Interlayer Phase Coherence in the Vortex Matter Phases of $Bi_2Sr_2CaCu_2O_{8+y}$

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The interlayer phase coherence in $Bi_2Sr_2CaCu_2O_{8+y}$ was quantitatively determined in a wide field range by using the Josephson plasma resonance (JPR). At the first-order transition (FOT), a novel frequency-independent JPR with sharp resonance width is found, indicating a jump in the interlayer phase coherence. Above the FOT, sample-moving magnetization measurements show an anomaly consistent with the report by Fuchs *et al.* [Phys. Rev. Lett. **80**, 4971 (1998)], where the interlayer phase coherence shows no anomaly. These results suggest the decoupling nature of the FOT, and can rule out the existence of the vortex line liquid state.

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Vortex matter phase diagram in high-T_c superconductors has recently attracted much attention, because it is very rich and complex compared with the conventional mixed-state phase diagram [1]. It has been established experimentally that there exists a first-order phase transition (FOT) line well below the mean-field upper critical field [2–4]. The magnitude of the FOT field depends strongly on the anisotropy of materials [5]; it lies in the 10^4–10^5 G range in less anisotropic $YBa_2Cu_3O_{7-\delta}$ [4] while it is in the 10^2–10^3 G region in highly anisotropic $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO) [5]. In BSCCO, the FOT line terminates at the critical point and is followed by the so-called second peak line [5], where the field dependence of the critical current has a peak. In addition to these lines, recent measurements of flux penetration through a sample surface by Fuchs *et al.* [6] suggested a possible new phase boundary above the FOT, which they labeled as the T_x line. The T_x line tends to merge with the FOT line at high temperatures. The nature of the T_x line, however, remains to be clarified. One possibility is that the new phase below the T_x and above the $T_{\rm FOT}$ line is a disentangled liquid of lines [7,8]. In this case the $T_{\rm FOT}$ line is the melting line and the T_x line is the decoupling line. Another possibility is that the $T_{\rm FOT}$ is a first-order decoupling rather than melting [9], and that the T_x is the melting of a pancake vortex lattice.

The most direct way to clarify the nature of these vortex phases is to investigate the coherence between the layers in each vortex phase. One of the powerful experimental probes for the interlayer coherence is the Josephson plasma resonance (JPR) [10]. The resonance can be used to determine precisely the plasma frequency ω_p along the c axis under a magnetic field. ω_p is a good measurement of the Josephson coupling, and is therefore related to the interlayer phase coherence $\langle \cos\phi_{n,n+1}\rangle$ by

$$\omega_p^2(H,T) = \frac{c^2}{\epsilon_0 \lambda_c^2(T)} \langle \cos\phi_{n,n+1}\rangle (H,T)\,, \qquad (1)$$

where ϵ_0 is the high frequency dielectric constant, λ_c is the c-axis penetration depth, $\phi_{n,n+1}$ is the gauge-invariant phase difference between the layers n and $n+1$, and $\langle\cdots\rangle$ denotes thermal and disorder averaging [11].

In this paper, we determined quantitatively the interlayer phase coherence by using JPR in BSCCO. Comparing the JPR results with the phase transition lines determined by the magnetization measurements in the same crystal, we find that the interlayer phase coherence drastically changes at the FOT and smoothly changes above the FOT, indicating that the decoupling occurs at the FOT and not at the T_x line.

Single crystals of BSCCO were grown by the floating zone method [12]. In this study, we used two crystals having different oxygen content: underdoped (sample A, $T_c = 84.6$ K) and optimally doped (sample B, $T_c = 90.1$ K). We determined vortex phase boundaries by global and local magnetization measurements using a commercial SQUID magnetometer (quantum design, MPMS-XL5) with the reciprocating sample option (RSO) and a micro-Hall probe [13]. The JPR was investigated in sample A by using the cavity perturbation technique with the microwave electric field E_ω parallel to the c axis [14].

