Effects of Vortex Pinning and Thermal Fluctuations on the Josephson Plasma Resonance in Tl$_2$Ba$_2$CaCu$_2$O$_{8+\delta}$ and YBa$_2$Cu$_3$O$_{6.5}$

Diana Dulić$^1$, S. J. Hak$^1$, D. van der Marel$^1$, W. N. Hardy$^2$, A. E. Koshelev$^3$, Ruixing Liang$^2$, D. A. Bonn$^2$, B. A. Willemsen$^4$

$^1$Laboratory of Solid State Physics, Materials Science Centre, Nijenborgh 4, 9747 AG Groningen, The Netherlands
$^2$Department of Physics and Astronomy, University of British Columbia, Vancouver, BC, V6T 1Z1, Canada
$^3$Material Science Division, Argonne National Laboratory, Argonne, IL 60439
$^4$Superconductor Technologies Inc., Santa Barbara, CA 93111-2310

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Infrared spectroscopy has been used to investigate the temperature dependence and c-axis magnetic field dependence of the Josephson plasma resonance in optimally doped Tl$_2$Ba$_2$CaCu$_2$O$_{8+\delta}$ thin films, and underdoped YBa$_2$Cu$_3$O$_{6.5}$ ortho-II single crystals. The resonances are directly related to the c-axis penetration depths, yielding low temperature, zero fields values of about 20 $\mu$m, and 7 $\mu$m respectively. While the temperature dependencies of the resonances in the two compounds are very similar, the magnetic field dependence in YBCO is much weaker. We attribute this weak magnetic field dependence to the lower anisotropy of YBCO, and discuss the observed behaviours in terms of thermal fluctuations and pinning of pancake vortices, valid for highly anisotropic layered superconductors.

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The Josephson plasma resonance (JPR) phenomenon provides direct information about the Josephson coupling between the CuO$_2$ planes in the highly anisotropic high $T_c$ superconductors. Studies of the temperature and magnetic field dependence of the JPR provide useful insights into the pinning and thermal fluctuations of vortices in the cuprate family. It is natural, to anticipate unusual magnetic field behavior in these highly anisotropic materials. Indeed, just as in any conventional type-II superconductor, if a DC magnetic field is applied perpendicular to the 2D planes it penetrates the sample in the form of vortices which, when the anisotropy is large, are not vortex lines but pancake vortices. For low magnetic fields and low temperatures, these pancake vortices may form a nearly perfect vortex lattice. Under these conditions there should be no magnetic field dependence of the JPR since $\omega_p^2(B,T) = \omega_p^2(0) \cos(\phi_{n,n+1}(r))$, where $\omega_p^2(0)$ is the plasma frequency in zero field, and $\phi_{n,n+1}(r)$ is the gauge-invariant phase difference between the neighboring layers $n$ and $n+1$. In zero field, $\phi_{n}(r)$ is independent of $r$ and independent of $n$ for zero c-axis current. In non-zero field, $\phi_{n}(r)$ becomes position dependent but $\phi_{n,n+1}(r)$ is everywhere zero, provided the vortex cores are lined up, as in a perfect lattice. However, due to the effects of pinning (at low temperatures), and thermal fluctuations (at higher temperatures) pancake vortices do not in general line up from layer to layer. Both regimes have been extensively studied theoretically by Bulaevskii and one of us (AEK), but there is very little data on the JPR in the low magnetic field regime. In this paper we present our studies of the temperature and field dependence of the JPR in two members of the high $T_c$ family with differing anisotropies.

Two types of reflectivity spectra were measured, each optimized to the type of sample: First normal incidence reflectivity spectra were recorded of a mosaic made of six ac-oriented single crystals of YBa$_2$Cu$_3$O$_{6.5}$ with ortho-II oxygen ordering, and a superconducting transition temperature of 58K. The mosaic was held together with epoxy and had an area of 6mm$^2$. Second, grazing incidence reflectivity measurements were made on epitaxially grown Tl$_2$Ba$_2$CaCu$_2$O$_{8+\delta}$ thin films, with a superconducting transition temperature of 98K. Dimensions of the films in the ab plane were 64 mm$^2$, and the thickness was 600-700 nm. Details of the sample preparation and growth methods have been reported elsewhere.

Here we report data in the far infrared FIR region (17-700 cm$^{-1}$) obtained using a Fourier transform spectrometer. A grazing angle of 80$^\circ$ was chosen to probe predominantly the c-axis response for p-polarization of the light. Absolute reflectivities were obtained by calibrating the reflectivities against the reflectivity of a gold film deposited in situ on the sample.

The reflection experiments were carried out in magnetic fields oriented along the c-axis, which could be varied continuously between 0 and 0.8T using a sliding permanent magnet, and calibrated using a GaAs 2D electron gas placed in the sample holder block, 1 mm underneath the sample. Details of the magnet-cryostat design are described elsewhere.

