Separation of Quasiparticle and Phononic Heat Currents in $YBa_2Cu_3O_{7-\delta}$

B. Zeini,[1] A. Freimuth,[1] B. Büchner,[1] R. Gross,[1] A. P. Kampf,[2] M. Kläser,[3] and G. Müller-Vogt[3]
[1]*II. Physikalisches Institut, Universität zu Köln, 50937 Köln, Germany*
[2]*Theoretische Physik III, Universität Augsburg, 86135 Augsburg, Germany*
[3]*Kristall- und Materiallabor, Universität Karlsruhe, 76128 Karlsruhe, Germany*
(Received 9 February 1998)

Measurements of the transverse (k_{xy}) and longitudinal (k_{xx}) thermal conductivity in high magnetic fields are used to separate the quasiparticle thermal conductivity (k_{xx}^{el}) of the CuO_2-planes from the phononic thermal conductivity in $YBa_2Cu_3O_{7-\delta}$. k_{xx}^{el} is found to display a pronounced maximum below T_c. Our data analysis reveals distinct transport (τ) and Hall (τ_H) relaxation times below T_c: Whereas τ is strongly enhanced, τ_H follows the same temperature dependence as above T_c. [S0031-9007(99)08592-0]

PACS numbers: 74.25.Fy, 72.15.Jf, 74.72.Bk

The study of heat transport in the superconducting state is well known to provide valuable information on the quasiparticle (QP) excitations and their dynamics. Compared to other probes of the QP dynamics such as the microwave conductivity thermal transport has the advantage of probing only the QP response, since the superfluid does not carry heat. On the other hand, a major complication in the analysis of the thermal conductivity is often a substantial phononic contribution k_{xx}^{ph} to the heat current. Such a situation is realized in the high-T_c superconductors (HTSC), where the heat current above T_c is known to be dominated by k_{xx}^{ph} [1]. Accordingly, the interpretation of experimental data is ambiguous: For example, the maximum in the temperature dependence of the thermal conductivity in the superconducting state of $YBa_2Cu_3O_{7-\delta}$ (YBCO) has been attributed to both, a maximum of the electronic as well as the phononic contribution [1–4]. A clear separation of the phonon and QP heat currents is difficult and up to now an unsolved problem.

It has been pointed out in Refs. [5,6] that the transverse thermal conductivity k_{xy}—the thermal analogue of the Hall effect—is free of phonons, i.e., k_{xy} is purely electronic. k_{xy} is related to the electronic thermal conductivity k_{xx}^{el} according to $k_{xy} = k_{xx}^{\mathrm{el}} \tan\alpha_R$ where α_R is the thermal Hall angle. From the Wiedemann-Franz law [7] one expects that α_R is equal to the electrical Hall angle α_H as obtained from the electrical (σ_{xx}) and Hall (σ_{xy}) conductivities via $\tan\alpha_H = \sigma_{xy}/\sigma_{xx}$. In conventional metals $\tan\alpha_H = \omega_c\tau$ where $\omega_c = eB/m$ is the cyclotron frequency and τ is the usual transport relaxation time. In contrast, in the normal state of the HTSC $\tan\alpha_H$ is highly anomalous and has a temperature dependence which is *distinctly* different from $\tau(T)$ [8–10]. Up to now no data on the QP Hall angle are available below T_c, but one may suspect that its behavior is anomalous as well. Therefore, in order to calculate k_{xx}^{el} from k_{xy} it is necessary to treat $\tan\alpha_R = \omega_c\tau_R$ as an additional independent parameter which must be determined experimentally.

In this Letter we determine both k_{xx}^{el} and $\tan\alpha_R$ below T_c in a single crystal of YBCO from combined measurements of k_{xy} and k_{xx} in high magnetic fields. Our main results are as follows: (1) The electronic thermal conductivity of the CuO_2-planes shows a pronounced maximum below T_c which is strongly suppressed by a magnetic field. (2) $\tan\alpha_R$, as extracted from the thermal transport data below T_c, displays the same temperature and magnetic field dependence as $\tan\alpha_H$ obtained from electrical transport data above T_c, and it passes smoothly through T_c. This shows that $\tau_R \simeq \tau_H$ and, remarkably, that τ_H and τ behave differently also below T_c.