Phase transitions.—As discussed by previous reports [2,5,12], the FOT temperature ($T_{\rm FOT}$) was determined by a step in the temperature dependence of the magnetization $M(T)$, and the second peak field ($H_{\rm sp}$) was determined by a peak in the field dependence of the magnetization $M(H)$ at temperatures below the critical point [see Fig. 1(b)]. We extended the $M(T)$ measurements to higher fields. Figure 1(a) shows $M(T)$ measured at high fields (in sample B) in the RSO mode of the SQUID magnetometer with 8 mm scan length. Above the irreversibility temperature ($T_{\rm irr}$), we found a distinct step in the reversible magnetization. If we plot the points of these new anomalies in the H-T phase diagram, the new line lies above the FOT line and tends to merge with the FOT line as shown in Fig. 1(b). Such a magnetization anomaly was also found in sample A, and we compare in Fig. 1(b) the phase transition lines in our samples with the reported transition lines in a slightly overdoped BSCCO ($T_c = 88$ K) by Fuchs *et al.* [6] including the T_x line. The

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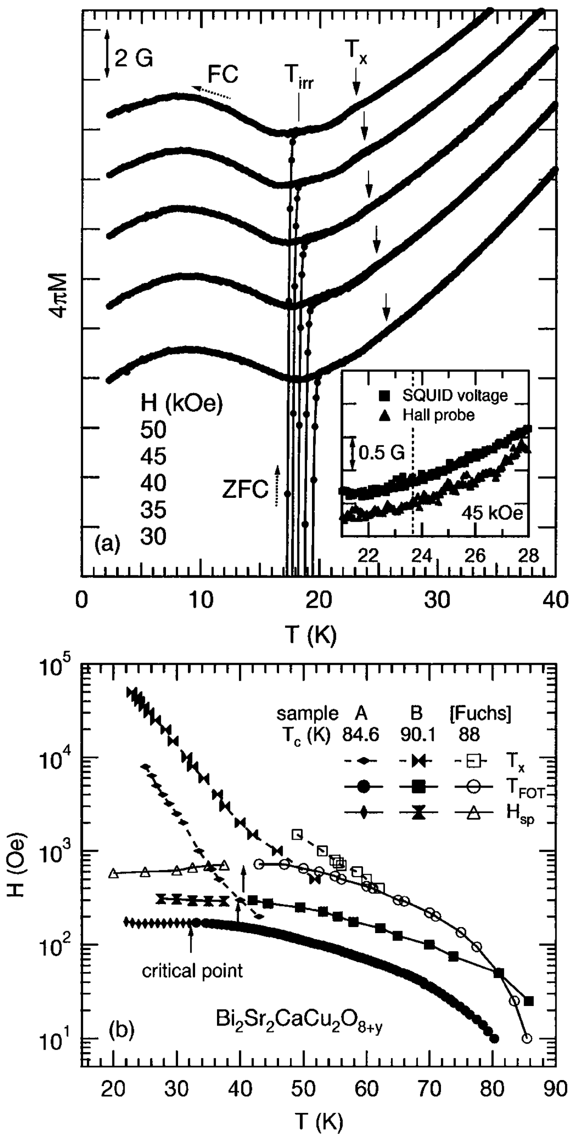

FIG. 1. (a) Temperature dependence of the magnetization in sample B measured by a SQUID magnetometer in zero-field cooling (ZFC) and field cooling (FC) procedures. The sample was scanned with a length of 8 mm. The inset shows the magnetization measured using two different techniques with sample stationary. (b) Phase diagram for samples A and B together with the reported results by Fuchs *et al.* [6].

transition lines systematically depend on the doping level of crystals, and the temperature dependence of our new line is quite similar to the T_x line. Thus we infer that the anomaly found in our measurements has the same underlying mechanism with that of the T_x line, and we also label our line as the T_x line.

We also found that the height of the magnetization step at the T_x line strongly depends on the scan length in the SQUID measurements (not shown), while the position of T_x remains unchanged. We note that the height of the step also depends on the applied field. It should be considered that the SQUID measurements were done in inhomogeneous field distributions. While the magnet we used has a good homogeneity ($\sim 10^{-4}$/cm), the field change during the 8 mm scan is an order of 1 Oe at $H = 10$ kOe. To check whether the transition is of thermodynamically first order, we measured magnetization with sample stationary using two independent techniques. One is the direct recording of the SQUID voltage without scanning the sample [3], and the other is the Hall probe magnetometry [13]. Typical results at 45 kOe are shown in the inset of Fig. 1(a). No anomaly was observed within the resolution (≤ 0.1 G). These results are consistent with previous Hall probe measurements [2,5,12], where no distinct step in magnetization was reported above the FOT. From these results, we interpreted that the anomaly found in the sample-moving magnetization measurements is a sign of a change in the vortex penetration from sample edges due to the small change of the applied field. The magnitude of the field change depends on the scan length and the magnitude of H, which may reflect the height of the apparent magnetization anomaly. This interpretation is consistent with the original explanation by Fuchs *et al.* [6] that the T_x line is a surface-barrier related transition.

