Josephson plasma resonance in \( \kappa-(BEDT-TTF)_2Cu(NCS)_2 \) for close to in-plane magnetic fields

A. E. Kovaleva, S. Hillb, J.S. Quallsb

a Department of Physics, University of Florida, Gainesville, FL 32611, USA
b Department of Physics, Wake Forest University, Winston-Salem, NC 27109, USA

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Abstract

We report detailed angle dependent Josephson plasma resonance measurements within the decoupled vortex liquid phase of the extreme two-dimensional organic superconductor \( \kappa-(BEDT-TTF)_2Cu(NCS)_2 \). The plasma resonance initially shows an approximately \( 1/\cos\theta \) dependence, followed by a sharp re-entrance for fields close to alignment with the layers (\( \theta = 0^\circ \)). This re-entrance may be attributed to an in-plane field dependence which may be directly related to the superconducting phase correlation function within the vortex state.

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

1. Introduction

It is well established that, within the mm-wave spectral range (30 to 300 GHz), a Josephson Plasma Resonance (JPR) dominates the interlayer electrodynamics in the mixed state of the quasi-two-dimensional (Q2D) organic superconductor \( \kappa-(BEDT-TTF)_2Cu(NCS)_2 \) [1,2]. It is also well documented that this JPR serves as an extremely sensitive tool for probing the structure of vortex phases in layered superconductors [3]. The JPR frequency, \( \omega_{\text{p}} \), depends explicitly on the Josephson coupling between layers; indeed, \( \omega_{\text{p}} \) is directly related to the spatial and temporal average of the function \( \langle \cos \varphi_{n+1}(r) \rangle \), where \( \varphi_{n+1}(r) \) is the gauge invariant difference in the phase of the order parameter between layers \( n \) and \( n+1 \), at position \( r \) within the layers. Application of a magnetic field \( (B_z) \) normal to the layers introduces pancake vortices into the sample, accompanied by large phase fluctuations. Due to the weak nature of the Josephson coupling in the title compound, the pancake vortices in adjacent layers become decoupled at relatively weak applied fields (\( \sim \)10 mT). This decoupling transition dramatically suppresses the interlayer phase coherence \( \langle \cos \varphi_{n+1}(r) \rangle \), which, in turn, suppresses \( \omega_{\text{p}} \). Theoretical and experimental studies within the vortex liquid phase have shown that the field and temperature \( (T) \) dependence of \( \omega_{\text{p}} \) may be described as

\[
\omega_{\text{p}}^2(B_z,T) \propto B_z^{-v} T^{-1},
\]

with \( v \) being slightly less than unity [1-3].

Our previous investigations have focused mainly on a transformation from a pinned vortex phase, to a depinned liquid state [1,2]. Here, we report preliminary data within the vortex liquid phase for fields close to alignment with the \( bc \)-plane (\( \parallel \) highly conducting layers). Application of an in-plane field \( (B_x) \) introduces an additional term in the phase difference \( \varphi_{n+1}(x,y) \) due to the vector potential associated with \( B_x \). This leads to a further suppression of \( \omega_{\text{p}} \), which is directly related to the Fourier transform of the phase correlation function \( S(r) = \langle \cos[\varphi_{n+1}(r) - \varphi_{n+1}(0)] \rangle \) [3]. Thus, angle dependent JPR measurements provide a direct means of extracting microscopic parameters associated with the superconducting state.

2. Experimental

A single \( \kappa-(BEDT-TTF)_2Cu(NCS)_2 \) crystal, with approximate dimensions 0.7x0.5x0.2 mm\(^3\), was used for these investigations. Interlayer microwave impedance measurements were carried out using a cavity perturbation technique which is described elsewhere [4]. Field orientation was achieved by rotating the magnetic field produced by a split-pair superconducting magnet relative to the rigid microwave apparatus; this approach is essential in order to maintain optimal coupling between the sample, cavity and the mm-wave network analyzer used as a source and detector. All data presented in this paper were obtained at a temperature of 4.3 K, and a frequency of 71.36 GHz, whilst sweeping the applied field at different fixed angles \( \theta \) relative to the least conducting \( a^* \) direction (\( \perp bc \)-plane).

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3. Results and Discussion

Fig. 1 plots microwave dissipation versus magnetic field, at various angles \( \theta \). The main broad peak corresponds to the JPR which we have reported previously [1,2]. The JPR peak position \( (B_{\text{res}}) \) follows an approximately \( 1/\cos\theta \) dependence up to \( \theta \approx 80^\circ \), whereas it reaches a maximum, tending towards zero-field as \( \theta \rightarrow 90^\circ \), as can be seen more clearly in Fig. 2 (open squares). This re-entrant behavior of the JPR may be attributed to the in-plane field component. An analytic expression for the angle dependence of the JPR may be obtained by assuming a Gaussian form for \( S(r) \), giving

\[
\omega_r^2 = \omega_p^2 (B_z, T) \exp \left( -\frac{\pi s^2 B_z^2}{\Phi_0 B_z} \right) \times \frac{1}{B \cos\theta} \exp \left( -\frac{\pi s^2 B \sin^2 \theta}{\Phi_0 \cos \theta} \right),
\]

where \( s \) is the interlayer spacing, and \( \Phi_0 \) is the flux quantum [3]. The dashed curve in Fig. 2 represents a fit to the above expression, while a better fit (solid curve) involves a slight modification to the pre-exponential factor such that \( B \cos\theta \rightarrow B \left[ \cos\theta + 0.1 \right] \); this fit also assumes fixed \( \omega_p = 2\pi f \) and \( B = B_{\text{res}} \), and yields a sensible value for \( s \approx 8 \) Å. This modification may have several explanations: it may reflect a limitation in the Gaussian approximation for \( S(r) \) [3]; or it may indicate that the pancake vortex contribution to \( \omega_p \) is not determined solely by \( B_z \). The latter may imply that a highly anisotropic 3D picture (as opposed to strictly 2D) offers the more realistic description of the pancake vortices in the title compound, or this may be indicative of paramagnetic pair breaking for large in-plane fields. Both of these effects have been considered in the context of other angle dependent parameters for \( \kappa\)-(BEDT-TTF)$_2$Cu(NCS)$_2$, such as \( H_{\text{c}2} \) [5].

The low-field resonance (LFR) in Fig. 1 (solid circles in Fig. 2) exhibits an opposing angle dependence to the JPR over the narrow angle range for which it is observed. We speculate that this resonance may be associated with the non-equilibrium critical state, since it is only observed for up-sweeps of the magnetic field; a similar behavior has been seen in \( \text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8 \) [6]. Clearly, further studies will be required to establish the mechanism for the LFR.

4. Summary

Within the vortex liquid phase, angle dependent electrodynamic investigations of \( \kappa\)-(BEDT-TTF)$_2$Cu(NCS)$_2$ reveal a re-entrance of the JPR frequency, \( \omega_p \), for fields close to alignment with the highly conducting layers. We are able to fit the angle dependence to a single analytic expression which is related to the superconducting phase correlation function. A sharp, low field, resonance is also observed in the vicinity of \( \theta = 90^\circ \), which appears to be associated with the non-equilibrium critical state.

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References