Electrical and thermal transport properties in high $T_c$ superconductors: effects of a magnetic field

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Abstract

Experimental studies of the electric and heat currents in the normal, superconducting and mixed states of high $T_c$ superconductors (HTcS) lead to characterization, complementary to data obtained from equilibrium property based techniques. A magnetic field superimposed on the superconducting sample generates magneto-transport phenomena, from which an excess electrical resistivity, an excess thermoelectric power, the Hall or the Nernst effect. Different behavioral effects allow one to distinguish various dissipation mechanisms, like quasi particle scattering, vortex motion dissipation and superconductivity fluctuations, in particular when the Corbino geometry is used. Moreover bulk measurements of the thermal conductivity and the electrothermal conductivity in a magnetic field give us sure indications of the order parameter symmetry. The location of the mixed state phase transition lines in the technological phase diagram of HTcS are briefly pointed out through precise measurements performed over broad temperature and magnetic field ranges. The results are mainly reviewed with the aim of defining further investigation lines.

keywords: magneto-transport phenomena, mixed state, high critical temperature superconductors, electrical resistivity, thermoelectric power, Nernst effect, Corbino geometry, thermal conductivity, electrothermal conductivity, order parameter symmetry, phase transition lines

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1 Introduction

The location of the various mixed state phases in the so-called technological phase diagram of high T\textsubscript{c} superconductors (HTcS) as well as the behavior of vortices are of major interest for inventing low temperature devices. Precise measurements (Sect. II) performed over broad temperature and magnetic field ranges can be analysed in order to unveil the vortex lattice phases, scattering processes and phase transition lines. The utility of a Corbino geometry is recalled in Sect. III.

Experimental studies of the electric and heat currents in the normal, superconducting and mixed states of HTcS have been made in SUPRAS [1] order to lead to fundamental characterizing parameters. Those properties are complementary to the data obtained from equilibrium property based techniques. In fact, the magnetic field imposed on the superconducting sample with an orientation parallel to the electric or temperature gradient generates \textit{magneto-transport phenomena}, from which one can deduce an excess electrical resistivity, or an excess thermoelectric power or an excess thermal conductivity (Sect. IV). Moreover if the magnetic field has an orientation perpendicular to the electric or temperature gradient (Sect. V), it generates the Hall and the Nernst effect respectively. Different features in these effects allow one to distinguish various dissipation mechanisms, like quasi particle scattering, vortex motion dissipation and superconductivity fluctuations, phase transition lines in the mixed state, and the order parameter symmetry as discussed in published papers by the SUPRAS group [1].

2 Experimental techniques and data

In the SUPRAS Measurements and Instrumentation Electronics Laboratory (MIEL) home made devices and experimental set-ups are developed in order to get fine data. In particular we have shown that we can simultaneously measure the electrical resistivity together with the thermoelectric power [2,3], the thermoelectric power together with the thermal conductivity [4,5] and the thermoelectric power, the thermal conductivity and the thermal diffusivity together in absence or presence of magnetic fields [6]. Confidence in the validity of the data recalled here below have been taken due to such set-ups and various tests like in [7].
3 Corbino geometry

A method, using a Corbino disk sample geometry, is described in refs. [8] and has been applied to study the resistive tails of sintered YBCO. When the transport current passes radially from the rim of the disk sample to its center, the two component potential drop signal \( W \) is detected below \( T_c \). It is assumed to be due to (i) quasiparticles \( W_q \) and (ii) vortex-core-motion \( W_\phi \) related contributions. When the contact pairs for \( W \) are placed radially, \( W_q(r) \) and \( W_\phi(r) \) are found to follow markedly distinctive functional dependences, providing a unique possibility to deconvolute the relative strengths of both contributions. The results obtained suggest that the mixed state dissipation of high-\( T_c \) superconductors is strongly influenced by the quasiparticle excitations, - a point of view not often shared or misrepresented.