The thermal conductivity tensor $\underline{k}$ is the sum of an electronic and a phononic part $\underline{k} = \underline{k}^{\mathrm{el}} + \underline{k}^{\mathrm{ph}}$. It is defined via the heat current density $\mathbf{j}_h = -\underline{k}\nabla T$ [11]. We assume that $\underline{k}^{\mathrm{ph}}$ remains diagonal even for $\mathbf{B} \neq 0$, i.e., $k_{xy}^{\mathrm{ph}} = 0$. In this case the transverse components of $\underline{k}$ are purely electronic. The transverse thermal conductivity, also called the Righi-Leduc effect, is measured as follows: In a magnetic field $\mathbf{B} = (0,0,B)$ a temperature gradient $\nabla_x T$ is applied in the x direction. Under the condition $j_{h,y} = 0$ a transverse temperature gradient $\nabla_y T$ is found in the y direction. Using the Onsager relations we find in this situation

$$j_{h,y} = k_{xy}\nabla_x T - k_{xx}\nabla_y T = 0\,, \qquad (1)$$

with $k_{xx} = k_{yy}$ for twinned crystals without in-plane anisotropy. k_{xy} can therefore be determined experimentally by measuring $\nabla_x T$, $\nabla_y T$, and the *total* longitudinal thermal conductivity k_{xx}.

Our measurements were carried out at constant temperatures with the magnetic field applied perpendicular to the CuO_2 planes. Typically, temperature gradients $\nabla_x T$ of order 0.5 K/mm were applied using a small manganin heater mounted on top of the samples. The resulting transverse temperature gradients $\nabla_y T$ of order 10^{-3} K/mm in magnetic fields up to 14 T were measured with AuFe-Chromel thermocouples calibrated in the same field range [12]. To eliminate offset voltages due to misalignment of the thermocouple we have measured for both field directions $\pm\mathbf{B}$ in order to determine the Righi-Leduc component of $\nabla_y T$ which must be antisymmetric with respect to field reversal. We have measured in two different modes: Either **B** was reversed at fixed temperature or we have heated the sample to temperatures above T_c before the field was reversed. Because of vortex pinning effects this latter mode was used for all low temperature measurements. We note that sweeping the magnetic field at fixed temperatures results in a strong hysteresis of k_{xx} in almost the entire temperature range below T_c, similar as reported in Ref. [13]; k_{xy}, which must be extracted from the asymmetry of the field dependence, can therefore not be determined by sweeping the magnetic field. We have tested our method by measurements on an insulator ($k_{xy} = 0$) and on simple metals [14]. Details of our experimental setup will be described elsewhere. The results presented here have been obtained on a high quality twinned single crystal of YBCO with dimensions 1.9 mm × 2 mm × 0.38 mm and with a superconducting transition at $T_c \simeq 90.5$ K.

Representative experimental results are shown in Fig. 1. k_{xx} has a pronounced maximum at $T_{\max} < T_c$ which is strongly suppressed by the applied magnetic field. The absolute value of k_{xx} (≈ 10 W/Km at T_c), the relative upturn of k_{xx} in zero field as characterized by the ratio $k_{xx}(T_{\max})/k_{xx}(T_c) \approx 1.6$ for our sample, as well as the sensitivity of the maximum to magnetic fields are consistent with previous results [1–3]. The overall temperature dependence of k_{xy} is similar to that of k_{xx} but the maximum of k_{xy} occurs at higher temperatures and the relative change below T_c is larger in comparison to k_{xx}. The absolute magnitude of k_{xy} is comparable to that reported previously in Ref. [6].

