**A. V. Inyushkin, A. N. Taldenkov, and V. V. Florent'ev.** *Heat conductivity of $LnBa_2Cu_3O_{7-x}$ single crystals.* Measurement of the temperature dependence of heat conductivity of solids yields significant information on the properties of quasiparticles (phonons, free charge carriers, and magnons) and their scattering by each other. Great interest is aroused by investigations of heat conductivity in high-temperature superconductors (HTSC) due to many reasons. First, the mechanism of superconductivity in these compounds is not clear yet and any additional information on the electron-phonon relaxation is important. Second, in a sufficiently wide temperature range below $T_s$ it does not appear to be possible to investigate the traditional galvanomagnetic properties, such as electrical resistivity, thermo-emf, and Hall effect. Such a restriction does not apply to the investigation of heat conductivity, which makes it possible to obtain information on the transport properties of high-temperature superconductors over a wide temperature range.

In the present paper the heat conductivity of single crystal samples of $LnBa_2Cu_3O_{7-x}$ in the *ab* plane and temperature range 8–250 K is investigated. Measurements were made in a modified setup of Ref. 1 by the method of a steady-state axial heat flux, using a four-contact technique. A sample in the form of a thin plate was pressed at one end into an indium base on a copper platform. With the help of a heater a temperature drop $\Delta T$ was established across the sample and measured by a differential manganin-Constantan thermocouple. A random error in measuring the heat conductivity was 20% for $T < 10$ K and was reduced to 3% in the domain $T > 100$ K. The main sources for a systematic error, which, according to estimates, can be 30%, were errors in measuring the geometric dimensions of the thinnest samples and the distance between thermocouple junctions. Single crystals of $LnBa_2Cu_3O_{7-x}$ ($Ln = Y$, $Y_{0.98}Gd_{0.02}$, $Y_{0.98}Yb_{0.02}$) grown by the solution-melt method were analyzed. The crystals were thin (12–50 $\mu$m) plates. The crystallographic *c* axis was directed along the normal to the plane of the plate. Note that using samples with 2% impurity of Gd and Yb had no special aim and was an insignificant circumstance for the given investigation. The superconducting properties were verified by measuring magnetic susceptibility in the fields of $\approx 1$ Oe with the frequency 667 Hz. The transition width of the best samples (YBCO-1,2,4) did not exceed 1 K. The YBCO-3 ceramic, synthesized according to cryochemical powder technology had a high density and displayed a narrow superconducting transition of about 2 K.

Temperature dependences of heat conductivity ($\varkappa(T)$) for CuO and $LnBa_2Cu_3O_{7-x}$ are given in Fig. 1. For crystalline CuO $\varkappa(T)$ is typical for dielectric singlecrystals and agrees well with the data from Ref. 2. Heat conductivity of $LnBa_2Cu_3O_{7-x}$ samples has a clearly expressed singularity at $T_s$. Note that the values of heat conductivity differ greatly for different samples. Temperature dependence and the value of heat conductivity of the YBCO-3 ceramic coincide with the data on heat conductivity of dense superconducting ceramics, which are known from the literature.

Among the $LnBa_2Cu_3O_{7-x}$ samples, given in Fig. 1, YBCO-1 differs greatly from the others (including those cited in the literature) both by a great value of $\varkappa(T)$ in the whole temperature range and by a considerable growth of $\varkappa(T)$ for $T < T_s$.

A weak temperature dependence of heat conductivity for $T > T_s$ deserves attention. Such behavior is typical for electron heat conduction $\varkappa_e$ of normal metals in the $T \approx T_D$ temperature range. However, according to the Wiedemann–Franz law, the estimate from above of the value of $\varkappa_e$ for HTSC singlecrystals of the YBCO compound yields the value which is ~30–50% of the total heat conductivity. In addition, the growth of $\varkappa(T)$ with a decrease in temperature below $T_s$ indicates that phonon-electron scattering decreases as a result of condensation of normal electrons. This fact points both at a significant value of phonon heat conduction $\varkappa_{ph}$ as compared with $\varkappa_e$ for $T > T_c$ and at the dominant part played by phonon-electron scattering in phonon heat transport at high temperatures as compared to three-phonon scattering processes, which yield a $\varkappa_{ph} \propto T^{-1}$ dependence (see CuO for $T > 100$ K, Fig. 1). It is also possible that in $YBa_2Cu_3O_{7-x}$, due to low-frequency optical branches, the

