Sharp Magnetoabsorption Resonances in the Vortex State of $Bi_2Sr_2CaCu_2O_{8+\delta}$

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We report the observation of narrow resonances in the absorption of mm wavelength radiation (30 to 50 GHz) in the vortex state of $Bi_2Sr_2CaCu_2O_{8+\delta}$. When the applied field **B** ($\parallel$ **c**) is swept at fixed frequency ω, the absorption displays two distinct Lorentzian peaks at the resonance fields B_0 and B_1. The resonance frequency decreases with increasing field, consistent with anticyclotronic behavior. At fixed ω, B_0 and B_1 also vary strongly with temperature T. B_0 and B_1 increase to a sharp maximum when T crosses the vortex solid-to-liquid transition line inferred from resistivity results. The coupling of cyclotron resonance with collective modes giving rise to an anticyclotronic mode is discussed.

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The direct observation of electronic absorption resonances (such as cyclotron absorption) in type II superconductors should provide a valuable way to probe properties of the vortex state. Such experiments are not feasible in low-T_c type II superconductors because materials with large upper critical fields H_{c2} (e.g., $A15$'s) are difficult to prepare with long electron mean free paths. In the cuprate superconductors, however, the situation is promising. Electronic lifetimes τ have been estimated from several experiments. In zero field, the value of τ near 4 K is estimated to be 6 ps in single-crystal 90 K $YBa_2Cu_3O_{7-\delta}$ (YBCO) [1]. In the vortex state, viscosity measurements provide a value for τ in the vortex core of 6 ps in 90 K YBCO and 2 ps at 3 K in 60 K YBCO [2]. The transmission of circularly polarized far-infrared radiation (50–200 cm^{-1}) was measured in YBCO thin films by Karrai *et al.* [3], who interpret their spectra as the high-frequency tail of a cyclotron resonance occurring at much lower frequencies. Because the spacing between Landau levels corresponds to only a few cm^{-1} in a 10-T field, we have undertaken a search with radiation in the microwave region. In the window 20–90 GHz, one may hope to observe transitions between discrete levels as true *resonances* in a field-swept experiment. The experiment of Matsuda *et al.* [2] demonstrated that bolometric techniques can detect the small (nW) absorption of 30 GHz radiation in the vortex state of YBCO crystals at low temperatures. Extending the investigation to single-crystal $Bi_2Sr_2CaCu_2O_{8+\delta}$ ("Bi:2212"), we have uncovered remarkably sharp peaks in the absorption. By independently varying the magnetic field B, frequency ω, and temperature T, we verify that the peaks correspond to the resonant excitation of an electronic mode that is coupled strongly to the vortex lattice. The mode displays novel characteristics qualitatively distinct from free-electron cyclotron absorption. In particular, the temperature dependence of the resonance fields reveals a line in the phase diagram of the vortex state. This line coincides with the solid-to-liquid transition line previously identified from dc picovoltametry measurements [4]. We compare below our resonance features with those inferred by Karrai *et al.* [3].

In the bolometric technique, the crystal is placed in a waveguide and exposed to microwave radiation modulated at a frequency of 7 Hz using a Dicke switch [2]. Absorption of the microwave by the sample produces a small temperature oscillation which is picked up by a bolometer (a flake of carbon) using phase-sensitive detection. To avoid microwave heating of the Ag contact pads on the bolometer, the latter is placed outside the waveguide, but thermally anchored to the sample by a sapphire substrate (inset, Fig. 1). The sample is glued to the sapphire with Omegabond 200. With an incident power of 1–10 mW, we are able to detect 1–10 nW absorption by the sample below 30 K. Most of the measurements are made with high-power Gunn-diode sources at 30 and 47.3 GHz. For continuous coverage between 30 and 50 GHz a sweeper (HP 8690B) is used. We verified that we were always in the linear-response regime by varying the incident microwave power.