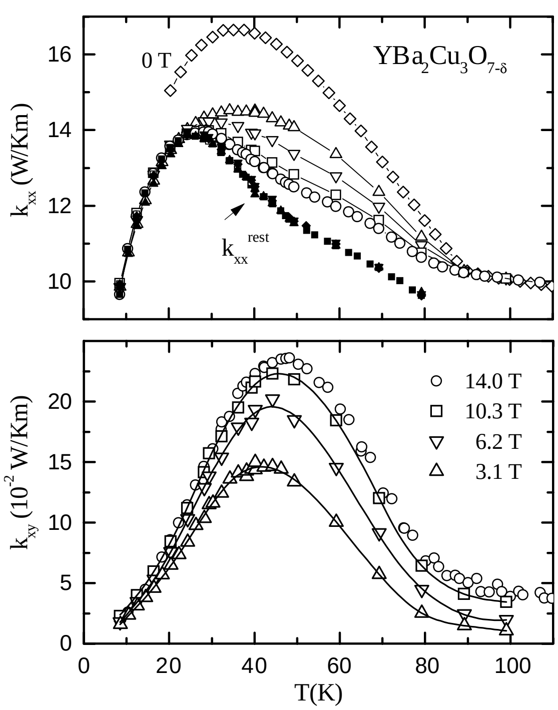

FIG. 1. Open symbols: k_{xx} (upper panel) and k_{xy} (lower panel) of $YBa_2pCu_3O_{7-\delta}$ as a function of temperature T for various fixed magnetic fields as indicated in the figure. Full symbols: $k_{xx}^{\rm rest}$ as obtained from our data analysis (see text).

For our data analysis we assume that in YBCO three channels of heat conduction are present:

$$k_{xx} = k_{xx}^{\rm el} + k_{xx}^{\rm ch} + k_{xx}^{\rm ph} = k_{xx}^{\rm el} + k_{xx}^{\rm rest}. \qquad (2)$$

Here $k_{xx}^{\rm el}$ is the electronic contribution from the CuO_2-planes (CuO_2 bilayers in YBCO) and $k_{xx}^{\rm ph}$ is that of the phonons. $k_{xx}^{\rm ch}$ describes a possible contribution from the CuO chains which are present in YBCO along the b direction of the orthorhombic structure. These chains are metallic for optimally doped samples and lead to a rather strong a-b anisotropy in untwinned crystals ($\sigma_{bb}/\sigma_{aa} \simeq 2$) [8]. In a twinned crystal they should contribute to the electrical and the heat conduction on average; a-b anisotropy is, of course, absent. In the subsequent data analysis $k_{xx}^{\rm ch}$ must be treated differently from $k_{xx}^{\rm el}$ since the CuO-chains as a quasi-one-dimensional channel for charge and heat transport should neither contribute to the transverse transport coefficients σ_{xy} and k_{xy} nor to the magnetic field dependence of the longitudinal ones.

We compare in Fig. 2 $\Delta k_{xx} = k_{xx}(B) - k_{xx}(0)$ and k_{xy}/B. Notably, these quantities have the same magnetic field dependence, i.e.,

$$\frac{\partial}{\partial B}\left(\frac{k_{xy}}{B}\right) \propto \frac{\partial k_{xx}}{\partial B}. \qquad (3)$$

