Influence of a low magnetic field on the thermal diffusivity of $Bi_2Sr_2CaCu_2O_8$

S. Dorbolo[1] and M. Ausloos[2]
[1]*SUPRAS, University of Liège, Montefiore Institute of Electricity B28, B-4000 Liège, Belgium*
[2]*SUPRAS, University of Liège, Institute of Physics B5, B-4000 Liège, Belgium*

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The thermal diffusivity of a Bi-2212 polycrystalline sample has been measured under a 1 T magnetic field applied perpendicularly to the heat flux. The magnetic contribution to the heat carrier mean free path has been extracted and is found to behave as a simple power law. This behavior can be attributed to a percolation process of electrons in the vortex lattice created by the magnetic field.

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I. INTRODUCTION

When a magnetic field is applied, it is well known that the superconductivity properties collapse: e.g., (i) the critical temperature T_c decreases,[1] (ii) the critical current density decreases,[2] (iii) the electrical resistance and (iv) the thermoelectrical power become finite below T_c,[3,4] (v) the thermal conductivity behaves anomalously, etc.[5,6] Indeed a magnetic field is known as a Cooper pair breaker. In fact the behavior of the mean free path of electricity and heat carriers in, e.g., high-T_c superconductor materials is a widely discussed problem particularly in the presence of a magnetic field.

Without a magnetic field, the thermal conductivity of these materials exhibits a hump below the critical temperature. The cause is not wholly clear or really understood: there are different viewpoints, based on the prominence of an increase of the mean free path of the phonons, thus with reduced scattering[7–10] or from an increase of the mean free path of electrons,[11–17] or a complicated combination of both due to the chemistry.[18] Note that the previously quoted references are only a microsample of a huge literature on the subject, but not all reports (more than 300) can be quoted here.

On the other hand, in presence of any *finite* applied magnetic field, this mean free path apparently decreases as indicated by the lowering of the thermal conductivity hump amplitude. The discussion of the findings pertain to the understanding of the mixed-state properties for *d*-wave (or *s*-wave as sometimes thought) superconductors, and the role of phonons and electrons in a magnetic field (see the above references in appropriate cases and also Refs. 19–21). If they are more or less well understood at high field and low temperature, their interpretation is not so trivial in regions where the various phase transition lines merge into each other, thus near T_c and at low field.[22]

Since the thermal diffusivity is related to the thermal conductivity, the same fundamental questions arise here—fewer studies are found. The thermal diffusivity is known to be a good probe for measuring the heat carrier mean free path[23–25] and even find out the relevance of Van Hove saddle points in high-T_c superconductors.[26] Discussing the thermal diffusivity behavior below and above T_c in the absence of a magnetic field has recently allowed us to distinguish the contribution of electrons and phonons in the dissipation process. On the other hand, comparison of the thermal diffusivity behaviors with and without a magnetic field below T_c should allow for extracting the contribution of the magnetic field. This would give interesting informations about electron-vortex interactions. (Calzona *et al.* have measured the diffusivity in a magnetic field. However, they used the phonon dissipation model for explaining heat conduction features and did not extract the magnetic contribution to the mean free path.[23] The behavior of this contribution can give very interesting informations about the vortex-heat carriers interaction below T_c.) Here we show that such a contribution can be extracted, even close to T_c and at rather low field. The experimental data are our own measurements on a polycrystalline Bi-2212 sample. Despite its polycrystalline morphology, the advantage of such a sample resides in the possibility to obtain it as a long bar out of a pellet, whence allowing a fine sensitivity of the measurements even at small field. This compound and sample are expected to be representative of most high-T_c superconductor materials, in particular of their anisotropic [two-dimensional (2D)] nature.

