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Flux jumps and melting of the vortex lattice in κ-$(ET)_2Cu(NCS)_2$

S. Hill[a,*], M. M. Mola[a], J. S. Qualls[b], J. S. Brooks[b]

[a] *Department of Physics, Montana State University, Bozeman, MT 59717, USA*
[b] *Department of Physics and NHMFL, Florida State University, Tallahassee, FL 32310, USA*

Abstract

The angular and temperature dependence of the DC magnetization of the organic superconductor κ-$(ET)_2Cu(NCS)_2$ has been investigated in high magnetic fields (up to 20 T) and at low temperatures (25–200 mK). In moderate fields, the mixed state of this layered superconductor exhibits a series of flux jumps, indicative of critical surface screening currents. At higher fields, a melting of the quasi-two-dimensional vortex lattice is observed below the irreversibility line.

Keywords: (Organic superconductors, Magnetic measurements, Superconducting phase transitions)

1. Introduction

In the absence of crystal defects, it is expected that magnetic flux will enter a type–II superconductor abruptly and uniformly at H_{c1}. In real crystals, however, metallurgic defects create potential wells which tend to pin vortices in place. For a system of interacting vortices, this pinning gives rise to a viscosity. Consequently, magnetic flux flow within the mixed superconducting state ($H_{c1} < H < H_{c2}$) is generally irreversible. At ultra-low temperatures, the effects of this irreversibility are most pronounced due to: i) the suppression of thermally activated de-pinning; and ii) the likely ordering of vortices into a rigid lattice (or glass).

In a typical field swept experiment, the rate at which flux creeps into the bulk of a crystal is usually exceedingly slow compared to the field sweep rate. Thus, one expects a critical state to develop near the sample surface: the build-up of flux gives rise to a magnetic field gradient with accompanying induced surface currents given by Maxwell's equation $\nabla \times \mathbf{B} = \mu_o \mathbf{J}$ [1]. Near absolute zero temperature, a boundary resistance tends to thermally isolate the sample from its surroundings. Viscous surface screening currents then cause runaway thermal instabilities, resulting in large portions of the sample entering the normal state. This transition allows magnetic flux to avalanche into the crystal interior, thereby dissipating the field gradient and the accompanying surface current. With no viscous currents flowing, the sample once again becomes superconducting and the process begins anew. Any thermodynamic measurement should see a series of discontinuities, or "flux jumps", in the crystal response as a function of applied magnetic field. This effect is expected to be most pronounced in the vortex solid phase, due to the rigidity of the flux lattice. In the liquid state, vortices easily slip past each other, and flux can migrate into the interior of the sample with relative ease.

2. Experimental

We have used a DC torque magnetometer to measure changes in the magnetization of a single crystal of κ-$(ET)_2Cu(NCS)_2$ [2], with approximate dimensions of $1\times1\times0.3$ mm^3. The torque beam was mounted on a single axis rotator, allowing for angle dependent measurements; an angle $\theta = 0^\circ$ corresponds to the applied field parallel to the least conductive ***a***-axis, while $\theta = 90^\circ$ corresponds to the field within the conducting ***bc*** plane. Temperature control was achieved using an Oxford Instruments ^{3}He/^{4}He dilution refrigerator. Magnetic fields were generated using a 20 T superconducting magnet at the National High Magnetic Field Laboratory; in all cases, the applied magnetic field was swept at a constant rate of 0.5 tesla/min.

3. Results and Discussion

The top panel of Fig. 1 shows magnetic torque, at 25 mK, for up and down sweeps made at 52°, 66° and 75°; the bottom panel shows expanded views of the high field

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[*] Corresponding author. Tel: +1-406-994-7175; fax: +1-406-994-4452;
E-mail: hill@physics.montana.edu

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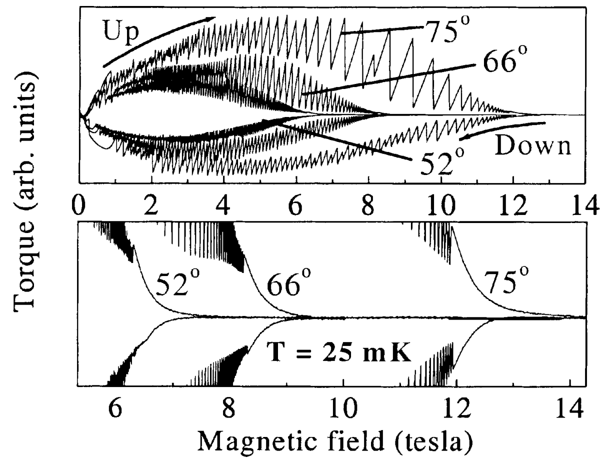

Fig. 1. Angle dependent magnetic torque; note the flux jumps.