This observation provides the key to our data analysis. We define

$$\tan \alpha_R = \omega_c \tau_R = \frac{k_{xy}}{k_{xx}^{\rm el}}, \qquad (4)$$

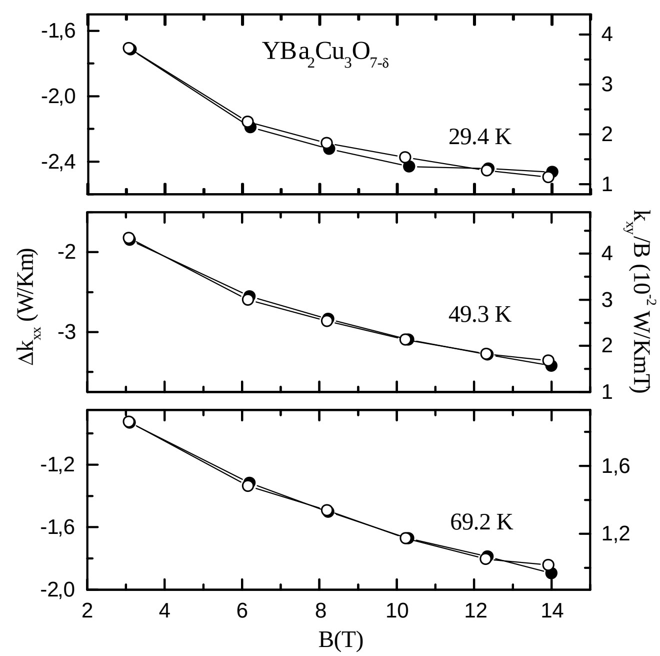

FIG. 2. $\Delta k_{xx} = k_{xx}(B) - k_{xx}(B = 0)$ (•) and k_{xy}/B (∘) versus magnetic field B at fixed temperatures given in the figure.

where $\tau_R(B,T)$ is a "relaxation time" introduced to parametrize the field and temperature dependence of $\tan\alpha_R$. Using Eqs. (2) and (4) we find

$$\frac{m}{e}\frac{\partial}{\partial B}\left(\frac{k_{xy}}{B}\right) = \tau_R\frac{\partial k_{xx}}{\partial B} + \left[k_{xx}^{\mathrm{el}}\frac{\partial \tau_R}{\partial B} - \tau_R\frac{\partial k_{xx}^{\mathrm{ph}}}{\partial B} - \tau_R\frac{\partial k_{xx}^{\mathrm{ch}}}{\partial B}\right]. \quad (5)$$

Apparently, our experimental results suggest that the term in brackets is zero. Since the three terms in brackets refer to three distinct channels of heat conduction this requires that τ_R, k_{xx}^{ph}, and k_{xx}^{ch} are separately field independent. Note that this is certainly reasonable in view of the origin of these contributions to the heat current.

Assuming thus that the three terms in brackets vanish τ_R can be calculated from our data by comparing k_{xx} and k_{xy}/B at different magnetic fields according to $e\tau_R/m = \Delta(k_{xy}/B)/\Delta k_{xx}$ [see Eq. (5)]. The result is shown in Fig. 3. Note that the values obtained for different magnetic fields coincide within the experimental accuracy consistent with the anticipated field independence of τ_R.

As a check of our result for τ_R we have also determined $e\tau_H/m = \sigma_{xy}/B\sigma_{xx}$ for the same sample from measurements of σ_{xy} and σ_{xx} in the normal state [14]. These data as well as their extrapolation [15] to temperatures below T_c are also shown in Fig. 3. The extrapolated values for τ_H^{-1} look very similar to τ_R^{-1} regarding the temperature dependence (see inset of Fig. 3), but they appear to be systematically larger by roughly a factor of 2. However, note that τ_R as extracted from the thermal transport data is clearly unaffected by the CuO chains and that this is also true for σ_{xy}. In contrast, σ_{xx} has a contribution from the CuO chains, i.e., $\sigma_{xx} = \sigma_{xx}^{\mathrm{pl}} + \langle\sigma_{xx}^{\mathrm{ch}}\rangle$, where $\sigma_{xx}^{\mathrm{pl}}$ is the electrical conductivity of the CuO_2 planes and $\langle\sigma_{xx}^{\mathrm{ch}}\rangle$ is an average of the chain contribution appropriate for a twinned crystal. With $\sigma_{xx}^{\mathrm{pl}} \approx \langle\sigma_{xx}^{\mathrm{ch}}\rangle$ [8] we conclude that $e\tau_H/m = \sigma_{xy}/B\sigma_{xx}$ is underestimated by a factor of 2. Correcting the normal state data for this factor we find excellent agreement between τ_H and τ_R, i.e., our data tell $\tau_R \simeq \tau_H$. This strongly supports the procedure of our data analysis.