In Fig. we show the grazing incidence reflectivity of Tl2212 for a range of temperatures in zero field, and for various magnetic fields at 4 K under field cooled (FC) conditions: The sample temperature was first increased above the phase transition, next the field was set at the...
desired value, the sample temperature was lowered to 4 K, and the spectra were recorded. This sequence was then repeated for each external field value. In Fig. 2 we present the FC normal incidence reflectivity of YBCO, with the electric field along the c-axis in the frequency region from 18-100 cm$^{-1}$ for various magnetic fields at 4K. In the figures we show only the low frequency part of the spectra since the only features in the spectra below 4K. In the figures we show only the low frequency part of the spectra. Except for the zero field data, all curves have been given vertical offsets.

![Graph showing Grazing Reflectivity of Tl2212](image)

**FIG. 1.** Top panel: Grazing incidence reflectivity of Tl2212 without external magnetic field at (from top to bottom) 10, 20, 30, 40, 50, 60, and 70 K. Bottom panel: Field cooled grazing incidence reflectivity of Tl2212 at 4 K in an external magnetic field of (from top to bottom) 0, 0.03, 0.06, 0.11, 0.17, 0.21, 0.23, 0.26, 0.29, 0.32, 0.36, 0.4, and 0.46 Tesla, perpendicular to the surface. Except for the zero field data, all curves have been given vertical offsets.

The intensity also exhibits hysteresis during cycling of the magnetic field (not shown). Briefly, this behaviour is caused by the self screening of the sample: As the field is applied perpendicular to the film, the outer parts of the film are penetrated by the field, while the central part of the film remains at $B = 0$. Assuming that the JPR is absent from the field penetrated region of the film, the spectra are just linear combinations of the zero field spectrum and the featureless high field spectrum. One can make this quantitative using the result of Mikheenko and Kuzovlev [18] for the distance from the center of the disk that is penetrated by the magnetic field: $a = R/\cosh(H/(2\pi j_{c}^{ab} d))$, where $R$ is the radius of the disk, $H$ is the applied field, $j_{c}^{ab}$ is the $ab$-plane critical current and $d$ is the thickness of the film. From comparison to Fig. 2 we obtained $j_{c}^{ab} = 6.7 * 10^{10}$ A/m$^2$, which is a reasonable value for a high quality film.

The resonance is due to the zero-crossing of Re(\epsilon_c(\omega)), for which we adopt the two-fluid expression appropriate for the superconducting state

$$
\epsilon_c(\omega) = \epsilon_S(\omega) - \frac{c^2}{\lambda_c^2(B, T) \omega^2} + \frac{4\pi i \sigma_{qp}(\omega)}{\omega} \tag{1}
$$
where $\lambda_c$ is the c-axis penetration depth, and $1/\lambda_c(B, T)^2$ represents the superfluid density appropriate for the c-direction. The pole-strength of the second (London) term, coming from the condensate provides directly, the superfluid density appropriate for the c-direction. The second term arises from dissipative currents due to quasi-particles, and determines the inter-layer Josephson coupling. If the coupling be-

As mentioned above, a DC magnetic field applied along the c-axis penetrates the cuprate superconductors in the form of pancake vortices. For sufficiently low fields and temperatures they form a vortex lattice, which for an ideal material would be composed of straight lines along the c-axis, and as a consequence have no influence on the inter-layer Josephson coupling. If the coupling between the layers is very weak, pinning and thermal fluctuations may be sufficient to destroy the alignment of the pancake vortices along the field direction. The resulting spatial fluctuations of the relative phases between the planes cause a suppression of the Josephson coupling between the layers. Below the irreversibility line, the vortex phase diagram is very rich, and similar richness is required of theories aimed at explaining all parts of the diagram. In the low temperature regime the main cause of misalignment of the pancakes is pinning due to impurities in the materials. At higher temperatures, thermal fluctuations take over and become the main cause for suppression of the Josephson current. Suppression of the Josephson coupling due to a magnetic field applied along the c-axis in the vortex lattice state was extensively studied theoretically by one of us (AEK) in both the low temperature (where the pinning is the most important contribution), and the high temperature (where thermal fluctuations play the most important role) regimes. In Ref. a model was developed where the influence of weak pinning on the Josephson coupling between layers was considered. A characteristic "decoupling" field $B_w$ was introduced, above which the JPR frequency saturates at a certain value. The vortex lines are destroyed by pinning, and $B_w$ is determined by the wandering length of the vortex lines. The following expression was derived for the effective Josephson coupling