In a simple kinetic model formalism, the thermal diffusivity α is defined as the ratio between the thermal conductivity κ and the volumic specific heat c, and can be thus expressed through

$$\alpha=\frac{1}{3}v l, \tag{1}$$

where v is the velocity of the heat carriers and l the mean free path. Assuming v to be a constant in a restricted range of temperature of interest, as here, the thermal diffusivity is thus an adequate (or direct) probe for measuring the mean free path of heat carriers. When a magnetic field is applied, l may be rewritten as usual within the linear superposition approximation as[27]

$$\frac{1}{l}=\frac{1}{l_0}+\frac{1}{l_{mag}}, \tag{2}$$

where l_0 and l_{mag} are the mean free paths of heat carriers, respectively, without and with the influence of an applied magnetic field. From Eqs. (1) and (2),

$$\frac{\alpha_0}{\alpha}=\frac{l_0}{l}=1+\frac{l_0}{l_{mag}}=1+\frac{\alpha_0}{\alpha_{mag}}, \tag{3}$$

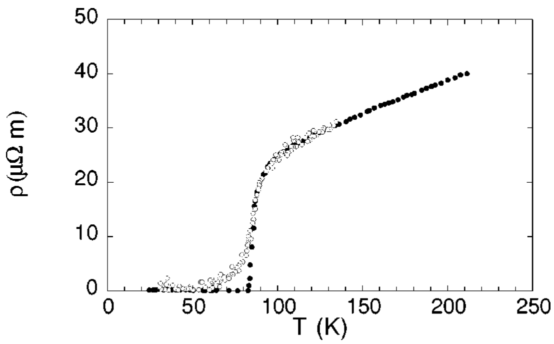

FIG. 1. Resistance of the Bi-2212 sample with (●) and without (○) an applied magnetic field perpendicular to the current vs the temperature.

where α_0 and α are the thermal diffusivities without and with magnetic field, respectively, and α_{mag} is the magnetic contribution to the thermal diffusivity.

These formulas serve as a basis for the discussion of the vortex-heat carrier interaction in the mixed phase near T_c. After a description of the synthesis and of the characterization of the sample in Sec. II, the measurements of the thermal diffusivity of the Bi-2212 sample are presented in Sec. III. The magnetic contribution to the mean free path is extracted and the results are then discussed.

II. SYNTHESIS AND EXPERIMENTS

Powders of Bi_2O_3, $SrCO_3$, $CaCO_3$, CuO, and PbO_2 were mixed mechanically together using an agathe mortar starting from a 2234 stoichiometry in order to obtain a 2212-BSCCO (Bi-2212) stoichiometric composition. This mixture was decarbonated at 800 °C for 20 h and melted in an alumina crucible at 1075 °C for 30 min in air. The liquid was quenched between two room-temperature copper blocks to form a glass. The pellets were heated in oxygen atmosphere on a barium zirconate substrates at 860 °C for 50 h.[28] Despite its polycrystalline morphology, the advantage of such a sample is that it can be long. This allows a better sensitivity for the measurement and the effect of a small field can be as such observed.

The electrical resistivity curve is represented in Fig. 1. The superconducting midpoint transition occurs around 85 K. At high temperature, the resistivity is linear with a 10 mΩ m resistivity at 0 K and about 40 mΩ m at 225 K. When a magnetic field is applied, the resistivity transition midpoint is shifted towards lower temperature, ca. 80 K for a 1.0 T field.

The thermal diffusivity has been measured as described in Ref. 29 and the technique is briefly recalled here. A rod is first cut out from one of the chemically characterized Bi-2212 pellets. One of the extremities of the bar is fixed to a heat sink, while the other is linked to a heater. Three thermocouples are set along the sample at equal distances from each other. A heat pulse is sent through the sample from one end and the change of temperature is recorded by one of the thermocouples. This operation is renewed three times, namely, once per thermocouple. The signals recorded by the two extreme thermocouples give the limit (''boundary'') conditions so as to compute the shape of the signal from the heat diffusion equation, at the middle thermocouple, for different *a priori* values of the thermal diffusivity. The results of such calculations are compared to the measured signal at the middle thermocouple. The best fit allows us to deduce the value of the thermal diffusivity at this temperature.

