Manipulating vortex motion by thermal and Lorentz force in high temperature superconductors

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By using thermal and Lorentz force, the vortex motion is successfully manipulated in the mixed state of underdoped La$_{2-x}$Sr$_x$CuO$_4$ single crystals and optimally doped YBa$_2$Cu$_3$O$_{7-\delta}$ thin films. A conclusion is drawn that the strong Nernst signal above $T_c$ is induced by vortex motion. In the normal state, in order to reduce the dissipative contribution from the quasiparticle scattering and enhance the signal due to the possible vortex motion, a new measurement configuration is proposed. It is found that the in-plane Nernst signal ($H \parallel c$) can be measurable up to a high temperature in the pseudogap region, while the Abrikosov flux flow dissipation can only be measured up to $T_c$.

This may point to different vortices below and above $T_c$ if we attribute the strong Nernst signal in the pseudogap region to the vortex motion. Below $T_c$ the dissipation is induced by the motion of the Abrikosov vortices. Above $T_c$, the dissipation may be caused by the motion of the spontaneously generated unbound vortex-antivortex pairs.

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I. INTRODUCTION

One of the core issues in high temperature superconductor is the origin of the pseudogap above $T_c$ in the underdoped region. In order to understand the physics of the pseudogap, many theoretical models have been proposed such as spin fluctuation, preformed cooper pair, charge stripes, d-density wave (DDW), etc. Among many of them, the pseudogap state has been considered as the precursor to the superconducting state. In the pseudogap region above $T_c$, a significant in-plane Nernst signals has been discovered by Xu et al. in the underdoped La$_{2-x}$Sr$_x$CuO$_4$ single crystal, and they attributed this signal to vortex-like excitations above $T_c$.

This result has been confirmed in other families of cuprate superconductors. By doing experiments with the magnetic field applied along different directions, Wen et al. gave a strong indication for a 2D feature of the Nernst effect in the pseudogap region of underdoped cuprate superconductors. About the origin of the strong Nernst signal above $T_c$, it remains highly controversial. Wang et al. suggested that the large Nernst signal supports the scenario where the superconducting order parameter disappears at a much higher temperature instead of $T_c$. Kontani suggested that the pseudogap phenomena including the strong Nernst signal can be well described in terms of the Fermi liquid with antiferromagnetic and superconducting fluctuations. Usishkin et al. proposed that the Gaussian superconducting fluctuations can sufficiently explain the Nernst signal in the optimally doped and overdoped region, but in the underdoped region the actual $T_c$ is suppressed from meanfield temperature by non-Gaussian fluctuation. Tan et al. believed that a preformed-pair alternative to the vortex scenario can lead to a strong Nernst signal. Alexandrov and Zavaritaky proposed a model based on normal state carrier without superconducting fluctuation, which, as they asserted, ‘can describe the anomalous Nernst signal in high-$T_c$ cuprate’.

It is thus strongly desired to investigate the feature of Nernst signal below and above $T_c$. One possibility is that the strong Nernst signal above $T_c$ is originated from or partly from the motion of vortex, but the structure and the feature of the vortices above $T_c$ is different from that below $T_c$. We thus measured the in-plane Nernst voltage and the resistance of the underdoped La$_{2-x}$Sr$_x$CuO$_4$ single crystals and optimally doped YBa$_2$Cu$_3$O$_{7-\delta}$ thin films in the magnetic field perpendicular to the ab-plane. Besides the temperature gradient, we applied a transverse current to manipulate the possible motion of the vortices. Especially we measured the longitudinal voltage in a new configuration which may reduce the dissipative contribution from the quasiparticle scattering and enhance the signal due to the possible vortex motion. In this new configuration, a strong signal measured from the Nernst leads above $T_c$ is observed in underdoped samples. The signal maybe caused by the motion of quasiparticles and vortex. Our results indicate that the Nernst signal above $T_c$ is contributed by vortex. The results were analyzed and we think that if strong Nernst signal in the pseudogap region is contributed by the vortex motion, vortices are different below and above $T_c$. Below $T_c$ the dissipation is induced by the motion of the Abrikosov vortices. Above $T_c$ the dissipation may be caused by the motion of the spontaneously generated unbound vortex-antivortex pairs (vortex plasma).
FIG. 1: Temperature dependence of resistance for La$_{1.89}$Sr$_{0.11}$CuO$_4$ single crystal (upper) and YBa$_2$Cu$_3$O$_{7-\delta}$ thin film (lower).