Figure 1 shows the absorption of microwave radiation at 47.3 GHz plotted against the field **H** applied normal to the a-b plane of Bi:2212 (in sweep-up and -down traces). In addition to the main resonant peak at B_0 ($\sim$2 T), there exists a secondary peak (at $B_1 \sim 0.5$ T). The slight hysteresis results from trapped flux in the crystal (in all subsequent figures, we display only the sweep-up trace). In the ten crystals of Bi:2212 studied, we observe these peaks in eight of them. In the remaining two, the widths are so broad that only vestigial "kinks" in the traces remain at B_0 and B_1. Between crystals, there exists a 30% variation in the values of B_0 and B_1 for fixed ω and T (this also argues against free-electron cyclotron resonance). However, the temperature dependence is closely similar in all crystals that have sufficiently well-resolved resonances. By performing similar studies with

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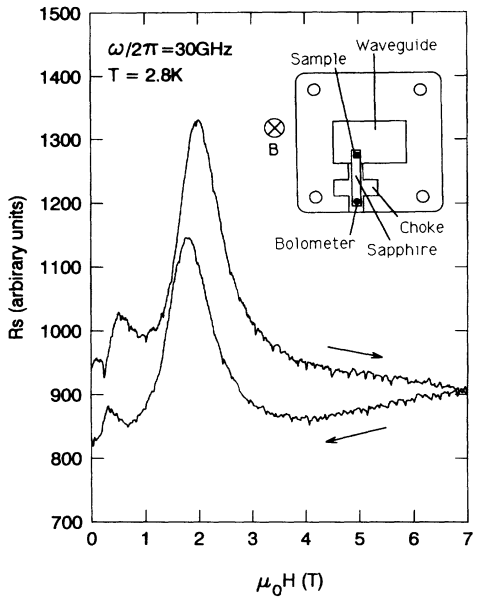

FIG. 1. The surface resistance R_s versus magnetic field observed at 30 GHz in $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystal (sample A) at 2.8 K. The absorption shows two prominent peaks. The slight hysteresis between sweep-up and -down traces is caused by flux trapping in the crystal. The crystal (c axis $\parallel$ **B**) is supported inside the waveguide by a thermally isolated sapphire plank (see inset). Microwave power at the bolometer is attenuated by the choke pattern cut into the flange.

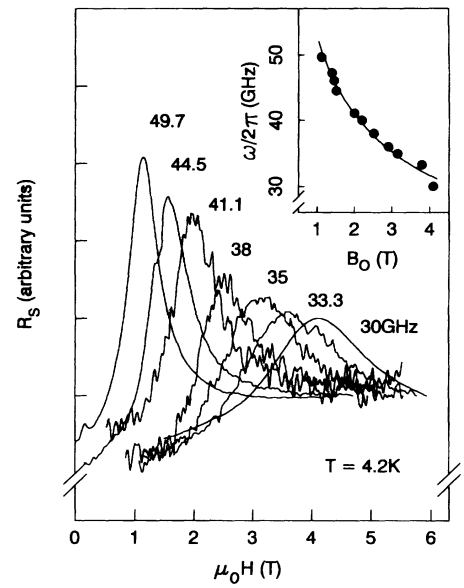

FIG. 2. A series of surface-resistance traces versus field in sample C′ for incident microwave frequency between 30 and 50 GHz, with T fixed at 4.2 K (main panel). To compensate for the varying power of the sweeper versus ω, we have normalized the curves so that the areas under the resonance are roughly equal. The inset shows the ω dependence of B_0. The solid line is a guide to the eye.

the empty waveguide, or with Bi:2212 replaced by a gold film or stainless steel pad, we have eliminated an extraneous origin for the resonances. The most convincing evidence, however, is the reproducibility of the B_0 versus T profile and the identification of a phase boundary line that was previously located by dc resistivity.

To determine the dispersion of the resonant mode, we have repeated the field traces at 11 frequencies between 30 and 50 GHz (focusing on the B_0 peak). For free electrons the cyclotron frequency $\omega_c = eB/m^*$ increases linearly with B (m^* is the effective mass and e the charge). In our experiment, however, quite the opposite behavior is observed (see Fig. 2). At $\omega = 30$ GHz, the resonant field equals 4.5 T at 4.2 K. As the frequency is increased to 50 GHz, B_0 falls monotonically to 1.1 T (inset, Fig. 2). A decreasing ω with increasing field usually signals the excitation of an "anticyclotronic" mode (see below). We remark that the systematic shift of B_0 as ω is tuned from 30 to 50 GHz provides rather conclusive evidence that the peak corresponds to resonant absorption in the sample.