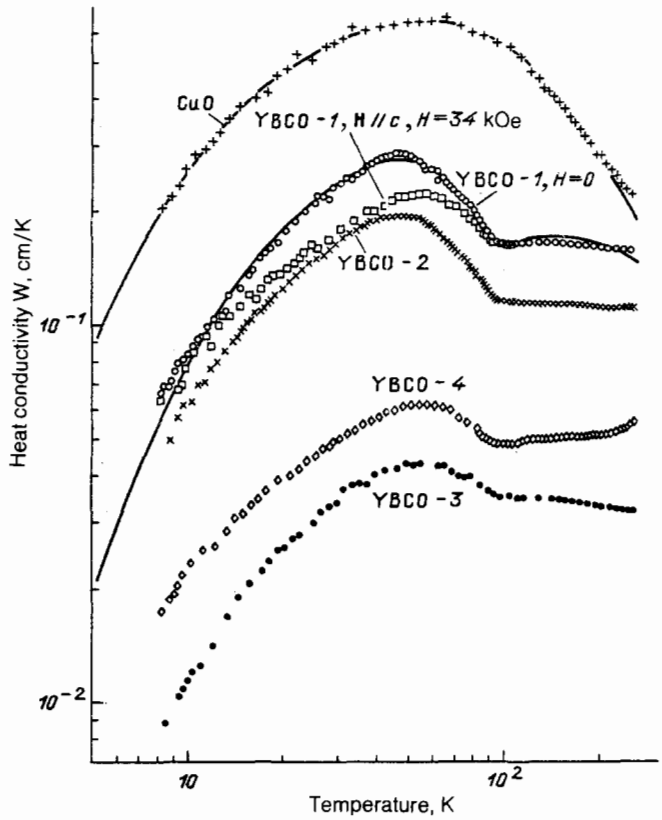


FIG. 1. Temperature dependence of heat conductivity of single crystal HTSC. Approximation results are represented by solid lines.

relaxation rate of phonons in three-phonon processes has a weak temperature dependence. Note that $\varkappa(T)$ of $YBa_2Cu_3O_{7-x}$ nonsuperconducting crystals, which can be considered, to a high degree of probability, as being purely phonon without electron-phonon scattering, also varies slightly with temperature for $T > 100$ K, according to the experimental data of Ref. 3.

Behavior of heat conductivity in conventional superconductors has been studied sufficiently well. A model for describing $\varkappa_{ph}(T)$ in the case of scattering of phonons by free charge carriers for conventional superconductors was suggested by Geilikman,[4] and by Bardeen, Rickayzen, and Tewordt[5] (BRT theory).

Taking into account the estimates of $\varkappa_e$ in YBCO crystals and also the low electron concentration for $T > T_s$ and the presence of a great number of scatterers for charge carriers (twin boundaries, oxygen vacancies), we assume that:

–the main contribution to heat conductivity is made by phonon heat transport;

–an increase in heat conductivity for $T < T_s$ is determined by a decrease in phonon-electron scattering due to electron condensation to Cooper pairs;

–a decrease in heat conductivity for $T < T_s/2$, after the maximum is achieved, is determined by the limitation on the phonon mean free path due to scattering by point defects and boundaries of the sample; here electron-phonon scattering becomes insignificant.

Electron heat conduction was assumed to be independent of temperature for $T > T_s$ (according to the Wiedemann–Franz law) and $\varkappa_e \propto \exp[-\Delta(T)/T]$ for $T < T_s$. To approximate the experimental data for CuO and YBCO-1 (solid lines in Fig. 1), we used the following formula:

$$\varkappa(T) = \varkappa_e(T) + \frac{k_B T^3}{2\pi^2 v_s}\left(\frac{k_B}{\hbar}\right)^3 \int_0^{T_D/T} \frac{x^4 e^x}{(e^x-1)^2 \tau^{-1}(x,T)}\,dx; \qquad (1)$$

$\Delta T$ is the BCS gap in the spectrum of electron excitations; $x = \hbar\omega/k_B T$ is the phonon reduced frequency; $T_D$ is the Debye temperature; $v_s$ is the sound velocity. (The two last quantities were taken from the literature.) The relaxation rate $\tau^{-1}(x, T)$ of phonons was represented as

$$\tau^{-1}(x,T) = \tau_b^{-1} + \tau_{pd}^{-1} + \tau_{3ph}^{-1} + \tau_{ph-e}^{-1}; \qquad (2)$$

$\tau_b^{-1} = v_s/d$ is the relaxation rate on the boundaries of the sample for the case of diffuse scattering; $d$ is the appropriate phonon mean free path; $\tau_{pd}^{-1} = A_{pd} x^4 T^4$ is the relaxation rate on point defects; $\tau_{3ph}^{-1} = A_{3ph} x^2 T^5$ is the relaxation rate in three-phonon processes; $\tau_{ph-e}^{-1} = A_{ph-e} x T g(x,\Delta)$ is the phonon-electron relaxation rate, and $g(x,\Delta)$ is the scattering function in BRT theory.

As a result of approximation a good agreement was achieved for the calculated dependence of heat conductivity for a CuO dielectric crystal using phonon scattering on the boundary of the sample ($\tau_b^{-1}$), point defects ($\tau_{pd}^{-1}$), and three-phonon scattering ($\tau_{3ph}^{-1}$). Applying the results to YBCO-1, we introduced into Eq. (1) $\varkappa_e$ and phonon scattering by free charge carriers; the value of $\varkappa_e$ for $T > T_s$ amounts to $\sim 30\%$ of the total, and this agrees well with the estimates from the Wiedemann–Franz law made by other authors. From $A_{ph-e}$, in the same way as it is given in Ref. 6, the electron-phonon interaction constant $\lambda_{tr} \sim 0.1$ was obtained, its value indicating a weak bond between electrons and acoustic phonons. The value of $2\Delta(0)/T_c \approx 5$ agrees well with the data $2\Delta(0)/T_c \approx 3-6$). from the literature. Note here that in the given case $\Delta(0)$ is estimated for the sample volume and not for the surface layer, which is typical for spectroscopic methods of determining the superconducting gap.

