Vortex transport entropy in the $H - T$ diagram of high $T_c$ superconductors

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Abstract.

The combination of Nernst effect and electrical resistivity measurements allows to extract the transport entropy carried by moving vortices. In high $T_c$ superconductors, the vortex-like fluctuations close and above $T_c$ can be detected with these tools if local phase coherence is still present. In this work we study the vortex transport entropy in the two milestone high $T_c$, YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) and Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (BSCCO). While below $T_c$ the YBCO entropy displays a mean field like behavior, close and above $T_c$ the entropy reveals typical features of strong superconducting fluctuations. The lower dimensionality in BSCCO enhances the strength of superconducting fluctuations in a wider region of the $H - T$ diagram and a mean field treatment can not be applied. In this region the vortex transport entropy remains unaffected by the presence of correlated defects.

1. Introduction

The displacement of vortices in the mixed state of type II superconductors under the influence of a thermal gradient, $\nabla T$, perpendicular to the internal magnetic field, $B$, produces a Josephson electrical voltage perpendicular to both, $B$ and $\nabla T$. This is the Nernst signal, which is essentially zero in the normal state [1], [2] and consequently it is an outstanding tool to detect thermal induced vortex displacements, in particular at fields or temperatures approaching the normal state.

In the linear response regime [3], if $\nabla T \parallel \hat{x}$ and $B \parallel \hat{z}$, the Nernst electric field is proportional to $(\nabla T)_x$. Within this regime, the thermal force per unit vortex length is [4]

$$F_T(H) = S_\phi(H,T)(\nabla T)_x$$

(1)

where $S_\phi(H,T)$ is the transport entropy per unit vortex length. In this limit and if vortex-pinning is absent, the impedance to vortex displacement is the flux flow vortex viscosity, associated with the flux flow electrical resistivity, $\rho_f$. Thus, the Nernst signal is found [2]

$$e_N(H,T) = \frac{E_y}{(\nabla T)_x} = \frac{\rho_f S_\phi(H,T)}{\phi_0}$$

(2)

where $E_y$ is the Nernst electrical field and $\phi_0$ the flux quantum. We see that from the measurement of the Nernst signal and flux flow resistivity the vortex transport entropy can be
determined. Theoretical calculations [5] have shown that within the limits of the Ginzburg-Landau theory the transport energy, \( U_\phi(T, H) = TS_\phi(H, T) \) is related to the thermodynamic equilibrium magnetization \( M(T, H) \) by \( U_\phi(T, H) = -\phi_0 M(T, H)L_D(T) \) and consequently [3]:

\[
U_\phi(T, H) = \frac{\phi_0}{4\pi} \frac{(H_{c2}(T) - H)}{(2\kappa_2^2 - 1) + 1} L_D(T)
\]  

where \( \beta_A = 1.16 \) in an hexagonal vortex lattice, \( \kappa_2 \) is the Ginzburg-Landau parameter and \( L_D \) is a numerical function, both weakly \( T \) dependent close to \( T_c \) [5],[3]. Expression (3) is valid for applied magnetic fields, \( H \), and temperatures close to \( H_{c2}(T) \) or \( T_{c2}(H) \), respectively. It shows that the vortex transport energy tends linearly to zero with either \( (H_{c2}(T) - H) \) or \( (T_{c2}(H) - T) \) depending on which variable, \( H \) or \( T \), is controlled in the experiments.

From (3) and since \( S_\phi(H, T) = 0 \) at either \( T = 0 \) or for \( H < H_{c1}(T) \) we see that a maximum in the Nernst signal as a function of \( H \) and \( T \) should appear. It is known that vortex displacement is reduced by the presence of structural defects acting as pinning centers [3], and consequently the maximum of \( e_N \) is usually determined by the field or temperature where pinning reduces vortex mobility to zero. In low \( T_c \) materials this fact restricts the \( H - T \) window in which the Nernst signal can be used to extract \( S_\phi(T, H) \). Despite of this, pioneering work [6] allowed to show a well defined maximum of \( e_N \) in the \( H - T \) phase diagram, in qualitative agreement with theoretical expectations.