A second unexpected feature of the resonance is its strong temperature dependence. Holding the frequency fixed (at 30 or 47.3 GHz), we have taken field traces at temperatures between 2.8 and 30 K. With increasing temperature, the peak at B_0 initially moves to higher fields (traces at 2.8 to 13 K in Fig. 3). Above 15 K, however, B_0 turns around and decreases with T (traces at 18 and 20 K). The nonmonotonic variation with temperature has been measured in a number of crystals (we display five of these in Fig. 4). In all crystals, the temperature profiles are remarkably similar. B_0 displays a distinct cusp at the temperature T_0 ($\sim$15 K in sample A). The weaker resonance B_1 has a similar profile (B_1 attains its maximum $T_1 \sim 20$ K in sample A). As stated above, the magnitudes of B_0 and B_1 for fixed ω and T are sample dependent. This variation is fortunate since it exposes an important feature in T_0 and T_1. Scrutiny of the complete data set shows that T_0 is low if the extremal value of B_0 is large and vice versa (the same is true of T_1). In Fig. 4, the dotted line connecting the maxima of B_0 and B_1 defines a smooth line $H_m(T)$ in the H-T phase diagram. For comparison, we also display the data points from Safar *et al.* [4] which define the solid-to-liquid phase boundary obtained from picovoltametry measurements. Given the uncertainties in both measurements, we are persuaded that $H_m(T)$ defines the same phase boundary. Thus, the temperature dependence of the resonance fields B_0 and B_1 changes qualitatively at the phase boundary between the two vortex states.

In Fig. 3, it is also apparent that the width of the main resonance ΔB_0 is a nonmonotonic function of temperature. Between 2.8 and 12 K, the width more than doubles. However, in the traces at 18 and 20 K, the width narrows again. By fitting a Lorentzian to the main resonance in

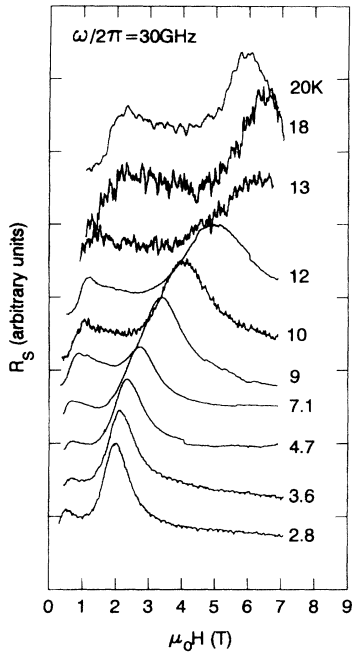

FIG. 3. A series of R_s vs field traces in sample A taken at several temperatures between 2.8 and 20 K, with $\omega/2\pi$ fixed at 30 GHz. Both the strong and weak resonances (B_0 and B_1) change with T in a nonmonotonic way (see text). The linewidth increases with T up to 13 K, and then narrows significantly at higher temperatures. The curves have been normalized to compensate for the decreasing sensitivity of the bolometer at high temperatures.

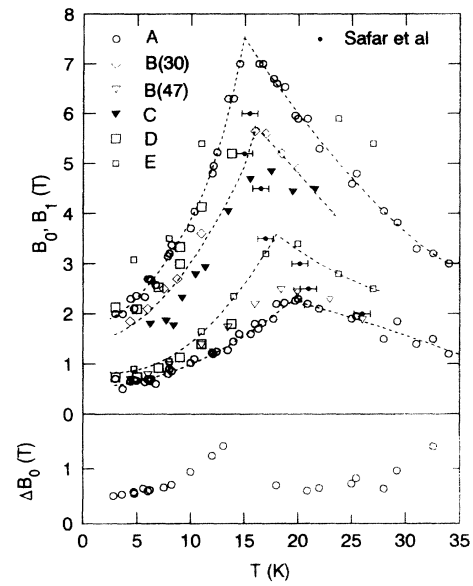

FIG. 4. (Upper panel) The temperature dependence of the resonance fields measured in five crystals of Bi:2212. Samples A and D were measured at 30 GHz, while C and E were measured at 47.3 GHz. Sample B, denoted by B(30) and B(47), was measured at both frequencies. In samples with the two peaks clearly resolved (A, D, and E), the same symbol (e.g., open circles for A) is used for both B_0 and B_1. The point at the higher field always represents B_0. Broken lines are drawn to guide the eye. The dotted line connecting all the cusps coincides with the solid-to-liquid transition points (solid circles) of Safar *et al.* [4]. The lower panel displays the T dependence of the linewidth ΔB_0 in sample A measured at 30 GHz.