Once τ_R is known the remainder of our analysis is straightforward: $k_{xx}^{\mathrm{el}}(B \neq 0)$ follows from Eq. (4) using the data for $k_{xy}(B)$, and k_{xx}^{rest} is obtained subsequently from Eq. (2) for each field strength. As a test for internal consistency we have verified that k_{xx}^{rest} is indeed field independent. Finally, $k_{xx}^{\mathrm{el}}(B = 0)$ follows from Eq. (2) using k_{xx}^{rest} and the zero field data for k_{xx}. We have also determined $k_{xx}^{\mathrm{el}}(B = 0)$ directly from Eq. (4) using an extrapolation of B/k_{xy} to $B = 0$ in good agreement with the results obtained from using k_{xx}^{rest} and Eq. (2).

In Fig. 4 we show $k_{xx}^{\mathrm{el}}(B)$ as obtained from our data analysis. k_{xx}^{el} represents the electronic thermal conductivity of the CuO_2-planes in YBCO. Our results thus confirm explicitly that k_{xx}^{el} is strongly enhanced below T_c. $k_{xx}^{\mathrm{el}} \propto Tn_{\mathrm{QP}}\tau$ implies that τ is strongly enhanced below T_c overcompensating the decrease of the QP number density $n_{\mathrm{QP}}(T)$ with decreasing temperature. This confirms

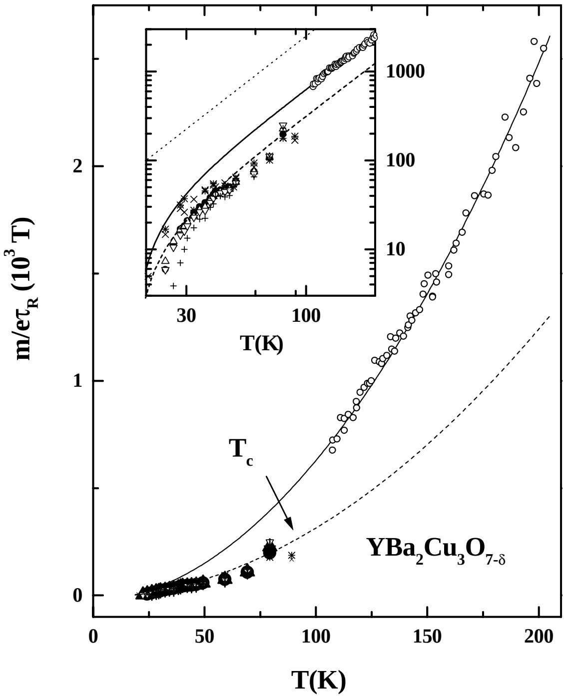

FIG. 3. $T < T_c$: $m/e\tau_R$ vs temperature T obtained from $e\tau_R/m = \Delta(k_{xy}/B)/\Delta k_{xx}$, where $\Delta(k_{xy}/B) = k_{xy}(B_1)/B_1 - k_{xy}(B_2)/B_2$ and $\Delta k_{xx} = k_{xx}(B_1) - k_{xx}(B_2)$. Different symbols correspond to different values of B_1 and B_2. $T > T_c$: $m/e\tau_H$ obtained from σ_{xy} and σ_{xx}. Solid line: extrapolated normal state data (see text). Dashed line: extrapolated normal state data divided by a factor of 2. Inset: The same data on a double logarithmic scale. The dotted line corresponds to a T^2 temperature dependence.

the results obtained for the QP relaxation time from the microwave conductivity [16].

