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LETTER TO THE EDITOR

Magneto-thermal conductivity of high-T_c superconductors: electron–vortex scattering contribution

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Abstract. The influence of a magnetic field on the thermal conductivity of high-T_c superconductors is described. A semi-phenomenological model which takes into account the influence of the magnetic field on the density of normal electrons as well as on the electron–vortex scattering is used, assuming that the energy levels of quasiparticles near the vortex cores are quantized and supposing that electrons are mainly scattered by these quasiparticles. The experimental results on an untwinned $YBa_2Cu_3O_{7-\delta}$ single crystal, on $YBa_2Cu_3O_{7-\delta}$ and $YBa_2(Cu_{0.95}Fe_{0.05})_3O_{7-\delta}$ ceramics are quite well reproduced with quite realistic values of the physical parameters.

The magneto-thermal conductivity $\kappa(B)$ of high-T_c superconductors was first theoretically analysed by Richardson *et al* [1] on the basis of a phonon model, i.e. supposing that the main carriers of heat are phonons [2–4] which are strongly scattered by the flux lines in the mixed state of these type II superconductors. They have studied the influence of a magnetic field on the thermal conductivity of twinned and untwinned single crystals of $YBa_2Cu_3O_{7-\delta}$ and they have found that their data were quite well reproduced by the phenomenological expression [1]

$$\kappa(B)^{-1} = 1/\kappa(0) + cB\exp(-dB^q) \tag{1}$$

where $\kappa(0)$ is the thermal conductivity in the absence of magnetic field and the second *term represents the thermal resistivity due to the scattering of phonons by vortices; c and d* are undefined temperature-dependent parameters adjusted to fit the data, while the exponent q was found to be temperature independent and equal to 1/4 for both their twinned and untwinned single crystals.

Richardson *et al* [1] have tentatively explained their results by assuming that phonons are moving as Bloch waves in the periodic potential of the vortex lattice which would become more regular as the field is increased. The authors have then proposed that the thermal conductivity could be a probe of the vortex state of high-T_c compounds. It is, however, quite surprising that the phonon contribution is smoothed when the field is increased, i.e. when the number of scattering centres is raised. Bougrine *et al* [5] have more fundamentally described the structure of $\kappa(B)$ by examining the interplay between different characteristic lengths and obtained a more general expression from which equation (1) can be derived. In fact, in the limit of small fields one recovers the well known Sousa expression [6].

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However, several theoretical and experimental results have recently suggested that the main structure of the thermal conductivity of high-T_c cuprates, i.e. the maximum observed below T_c in the absence of a magnetic field, could be due to the contribution of normal electrons in the CuO_2 planes [7–10]. Consequently, it can be thought that the magnetic field dependence of the thermal conductivity of high-T_c superconductors might mainly arise from the scattering of normal electrons by the vortex cores. We investigate such a possibility here and obtain a coherent picture.

By analogy with equation (1), the total magneto-thermal conductivity $\kappa(B)$ is written

$$\kappa^{-1}(B, T) = \kappa^{-1}(0, T) + \kappa_{e\text{-}v}^{-1}(B, T) \tag{2}$$

where $\kappa(0, T)$ is the thermal conductivity in the absence of a field and $\kappa_{e\text{-}v}(B, T)$ the thermal resistivity due to the scattering of electrons by the vortex cores. Notice that the phonon background as well as the electron–phonon scattering and the role of defects is contained in $\kappa(0, T)$. The magnetic induction dependence of κ is thus assumed to be only due to the electron–vortex scattering, in contrast to the phonon–vortex scattering assumed in [1].

In order to derive the electron–vortex scattering contribution, we have considered the well known Boltzmann based kinetic formula [8, 11]

$$\kappa_{e\text{-}v}(B, T) = \frac{\pi^2}{3}\frac{k_B^2 T}{m^*} n_e(B, T)\tau_{e\text{-}v}(B, T) \tag{3}$$

where m^* is the effective mass of electrons, n_e the normal electron concentration and $(\tau_{e\text{-}v})^{-1}$ the electron–vortex scattering rate.

