Coupling Transition of the Vortex Liquid in $Bi_2Sr_2CaCu_2O_{8+\delta}$ with Columnar Defects

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The interlayer Josephson coupling in the vortex fluid phase of heavy-ion irradiated $Bi_2Sr_2CaCu_2O_{8+\delta}$ is probed by Josephson plasma resonance. The introduction of columnar defects changes the nature of the vortex liquid dramatically. We show that two types of vortex liquid, the well-coupled and the decoupled pancake vortex liquids, appear in the irradiated crystals. The pancake vortices tend to couple with increasing magnetic field, which is opposite to the pristine crystal. The double resonance peaks appear as a function of field in a narrow temperature range well above the irreversibility line. This implies an occurrence of the coupling transition in the liquid phase. [S0031-9007(97)04422-0]

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The nature of the flux-line structure and the phase transition between different vortex states have become central issues in the study of the physics of the vortex state of superconductors. In high-T_c superconductors (HTSC), strong thermal fluctuations result in a noticeable change in the nature of the vortex state [1]. In sufficiently clean crystals, the vortex solid melts into a liquid through a first-order-phase transition (FOPT), which has been recently confirmed by thermodynamic measurements of $Bi_2Sr_2CaCu_2O_{8+\delta}$ [2] and $YBa_2Cu_3O_{7-\delta}$ [3]. Moreover, several experiments have revealed that the loss of long range out-of-plane correlation of the pancake vortices occurs simultaneously at FOPT [4]. Particularly, in $Bi_2Sr_2CaCu_2O_{8+\delta}$ with extremely large anisotropy, it has been demonstrated that at FOPT the vortex lattice also dissociates into a decoupled pancake liquid in which even short range out-of-plane correlation becomes negligible [5]. Accordingly, almost the entire regime of the liquid phase in $Bi_2Sr_2CaCu_2O_{8+\delta}$ is well described by the concept of the decoupled pancake. On the other hand, it is well established that the introduction of columnar defects (CDs) by the heavy-ion irradiation causes a dramatic enhancement of the out-of-plane correlation of pancake vortices. The introduction of CDs results in the appearance of a second-order Bose-glass (BG) transition line which is shifted to a significantly higher field compared to FOPT of the pristine material [6]. However, despite the fact that there is much experimental evidence to support this BG transition [7], the nature of the vortex liquid above the transition remains unclear. Transport measurements on irradiated $Bi_2Sr_2CaCu_2O_{8+\delta}$ imply that the vortex may move as a linear object rather than as a decoupled pancake [8]. On the other hand, magnetization measurements in the liquid phase suggest that the decoupled pancakes are placed randomly within CDs at low fields [9]. The question is, then, how does the well-coupled liquid dissociate into the liquid of the decoupled pancake with B and T? There are no explicit predictions, nor has there been any detailed experimental investigations of the out-of-plane correlation in the liquid phase of HTSC with CDs.

To understand the nature of the vortex state of HTSC, knowledge of the interlayer Josephson coupling is essential, because it depends strongly on the correlations of pancake vortices in adjacent layers. In this paper, we investigate the Josephson coupling of the vortex liquid phase of $Bi_2Sr_2CaCu_2O_{8+\delta}$ with CDs by means of Josephson plasma resonance (JPR), which enables us to quantitatively determine the magnitude of the interlayer phase coherence [10,11]. We provide strong evidence that the introduction of CDs leads to the appearance of two types of vortex liquid: the well-coupled and the decoupled pancake liquids. We show for the first time that the pancake vortices tend to couple with B, in contrast to the pristine crystal. The result of JPR implies an occurrence of a coupling transition in the liquid phase.