Josephson plasma resonance.—We now investigate the JPR in sample A at 11 microwave frequencies which covers all of the vortex phases. Figure 2 shows the microwave absorption as a function of field at 40 K at several frequencies. The resonant peaks were found at H_p, where the plasma frequency ω_p coincides with the microwave frequency ω. Above the FOT, the resonance field H_p decreases with increasing frequency, which is known as an anticyclotronic frequency dependence of the JPR [10]. In contrast, the resonance becomes almost independent of frequency at the FOT, and at the same time the width ΔH_p of the resonance becomes very small. Below the FOT, H_p decreases with increasing frequency again and the resonance becomes broader and hysteretic because of the trapped field in the vortex solid state.

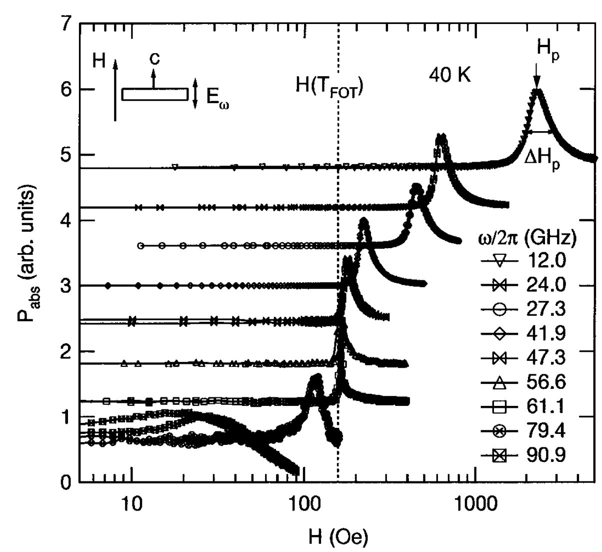

FIG. 2. Microwave absorption as a function of field at several microwave frequencies in sample A at 40 K. All data are normalized arbitrarily and shifted vertically for clarity.

The temperature dependences of the resonance field H_p and the normalized width $\Delta H_p/H_p$ are shown in Fig. 3, together with the transition lines determined in the same crystal. This figure clearly demonstrates that the resonance field H_p is independent of frequency and the width becomes quite sharp at the FOT line. In a range of about 40 to 70 K, for example, H_p at 61.1 GHz (open squares) coincides with that at 56.6 GHz (open triangles) and they exactly follow the FOT line, where $\Delta H_p/H_p$ at these frequencies is quite small. Above 70 K, however, H_p at these frequencies are below the FOT line and show an anticyclotronic frequency dependence.

In contrast to such a novel frequency-independent JPR at the FOT line, we found no definite anomaly both in the temperature and frequency dependences of H_p at the T_x line, which will be discussed later.

Interlayer phase coherence.—Let us analyze these JPR data to extract the interlayer phase coherence using Eq. (1). First, we evaluate the zero-field plasma frequency $\omega_p(0,T) = c/\sqrt{\epsilon_0}\,\lambda_c(T)$, which is plotted in the inset of Fig. 4(a). The temperature dependence of $\omega_p^2(0)$ roughly follows the Ambegaokar–Baratoff-type temperature dependence for the Josephson critical current [15], which is consistent with the previous report in $La_{2-x}Sr_xCuO_4$ [16]. A fit to this temperature dependence of $\omega_p^2(0)$ gives a zero-temperature plasma frequency of 105 GHz, from which we estimate $\lambda_c(0) = 185\ \mu$m by using $\epsilon_0 = 6$ [17]. Second, we fix the temperature and extract the field dependence of the interlayer phase coherence $\langle\cos\phi_{n,n+1}\rangle$ ($\propto\omega_p^2$) using H_p at 11 different frequencies. The result at 35 K is shown in Fig. 4(a) together with positions of the FOT and T_x lines. It is demonstrated that the interlayer phase coherence changes at the FOT. Above the FOT, $\langle\cos\phi_{n,n+1}\rangle$ shows $1/H$ dependence which is consistent with a theoretical calculation