The discovery of an anomalous Nernst signal above \( T_c \) in high-\( T_c \) superconductors by Ong and collaborators [7] has triggered intensive research along this decade. While these authors have suggested an scenario dominated by strong phase fluctuations of the superconducting order parameter or vortex-like fluctuations, in agreement with [8] and [9], another explanations based in amplitude fluctuations within the G-L theory context [10],[11] have also been proposed. In high \( T_c \) superconductors, the wide extension of the vortex liquid in the \( H - T \) diagram [12] gives us an unique opportunity to study the vortex transport entropy in these materials. This work presents Nernst effect and electrical transport measurements in the two milestone high-\( T_c \) superconductors, YBCO and BSCCO with and without columnar defects, CD. In BSCCO-OPT, its extremely high anisotropy (\( \gamma \sim 150 \)) should enhance fluctuations effects [13] in contrast to YBCO-OPT, in which \( \gamma \sim 7 \).

2. Experimental Details

The YBCO and BSCCO single crystals were grown using a self flux technique and annealed for optimal doping as described in [14] and [15]. The columnar defects, nearly parallel to the \( c \) crystal axis, with a density of \( B_\phi = 3 \) T were created by irradiation at TANDAR irradiation facility, Argentina [16],[17]. The Nernst and electrical transport measurements techniques were described elsewhere [14],[17],[18] with \( H || c \).

3. Results and discussion

Fig.1 shows the field and temperature dependence of the Nernst signal in the YBCO-OPT crystal without CD. It is clearly seen that sweeping \( T \) at fixed \( H \) or sweeping \( H \) at fixed \( T \) a maximum in \( e_N \) is reached (\( T_{max} \) and \( H_{max} \) respectively). Below \( T_{c1} \), both maxima seem to coincide in the case of YBCO-OPT, as seen in Fig.1 and in the \( H - T \) diagram of Fig.2 (b).

When \( U_\phi \) is extracted in the YBCO crystals with and without CD using the Nernst and electrical transport measurements across equation (2), a corresponding maximum below \( T_c \) does not appear in \( U_\phi \), as shown in Fig.2 (a). This evidence indicates that the \( e_N \) maximum in YBCO-OPT below \( T_c \) is controlled by vortex-pinning and mobility and it has not influence in the thermodynamic limit. More important, the \( U_\phi \) for samples with and without CD coincide in a wide range of temperatures close and above \( T_c \) for all fields investigated, from 3 to 10 T within our experimental resolution [19], an example is shown in Fig.2 (a) at \( H = 8 \) T. This
Figure 1. The Nernst signal as a function of $T/T_c$ and $H$ in YBCO-OPT.

Figure 2. (a) $U_\phi$ vs. $T/T_c$ in YBCO at $H = 8$ T for the irradiated (red triangles) and the non-irradiated sample (black squares, interpolation with small symbols). The mean field like linear behavior is also shown (blue line). Inset: $S_\phi$ vs. $H$ in non-irradiated YBCO at $T/T_c = 1.01$ and 0.98. (b) $H-T$ diagram. The line $T_{max}$ (up triangles) and $H_{max}$ (squares) for the non-irradiated YBCO sample and $T_{c2}$ (circles and linear fit) are shown.

result strongly suggests that the vortex liquid and the superconducting fluctuations behave like an ideal system in this regime, unaffected by the presence of structural defects.