On one hand, we have used the expression for the normal electron concentration as phenomenologically derived from the structure of the electronic specific heat C_e [12]

$$n_e(T, B) = n_0 \exp\left(-\frac{\Delta(T, B)}{k_B T}\right) \tag{4}$$

where n_0 is the steady-state electron concentration in the normal state and Δ the Ginzburg–Landau superconducting energy gap. The temperature and magnetic induction B dependence of Δ in type II superconductors is given by [12, 13]

$$\Delta(T, B) = \Delta(0, 0)\frac{T_c(B)}{T_c}\sqrt{1 - \frac{T}{T_c(B)}}\sqrt{1 - \left(\frac{B}{\mu_0 H_{c2}(T)}\right)^2} \tag{5}$$

where $\Delta(0, 0)$ is the superconducting energy gap at zero temperature in the absence of a field, μ_0 the permittivity in free space, $T_c(B)$ the magnetic induction dependence of the critical temperature which is decreased as the induction is increased [14]

$$T_c(B) = T_c(0)\left[1 - \left(\frac{B}{\mu_0 H_{c2}}\right)^{2/3}\right] \tag{6}$$

and $H_{c2}(T)$ the temperature-dependent upper critical magnetic field. Such a field is governed by [15]

$$H_{c2}(T) = H_{c2}(0)\left[1 - \left(\frac{T}{T_c}\right)^2\right]. \tag{7}$$

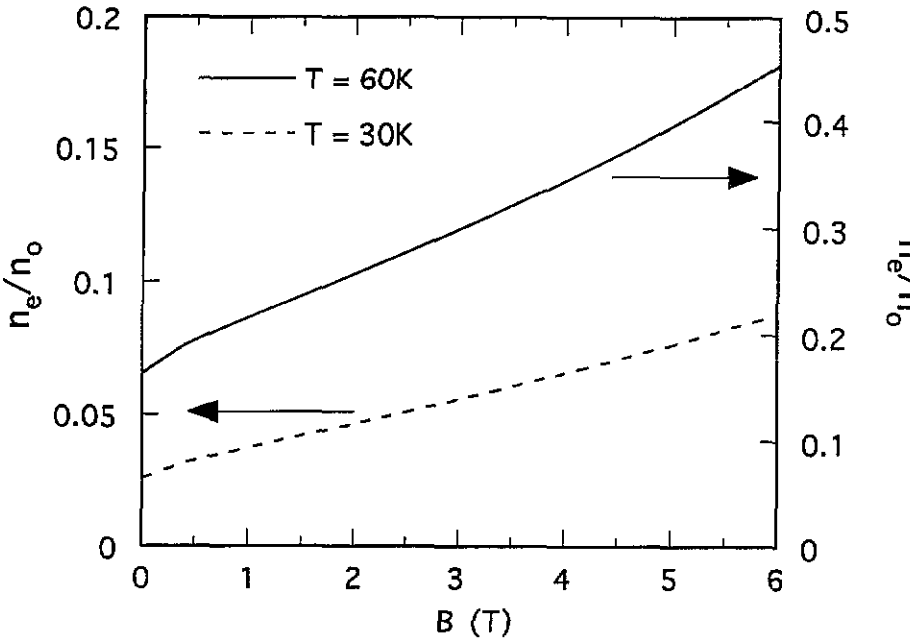


Figure 1. Normal normalized electron concentration n_e/n_0 as a function of the magnetic induction B for different temperature values.

The influence of the magnetic induction on the normalized electron concentration n_e/n_0 is shown in figure 1 at different temperatures. The density of normal electrons increases with the magnetic induction as the field breaks Cooper pairs and decreases when the temperature is decreased due to the condensation into Cooper pairs below T_c.

On the other hand, Caroli *et al* [16] have shown that the electronic structure of a vortex consists of quasiparticles which occupy discrete energy levels separated by a quantum of the order of $\hbar^2/m^*\xi^2(0)$ where $\xi(0)$ is the zero temperature coherence length [17]. Specifically, this quantum of energy lies between 5 and 10 meV in high-T_c cuprates. The scattering rate of heat carrying normal electrons by these quasiparticle excitations in the core of vortices reads [18]

$$\left(\tau_{e\text{-}v}\right)^{-1} = \alpha(T)\frac{B}{\mu_0 H_{c2}} \tag{8}$$

where $\alpha(T)$ is given in cgs units by

$$\alpha(T) = \frac{e^5\mu_0 H_{c2}}{\hbar^2 c\epsilon_F^2}\sum_j \frac{\sqrt{\Delta^2(0,0)-\epsilon_j^2}}{1+\exp(2\epsilon_j/k_B T)} \tag{9}$$

where $\epsilon_j = j\hbar^2/m^*\xi^2(0)$.