4 Longitudinal effects

4.1 Temperature averaging

Among our on-going investigations about the mixed state we have been intrigued by the various lines used to dissect the \((B, T)\) plane. We have shown that a distribution of vortex lattice melting temperatures is rather usual in fact, and should smear quite a bit the theoretical features. In the mixed state part of the technological phase diagram of Bi-2212 tapes [9] we have been able to fit \( R(T) \) data over a wide range of temperature and fields. A related procedure has been followed for discussing the vortex lattice melting and viscosity in \( Y_{0.6}Dy_{0.4}Ba_2Cu_3O_{7-x} \) superconductor studied by electrical resistivity measurements [10]. It has been pointed out that the vortex lattice melting transition should not be confused with the irreversibility line of magnetic studies nor with the percolation temperature line for electrical resistivity.

4.2 Activation energy

An unusual stretched exponential \( B \, \exp(-B^{1/4}) \) behaviour for the excess thermal resistivity in the temperature range near \( T_c/2 \) was obtained by Bougrine et al. [11]; see also ref. [12]. The former authors have derived the origin of such a theoretical law from a model including bound and free vortices on intragranular and intergranular defects. The exponent \((1/4)\) was shown to be
a particular value specific to the $(B, T)$ regime. In fact characteristic lengths like the mean free path, the penetration depth and the characteristic defect size control the value of the exponent in the stretched exponential. In the original paper, the theory was intended to follow the first line of approach proposed for modifications of the superconducting state by the normal state below $T_c$, i.e. a modification of the phonon mean free path. However the paper can be (better) read again considering that the modification is due to the behaviour of electron, or the quasi-particle, mean free path variation instead.

4.3 Field dependence of excess quantities

We have also examined whether some information on the order parameter symmetry could be obtained from excess quantities, by removing the temperature dependence. It is known that an $s$-wave gap parameter leads to exponential dependence of properties, but $d$-waves imply power laws. This is known for the temperature dependence. We have searched for the same effect due to the magnetic field influence, i.e. mainly in the mixed state, plotting the excess quantity

$$\Delta Q(T, B) = Q(T, B) - Q(T, 0).$$

(1)

where $Q$ is the electrical resistivity $\rho$ or the Seebeck coefficient $S$ for example. The subsequent analysis makes uses of the temperature integral of $\Delta Q(T, B)$, called the area $A_Q$, between $T_1$ and $T_2$, where $T_1$ is taken much below the field dependent percolation temperature and $T_2$ is taken much above the superconductivity onset temperature. This method has the advantage of somewhat eliminating extrinsic contributions. Next it also reduces the necessity of precisely measured data and high calibration. Finally, it eliminates the temperature and emphasizes the field dependence. We have observed a linear law, i.e. $\log(A_Q) = a_Q \log(B) + b_Q$, and extracted $a_Q$. The $a_Q$ values can be related to the field dependence appearing in the density of states and the quasi-particle scattering relaxation time dependence appearing in the kinetic definition of transport properties. They depend on whether the order parameter has a $d$- or $s$-wave symmetry. A summary of exponents is given in ref. [13]. They markedly indicate simple fractional values related to the fact that the symmetry of the order parameter is likely to be of $d$-type.
4.4 Electrothermal conductivity

We have looked at the electrothermal conductivity, obtained from the ratio of the thermopower to the electrical resistivity $\rho$ [14,15]. The electrothermal conductivity is a very convenient property, because it is, in principle, independent of the vortex viscosity and has nothing to do with vortex motion. It only measures the dissipation of normal quasiparticles, through some $P_{pq}$ term, both inside and outside the vortex core. The electrothermal conductivity can be measured in the set-up [2] in which we measure simultaneously $\rho$ and $S$ from 20 K to room temperature. It was of interest to observe the effect in the vicinity of the critical temperature and in the mixed state.

Working out the $s$-wave and $d$-wave theory for $P_{pq}$, we have used the resulting theoretical formulae for fitting the experimental data. The parameters coming out from an $s$-wave picture are noticeably wrong in the order of magnitude. A fit using the $d$-wave theoretical formulae lead to very nice fits and very reasonable values of the parameters. I stress that this is to my knowledge the only data showing the type of order parameter symmetry at this time in the vicinity of the critical temperature in HTcS.

