu_3O_7$ sample.

ii) If we assume the existence of a larger maximum energy gap $\Delta_0 \geq 1.5\Delta_{BCS}$ as reported by tunneling experiments, only the weak coupling phonon conduction model under d-wave symmetry is compatible with the experimental observation. If Δ_0 is of almost the same magnitude as Δ_{BCS}, the phonon conduction under s-wave coupling may also reproduce the experimental results.

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