Magnetic-field dependence of electrothermal conductivity in YBCO

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1 Introduction Transport property measurements as a function of applied magnetic fields are an important test in order to determine some physical parameters of superconductors like dimensionality, irreversibility, order-parameter symmetry, etc. The electrothermal conductivity (P) is a transport property that relates electrical and thermal currents and can be considered as a direct search of the mixed state in superconductors. It is known that P(B, T) below Tc is nearly independent of the magnetic field in conventional low Tc superconductors and displays the same value as its normal state value. However, P(B, T) changes markedly as the field is lowered in high Tc materials [1–5]. Because of the difference in the vortex structure for s and d-wave symmetries and because of the different types of quasiparticles-vortex scattering mechanisms and the related relaxation times, it is possible to observe the character of the OPS using magnetotransport measurements.

The growing number of experimental and theoretical works on this subject suggests that the character of the OPS in HTS is mainly d_{xy},\rho-wave type. However, a definite conclusion is still lacking. Controversy remains mainly around different aspects like: the existence of mixing s and d symmetries, the existence of a complex id, component and its relative weight, the symmetry dependence of doping level, the influence of extrinsic or intrinsic effects, etc. [6–13].

In this work we determined experimentally the magnetic-field dependence in the mixed state of the electrothermal conductivity (P), of YBCO (123) superconducting samples. The P(B, T) data were determined from resistivity and thermopower measurements were analyzed in terms of theoretical models and showed a behavior consistent with an order-parameter symmetry (OPS) of d_{xy},\rho-wave type.

Experimental measurements of the electrothermal conductivity (P) near Tc, as a function of external magnetic field were carried out in undoped YBCO (123) superconducting samples. The electrothermal conductivity which relates electrical and thermal currents, depends on the applied magnetic field in high Tc materials, contrary to conventional low Tc superconductors where P is nearly independent of the magnetic field. The experimental P(B, T) data determined from resistivity and thermopower measurements were analyzed in terms of theoretical models and showed a behavior consistent with an order-parameter symmetry (OPS) of d_{xy},\rho-wave type.

The thermoelectric phenomena, which are produced by an electric current J and heat current, are given by

\[ J = \sigma E - \hat{P} \nabla T, \]

\[ U = -(T\hat{P}) E - \kappa \nabla T, \]

where \sigma and \kappa are the electric conductivity and the thermal conductivity, respectively.

Under open-circuit conditions the thermopower tensor \( S, E = \hat{S} \nabla T \), is \( \hat{S} = \hat{P} \hat{\rho} \) and the longitudinal thermopower is

\[ S_{xx} = P_{xx}\rho_{xx} - P_{xy}\rho_{xy}, \]

where \rho is the resistivity tensor. The last term is the Nernst voltage times the tangent of the Hall angle, which is negli-
gible for high \( T \r) materials due to the small size of the Hall angle in comparison to thermopower and Nernst voltages.

In consequence, the electrothermal conductivity \( P \) for the cuprates is given by the scalar ratio between thermopower and electrical resistivity [4],

\[
P = \frac{S}{\rho}.
\]

In order to describe the experimental behavior of \( P(B, T) \) observed in the mixed state of HTS, it can be considered as a sum of two contributions: \( P = P_n + P_{qp} \), where \( P_n \) is the normal state electrothermal conductivity which is nearly independent of magnetic field, and \( P_{qp} \) the magnetic-field-dependent quasiparticle contribution given by the quasiparticle-vortex scattering that is related with the OPS.

Taking into account that the electronic structure of a planar vortex consists of quasi-particles that occupy discrete energy levels, the electron-vortex scattering rate \( \tau^{-1} \) can be calculated in the Born approximation considering linear combinations of wave functions that describe these bound states. In this case two different symmetries have been considered for the gap parameter: an anisotropic \( s \)-wave type and a \( d_{\pm \pm} \)-wave type and the following expressions for the electrothermal conductivity were obtained [13–17]:

a) Anisotropic \( s \)-wave

\[
P_{qp}^s = P_0^s \frac{1 + (B/B_c) \tau}{1 - (B/B_c)^2},
\]

where

\[
P_0^s = \frac{16(1 + 2n^2) k_B^2 T \hbar^4 \epsilon^2}{3 (2 m^* )^{3/2} (\epsilon^2/\hbar^2)^2} \left[ \sum_{\pm} \frac{\Delta^2 - \epsilon^2}{1 + e^{(\epsilon \mp \Delta)/k_B T}} \right]^{-1} n_{qp}(T),
\]

b) \( d_{\pm \pm} \)-wave type

\[
P_{qp}^s = P_0^s \frac{1 + (B/B_c) \tau}{1 - (B/B_c)^2},
\]

where

\[
P_0^s = \frac{16}{3} \frac{k_B^2 T \hbar^4 \epsilon^2}{d (2 m^* )^{3/2} (\epsilon^2/\hbar^2)^2} \left[ \sum_{\pm} g(n, l) \frac{\Delta^2 - \epsilon^2}{1 + e^{(\epsilon \mp \Delta)/k_B T}} \right]^{-1} n_{qp}(T),
\]

\[g(n, l) = \left[ \frac{(1/n)}{\Gamma(l + 1/2) \Gamma(l + 1)} \right] \frac{F(l + 1/2, -l + 1/2; l + 1; 1)}{F(l + 1/2, -l + 1/2; l + 1; 1)} \]

and \( F \) the hypergeometric function for a superconductor with a \( d_{\pm \pm} \) gap.

