Determination of the vortex structure in \( \kappa-(ET)_2\text{Cu(NCS)}_2 \) by Josephson plasma resonance

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Abstract

Observation of a Josephson plasma resonance in \( \kappa-(ET)_2\text{Cu(NCS)}_2 \), below \( T_c \) (\( \sim 10 \) K), enables investigation of the vortex phase diagram within the mixed state of this highly anisotropic type-II superconductor. Temperature dependent studies seem to indicate a transition in the vortex structure near the irreversibility line, not previously observed in this material using this technique. We also show that the frequency dependence of the resonance between 28-153 GHz is best described by a week pinning theory previously derived by Bulaevskii et al.

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

1. Introduction

A Josephson plasma resonance (JPR) has been observed in a variety of layered, type-II superconductors [1–3], and has proven to be an extremely effective tool for probing the mixed state vortex phase diagram. Below \( T_c \), this plasma mode dominates the microwave response of the crystal along the least conducting direction, with a frequency (\( \omega_p \)) that is proportional to the square root of the maximum interlayer current density, \( J_m(B,T) \) [4].

Upon application of a DC magnetic field parallel to the least conducting axis, a mixed state is created in which quantized flux tubes penetrate the sample generating supercurrent vortices within the superconducting layers. The interlayer Josephson coupling (i.e. \( J_m \)) depends explicitly on the vortex density, as well as on the correlation between the locations of vortices in adjacent layers. Consequently, \( J_m \) and \( \omega_p \) are rather sensitive to any changes in ordering of the vortices [4], and measurements of \( \omega_p \) provide a direct probe of the vortex structure [1-5].

2. Experimental

We have studied several single \( \kappa-(ET)_2\text{Cu(NCS)}_2 \) crystals, with approximate dimensions of 0.7x0.5x0.2 mm\(^3\). Microwave impedance measurements were carried out using a cavity perturbation technique over the frequency range from 28 to 153 GHz. This narrow-band technique, which is described elsewhere [5,6], necessitates holding the probe frequency constant, while varying \( \omega_p \) via the magnetic field strength, i.e. by varying the flux density. In every case, the DC magnetic field was applied along the least conducting sample (\( \alpha \)-) axis, and swept from 0–8 tesla at a constant rate of approximately 1 tesla/min.

3. Results and Discussion

Fig. 1 plots microwave dissipation versus magnetic field, for 1 K intervals between 2 and 10 K; the measurement frequency is 153 GHz. Note that, as the temperature is increased from 2 to 4 K, the peak feature (indicated by an arrow) associated with the JPR moves to higher magnetic fields. We attribute this to an increase in the interlayer Josephson coupling (see Ref. [5]). In this field range, and at temperatures below 5 K, the vortices are thought exist in a quasi-two-dimensional (Q2D) solid phase, exhibiting long range order within each layer [7]. However, due to random pinning and weak interlayer coupling, little or no correlation in the locations of vortices in adjacent layers is expected. Hence, this Q2D vortex solid phase, together with disorder (pinning), results in weak interlayer Josephson coupling. The apparent increase in this coupling upon raising the temperature from 2 to 4 K is brought about by increased thermal fluctuations of the

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vortices about their mean positions, i.e. an increase in the thermally averaged correlation in the locations of vortices in adjacent layers.

Upon increasing the temperature above 4 K, the JPR position begins to move back to the lower fields, corresponding to a decrease in the interlayer Josephson coupling. This so-called “cusp” – the point in the B-T phase diagram at which the temperature dependence of the resonance changes – falls on, or near, the irreversibility line for this material. One possible explanation for the cusp involves a melting of the Q2D vortex lattice. Above a field dependent critical temperature $T_c^*(B)$, thermal fluctuations enhanced by low dimensionality will ultimately cause the mean thermal displacements of the vortices to exceed some critical value, at which point long range order is lost, i.e. the Q2D vortex lattice melts. The observed opposite temperature dependence of $\omega_p$ is to be expected in the liquid vortex phase since, in the absence of any long range order, increasing the temperature will serve only to reduce the interlayer Josephson coupling.

Another possible explanation for the cusp behavior involves a depinning transition. In this scenario, increased thermal fluctuations cause the individually pinned Q2D vortex lattices to undergo larger and larger collective oscillations about their mean positions, up to some critical depinning threshold, whereupon, at a critical temperature $T_c^*(B)$, they become completely dc-pinned, or mobile. Such a transition would be indistinguishable from melting using our technique and, in both cases, opposite temperature dependences for the JPR frequency are expected above and below $T_c^*(B)$.

Finally, in Fig. 2, we plot $\omega_p^2$ versus magnetic field, at a temperature of 2 K. Previously, it was assumed for this material that $\omega_p^2$ follows a power law dependence on magnetic field [3], in analogy to the high $T_C$ cuprates [1]. However, by measuring over a wide frequency range, we find that a power law fits the data poorly. Instead, using a weak pinning theory derived by Bulaevskii et al. [4], we fit the data using a decaying exponential, where $\omega_p^2 \approx \exp\left[-(B/B_D)^{3/2}\right]$; $B_D$ characterizes the field above which interlayer coherence is lost. From this fit, we are able to extract material parameters, such as the interlayer penetration depth ($\lambda_1 = 90 \mu m$), and the in-plane critical current density ($J_C = 3.5 \times 10^4 A/cm^2$). Both of these values prove consistent with those obtained by other methods.

4. Conclusions

Through JPR measurements, we have observed a transition in the magnetic vortex structure in the organic superconductor $\kappa$-(ET)$_2$Cu(NCS)$_2$. In particular, we see a cusp in the temperature dependence of the plasma resonance, which may be due to either Q2D vortex lattice melting or depinning. We have also shown, by measuring over a wide frequency range, that this material seems to follow a weak pinning theory predicted for ultra-clean samples [4].

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References