The $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals were grown using the traveling-solvent-floating-zone technique. The crystals were subsequently irradiated at GANIL (Caen, France) with a 5.8-GeV Pb-ion beam aligned parallel to the c axis. Matching fields B_Φ of 0.3 and 1 T were selected. The superconducting transition temperature T_c of the pristine sample was 85.7 K and the irradiation did not change T_c. The microwave electric fields $\mathbf{E}_{ac}$ of 30 and 45 GHz were applied parallel to the c axis in TE_{102} mode rectangular Cu cavities to generate the Josephson plasma oscillation [10]. The measurements of the angular dependence of the resonance were carried out in the split pair magnet that provides a transverse field. The microwave cavity was rotated in the magnet with a precision of 0.01°, keeping $\mathbf{E}_{ac} \parallel c$.

The Josephson plasmon frequency ω_{pl} is related to the maximum Josephson critical current j_J by $\omega_{pl} = (8\pi^2 c s j_J/\epsilon_0\Phi_0)^{1/2}$, where ϵ_0 is the dielectric constant, s is the layer spacing, and Φ_0 is the flux quantum. The Josephson plasmon strongly couples to the vortex. The field dependence of the plasmon frequency is written as [10,12,13]

$$\omega_{pl}^2(B,T) = \omega_{pl}^2(0,T)\langle\cos\varphi_{n,n+1}\rangle . \quad (1)$$

Here $\langle\cos\varphi_{n,n+1}\rangle$ represents the thermal and disorder average of the cosine of the gauge invariant phase difference between layer n and $n+1$. When the pancakes form straight lines along the c axis, $\langle\cos\varphi_{n,n+1}\rangle$ is equal to unity. A displacement of the pancake vortices reduces $\langle\cos\varphi_{n,n+1}\rangle$ from unity. With increasing disorder, $\langle\cos\varphi_{n,n+1}\rangle$ decreases monotonically. In a layered superconductor, a strong suppression of $\langle\cos\varphi_{n,n+1}\rangle$ and hence ω_{pl} occurs due to thermal fluctuations and pinning in the fields perpendicular to the layers [12–14]. When ω_{pl} coincides with the microwave frequency ω in the fields, a resonant absorption of the microwave occurs. Thus JPR gives direct information of the vortex alignment along the c axis through $\langle\cos\varphi_{n,n+1}\rangle$.

Figure 1 shows the T dependence of the resonance field B_0 in $\mathbf{B} \parallel c$ at 45 GHz for irradiated samples with $B_\Phi = 0.3$ and 1 T together with B_0 for the pristine crystal. The resonance was measured under field-sweep (FS) and field-cooling (FC) conditions. The resonance was measured by sweeping B at a constant T for FS, while

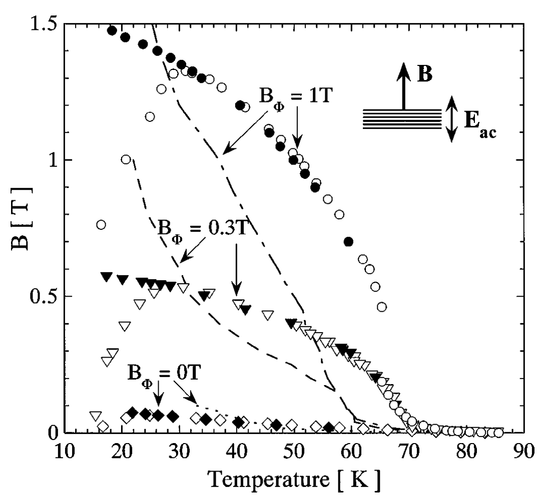

FIG. 1. T dependence of B_0 for an irradiated crystal with $B_\Phi = 0.3$ (triangles) and 1 T (circles) at 45 GHz together with B_0 for a pristine crystal (diamonds). The magnetic field is applied parallel to the c axis. Open and filled symbols represent the data taken at FS and FC conditions, respectively. The dotted, dashed, and dash-dotted lines represent IL for $B_\Phi = 0, 0.3$, and 1 T, respectively.