Here, \( n_{qp}(T) \) is the quasiparticle density, and \( \Delta \) is the order parameter or superconductor gap. The distance between superconducting planes is given by \( d \), and \( \epsilon \) the superconductor electric permeability. \( B_{c2} \) is the upper critical field.

2 Experimental Polycrystalline samples of YBCO with nominal composition \( \text{YBa}_2\text{Cu}_3\text{O}_{6.8} \) were prepared by the solid-state reaction method. The crystalline structure corresponding to the well-oxygenated superconducting YBCO-123 phase was determined by X-ray diffraction techniques and it correlated well with other YBCO superconducting characteristics like \( T_c \sim 90 \text{ K} \) and transition widths of around \( 3 \text{ K} \) determined at zero magnetic fields by resistive methods.

The electric and thermoelectric measurements were carried out in the temperature range between 77 K and 120 K in the presence of an applied magnetic field perpendicular to the sample’s surface that varied between \( 0.2–1.2 \text{ T} \). The electrical resistivity measurements \( \rho(T) \) were performed using the standard four probe d.c. method and the thermopower \( S(T) \) data were collected by the differential technique with a temperature gradient \( \Delta T \sim 0.1 \text{ K} \) across the sample. The absolute accuracy of the thermopower was estimated as \( \sim 3\% \). On the other hand the behavior of \( \rho(T) \) and \( S(T) \) as a function of magnetic field below \( T_c \) showed the usual broadening of both coefficients [16–19].

3 Results and discussions Figure 1 displays the behavior of the excess electrothermal conductivity \( \Delta P \) as a function of magnetic field for different temperatures in YBCO 123 samples. The excess electrothermal conductivity in the mixed state was determined as \( \Delta P = P - P_n \), where \( P \) is the electrothermal conductivity in the mixed state and \( P_n \) the electrothermal conductivity in the normal state. As observed, \( \Delta P \) increases by decreasing the applied magnetic field. However, this increase becomes noticeable at both low magnetic fields and low temperatures. The \( P_n \) measurements carried out in these samples also verified, within the experimental error, that this value is nearly in-

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**Figure 1** Excess electrothermal conductivity (\( \Delta P \)) of YBCO (123) samples as a function of magnetic field at different temperatures. The lines are only guides to the eye.
dependent of applied magnetic field at both high field and temperature as observed in Figs. 1–3.

The electrothermally conductivity, as the experimental ratio between thermopower electric field and resistive electric field, is also independent of the magnetic field, which has been attributed to a local backflow current density produced by each vortex. The measured field-independent value in the mixed state ($P_e$) should be identical to the normal state value ($P_n$), because the current is determined by the normal core excitations as established experimentally by Clayhold et al. [4] in HTS at high fields and temperature and by Fiory and Serin [5] in superconducting and normal niobium.

Assuming the correlation between excess electrothermal conductivity ($\Delta P$) and the quasiparticle contribution due mainly to quasiparticle-vortex scattering ($P_{qp}$), as established by Houssa et al. [18, 21], Figs. 2 and 3 display the quasiparticles contribution ($P_{qp}$) at different temperatures as a function of applied magnetic field. The solid lines are the best fits of the experimental data to Eqs. (5) and (6), respectively, with $B_{cz}$ and the amplitude $P_o$ as free parameters.

As observed, the best correlation between experimental data and the predictions of the theoretical model (Fig. 3) corresponds to a d-wave-type symmetry. The obtained upper critical field values $B_{cz}(0)$ for the studied samples varied around 100 T. The quasiparticles density determined from $P_{qp}^e(T)$ was placed between 1.6 and $1.8 \times 10^{21}$ cm$^{-3}$, which is in agreement with those reported in the Refs. [7, 20–24].

On the contrary, using as s-wave type symmetry (Fig. 2) the obtained values of $B_{cz}(0)$ and $n_p(T)$ as free parameters are smaller and remain in the order of 50 T and $1.0 \times 10^{21}$ cm$^{-3}$, respectively.

4 Conclusions

The experimental data of electrothermal conductivity $P$ in YBCO 123 polycrystalline samples showed a marked magnetic-field dependence at low fields and low temperatures.

The behavior of experimental data corresponding to excess electrothermal conductivity ($\Delta P$) showed a better agreement with superconductor gap with a d$_{x^2-y^2}$-wave-type symmetry. In this case, a correlation between ($\Delta P$) determined by $\rho(T)$ and $S(T)$ measurements and the quasiparticle contribution $P_{qp}$ to electrothermal conductivity was assumed.

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References