Measurements of heat conductivity were carried out for YBCO-1 crystal in a constant magnetic field up to 34 kOe, which was oriented perpendicularly to the temperature gradient. The temperature dependence of the heat conductivity for $H = 34$ kOe and $H \| c$ is given in Fig. 1. No difference was found between "field cooled" and "zero field cooled" dependences. A reduction in heat conductivity with an increase in the magnetic field is observed in the $15\ K < T < T_s$ temperature range. In our opinion, this is due to phonon scattering by free electrons in the centers of vortices ($H > H_{s1}$). The field dependences of heat conductivity can be handled by representing $\tau_{ph-e}^{-1}$ in Eq. (1) in the following form: $\tau_{ph-e}^{-1} = A_{ph-e} x T [g(x,\Delta)(1 - N(H)] + A_{ph-e} x T N(H)$, where $N(H)$ is the concentration of normal electrons, localized in vortex centers, which is averaged over the sample volume. Extrapolating $N(H)$ to the value of $N(H_{s2}) = 1$, we have obtained the estimates for $H_{c2}^{ab} \approx 500$ kOe, $H_{c2}^{c} \approx 3000$ kOe and $\xi_{ab} \approx 30$ Å, $\xi_c \approx 4$ Å at $T = 45$ K.

We explain the absence (with experimental accuracy) of a dependence of $\varkappa(T)$ on the magnetic field for $T < 15$ K by the disappearance of phonon-electron scattering, since the phonon wavelength $\lambda_{ph}$ exceeds the characteristic size of a vortex ($\lambda_{ph} \gg 2\xi_{ab}$). Calculating $\lambda_{ph}$ for $T \approx 10$–$40$ K makes it possible to give an independent estimate of the coherence length $\xi_{ab} \approx 30$–$20$ Å, which is in good agreement with the values given above and the data from other investigations.

The dependence of YBCO-1 heat conductivity on the angle between the direction of the magnetic field ($H = 34$ kOe) and the $c$-axis of the crystal for two temperatures is given in Fig. 2. The observed anisotropy is determined, in our opinion, by the difference of the coherence lengths in the $ab$ plane and along the $c$-axis. Our estimate of anisotropy of coherence length (for both temperatures) yields $\xi_{ab}/\xi_c \approx 7$, which agrees well with the literature data. Here it is necessary to note that a sufficiently great value of experimental

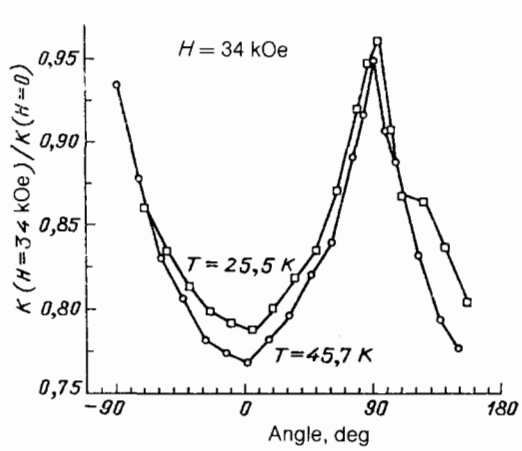


FIG. 2. Heat conductivity of YBCO-1 as a function of a magnetic field orientation with respect to the $c$-axis at $T = 25.5$ and $T = 45.7$ K.

measurement error (for $\phi = 90°$) does not enable us to know if there are vortices perpendicular to the $c$-axis in these compounds. To clear up these questions it is necessary to have more accurate measurements of the angular dependence of heat conductivity, which are being developed now.

The authors express their gratitude to O. K. Mel'nikov and A. B. Bykov for providing samples and also to Yu. M. Kagan, L. B. Dubovskiĭ, and E. Z. Meĭlikhov for useful discussions and valuable remarks.

[1] A. V. Inyushkin, A. N. Taldenkov, and V. V. Florent'ev, Prib. Tekh. Eksp. No. 3, 211 (1988) [Instrum. Exp. Tech. (USSR)] **31**, 783 (1988)].
[2] A. Jezowski, Solid State Commun., **71**, 419 (1989).
[3] S. J. Hagen, Z. Z. Wang, and N. P. Ong, Phys. Rev. B, **40**, 9389 (1989).
[4] B. T. Geĭlikman, *Research in Low-temperature Physics* [in Russian], Atomizdat, M., 1979.
[5] J. Bardeen, G. Rickayzen, and L. Tewordt, Phys. Rev., **113**, 982 (1959).
[6] L. Tewordt and Th. Wolkhausen, Solid State Commun., **70**, 839 (1989).

Translated by Zhanna Suslovich