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Nernst effect studies of Cooper pair fluctuations

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ABSTRACT

In this proceeding, we summarize the experimental work leading to the discovery of the Nernst signal generated by Cooper pair fluctuations. We will show that this Nernst signal has remarkable characteristics that enable an unambiguous identification of these fluctuations. In particular, the Nernst coefficient evolves symmetrically with respect to temperature and magnetic field, reflecting the symmetric role of the correlation and magnetic lengths. In the field dependence of the Nernst signal, this leads to a characteristic maximum at the Ghost Critical Field, $B^* = \frac{\Phi_0}{2\pi\xi^2}$. These results provide a solid reference against which studies of superconducting fluctuations in unconventional superconductors or in the quantum regime should be confronted.

1. Introduction

For any 2nd order phase transition, fluctuations of the order parameter are expected above the critical temperature T_c. With this respect, tri-dimensional conventional superconductors are particularly simple. Due to the large size ξ_0 of Cooper pairs, the Ginzburg–Levanyuk criterion $G_i \sim \left(\frac{T_c}{E_F}\right)^4$ is very small, which implies that from slightly above T_c to arbitrary high temperature, the superconducting fluctuations can be described by Gaussian fluctuations [1]. Involving fluctuations of both the amplitude and phase of the superconducting order parameter, these fluctuations are also called Cooper Pair Fluctuations (CPFs).

Early experimental observations of CPFs were obtained through measurements of paraconductivity [2] and magnetic susceptibility [3]. The sensitivity of these probes is limited to a narrow region above T_c [4] as a consequence of the large contribution from normal electrons that overcomes the small contribution of CPFs to these coefficients.

In contrast, we found that the Nernst signal provides a remarkable probe of CPFs up to very high temperature ($30 \times T_c$). These data have been already discussed in previous publications [5–7] and reviews [1,8,9]. More than ten years after the first observation [5] on $Nb_{0.15}Si_{0.85}$, these experimental data and their interpretation have not been challenged, instead, these results have been comforted by the identification of the Nernst signal generated by CPFs in hole-doped [10] and electron-doped cuprates [11]. In this proceeding, we review the main characteristics of the Nernst signal generated by CPFs, focusing on the data acquired on $Nb_{0.15}Si_{0.85}$ [5,6].

2. Results

The Nernst effect is the transverse thermoelectric response, $N = E_y/\nabla_x T$, of a sample submitted to a thermal gradient and a magnetic field applied perpendicular to sample plane. The Nernst coefficient is defined as $\nu = N/B$ and within linear response theory, the Peltier conductivity tensor is defined as:

$$\begin{pmatrix} \mathbf{j}_e \\ \mathbf{j}_{th} \end{pmatrix} = \begin{pmatrix} \hat{\sigma} & \hat{\alpha} \\ \hat{\tilde{\alpha}} & \hat{\kappa} \end{pmatrix} \begin{pmatrix} \mathbf{E} \\ \nabla \mathbf{T} \end{pmatrix} \tag{1}$$

From the condition, $\mathbf{j}_e = 0$, one gets:

$$N = \frac{\sigma_{xx}\alpha_{xy} - \sigma_{xy}\alpha_{xx}}{\sigma_{xx}^2 + \sigma_{xy}^2} \tag{2}$$

In the materials discussed here, the transverse Hall coefficient σ_{xy} is very small, this simplifies the relationship between the Nernst coefficient and the Peltier coefficient α_{xy}:

$$\nu \approx \frac{\alpha_{xy}}{B\sigma_{xx}} \tag{3}$$

The description of the Nernst measurement setup and details on the two $Nb_{0.15}Si_{0.85}$ samples can be found in [8].

Fig. 1 shows the magnetic field dependence of the Nernst signal for $Nb_{0.15}Si_{0.85}$ [5,6,8]. The field dependence of the Nernst signal displays a maximum. For $T > T_c$, the field position B^* of this maximum increases with increasing temperature. For $T < T_c$, this field position B^* decreases with increasing temperature. Plotting the field B^*, above and below T_c, on the phase diagram, Fig. 1c, shows that B^* goes to zero right at T_c.