4.5 Magnetothermal conductivity

The influence of a magnetic field on the thermal conductivity is similar in various high-$T_c$ cuprates: the magneto-thermal conductivity $\kappa(B)$ is observed to decrease as the magnetic induction $B$ is increased and this relative decrease is less pronounced when the temperature is raised. The first phenomenological model of the magneto-thermal conductivity of high-$T_c$ superconductors assumed that phonons were moving as Bloch waves in a periodic vortex lattice potential, thus supposing that the vortex lattice is quite regular. It has been noticed that the influence of a magnetic field on the transport properties in a field are quite similar in various high-$T_c$ cuprates and the temperature dependence could be well described by rather considering an electronic origin of the peak observed below $T_c$ [17,18] together with assuming a $d_{x^2-y^2}$-wave gap parameter and Van Hove singularities in the electronic spectrum [19], see previous subsections.

We have compared the field dependence of the electronic contribution $\kappa_e$ to the thermal conductivity of a $d$-wave superconductor both for $s$-wave or $d$-wave order parameter symmetry cases [20-22]. We have undoubtlessly shown that experimental results on various high-$T_c$ materials can be well
described by the $d$-wave model though only with a small difference between the deduced physical parameters from the $s$-wave case in absence of field. However, the theoretical field dependence of $\kappa_e$ at very low temperature has been shown by Houssa et al. to be incompatible with our calculations on the magneto-thermal conductivity of an $s$-wave superconductor. The data on $YBa_2Cu_3O_{7-\delta}$ and $Bi_2Sr_2CaCu_2O_8$ is much better reproduced with a $d$-wave gap parameter [21,22].

From several publications discussing data on $Bi$-, $Hg$-, and $RE$- based superconductors ($RE =$ rare earth) taken for thermomagnetic effects, it has been shown that interesting parameter values can be obtained on vortex and quasi particle scatterings in the mixed state of such superconducting ceramics materials [22].

## 5 Transverse effects

Pekala et al., in several publications [23], have found that the Nernst voltage is an interesting property to be further studied in order to probe the $(B,T)$ phase diagram and observe the position and temperature dependence of phase transition field lines (PTFL), like the upper critical field $B_{c2}$ line”, the ”melting (m) line”, the ”irreversibility (i) line”, the ”glass (g) transition line”, the ”electrical resistivity percolation (p) line” and several ”structural PTFL” separating regions in which the vortices form a triangular (t) or square (s) lattice. Below the $B_{c2}$ PTFL, in the so-called liquid phase, it has been recently predicted that a PTFL exists between the critical fluctuation (f) (Ginzburg-Levanyuk) PTFL and the m-line. The excess thermoelectric power and Nernst effect can serve to obtain characteristic PTFL in the mixed state by looking at the singularities, i.e. break in slopes, in quantities like $\rho(T)$, $S(T)$, or $N(T)$ at fixed $B$ values. The number of PTFL is exactly that predicted from previous reviews [24] plus one from a new theoretical prediction in ref. [25] in the liquid phase itself. The case of $Bi$-based HTcS ceramics has been used for illustration in the oral presentation and will be discussed elsewhere in detail [26].
6 Conclusions

Part of the discussion in these reports has been centered on our SUPRAS way to get some information on the order parameter symmetry from transport properties through the analysis of the temperature (integrated or not) excess quantity field dependence in the mixed state.

I stress that bulk measurements of the thermal conductivity and the electrothermal conductivity in a magnetic field give as sure indications of the order parameter symmetry as more microscopic techniques, both at low temperature and even in the vicinity of the critical temperature. The results can be reviewed mainly from our work on Hg-, Bi- and RE- based superconductors with the aim of defining further investigation lines. However much other groups have contributed to such investigations. We quote them in our publications, but they are omitted here for lack of space.

These findings result from SUPRAS [1] group role and objectives, set-up as early as 1988. Nowadays the theoretical and experimental amount of data allows us to pursue more technical problems.

Acknowledgments

I greatullly thank R. Nicolsky for inviting me to ICMC'2000 in Rio de Janeiro, and G. Fraga, J. Schaff and P. Pureur for making my stay so easy in Porto Alegre, and Brasil, before and during the meeting. The reported work would not have been possible without the intense activity of the leading members of the SUPRAS group, be they rather permanent or long term visitors, whom I thank, i.e. H. Bougrine, P. Clippe, R. Cloots, S. Dorbolo, K. Durczewski, M. Houssa, J. Mucha, S. K. Patapis, M. Pekala, A. Pekalski, A. Ruilmont, S. Sergeenko, Ph. Vanderbemden, H.W. Vanderschueren and N. Vandewalle (in alphabetical order).
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