From equation (3) is possible to extrapolate the $U_\phi$ mean field like linear behavior to $U_\phi = 0$ to obtain $T_{c2}$, as shown in Fig.2 (a). The results are shown in the $H-T$ diagram of Fig.2 (b) and at first glance, they agree with a mean field behavior of YBCO-OPT. Close and above $T_c$, there is a $U_\phi$ depart from the mean field like behavior, as seen in Fig.2 (a). When the field
is swept at fixed $T$ in this region, a maximum in $e_N$ is reached, $H_{max}$, see Fig.1, and it also appears when $S_\phi$ is extracted, as shown in the inset of Fig.2 (a). In linear order in $H$, these results are in concordance with the predicted 3D-anisotropic behavior of $S_\phi$ by Ussishkin et al. [10]. In this theoretical context, amplitude fluctuations of the order parameter are the most relevant contribution to $S_\phi$.

Fig.3 shows the field and temperature dependence of the Nernst signal in the BSCCO-OPT crystal without CD. In accordance with the Ginzburg criteria [13], the higher anisotropy of BSCCO-OPT compared with that of YBCO-OPT amplifies fluctuations effects, extending the Nernst signal to a wider region of the $H−T$ diagram, see Fig.3. Since mobility has a smooth variation close and above $T_c$ [19], $S_\phi$ and $e_N$ present the same shape in the $H−T$ diagram, see equation (2). Hence, from Fig.3 it follows that the low dimensionality of BSCCO-OPT prevents that a mean field treatment can be applied to this compound.

**Figure 3.** The Nernst signal as a function of $T/T_c$ and $H$ in BSCCO-OPT.

**Figure 4.** $H−T$ diagram of BSCCO. The lines $T_{max}$ and $H_{max}$ for the irradiated (filled and open up triangles respectively) and non-irradiated samples (filled and open down triangles respectively) are shown. $T_{max}$ (squares) and $H_{max}$ (circles) at high magnetic fields correspond to [20].

In BSCCO-OPT, $T_{max}$ does not coincide with $H_{max}$ in the whole range of fields investigated, see Fig.3. If the high magnetic field data of Ong and collaborators are taken into account
[20], both maxima in BSCCO seem to merge in one single maximum, as shown in the $H - T$ diagram of Fig.4. The exactly same behavior occurs in the BSCCO sample with CD, see Fig.4. Consequently, these BSCCO features are mobility and pinning independent, and they also appear in the thermodynamic properties $S_\phi$ and $U_\phi$.

In this laminar material, the $S_\phi$ behavior can be governed by phase [9] or amplitude fluctuations [10] of the order parameter. In both cases [9],[10],[21], the 2D vortex transport energy follows the magnetization, $U_\phi \propto M$. Hence, the magnetization in BSCCO-OPT should also display these maxima features, as previous measurements anticipate [22].

In BSCCO-OPT, the loss of metallicity along the $c$ axis direction, which is reflected in the $c$ axis resistivity [19],[23] it is the responsible of the fluctuations enhancement and the depart from the mean field like behavior. In YBCO-OPT, the $c$ axis resistivity is metallic [24], fluctuations effects are less pronounced and a mean field treatment is still applicable. In this sense it would be of great interest a study of the vortex transport entropy and the $c$ axis resistivity when the anisotropy is changed gradually, like in oxygen deficient YBCO samples. Previous measurements in these crystals [25],[26],[27] confirm their similarity with BSCCO-OPT.

4. Conclusion
In conclusion, the study of the vortex transport entropy in the two paramount high-$T_c$ has revealed new features of the vortex liquid and of the vortex-like fluctuations. While in YBCO-OPT a mean field like linear behavior of $U_\phi$ is still present, the higher anisotropy of BSCCO-OPT enhances fluctuations effects and it prevents the application of a mean field like treatment. Below $T_c$, there are no maxima in the $S_\phi$ of YBCO-OPT, but there is a splitting of maxima in the corresponding $S_\phi$ of BSCCO-OPT. Close and above $T_c$ a maximum sweeping $H$ at fixed $T$, $H_{max}$, appears in the $S_\phi$ of both compounds. This a typical fingerprint of superconducting fluctuations [9],[10]. In this region the vortex liquid remains unaffected by the presence of structural defects.

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