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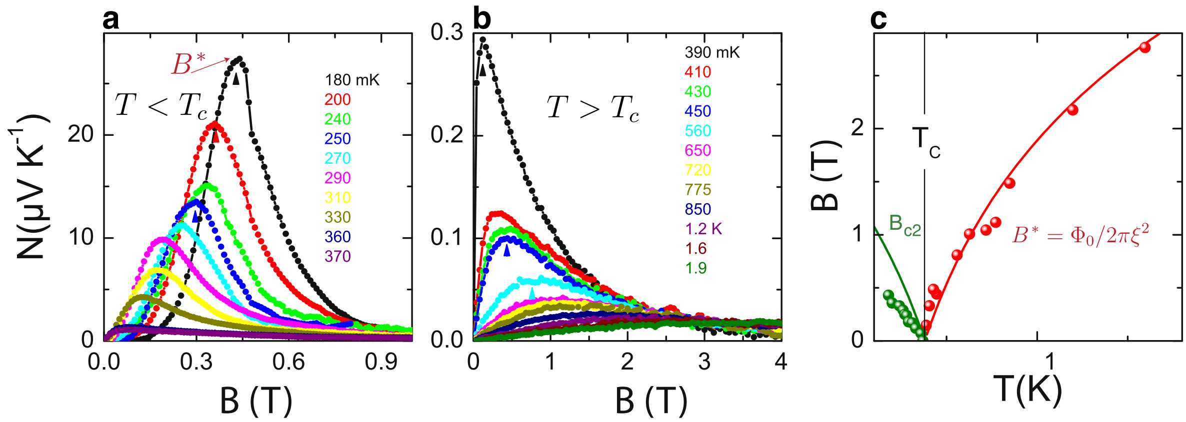

Fig. 1. Nernst signal in $Nb_{0.15}Si_{0.85}$ measured below (a) and and above (b) T_c. Maxima at B^* are indicated by arrows. Below T_c, B^* increases with decreasing temperature. Above T_c, the temperature dependence of B^* is reverted, it increases with increasing temperature. (c) The field scale B^* as a function of temperature for $Nb_{0.15}Si_{0.85}$. B^* vanishes at T_c. Below T_c, this is the field at which the vortex Nernst signal peaks. Above T_c, it represents the GCF. It follows $B^* = \frac{\Phi_0}{2\pi\xi^2}$.

This observation clearly indicates that the nature of superconducting fluctuations at the origin of the Nernst signal observed above T_c is fundamentally distinct from below T_c. Below T_c, the Nernst signal is generated by long-lived vortices of the vortex liquid. Above T_c, it is generated by CPFs.

The typical size of these superconducting fluctuations is set by the correlation length, ξ. Upon cooling, this correlation length increases and diverges at the approach of the superconducting transition following $\xi = \xi_0\varepsilon^{-1/2}$.

Treating the fluctuations of the SOP in the Gaussian approximation, Ussishkin et al. [12] obtained a simple analytical formula, valid close to T_c and restricted to the zero-magnetic field limit:

$$\frac{\alpha_{xy}^{SC}}{B} = \frac{1}{6\pi}\frac{k_B e^2}{\hbar^2}\xi^2 \tag{4}$$

According to this equation, the coefficient $\nu \approx \alpha_{xy}^{SC}/B$ is independent of magnetic field. Fig. 2 shows that, at low magnetic field, the Nernst coefficient is indeed constant. From these data, the value of in the zero magnetic field limit ($B \to 0$) is extracted and compared to Eq. (4), shown Fig. 2b, where quantitative agreement is observed. More elaborated theoretical calculations of the Nernst signal generated by CPFs [8,13–15] have been found to agree quantitatively with the Nernst data presented here on the full range of temperature and magnetic field.

From this analysis in the zero magnetic field limit, one understands that the amplitude of the Nernst coefficient is set by a single characteristic length, the size of superconducting fluctuations [6,7]. In the zero-field limit, this size is set by the correlation length, ξ. In the high field limit, the size of superconducting fluctuations is reduced, its value is set by the magnetic length, $\ell_B = (\Phi_0/2\pi B)^{1/2}$, when this length is shorter than the correlation length at zero magnetic field.