for FC it was measured by sweeping T at a constant B. The introduction of CD causes a striking enhancement of B_0 and dramatically changes the T dependence of B_0 from a concave to a convex line at low temperatures. The enhancement of B_0 provides direct evidence that the pancakes tend to form straight lines along the c axis due to CDs. In Fig. 1 irreversibility lines (IL), determined by magnetization measurements for corresponding crystals, are also plotted. Irradiation causes a large shift of IL to a higher field [15]. It has been suggested that the vortices are in the BG phase at low temperatures and below B_Φ and that BG melts into the liquid near IL [8]. Below IL, B_0 for FS decreases rapidly with decreasing T. Below IL, it has been demonstrated that the FS leads the vortex system to a strong nonequilibrium state [5]. In this paper we focus on the resonance above IL, where the vortices are in the equilibrium state and the FS data coincide with the FC data. The resonance below IL has been discussed quite recently by Hanaguri *et al.* [16].

Above IL, there are three characteristic regimes of resonance. In the regime $B > B_\Phi$, B_0 decreases gradually with T. The first feature appears at $B \simeq B_\Phi$, the point at which the slope of the T dependence of B_0 changes slightly. At $B < B_\Phi$, an increase in temperature causes a rapid decrease for B_0, indicating a rapid decrease in the strength of the Josephson coupling. The second feature appears at a characteristic temperature ~70 K, above which B_0 of the irradiated crystals approaches closely to that of the pristine crystal. Figures 2(a) and 2(b) depict a resonance near 70 K at 45 GHz for $B_\Phi = 0.3$ and 1 T, respectively. For $B_\Phi = 0.3$ T, the resonance shows an anomalous broadening between 67 and 69 K. This anomaly can be seen more strikingly for $B_\Phi = 1$ T, in which another resonance peak with a lower field appears at ~63 K and two resonance peaks coexist. A further increase in temperature causes a rapid decrease in the intensity of the higher resonance line.

The double resonance peaks may be caused by an inhomogeneous distribution of CDs inside the crystal. However, we can rule out such a possibility for the following reasons. First of all, averaging of the JPR frequency takes place on the scale of the Josephson length, $\lambda_J = \gamma s$ (>5000 Å) [13]. Inhomogeneity in CDs concentration on this or a smaller scale leads to a single peak in JPR but with some line broadening. At $B_\Phi =$ 1 T the average distance between CDs is 450 Å and the scale of inhomogeneity in CDs concentration is about the same. Thus, inhomogeneity cannot lead to a multiple peak structure in JPR. Second, the observation of the double resonance is restricted to a narrow temperature range. Finally, this anomaly is observed in all of the crystals we prepared. We have therefore concluded that the double peaks are intrinsic to a crystal with CDs.

We next discuss the double peak structure and its importance for understanding the nature of the vortex liquid. At first we demonstrate that the resonance at

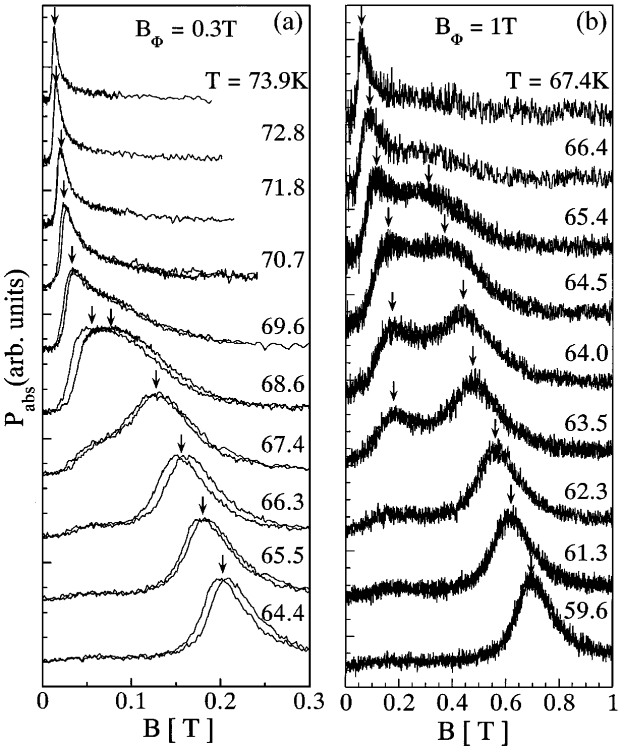

FIG. 2. Josephson plasma resonance for the crystals with (a) $B_\Phi = 0.3$ T and (b) $B_\Phi = 1$ T at 45 GHz at high temperatures. The magnetic fields are swept from $+7$ to -7 T through zero field ($\mathbf{B} \parallel c$). The resonance line in the positive and negative fields coincides almost exactly. The arrows indicate the resonance peaks.