II. EXPERIMENTAL TECHNIQUES

The La$_{1.89}$Sr$_{0.11}$CuO$_4$ single crystals measured in this work were prepared by the traveling solvent floating-zone technique[16]. The perfect crystallinity of the single crystals was characterized by X-ray diffraction patterns[16]. The single crystal sample is shaped into a bar with the dimensions of 10 mm (length) × 1 mm (width) × 0.5 mm (thickness). The crystal along the length direction is [110]. The optimally doped YBa$_2$Cu$_3$O$_{7-\delta}$ thin films were prepared by co-evaporation on MgO substrates with dimensions of 10 mm (length) × 1 mm (width), and the thickness of the film is about 5000 angstrom. We annealed the YBa$_2$Cu$_3$O$_{7-\delta}$ film to underdoping state and measured the Nernst voltage in the mixed and normal state. The resistance characteristics of the samples measured is shown in FIG. 1.

The measurement configuration in our experiment is illustrated in FIG. 2. The magnetic field is applied along the c-axis of the samples. The $R(H)$ curves of the samples were obtained by standard four-point method at different temperatures. A heater with a power of 1 mW (for the single crystal) or 9 mW (for the thin film) producing the thermal gradient is adhered fast on one end of the samples is adhered fast on a cold sink. Along the direction E-F (perpendicular to the thermal gradient) the Nernst voltage signal $V_N$ is measured. Two thermometers are attached onto the sample to detect the temperature gradient of the samples. In order to control the vortex motion by Lorentz force, we applied a direct transverse current of 3 mA along A-B and measured the longitudinal voltage between the points C and D. Since the DC current here can exert a Lorentz force to the vortices down or against the thermal stream direction, the motion of the vortex can be manipulated by thermal and/or Lorentz force. All leads are stuck onto the samples by solidified silver paste at corresponding electrodes with the contact resistance below 0.1 Ω. All measurements are based on an Oxford cryogenic system (Maglab-12) with temperature fluctuation less than 0.04% and magnetic fields up to 12 T. The Nernst voltage and the longitudinal voltage are measured by a Keithley 182-Nanovoltmeter with a resolution of about 5 nV in present case. During the measurement for Nernst and longitudinal voltage the magnetic field is applied parallel to c-axis and swept between 12 to -12 T. The Nernst signal $V_N$ is obtained by subtracting the positive field value with the negative one in order to remove the Faraday signal during sweeping the field and the possible thermal electric power due to asymmetry of the electrodes. The Longitudinal signal $V_L$ is obtained by averaging the data obtained from positive field and the negative field.

FIG. 2: The configuration for measuring the Nernst and Longitudinal voltage of La$_{1.89}$Sr$_{0.11}$CuO$_4$ single crystal (right) and YBa$_2$Cu$_3$O$_{7-\delta}$ thin film (left). The Nernst voltages $V_N$ can be obtained between E and F when the samples are heated by the heaters on one end and the longitudinal voltage $V_L$ can be obtained between C and D when a DC current $I$ is applied along A-B direction.
III. RESULTS AND DISCUSSION