We also find that k_{xx}^{el} is very sensitive to magnetic fields contrary to what is observed in the normal state, where the total thermal conductivity and thus k_{xx}^{el} is field independent. It is straightforward to attribute the field dependence below T_c to an additional scattering mechanism [17] characteristic for the superconducting state such as scattering of QPs on vortices [6,18,19]. Assuming the corresponding scattering rate τ_v^{-1} to be proportional to the number of vortices $n_v \propto B$ one expects for the total scattering rate that $\tau^{-1} = \tau_{\mathrm{in}}^{-1} + \tau_v^{-1} = \tau_{\mathrm{in}}^{-1} + \alpha B$. Here, τ_{in} includes the same scattering processes as in the normal state, i.e., it has in general an elastic defect and an inelastic contribution; the latter collapses below T_c. Using $k_{xy} = k_{xx}^{\mathrm{el}}\omega_c\tau_R = L(T)T\sigma_{xx}\omega_c\tau_R$ where L is the Lorentz number and $\sigma_{xx} = n_{\mathrm{QP}}(T)e^2\tau/m$ we find

$$\frac{B}{k_{xy}} = C(T)\tau^{-1} = C(T)\,(\tau_{\mathrm{in}}^{-1} + \alpha B)\,, \quad (6)$$

where $C(T) = m^2/(LTn_{\mathrm{QP}}e^2\tau_R)$ depends only on temperature. Thus a plot of B/k_{xy} vs B should yield a straight line. This is indeed the case as shown in Fig. 4. We note that by assuming α to be temperature independent $\tau_{\mathrm{in}}(T)$ can be extracted from the slope and the intersection of the

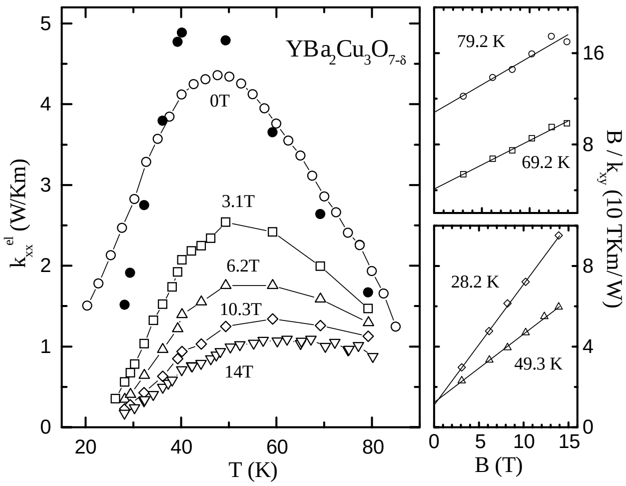

FIG. 4. Left panel: Electronic thermal conductivity $k_{xx}^{\mathrm{el}}(B)$ of the CuO_2 planes as a function of temperature for various magnetic fields as indicated in the figure. The zero field data have been obtained from $k_{xx}^{\mathrm{el}}(B = 0) = k_{xx}(B = 0) - k_{xx}^{\mathrm{rest}}$ ($\circ$) as well as from an extrapolation of B/k_{xy} to $B = 0$ ($\bullet$). Right panels: B/k_{xy} as a function of magnetic field B at various fixed temperatures given in the figure.

B/k_{xy} vs B curves (to within the constant factor α). We find that τ_{in} increases strongly below T_c [14].

k_{xx}^{rest} as obtained from our data analysis is shown in Fig. 1. Remarkably, k_{xx}^{rest} shows a pronounced maximum below T_c, too. This maximum may be due to the phononic contribution [1]. However, it may also arise from the chain contribution. The latter has previously been determined experimentally from the a-b anisotropy of k_{xx} in detwinned single crystals of YBCO [2,20]. k_{xx}^{ch} shows a pronounced maximum below T_c with an overall temperature dependence similar to that found here for k_{xx}^{rest} [20]. Furthermore, the field independence of k_{xx}^{rest} implies that the phononic contribution k_{xx}^{ph} is independent of B. Such a conclusion has recently been drawn also on the basis of low temperature results for the thermal conductivity in Bi-based HTSC [21].

Finally, our data show clearly that $\tau_R \simeq \tau_H$ and that—as in the normal state—τ_H and τ behave differently also below T_c. In particular, whereas τ is strongly enhanced below T_c, τ_H is unaffected by the superconducting transition and shows the same temperature dependence as above T_c. This finding should provide important information for the theoretical understanding of transport phenomena in the cuprates.