Above T_c, this crossover is responsible for the observed maximum at B^* in the field dependence of the Nernst signal, shown Fig. 1. At low magnetic field, the Nernst coefficient ν is constant and so the Nernst signal $N = \nu B$ increases linearly with field. As the field reaches B^*, the Nernst coefficient decreases because the magnetic length becomes smaller than the zero-field correlation length, $\ell_B < \xi$. This leads to a

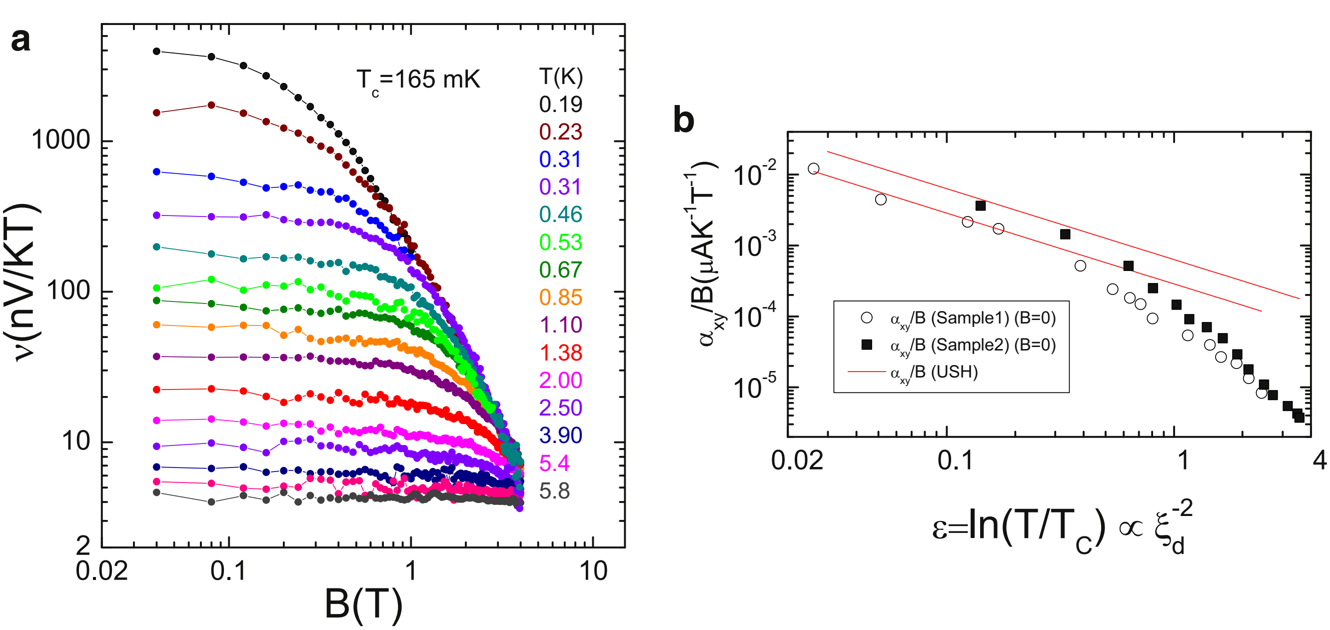

Fig. 2. (a) Nernst coefficient, ν, as function of magnetic field in $Nb_{0.15}Si_{0.85}$ measured at temperatures exceeding T_c. At low magnetic field ($B < B^*$), the Nernst coefficient is independent of magnetic field with a magnitude set by the temperature-dependent correlation length. At high magnetic field ($B > B^*$), the Nernst coefficient becomes independent of temperature with a magnitude determined by the magnetic length. (b) $\frac{\alpha_{xy}}{B} = \sigma_{xx}\nu$ in the zero-field limit extracted from the measured Nernst coefficient and conductivity in $Nb_{0.15}Si_{0.85}$.