A. Pure Nernst Signal

FIG. 3 shows the Nernst voltage measured on the La$_{1.89}$Sr$_{0.11}$CuO$_4$ single crystal with a thermal gradient along [110] (length) direction at temperatures from 5 K to 180 K. In low temperature region, the Nernst signal is dominated by the motion of Abrikosov vortices. One can see that the Nernst signal is precisely zero when the vortices are frozen in the case of 5, 10 and 15 K. The flow of vortices after melting leads to a Nernst signal increasing drastically with $H$. A strong in-plane Nernst signal resulting from vortices flow can also be seen in the curves for 20, 25, 30 K, and can be measured far above $T_c$ (29.3 K for our sample). When the temperature is above 80 K, the signal becomes negative and gradually approaches a background. When the temperature is above 150 K the Nernst signal becomes insensitive to temperature and does not change anymore with $T$. Similar results appear in the Nernst voltage measured on the underdoped YBa$_2$Cu$_3$O$_{7-\delta}$ thin film, though it is not as strong as that of La$_{1.89}$Sr$_{0.11}$CuO$_4$ single crystal sample. But no strong Nernst signal above $T_c$ is observed in optimally doped YBa$_2$Cu$_3$O$_{7-\delta}$ thin film.

B. Flux Flow Resistance

FIG. 4 shows the $R(H)$ curves of the La$_{1.89}$Sr$_{0.11}$CuO$_4$ single crystal at temperatures from 10 to 80 K measured by standard four-point method. A zero resistance can be seen when the flux lattice is frozen at the low temperature of 10, 15 and 20 K. The Abrikosov flux flow dissipation after vortex melting can be seen in higher temperature region. But the curvature due to the motion of Abrikosov vortices disappears when the temperature is above $T_c$. The dissipation becomes very weakly dependent on $H$ in the normal state, which can not be explained by the motion of Abrikosov vortices.

C. Longitudinal Signal

The dissipation shown above may be comprised of the contributions of both the flux flow and the quasiparticle scattering. The new configuration in our experiment can reduce the dissipative contribution from the quasiparticle scattering and enhance the signal due to the possible vortex motion if we send a current between A-B and measure the voltage between C-D. As shown in FIG. 2, the current was applied in A-B direction, and the longitudinal voltage between the points on the side of the sample C and D was measured. As the C-D direction is perpendicular to the current direction and the two points are located outside the regime where the main current can reach, so the voltage induced by the motion of quasiparticles is practically reduced; while the motion of the vortex crossing C-D induced by the current pump can be detected and are enhanced relatively as a consequence. The results of the longitudinal voltage measurement for underdoped single crystal at the temperature 5~100 K and optimally doped YBa$_2$Cu$_3$O$_{7-\delta}$ thin film at the temperature 72~100 K are shown in FIG. 5 and FIG. 6 respectively. We can see in both figures the similar dissipation manner as that of the resistance of the samples in magnetic field shown in FIG. 4. The dissipation deriving from the motion of Abrikosov vortices disappears when the temperature is above $T_c$, where the dissipation of the samples is independent on magnetic field at fixed temperatures.

The results from the measurement of Nernst voltage, resistance and longitudinal voltage of our samples at different temperatures may indicate different vortices below and above $T_c$, provided that the dissipation is attributed
to the vortex motion. Apparently, below $T_c$ the dissipation is induced by the motion of the Abrikosov vortices. The Abrikosov vortex dissipation leads to the resistance in mixed state and, at the same time, the phase slip caused by the motion of Abrikosov vortices along the thermal gradient leads to strong Nernst signal. The longitudinal voltage below $T_c$ shows a non-linear field dependence which indicates the feature of Abrikosov flux flow.

Above $T_c$, the dissipation may be caused by the motion of the spontaneously generated vortex-antivortex pairs. According to the theory derived by Berezinsky and by Kosterlitz and Thouless (BKT), just below a transition temperature $T_{BKT}$, in samples there are thermally excited vortices and antivortices binding in pairs, even in the absence of an external magnetic field. Above $T_{BKT}$ the pairs unbind to form vortex plasma which can flow freely as pancake vortices with their cores confined inside individual superconducting layers. The possibility of this BKT transition was verified and studied in layered HTS system. In the region above $T_c$, the magnetic field applied on the samples influences the neutral vortices plasma, and polarizes part of the vortices. The dissipation caused by vortex and antivortex on the total resistance is the same, although the moving directions of them are different. In other words, the dissipation resulted from the current driven vortex motion is not related to the polarization of, but to the total number of the vortex and the antivortex in the sample, which is constant when changing $H$. So the resistance of the sample in magnetic field above $T_c$ is weakly dependent on the magnetic field as illustrated in FIG. 6. For the same reason, the longitudinal voltage induced by the motion of the vortex plasma in the normal state is also independent on the magnetic field.