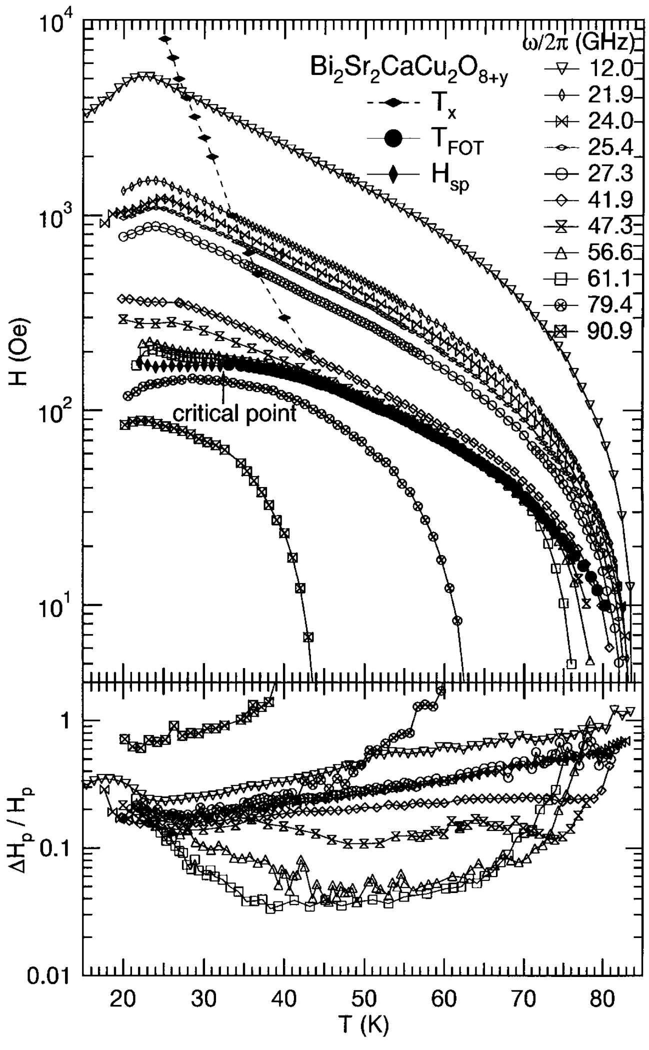

FIG. 3. Upper panel: temperature dependence of the Josephson plasma resonance field H_p at 11 frequencies in sample A. The phase transition lines are also plotted. Lower panel: temperature dependence of the normalized resonance width. Data at 21.9 and 25.4 GHz are omitted for clarity.