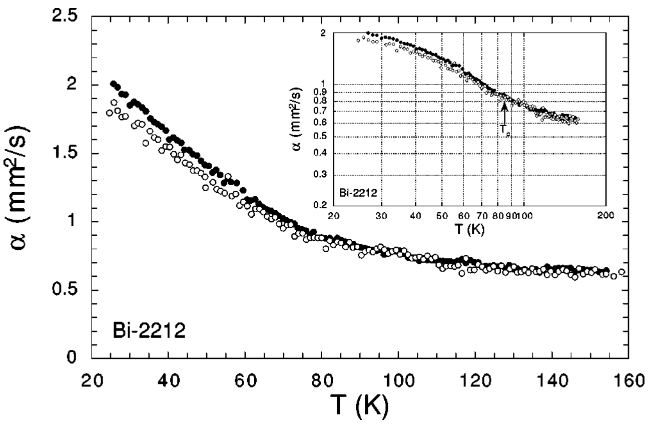

FIG. 2. Thermal diffusivity without and with a 1.0 T applied magnetic field vs the temperature, ● and ○, respectively. The inset represents the same quantities in a log-log plot. The arrow indicates the critical temperature.

III. RESULTS AND DISCUSSION

In Fig. 2, the thermal diffusivity is shown between 20 and 160 K. The solid circles (●) represent the thermal diffusivity α_0 without any magnetic field. As for the open circles (○), they symbolize the results with a 1.0 T magnetic field applied perpendicularly to the heat flux α. The two curves are seen to be superposed on each other at high temperature. Such a magnetic field is indeed too small to create any visible effects on thermal properties in the normal state. On the other hand, the thermal diffusivity behaves differently below the critical temperature with and without a magnetic field: in the presence of a magnetic field the diffusivity is slightly lower. Thus the magnetic field shows its expected pair breaker role. In the framework of the electronic model for heat transport,[11–13] that means that the electron-electron scattering is enhanced or, in other words, that electrons have a decreasing mean free path.

The inset of the Fig. 2 is the thermal diffusivity with and without the 1.0 T magnetic field in a log-log plot. This plot emphasizes that a break in the slopes occurs at 85 K, the critical temperature of the Bi-2212 phase. This should be expected from our previous report.[25] The change in magnitude is due to the sudden increase of the mean free path of electrons below T_c. They are indeed less scattered by their counterparts since some electrons belong to condensed Cooper pairs in this temperature range. Thus the visible deviation between the thermal diffusivity with and without a magnetic field shows that even a small magnetic field (1.0 T here) markedly acts on thermal transport in the superconducting phase.

The magnetic contribution to the mean free path can be

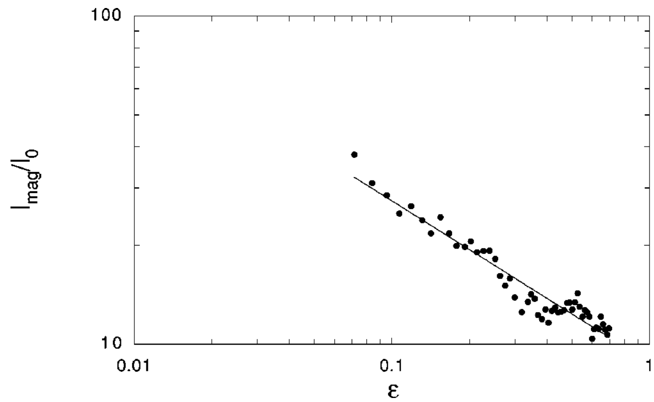

FIG. 3. Normalized magnetic contribution of the mean free path plotted as a function of the reduced temperature.

obtained from Eq. (3). The results are shown in Fig. 3, i.e., l_{mag}/l_0 versus the reduced temperature $\varepsilon = |T - T_c|/T_c$. Notice that some numerical smoothening data is necessary in order to reduce error bar propagation. It is seen that the normalized value l_{mag}/l_0 behaves as a power law with an exponent found to be equal to -0.5.