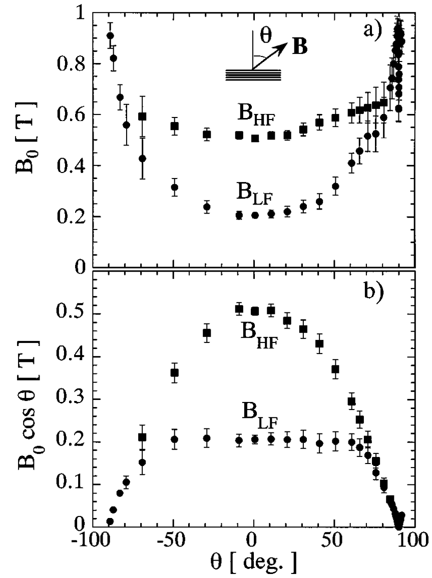

FIG. 3. (a) Angular dependence of the lower ($B_{\rm LF}$, filled circle) and higher ($B_{\rm HF}$, filled squares) resonance fields at 63.5 K in Fig. 2(b). (b) Same data plotted as a function of the field component parallel to the c axis, $B_0 \cos\theta$.

higher fields occurs in the well-coupled liquid phase while the resonance at lower fields occurs in the decoupled pancake liquid phase. Figures 3(a) and 3(b) show the angular dependence of the higher and lower resonance fields for $B_\Phi = 1$ T at 63.5 K. Here θ is the angle between the c axis and **B**. When **B** is tilted away from the c axis, the lower resonance field increases rapidly. On the other hand, the higher resonance field barely increases with $|\theta|$ for $|\theta| \lesssim 60°$. Both resonance lines merge at $|\theta_c| \sim 80°$. Further increase of $|\theta|$ increases B_0 rapidly. The resonance field displays a reentrant cusp when **B** is very close to alignment with the *ab* plane within $\pm 2°$. This phenomena is closely related to the formation of Josephson vortices in a parallel field [11,12]. The fact that the higher resonance is insensitive to the field direction indicates that *the pancake vortices are well coupled along the c axis at high fields.* In Fig. 3(b) the field component perpendicular to the layers, $B_0 \cos\theta$, is plotted as a function of θ. The lower resonance is well scaled by $B_0 \cos\theta$ for $|\theta| \lesssim 60°$. Moreover, although we do not show it here, the ω and T dependence of the lower resonance field above $\sim$70 K for both $B_\Phi = 0.3$ and 1 T crystals is well described by the high temperature expansion theory of Koshelev [12], which assumes a decoupled pancake liquid phase. These results indicate that the vortices are 2D in nature, *i.e., in the decoupled liquid phase at low fields* [17]. Thus the resonance in an oblique field provides strong evidence of the existence of two types of vortex liquids.

An important and unexpected feature in Figs. 3(a) and 3(b) is that the pancake vortices tend to *couple* with B. This tendency is opposite to the unirradiated crystal in which vortex lines tend to decouple with B [14]. Such behavior in the irradiated crystals may be explained qualitatively by the following picture. Decoupling of pancakes above IL at $B \ll B_\Phi$ is caused by a gain in entropy when vortices randomly occupy positions available inside CDs. As B approaches B_Φ the concentration of unoccupied sites inside CDs drops and the gain in entropy decreases. Then attractive interaction of pancakes in different layers drives the system back to the aligned phase. Detailed discussion of this picture is given in Ref. [18].

