Magnetothermal instabilities and melting of vortex lattice in $\kappa$-(BEDT-TTF)$_2$Cu(NCS)$_2$

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Abstract. We have measured the magnetothermal effect of $\kappa$-(BEDT-TTF)$_2$Cu(NCS)$_2$ in a wide field range, and clearly observed the temperature spikes due to the flux jumps and the quasi-periodic temperature oscillations before the flux jumps in the two dimensional (2D) vortex lattice phase. The temperature dependence of the magnetothermal effect suggests that the melting transition from the 2D vortex lattice to the vortex liquid phase in low temperature is driven by quantum fluctuations rather than thermal one.

1. Introduction
The melting of the Abrikosov vortex lattice into a vortex liquid phase at low temperatures in highly anisotropic layered superconductors has drawn considerable interest, because quantum fluctuations are expected to play an important role. One of model systems to investigate the effect of quantum fluctuations on the vortex phases is a layered organic superconductor $\kappa$-(BEDT-TTF)$_2$Cu(NCS)$_2$, which has a large anisotropy parameter as in the high temperature superconductor, Bi$_2$Sr$_2$CaCu$_2$O$_8$. In $\kappa$-(BEDT-TTF)$_2$Cu(NCS)$_2$, a three dimensional flux line lattice exists only below 7 mT in low temperatures [1], and a two dimensional (2D) pancake vortex lattices in adjacent layers are decoupled above this field. In this 2D vortex lattice phase, the abrupt jumps in the magnetic torque have been reported, which are understood as the “flux jumps” due to an avalanche behavior associated with the reorganization of the vortices [2, 3]. It is considered that the 2D vortex lattice melts to a liquid phase at a certain field even in a very low temperature, where quantum fluctuations are dominant over thermal one [2, 3].

In this study, we have measured the magnetothermal effect of $\kappa$-(BEDT-TTF)$_2$Cu(NCS)$_2$ in a wide field range. We show abrupt temperature spikes due to the flux jumps and the quasi-periodic temperature oscillations before the flux jumps for the first time. The temperature and the field angle dependences of the magnetothermal effects were also measured to clarify the nature of the melting transition.

2. Experiment
Single crystals of $\kappa$-(BEDT-TTF)$_2$Cu(NCS)$_2$ were obtained by electrochemical oxidation described elsewhere [4]. The approximate dimensions were $2 \times 0.5 \times 0.1$ mm$^3$ with the weight
of 0.21 mg. The sample was attached to a small RuO$_2$ temperature sensor with a small amount of grease, and mounted inside a miniature vacuum cell. The measurements were carried out by using a dilution refrigerator with a superconducting magnet at NIMS.

3. Results
Figure 1 shows the temperature variation of the sample as a function of the magnetic field applied perpendicular to the conducting $bc$-layers. The magnetic field was swept at a constant rate of 0.2 T/min at a constant cryogen bath temperature of 140 mK. As the field increases, the sample temperature goes up rapidly, and then show remarkable scattering behavior. This behavior is reminiscent of the abrupt magnetization jumps observed in the torque measurements, which are understood as “flux jumps” in the vortex lattice phase [2, 3]. The temperature spikes observed in this study can be also ascribed to flux jumps, as discussed later. The temperature jump becomes smaller as the field increases, and then stops at a field denoted as $B_m$. The field $B_m$ linearly decreases with increasing temperature, as shown in the inset of figure 1. Figure 2 shows the data at a slow sweep rate of 0.05 T/min. In the figure, quasi-periodic temperature oscillation before each flux jump is clearly seen. This oscillation is quite similar to that reported in YBa$_2$Cu$_3$O$_7$ [5]. The field angle dependence of $B_m$ at 140 mK is shown in figure 3, where $\theta$ is the angle between the magnetic field and a direction normal to the conducting $bc$-layers. The solid line is a fit to the 2D Ginzburg-Landau theory:

$$\left| \frac{B_m(\theta) \cos \theta}{B_{m\perp}} \right| + \left( \frac{B_m(\theta) \sin \theta}{B_m||} \right)^2 = 1$$

![Figure 1](image.png)

**Figure 1.** Temperature variation of the sample as a function of the magnetic field applied perpendicular to the conducting $bc$-layers.
Figure 2. Temperature variation of the sample at slow field sweep. The temperature oscillation is clearly seen before each flux jump.

Figure 3. Angle dependence of the melting field $B_m$. The solid line is a fit to the 2D Ginzburg-Landau theory.

with $B_{m,\perp} = 3.6$ T and $B_{m,\parallel} = 29$ T, where $B_{m,\perp}$ and $B_{m,\parallel}$ denotes the field for $B \perp bc$ and $B \parallel bc$, respectively.

4. Discussion
In the 2D vortex lattice phase, the crystal defects collectively pin the pancake vortex lattice in each layer. As a result, the flux builds up near the sample surface as the field increases, which causes field gradient at the sample edge and associated surface current. The viscous flow of vortices causes local heating, which reduces the critical current density. When the sample is isolated from the surrounding cryogen bath, thermal instability due to the local heating is enhanced. This instability may initially have some periodic behavior, which leads to the temperature oscillation before the flux jumps [5, 6]. When the field gradient at the edges exceeds a critical value, the vortex lattice is depinned, and then a large number of vortices flow rapidly inside the sample (flux jump), causing a temperature spike, as in figure 1 and figure 2. After the spike, the large field gradient at the edges is reduced (the vortex lattice is pinned), and then the sample quickly cools again. When the vortex lattice melts, the vortices are not pinned collectively. Therefore $B_m$ observed in this study can be defined as the melting field of the vortex lattice.

The temperature dependence of $B_m$ coincides well with the irreversibility field $B_{irr}$ determined by the torque measurements [2]. The field angle dependence of $B_m$ (figure 3) also agrees with the result of $B_{irr}$ [3]. Indeed, it is considered that the melting occurs at $B_{irr}$, because no flux jumps are observed in torque measurements above $B_{irr}$ [2, 7]. The linear dependence in $T$ is in disagreement with $B_m \propto \exp(a/T)$ in the 2D vortex lattice region based on the melting driven by the thermal fluctuations [8]. It suggests that the melting transition in low temperatures is driven by quantum fluctuations rather than the thermal one, as previously pointed out by the torque measurements [2].

On the other hand, Mola et al. defined $B_m$ as a kink in the magnetization just below $B_{irr}$ when the magnetic field is largely tilted from $B \perp bc$-layers [3]. They determined $B_m$ for $B \perp bc$-layers by scaling the data, and report that the temperature dependence of $B_m$ exhibits negative
curvature below 130 mK, though $B_{irr}$ is linear in $T$. Their data are not connected to $B_m$ in our data smoothly. This inconsistency can be attributed to the difference in sample quality. In tilted magnetic field, a lot of Josephson vortices lie in the insulating (anion) layers. The presence of the Josephson vortices may result in some different mechanism of the pancake vortex dynamics, because the Josephson vortices and the pancake vortices are correlated.

5. Summary
In $\kappa$-(BEDT-TTF)$_2$Cu(NCS)$_2$, the temperature spikes due to the flux jumps and the quasi-periodic temperature oscillations were clearly observed in the magnetothermal effect for the first time. It supports the previous picture of the flux jumps in this material. The linear temperature dependence of the melting field $B_m$ coincides well with the irreversibility field $B_{irr}$, and suggests that the melting transition from the 2D vortex lattice to the vortex liquid phase is driven by quantum fluctuations rather than thermal one in low temperatures.

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