$$E_{eff}^j - E_j = -\frac{E_J B}{B_w}$$

Here $E_J$ is Josephson energy per unit area, which is related to the c-axis penetration depth via $E_J = \Phi_0^2/(16\pi^3\lambda_c^2 d)$, where $\Phi_0$ is the elementary flux quantum, and $d$ is the interlayer distance. With this expression we can calculate the Josephson energies per unit area with the result $E_J = 1.6 \cdot 10^{-8}$ erg/cm$^2$ for Tl2212, and $E_J = 1.5 \cdot 10^{-5}$ erg/cm$^2$ in YBCO. In the inset of Fig. we show the fit to Eq. at 4K from which we obtain values for $B_w = 1.40 \pm 0.02$ T in Tl2212. In YBCO the field dependence is much weaker (Fig. ), corresponding to $B_w = 30 \pm 10$ T. Now, we can pose the question why YBCO has a weaker field dependence than Tl2212. From the discussion above it is clear that it can either be due to the higher purity of the sample or to the more three dimensional nature of YBCO. The theoretical prediction for $B_w \sim E_J\Phi_0/U_p$ from Ref. , where $U_p$ represents the pinning potentional can help us resolve this problem. The ratios of the 'decoupling' fields for Tl2212 and YBCO should scale as $B_{wTl}/B_{wY} = (E_J^{Tl}/E_J^Y)/(U_p^{Tl}/U_p^Y)$. Since we have already determined the Josephson coupling constants $E_J$ and the decoupling fields $B_w$, we have sufficient experimental information to estimate the ratio of the pinning potentials,providing $U_p^Y/U_p^{Tl} \approx 0.44$. In the strongly anisotropic material Bi2212 $\lambda_c(0) = 110\mu$m, corresponding to $E_J = 6.0 \cdot 10^{-6}$ erg/cm$^2$, while $B_w \approx 0.12$ Tesla. In the same way as for YBCO we can estimate, that $U_p^{Bi}/U_p^{Tl} = 0.43$. The ratio’s of the 'decoupling' fields of these three compounds are $B_{wTl}/B_{wBi} = 1 : 12 : 250$. The ratio’s of the pinning potentials are $U_p^{Bi}/U_p^{Tl} : U_p^Y = 1 : 2 : 1$, which does not correlate with $B_w$ in Bi2212, Tl2212, and YBCO. On the other hand, the relative values of the Josephson coupling energies are $E_J^{Bi}/E_J^{Tl} : E_J^Y = 1 : 27 : 250$, from which we can conclude that the spread of $B_w$’s over two orders

![Grazing Reflectivity](image_url)
of magnitude is a consequence of the strong material dependence of the interlayer Josephson coupling constant.

As temperature is increased towards Tc, a cross-over may take place to a different type of magnetic field suppression of the JPR, where the pancake vortices become progressively misaligned due to thermal fluctuations. In Ref. [10] it was shown for low fields in the thermal fluctuation regime, that \( \omega J(0,T) - \omega J(B,T) \propto B \) in the low field region, with a gradual downward curvature at higher field values, similar to our experimental data [10]. The numerical calculation for the present case is shown in Fig. 3, for T=70K, using the experimental values for \( \lambda_{ab}(T) = 245 \text{nm} \) [12,20,21], and \( \lambda_c(T) = 24.2 \mu m \) as the (only, experimentally fixed) parameters. We see, that, although the field dependence predicted by the thermal fluctuation model is close to the observations at 70K, still the experimental field dependence is weaker than in the calculation. This is probably due to the fact, that there is still a significant contribution from pinning even at 70K. This is also born out by the fact, that in Fig. 3 there is no indication of a sudden change of the field dependence as a function of temperature. A quantitative theoretical framework of these observations would require a unified theoretical model, which takes into account both the influence of pinning and of thermal fluctuations on the Josephson coupling.

In conclusion, we have studied the c-axis Josephson plasma resonance in Tl2212 and YBCO as a function of temperature and low magnetic field. In the low temperature regime the observed behaviour of Tl2212 fits very well the model of vortex disorder due to weak pinning [11] while above 50 K, good quantitative agreement with model calculations provides evidence for the presence of disorder due to thermally fluctuating pancakes [10]. We attribute the weaker magnetic field dependence of the resonance in YBCO to the lower anisotropy.

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\[ \omega(B,T)^2 / \omega(0,T)^2 \text{ of Tl2212 at 70 K and the theoretical prediction based on Ref. 10 with the the parameters } \lambda_{ab} = 245nm, \lambda_c = 24.2 \mu m \text{ for the in-plane and c-axis penetration depth.} \]

FIG. 4. Magnetic field dependence of \( \omega(B,T)^2 \) normalized to the value at zero field at 4K (field-cooled) in Tl2212 for temperatures from top to bottom: 10K, 20K, 30K, 40K, 50K, 60K, 70K. Inset: 4K data, with a fit to Eq 3 using \( B_{w} = 1.40T \).

FIG. 5. Comparison between the experimental values of \( \omega(B,T)^2 / \omega(0,T)^2 \) of Tl2212 at 70 K and the theoretical prediction based on Ref. 10 with the the parameters \( \lambda_{ab} = 245nm, \lambda_c = 24.2 \mu m \) for the in-plane and c-axis penetration depth.

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