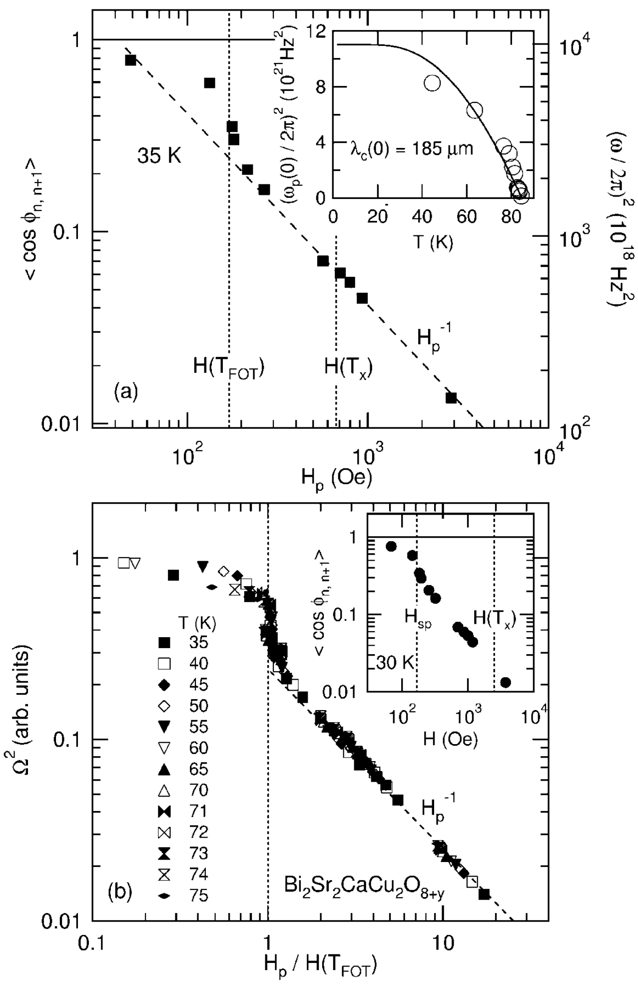

FIG. 4. (a) Field dependence of the interlayer phase coherence at 35 K, which is proportional to ω_p^2. The dashed line is a $1/H$ dependence. The inset shows the temperature dependence of ω_p^2 at zero field. Solid curve is a fit to the Ambegaokar-Baratoff temperature dependence. (b) A scaling for the interlayer phase coherence as a function of the normalized field [see Eq. (2)]. The inset shows the field dependence of the interlayer phase coherence below the critical point.

[18] assuming the decoupled pancake liquid state. Furthermore, at the T_x line there is no definite anomaly in the interlayer phase coherence. From these results we conclude that *the decoupling occurs at the FOT line, not at the T_x line*. Moreover, we note that the first-order decoupling transition was also found in a layered organic superconductor κ-(BEDT-TTF)$_2$Cu[N(CN)$_2$]Br [19].

To see the decoupling transition more clearly, we try a scaling analysis using data at different temperatures. If we use the relation $\omega_p^2 \propto 1/H$ above the FOT, we can separate the temperature and field dependences of plasma frequency by $\omega_p^2(H,T) = g(T)/H$, where $g(T)$ is a temperature-dependent function. If we define

$$\Omega^2 = \omega_p^2 H(T_{\mathrm{FOT}})/g(T), \tag{2}$$

Ω^2 can be scaled by the normalized field $h = H/H(T_{\mathrm{FOT}})$ as $\Omega^2 = 1/h$ above the FOT. We use the temperature dependence of H_p at the lowest frequency (12.0 GHz) as $g(T) = \omega^2 H_p(T)$, where H_p is always above the FOT. The result of the scaling is demonstrated in Fig. 4(b) at temperatures between 35 to 75 K. The $1/h$ scaling can be seen above the FOT, and Ω^2 abruptly changes at the FOT, which just corresponds to the frequency-independent JPR. Now we can clearly conclude that the FOT is the first-order decoupling transition with an abrupt change in the interlayer phase coherence. Note that the interlayer phase coherence below the FOT has a weaker field dependence than $1/H$, suggesting that vortex lines are well coupled (not decoupled) just below the FOT, consistent with the decoupling scenario of the FOT [9].

Such an interpretation can also explain the width of the resonance. At the FOT, the plasma frequency changes dramatically in a very narrow field region, which results in a very sharp JPR at a fixed frequency as observed in our measurements.

Below the critical point, we can also extract the field dependence of interlayer phase coherence. In the inset of Fig. 4(b) we plot $\langle \cos\phi_{n,n+1} \rangle (H)$ at 30 K and compare it with the second peak field (H_{sp}). At about H_{sp}, the interlayer phase coherence strongly changes. This is strong experimental evidence for the decoupling nature of the second peak. Such a loss of interlayer coherence at H_{sp} is consistent with disorder-induced decoupling [20] or entanglement [21] scenarios for the second peak.

Our results clearly indicate that vortices above the FOT line are decoupled in BSCCO, and can rule out the possibility of the line liquid state above the FOT. One of the remaining possibilities is the decoupled solid or supersolid phase, where the pancake has an order in the planes [9,20]. This scenario predicts weak Bragg peaks in the small angle neutron scattering, as observed in recent measurements [22,23]. In this case, the T_x line is the melting of the pancake solid. However, there is no evidence that the T_x line is the thermodynamic phase transition. Thus there remains another possibility that it is related to an unknown effect peculiar to the sample surface.

In summary, we observed a sharp frequency-independent JPR at the FOT indicating the loss of interlayer phase coherence. The sample-moving magnetization measurements revealed a clear but scan-length-dependent anomaly, suggesting the existence of a surface-barrier related transition (T_x line). At the T_x line we found no anomaly in the interlayer phase coherence, which can rule out the possibility of the line liquid state in BSCCO. In view of the fact that the existence of the line liquid state has been proposed in less anisotropic $YBa_2Cu_3O_{7-\delta}$ [8,24], it is important to investigate how the phase diagram depends on the anisotropy of materials.

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