Quantum vortex liquid state in the quasi two dimensional organic superconductor κ-(BEDT-TTF)$_2$Cu(NCS)$_2$

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Abstract

We report the transport properties in the quantum vortex liquid (QVL) state of the layered organic superconductor κ-(BEDT-TTF)$_2$Cu(NCS)$_2$. A steep change of the resistivity in the vortex liquid state is observed below about 1 K. In the low resistance state at lower temperatures, finite resistivity persists at least down to 100 mK. The finite residual resistivity may result in QVL assisted by the strong quantum fluctuations. A non-ohmic behavior appears only in the low resistance state, but not in the thermal vortex liquid (TVL) state at high temperatures. These transport properties are similar to the observations discussed as the vortex slush state in the high-T_c oxides.

Key words: organic superconductor; κ-(BEDT-TTF)$_2$Cu(NCS)$_2$; quantum vortex liquid; non-ohmic resistivity

Vortices in the layered superconductors (i.e. high-T_c superconducting oxides, organic superconductors) have strong thermal fluctuations, which have been extensively studied [1]. Quantum fluctuations on the superconductivity and also the vortices are expected to become potentially important at low temperatures on the materials fairly affected by the thermal fluctuations [2]. The vortex liquid state in the quasi two dimensional (Q2D) organic superconductor κ-(BEDT-TTF)$_2$Cu(NCS)$_2$ has been found even at $T \sim 0$ K, resulting from the quantum fluctuations instead of the thermal one [3]. The liquid state is explained as the quantum vortex liquid (QVL) from several theoretical approaches. The transport properties in the QVL state are expected to show some characteristic phenomena such as an insulating behavior [2]. We report the dc transport properties of the title organic superconductor in the QVL state.

High quality single crystals were grown by an electrochemical oxidation method. The in-plane resistivity was measured by means of a conventional dc four terminal method. The samples were cooled slowly from room temperature to 4.2 K in 48 hours in order to avoid the disorder of the terminal ethylene group of the BEDT-TTF molecules. The samples were directly immersed in the liquid ^{3}He or the dense ^{3}He gas.

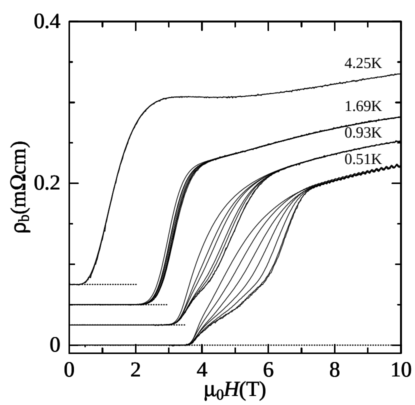

Fig. 1. The magnetic field dependence of the in-plane resistivity with several current densities in the filed perpendicular to the plane. The applied dc currents are 500, 200, 100, 50, 20, 10 and 5 μA from top to bottom curves at 0.51, 0.93 and 1.69 K, and 500, 100 and 10 μA at 4.25 K.

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Figure 1 shows the magnetic field dependence of the in-plane resistivity in the field perpendicular to the plane with different dc current density. The applied currents at 0.51, 0.93 and 1.69 K are 500, 200, 100, 50, 20, 10 and 5 μA , and 500, 100 and 10 μA at 4.25 K from top to bottom curves at each temperature. The current density corresponding to 500 μA is 1.53 A/cm^2. The transition curves below about 1 K indicate large non-ohmic behavior. In the low current density, for example at 0.51 K, a steep resistance drop appears at 6.5 T. The low resistance state following the resistance drop continues down to the field where the resistivity becomes zero. With increasing the current density, however, the feature of the resistance drop becomes unclear and the region of the low resistance state shrinks. No such low resistance state is recognized at 1.69 K. The temperature dependence of the resistivity in magnetic fields also demonstrates the low resistance state down to 100 mK. (The figure is not shown here.)

Figure 2 shows the phase diagram of vortices in the magnetic field perpendicular to the Q2D plane of κ-(BEDT-TTF)$_2$Cu(NCS)$_2$. The hatched low-T, low-H region is the vortex solid state (S), which is characterized by the zero resistance and the irreversible magnetization. The squares and circles are the irreversible field $H_{\rm irr}$ determined by the magnetic torque [3] and SQUID [4] measurements, respectively. The pluses and crosses are the mean field upper critical field $H_{\rm c2}$ obtained by the specific heat [5] and the magnetization [6]. The solid and dotted lines are the guide for eyes. Above the $H_{\rm irr}$ line the vortices do not have the long range order resulting in the vortex liquid state. The liquid state (TVL) is considered to be formed by melting the vortex pancake assisted by the thermal fluctuations. The broken line ($H_{\rm l}$) separates the vortex liquid state into two regions. One is the TVL state at higher T, and another the non-ohmic and low resistance state at lower T. This low resistance state persists down to at least 100 mK in $H_{\rm irr} < H < H_{\rm c2}$ at $T \sim 0$ K. The finite residual resistivity even at $T \sim 0$ K demonstrates that the QVL state is realized there by the quantum fluctuations.

The transport properties in the low resistance state below $H_{\rm l}$ are resemble in those observed in the vortex slush phase between the vortex liquid and glass phases of the high-$T_{\rm c}$ oxide superconductors having the intermediate range of the disorder [7,8]. The vortex slush phase has the short range order of the vortices, which is characterized by the non-ohmic resistivity. The transition between the vortex liquid and slush phases appears as a steep resistance drop but not to zero, and also a small magnetization jump. This transition is thought to be an incomplete first order phase transition at the same transition field and temperature of the original one hidden by the disorder effect. In addition the second order vortex glass transition line appears between

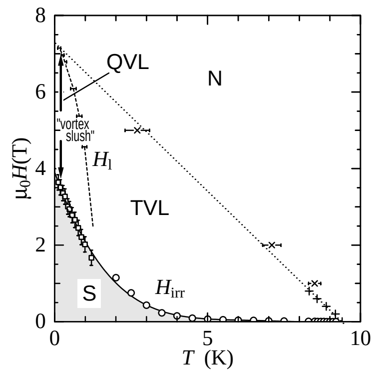

Fig. 2. The vortex phase diagram of κ-(BEDT-TTF)$_2$Cu(NCS)$_2$. The symbols and lines are referred to the text.

the vortex slush and glass phases.

Let us discuss the correspondence between the non-ohmic and low resistance state found in this material and the vortex slush phase with a short range order of vortices. The $H_{\rm l}$ line in this material seems to be a melting line in the case of no quantum fluctuations and the ideal clean system. In this case, the solid-liquid transition line ($H_{\rm irr}(T)$ or the melting line) should be terminated at the same point of $H_{\rm c2}$ around 7 T at $T \sim 0$ K because of no thermal fluctuations. The quantum fluctuations and finite amount of disorders in the real clean system push the actual solid-liquid line ($H_{\rm irr}$) down to about 4 T even at $T \sim 0$ K. The resulting vortex liquid could be QVL at low temperatures. The hidden original solid-liquid line may appear as $H_{\rm l}$ where the short range order of vortices starts to grow, but it does not develop to the long range order with the zero resistivity. In order to confirm these scenario, it is important to investigate the thermodynamic properties at $H_{\rm l}$ and the way of the connection of the $H_{\rm l}$ and $H_{\rm irr}$ lines.

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