This power law behavior and the exponent value itself remind us of the Azlamazov-Larkin law[30,31] for the paraconductivity in its mean-field regime. The law is usually studied between the onset temperature T_o and T_c, thus above T_c. However, the Azlamazov-Larkin law holds also below T_c because of the scaling hypothesis universality. The temperature region which is here above studied extends much below the critical temperature and the precision of the data near T_c cannot be expected to lead to critical fluctuations studied *per se*, but the mean-field exponent of superconductivity fluctuations might be probed. It can be shown that the same type of contribution exists in the electrical ($\Delta\sigma$) and thermal ($\Delta\kappa$) paraconductivity.[32–35] With the trivial change of variables on the temperature axis $T_c \rightarrow 0$ and $T_o \rightarrow T_c$, respectively, we can write $\Delta\sigma \simeq \Delta\kappa \simeq \Delta\alpha$, for the *parathermal diffusivity*, the Δ notation indicating in both cases the deviation from the normal-state behavior. Remembering that

$$\Delta\sigma_{3D} = \frac{e^2}{32\hbar\,\xi(0)}\,\varepsilon^{-1/2} \tag{4}$$

for a 3D type of fluctuation,[30,31] and assuming that 1 T is a low field such that the Azlamazov-Larkin law is still obeyed, we can from the amplitude obtain an estimate of the shortening of the zero-temperature coherence length ξ between zero and 1 T field. A simple numerical calculation leads to $\ell_0(0)/\ell_{mag}(0) = 0.938$.

As, e.g., for neutron scattering processes in disordered 2D (magnetic) systems[36] the total inverse correlation length can be assumed to be the sum of a strictly thermal term and a geometrical term linked (in that case) to the disordered network, i.e., a relation similar to Eq. (2) for ξ. This analogy indicates that the found power law behavior can be interpreted as resulting from a percolation process of heat carrier through a complicated vortex state[19,37] and further justifies the analogy with the Azlamazov-Larkin law *for heat carriers in the mixed state* at low fields. One might also wonder why a 3D behavior (and exponent) is found rather that the exponent, i.e., $\simeq -1.0$, corresponding to a 2D behavior, since Bi-2212 is expected to have an effective dimensionality closer to 2 than 3. The argument stems from the anisotropy itself. At the critical temperature itself, the coherence length diverges and one expects a 3D behavior. When departing from T_c the effective dimensionality signature should appear, thus leading here to a 2D behavior. However, this lasts as long as the temperature is in the temperature range limited by the onset of the true critical regime, i.e., the Ginzburg-Levanyuk temperature,[31] and by the Lawrence-Doniach temperature, in anisotropic systems.[32] Away from the Lawrence-Doniach temperature, up to the onset temperature, or at low temperature down to the temperature at which the coherence length saturates, one should recover a 3D regime.[22] In Bi-2212, this (Ginzburg-Levanyuk and Lawrence-Doniach) temperature range is estimated to be 50 K, $\sim J_z = 4.1$ meV,[14] the exchange integral along the *c* axis. The data where the exponent 1/2 is found are far away from the critical regime, and thus are a signature of the geometrical disorder intrinsic to the polycrystalline system.

IV. CONCLUSION

The mixed state of high-T_c superconductors still has to reveal many features and to be understood. Electrical and transport properties contain the signature of the various vortex phases, and to distinguish them is not so trivial. Here the magnetic contribution to the mean free path of heat carriers in a high-T_c superconductor has been extracted in the low-field and near-T_c regions. It has been found to increase below T_c as a power law characterized by a 1/2 exponent. This behavior is linked to a percolation process of the electron scattering in the vortex network characterizing the mixed state. We should emphasize that the above (temperature, field) conditions are not rather the usual ones for probing the mixed state. If the diffusivity were not so hard to measure, its sensitivity to physical phenomena would be a bonus for interesting conclusions. Such a remark may suggest new ways of probing and hence understanding the (B,T) phase diagram.

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