The normalized electron–vortex scattering rate $(\tau_{e\text{-}v}/\tau_0)^{-1}$, where $\tau_0^{-1} = (e^5\mu_0 H_{c2}/\hbar^2 c\epsilon_F^2)\sum_j\sqrt{\Delta^2(0,0)-\epsilon_j^2}$, as a function of the reduced temperature T/T_c is shown in figure 2 for several values of the magnetic induction B. Electrons are thus more strongly scattered by the vortices when the temperature is increased for a fixed value of the magnetic induction. The above picture also takes into account the fact that the number of (thermally excited) quasiparticles in the vortex cores is indeed increasing with temperature. Besides, the electron–vortex scattering rate increases when B is increased. This is more in line with usual physical thinking than the weaker phonon scattering contribution at large field assumed as a plausible model in [1].

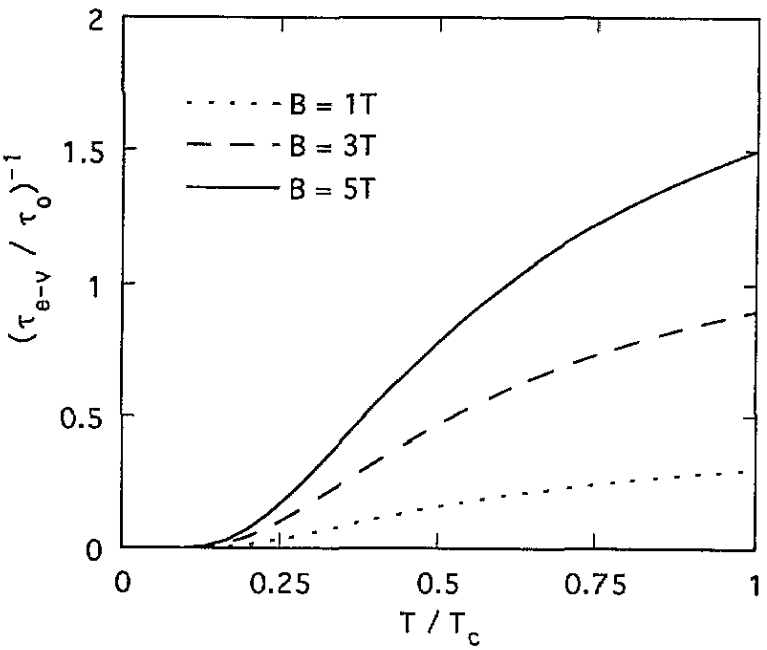


Figure 2. Normalized electron–vortex scattering rate $(\tau_{e\text{-}v}/\tau_0)^{-1}$ versus reduced temperature T/T_c for different values of the magnetic induction B.

Table 1. Physical parameters of the different samples obtained by the fit of equations (2)–(9) to various experimental data. $\Delta(0, 0)$ is the superconducting energy gap at zero temperature and zero field, $H_{c2}(0)$ the upper critical field at zero temperature, α the temperature-dependent electron–vortex scattering rate defined by equation (9), ϵ_F the Fermi energy and $\xi(0)$ the zero temperature coherence length.

Sample	$\Delta(0, 0)$ (meV)	$H_{c2}(0)$ (T)	$\alpha(T)$ (10^{12} s^{-1})	ϵ_F (eV)	$\xi(0)$ (Å)
$YBa_2Cu_3O_{7-\delta}$ (single crystal)	14.5	81.2	2.3 ($T = 31$ K) 28.6 ($T = 61$ K)	0.35	25.3
$YBa_2Cu_3O_{7-\delta}$ (ceramics)	15.2	80.7	6.9 ($T = 40$ K)	0.32	23.1
$YBa_2Cu_3O_{7-\delta}$ + 5% Fe (ceramics)	13.8	80.5	17.8 ($T = 40$ K) 83.2 ($T = 50$ K)	0.21	20.6

Experimental results of Richardson *et al* [1] on the magnetic induction dependence of the thermal conductivity $\kappa(B)$ of an untwinned single crystal of $YBa_2Cu_3O_{7-\delta}$ are reproduced in figure 3 and those of Bougrine *et al* [5] on polycrystalline samples of $YBa_2Cu_3O_{7-\delta}$ and