In the case of Nernst effect a different consequence appears in the pseudogap region. The vortex plasma redirected by the external magnetic field moves across E-F along the thermal gradient, leading to the phase slips and a transverse Nernst electric field $E_y$ appears consequently. The direction of the $E_y$ caused by the vortex is different from that of the $E_y$ caused by the antivortex moving along the same direction. So the direction and strength of $E_y$ is not determined by the total number but by the amount of the difference between vortex
FIG. 7: The result of $V_{EF}$ at the temperature of 20 K with/without a temperature gradient along the length direction and a transverse current along A-B on the La$_{1.89}$Sr$_{0.11}$CuO$_4$ single crystal. Different symbols represent the case of $I = 0$ (solid triangles), $I = 0.1$ mA (solid circles), $I = 0.1$ mA (open circles) with thermal gradient, and $I = 0.1$ mA (solid squares), $I = -0.1$ mA (open squares) without thermal gradient. The heating power is 1.0 mW. For the convenience of comparison, all the curves have been shifted along $V_{EF}$ axis and the values of $V_{EF}$ is zero when $H = 0$ after the shift.

and antivortex, i.e. by the sign and the amount of the net vortex. The density of the net vortex in the samples increases with increasing external magnetic field, leading to the increase of Nernst voltage with $H$ in the field range of our experiment. The 2D feature of the Nernst effect in the pseudogap region of underdoped cuprate superconductors has been proved by the experiments of Wen et al.\cite{10}, which supports our postulation above.

D. Manipulating Vortex Motion by Thermal and Lorentz Force

The Nernst signal and the longitudinal voltage as the result from the motion of vortex manipulated solely by the thermal gradient and solely by Lorentz force are discussed above. Now let’s go on to discuss the result of manipulating the motion of the vortex by the thermal gradient and the Lorentz force together. With a transverse current applied along A-B direction and a temperature gradient along the length direction of the La$_{1.89}$Sr$_{0.11}$CuO$_4$ single crystal at the same time, the voltage $V_{EF}$ between the Nernst leads E and F are measured.

FIG. 8 shows the result of $V_{EF}$ at 80 K with the current of 0 mA, 3 mA and -3 mA. In FIG. 8 all the curves have been moved along $V_{EF}$ axis and hence the values of $V_{EF}$ is zero when $H = 0$ for the convenience of comparison. Now let’s go on to discuss the result of manipulating the motion of the vortex by the thermal gradient and the Lorentz force together. With a transverse current applied along A-B direction and a temperature gradient along the length direction of the La$_{1.89}$Sr$_{0.11}$CuO$_4$ single crystal at the same time, the voltage $V_{EF}$ between the Nernst leads E and F are measured.

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is also contributed by flux motion, although the vortex structure and feature may be very different below and above $T_c$.

IV. CONCLUSIONS

The in-plane resistance, Nernst voltage and longitudinal voltage in a new experimental configuration of the underdoped La$_{1.89}$Sr$_{0.11}$CuO$_4$ single crystal and optimally doped YBa$_2$Cu$_3$O$_{7-\delta}$ thin film are measured by sweeping magnetic field at fixed temperatures. The vortex motion is successfully manipulated by using thermal and / or Lorentz force in the mixed and normal states of the samples. The Nernst signal in the normal state is observed. The signal maybe caused by the motion of quasiparticles or vortex or both. Our results indicate that Nernst signal above $T_c$ may be contributed by vortex motion, though the contribution of the quasiparticle has not been excluded. Different vortices below and above $T_c$ are expected if the strong Nernst signal in the pseudogap region was attributed to the vortex motion. Below $T_c$, the dissipation is induced by the motion of the Abrikosov vortices. Above $T_c$, the dissipation may be caused partly by the motion of the spontaneously generated unbound vortex-antivortex pairs (vortices plasma).

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