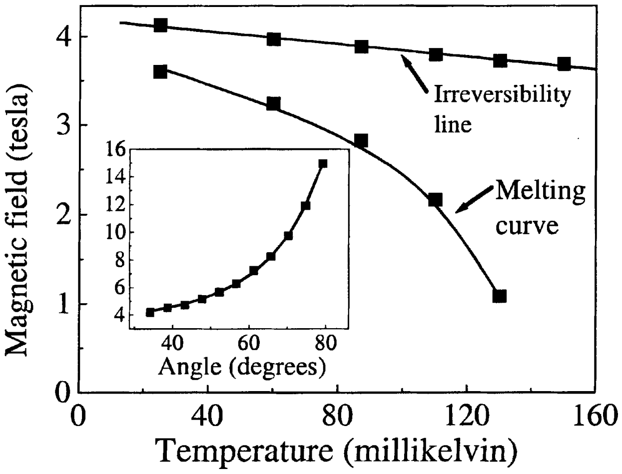

Fig. 2. Angle and temperature dependence of the melting transition.

tails of these measurements. Flux jumps are obvious, as has previously been reported in this [3] and other [4] materials. However, notice how the flux jumps stop abruptly above a characteristic angle (and temperature) dependent field $H_m(\theta,T)$. A decoupled quasi-two-dimensional (Q2D) vortex lattice is known to exist over a large portion of the superconducting phase diagram in κ-$(ET)_2Cu(NCS)_2$ [2]. Consequently, we attribute this cessation of the flux jumps, just below the irreversibility line, to a melting of the Q2D vortex lattice. To substantiate this claim, we look at the angle and temperature dependence of $H_m(\theta,T)$.

In the inset to Fig. 2, we plot H_m as a function of θ; the solid line is a fit to a scaling law of the form $H_m(\theta,T) = H_m(T)[\alpha^{-2}\sin^2\theta + \cos^2\theta]^{-1/2}$ [2,5,6], where α characterizes the anisotropy. From this fit we obtain a value for the melting field at $\theta = 0^\circ$ and 25 mK of $H_m = 3.56$ T, which is in good agreement with the accepted value [6]. The value of $\alpha \approx 7$ is also in good agreement with the value obtained from fits to the angle dependence of H_{c2} in this same material [7].

The temperature dependence of H_m, measured at $\theta = 47^\circ$ (scaled to $\theta = 0^\circ$ using the above relation), is plotted in the main panel of Fig. 2, along with the irreversibility field H_{irr}. The solid line through the H_m data is a fit using the functional form $H_m(T) = H_m(0)[1-T/T^*]^{\mu}$. From this fit, we find $H_m(0) = 3.88$ T, $T^* = 0.13$ K and $\mu \sim {}^1/_3$. Similar values were obtained for measurements made at $\theta = 74^\circ$ and scaled in a similar fashion.

For classical, thermally induced melting, $T^* = T_c$ and a value of μ in the range 1.5 to 2 is expected, depending on the degree of anisotropy and on the nature of the interactions between superconducting layers [8,9]; clearly, this scenario is inappropriate here. Instead, we believe that the negative curvature ($\mu < 1$) associated with the melting of the vortex lattice at $T \approx T_c/100$ is a direct result of a crossover from the classical thermal limit to a quantum regime. Indeed, similar behavior has been observed at ultra-low temperatures in thin film superconductors [10]. Due to this crossover, the relevant temperature is no longer T_c, but the temperature at which quantum fluctuations become dominant, *i.e.* $T^* \approx 150$ mK. In this scenario, the first-order melting curve is expected to extrapolate to a $T = 0$ K quantum critical point below H_{c2}, resulting in a quantum vortex liquid state in the region $H_m < H < H_{c2}$.

4. Conclusions

In conclusion, we have observed flux jumps in the magnetization of κ-$(ET)_2Cu(NCS)_2$. These flux jumps come to an abrupt halt at a temperature and angle dependent field, $H_m(\theta,T)$, which we attribute to a melting of the Q2D vortex lattice. The angle dependence of the transition is consistent with the anisotropic nature of this material, while the temperature dependence suggests that quantum rather than thermal fluctuations drive the melting transition in this ultra-low temperature regime.

5. Acknowledgements

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