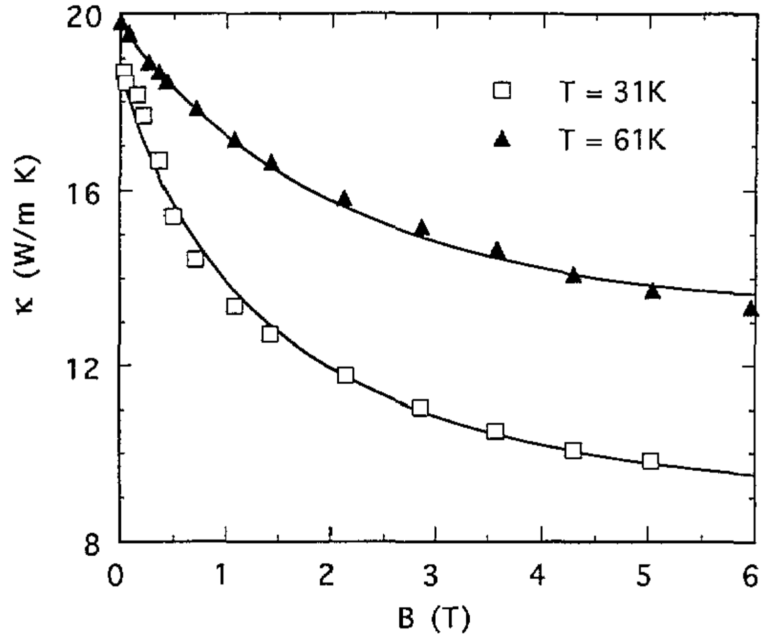


Figure 3. Magnetic induction dependence of the thermal conductivity of an untwinned single crystal of $YBa_2Cu_3O_{7-\delta}$ at two different temperatures from [1].

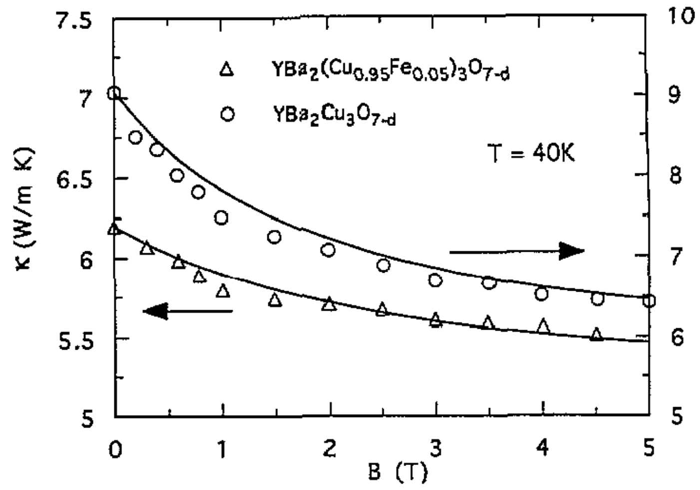
$YBa_2(Cu_{0.95}Fe_{0.05})_3O_{7-\delta}$ are shown in figure 4. Notice the wide difference between the critical temperature of 'pure' $YBa_2Cu_3O_{7-\delta}$ samples which is about 92 K and that of the Fe-doped sample which is about 70 K.

It is observed that κ decreases rapidly for $B < 2$ T and then 'saturates' for higher values of the induction. Moreover, the relative decrease of $\kappa(B)$ is less important when the temperature is increased.

Theoretical curves obtained from equations (2)–(9) are also shown in figure 3 and figure 4. The normal state electron concentration was taken to be $n_0 = 1.7 \times 10^{28}$ e m^{-3} and the effective mass of an electron assumed to be $m^* = 4m_0$ [19]. Agreement between experimental and theoretical results is quite reasonable. The physical parameters obtained from the fits (see table 1) are in good agreement with values found in the literature [19, 20]. Most importantly it is observed that $\kappa(B)$ can lead to characteristic parameters like the Fermi energy ϵ_F and the coherence length $\xi(0)$ as derived from the scattering rate α (equation (9)).

From a physical point of view, the experimental results can be interpreted as follows. As the magnetic induction is increased, the scattering rate of electrons due to the collisions by the core of vortices increases and $\kappa(B)$ is decreased. On the other hand, the density of nomal electrons is increasing with the induction. Quite interestingly, this compensates the increasing scattering rate, which leads $\kappa(B)$ to saturate at higher fields. Besides, the more important decrease of $\kappa(B)$ when the temperature is decreased (see figure 3) can be interpreted by this model. As a matter of fact, the normal electron density vanishes rapidly with temperature due to the condensation into Cooper pairs: $n_e/n_0(60\ \mathrm{K}) \simeq 0.2$ whereas $n_e/n_0(30\ \mathrm{K}) \simeq 6 \times 10^{-3}$. *Consequently, the normal electron concentration compensates the* scattering rate less importantly as the temperature is lowered and this results in a stronger decrease of $\kappa(B)$.