The multiple peak structure in the resonance can be accounted for naturally by considering an *increase* of $\omega_{\rm pl}$ with B in some regime. If $\omega_{\rm pl}$ jumps to *higher* frequency at the coupling transition field $B_{\rm cp}$, as schematically shown in the inset of Fig. 4(a), the resonance occurs twice when we sweep B with a fixed frequency between ω_1 and ω_2. On the other hand, if $\omega_{\rm pl}$ increases without an accompanying discontinuous jump, a third peak, in which B_0 increases with frequency, should be observed between the two other main peaks. The former case implies an occurrence of the first order phase transition because the Josephson coupling strength changes discontinuously. On the other hand, the latter case suggests a strong crossover or continuous phase transition. In the present experiment, we did not observe a third peak in any

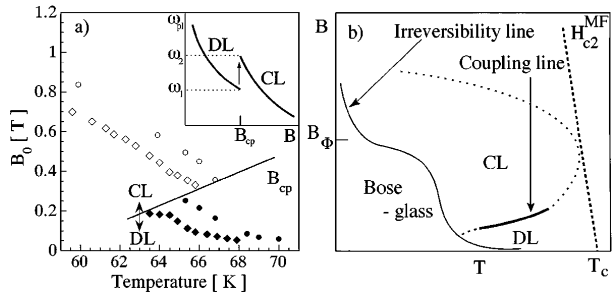

FIG. 4. (a) T dependence of B_0 for $B_\Phi = 1$ T at 30 (circles) and 45 GHz [diamonds, Fig. 2(b)]. Filled and open symbols represent the lower and higher resonance branches, respectively. The thin solid line represents the coupling line that separates the coupled-liquid (CL) and decoupled-liquid (DL) phases. Inset: Schematic figure of the B dependence of ω_{pl}. ω_{pl} shows a jump at the coupling point B_{cp}. (b) The B-T phase diagram of the coupled liquid (CL) and decoupled liquid (DL). The solid line displays the coupling line determined by the result seen in (a). For detail, see the text.

crystals. Nevertheless, we note that the double resonance is only a necessary rather than a sufficient condition of the first order transition, because the plasma frequency is not a thermodynamic quantity although it is very sensitive to the interlayer coupling strength. This transition has never been detected by magnetization measurements [9]. The main reason for this may be that the transition occurs deep inside the reversible magnetization regime where the magnetization is extremely small. Moreover, the change in magnetization is expected to be very small because the Josephson energy is a small part of the total free energy. Therefore very precise thermodynamic measurements are needed to uncover the existence of the phase transition.

The jump of ω_{pl} in the ω-B plane corresponds to the jump of B_0 at the coupling line in the B-T plane. In this case, the end points of the resonance branches of the coupled and decoupled liquids should lie on the coupling line. Figure 4(a) displays the resonance fields for $B_\Phi = 1$ T at 30 and 45 GHz. The end points for both frequencies lying on the same coupling line seems to be consistent with a discontinuity in ω_{pl}. B_{cp} increases gradually with increasing T. We finally discuss the vortex phase diagram inferred from the present results [Fig. 4(b)]. Further decrease of B from the decoupled liquid phase should lead to the frozen vortex state in which pancakes form a line crystal inside CDs. It appears that IL coincides with this liquid-solid melting line. If the melting and decoupling occur at the same time as that of the pristine material [18], the coupling line would merge with IL with decreasing B. At $B \gg B_\Phi$, on the other hand, the vortices should be decoupled again because the influence of CDs becomes negligible. Consequently, B_{cp} increases with decreasing T above B_Φ. Thus the reentrant behavior of the coupling state is expected.

In summary, the introduction of CDs leads to the appearance of two types of vortex liquid in $Bi_2Sr_2CaCu_2O_{8+\delta}$. The pancake vortices tend to couple with B. The double resonance peaks appear in a narrow temperature range well above the irreversibility line. This implies an occurrence of the coupling transition in the liquid phase.

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