In summary, we have presented a separation of the QP and phononic contributions to the thermal conductivity below T_c in YBCO based on measurements of the longitudinal and transverse thermal conductivity in high magnetic fields. Our data analysis shows explicitly that the QP contribution to k_{xx} is strongly enhanced below T_c and that it is the QP contribution to the heat current which is responsible for the magnetic field dependence of k_{xx}. We find that—as in the normal state—two relaxation times must be distinguished also below T_c: Whereas the QP relaxation time τ is strongly enhanced below T_c and magnetic field dependent, the Hall relaxation time τ_H remains independent of B below T_c and has the same temperature dependence as above T_c.

We are particularly grateful for stimulating discussions with W. Brenig, Ch. Bruder, M. Galffy, P. J. Hirschfeld, T. Kopp, D. Rainer, S. Uhlenbruck, and P. Wölfle. This work was supported by the Deutsche Forschungsgemeinschaft through SFB 341.

[1] C. Uher, in *Physical Properties of High Temperature Superconductors*, edited by D. M. Ginsberg (World Scientific, Singapore, 1992), Vol. 3.
[2] R. C. Yu *et al.*, Phys. Rev. Lett. **69**, 1431 (1992).
[3] S. D. Peacor *et al.*, Phys. Rev. B **44**, 9508 (1991).
[4] J. L. Cohn *et al.*, Phys. Rev. Lett. **71**, 1657 (1993).
[5] A. Freimuth *et al.*, J. Low Temp. Phys. **95**, 383 (1994).
[6] K. Krishana *et al.*, Phys. Rev. Lett. **75**, 3529 (1995).
[7] The generalized Wiedemann-Franz law relates the electrical and thermal conductivity tensors, $\underline{\sigma}$ and $\underline{k}$, respectively, according to $\underline{k} = LT\underline{\sigma}$. L is the Lorentz number.
[8] Y. Iye, in *Physical Properties of High Temperature Superconductors*, edited by D. M. Ginsberg (World Scientific, Singapore, 1992), Vol. 3.
[9] T. R. Chien *et al.*, Phys. Rev. Lett. **67**, 2088 (1991).
[10] P. W. Anderson, Phys. Rev. Lett. **67**, 2092 (1991).
[11] The heat current due to vortex motion is negligibly small [14].
[12] The thermal conductance of the thermocouple was about 0.5% of that of the sample. The calibration was performed against an insulator above 30 K and against a second thermocouple of the same type placed in zero magnetic field below 30 K [see C. K. Chiang, Rev. Sci. Instrum. **45**, 985 (1974); and Ref. [14]].
[13] H. Aubin *et al.*, Science **280**, 9a (1998).
[14] B. Zeini, Ph.D. thesis, Universität zu Köln, (Shaker, 1997); B. Zeini *et al.* (to be published).
[15] We have fitted the resistivity ρ and the inverse Hall coefficient R_H^{-1} to $a + bT$ and to $\tilde{a} + \tilde{b}T$, respectively, where a, b, $\tilde{a}$, and $\tilde{b}$ are constants. $e\tau_R/m$ was then obtained from $e\tau_H/m = \sigma_{xy}/B\sigma_{xx} \simeq R_H/\rho$.
[16] D. A. Bonn and W. N. Hardy, in *Physical Properties of High Temperature Superconductors*, edited by D. M. Ginsberg (World Scientific, Singapore, 1996), Vol. 5.
[17] A magnetic field dependence of k_{xx}^{el} may also result from the field dependence of n_{QP} in unconventional superconductors [G. E. Volovik, JETP Lett. **58**, 469 (1993)). However, n_{QP} and thus k_{xx}^{el} should increase with B contrary to the behavior of k_{xx} found here.
[18] M. B. Salamon *et al.*, J. Supercond. **8**, 449 (1995).
[19] R. M. Cleary, Phys. Rev. **175**, 587 (1968).
[20] R. Gagnon *et al.*, Phys. Rev. Lett. **78**, 1976 (1997).
[21] K. Krishana *et al.*, Science **277**, 83 (1997).