Notice also that it is not necessary to assume that the vortex state is of the Bloch form,



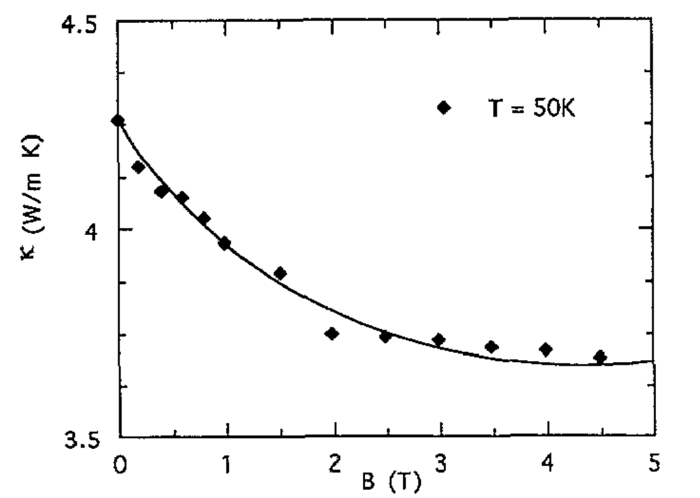


Figure 4. Top, magnetic induction dependence of the thermal conductivity of $YBa_2Cu_3O_{7-\delta}$ ceramics (○) at $T = 40$ K and of $YBa_2(Cu_{0.95}Fe_{0.05})_3O_{7-\delta}$ ceramics (Δ) at the same 40 K temperature from [5]. Bottom, magnetic induction dependence of the thermal conductivity of $YBa_2(Cu_{0.95}Fe_{0.05})_3O_{7-\delta}$ ceramics (♦) at $T = 50$ K from [5].

as Richardson *et al* [1] did in order to interpret their results. The vortex state can be disordered in our model, as it is most likely indeed in such YBCO materials.

We conclude that the magneto-thermal conductivity of high-T_c superconductors can mainly be interpreted by assuming that the main carriers of heat are electrons scattered by the core of vortices in the mixed state of these type II superconductors. An extension of this model to the case of d-wave pairing which is likely to occur in high-T_c cuprates should also be of interest.

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References

[1] Richardson R A, Peacor S D, Nori F and Uher C 1991 *Phys. Rev. Lett.* **67** 3856
[2] Tewordt L and Wölkhausen Th 1989 *Solid State Commun.* **70** 839
[3] Uher C 1990 *J. Supercond.* **3** 337
[4] Peacor S D, Richardson R A, Nori F and Uher C 1991 *Phys. Rev.* B **44** 9508
[5] Bougrine H, Sergeenkov S, Ausloos M and Mehbod M 1993 *Solid State Commun.* **86** 513
[6] Sousa J B 1971 *Physica* **55** 507
[7] Yu R C, Salamon M B, Lu J P and Lee W C 1992 *Phys. Rev. Lett.* **69** 1431
[8] Ausloos M and Houssa M 1993 *Physica* C **218** 15
[9] Allen P B, Du X, Mihaly L and Forro L 1994 *Phys. Rev.* B **49** 9073
[10] Houssa M and Ausloos M *Phys. Rev.* B **51** at press
[11] Ziman J M 1963 *Electrons and Phonons* (Oxford: Clarendon)
[12] Tilley D R and Tilley J 1990 *Superfluidity and Superconductivity* (Bristol: Hilger)
[13] Meservey R and Schwartz B B 1969 *Superconductivity* ed R D Parks (New York: Dekker) p 151
[14] Tinkham M 1988 *Phys. Rev. Lett.* **61** 1658
[15] Saint-James D, Thomas E J and Sarma G 1969 *Type II Superconductivity* (Oxford: Pergamon)
[16] Caroli C, De Gennes P G and Matricon J 1964 *Phys. Lett.* **9** 307
[17] Karraï K, Choi E J, Dunmore F, Liu S, Drew H D, Li Qi, Fenner D B, Zhu Y D and Zhang F-C 1992 *Phys. Rev. Lett.* **69** 152
[18] Arranz M-A, Pogorelov Y, Villar R and Vieira S 1994 *Proc. 8th CIMTEC (Florence, 1994)*
[19] Harshman D R and Mills A P 1992 *Phys. Rev.* B **45** 10684
[20] Friedl B, Thomsen C and Cardona M 1990 *Phys. Rev. Lett.* **65** 915