sample A, we have extracted values for ΔB_0 and plotted them in the lower panel in Fig. 4 (ΔB_0 cannot be reliably determined between 14 and 17 K because B_0 exceeds our maximum field). Between 2.8 and 14 K, ΔB_0 increases monotonically. However, as the phase boundary line is crossed, ΔB_0 decreases abruptly before increasing again. This sharp change indicates that the relaxation processes responsible for the line broadening may be quite different in the two regimes. The behavior of the linewidth provides further evidence that the resonance is coupled to the vortex lattice and sensitive to changes associated with crossing the phase boundary. Interestingly, the T dependence of the linewidth is different on the two sides of the transition. Approaching the boundary from the low-temperature side, ΔB increases rapidly, whereas from the high-temperature side it decreases slowly to a minimum before rising rapidly. This suggests a cusp or discontinuity at the transition. In contrast, B_0 itself increases for both approaches. The close fit of the line shape by a Lorentzian also allows an estimate of the damping parameter γ_0 (via $\omega/\gamma_0 \sim B_0/\Delta B_0$). At 4.3 K, ΔB_0 varies from 0.87 T at 30 GHz to 0.28 T at 50 GHz, which implies that γ_0 increases from 1.3 to 2.8 cm^{-1} between the two frequencies.

We next discuss models that have guided our thinking about the experiment. An important feature of our results is the decrease in the resonance energy with increasing field. The appearance of such anticyclotronic modes seems pervasive whenever a free-carrier cyclotron mode couples to a resonance mode in the system [5]. The simplest case is the example of electrons trapped in a weak central-force potential (for example, in quantum dots [6]). In a field, the coupled modes are given by the roots of $\omega^2 - \omega\omega_c - \omega_{\mathrm{pot}}^2 = 0$, where ω_{pot} is the harmonic frequency of the potential. The lower-frequency mode, $\omega_- = (\omega_c/2)[1 - (1 + 4\omega_{\mathrm{pot}}^2/\omega_c^2)^{1/2}]$, represents a resonance that decreases with field, and a sense of circulation opposite to that of free cyclotron motion (the higher root ω_+ is cyclotronic and approaches ω_c at high fields). A system that bears closer resemblance to our problem is the Wigner crystal (or charge density wave) in 2D [7]. In zero field, the electron crystal has two collective excitations, an acoustic mode linear in the wave vector q, and a plasmon ($\sim\sqrt{q}$). In a magnetic field the two modes hybridize to produce a high-energy mode near ω_c and a second low-lying mode that disperses as $\omega(q,B) \sim \Omega^2(qa)^{3/2}/\omega_c$ (Ω is a frequency characterizing the lattice stiffness and a the lattice spacing). Again, the lower mode decreases with increasing B [7]. The ω vs. B behavior shown in Fig. 2 suggests that our

resonance is anticyclotronic in character. In type II superconductors, such modes may exist as low-lying and long-lived collective excitations of the vortex lattice, in analogy with modes in the Wigner crystal. To verify this hypothesis, we intend to go to higher frequencies to detect the upper branch of the hybrid mode.

In their far-infrared transmission experiment on thin-film YBCO Karrai *et al.* [3] and Choi *et al.* [8] interpret their high-frequency spectra (40–220 cm^{-1}) as the high-frequency tail of a cyclotron-active resonance occurring at much lower ω (the cyclotron mass inferred, $m_c \sim 3.1 m_0$ corresponds to a resonance at 4.3 cm^{-1} in a 14-T field). If we extrapolate our dispersion in Fig. 2 to 14 T, we expect the resonance to occur at 19 GHz = 0.65 cm^{-1}, about a factor of 7 lower than their inferred frequency. Moreover, our damping parameter γ_0 is much smaller than that of Karrai *et al.* (1–3 cm^{-1} versus 40 cm^{-1}). In view of these differences and the different cuprates investigated, our resonance line seems unrelated to that proposed by Karrai *et al.*

Theoretical issues in cyclotron absorption in vortex systems have been discussed by Hsu [9]. When pinning of vortex lines is important, Hsu finds that the oscillator strength in the core polarization mode is shifted to a cyclotron-active mode at $\omega = \omega_c + \omega_{\mathrm{pin}}^2/\Omega_0$ (Ω_0 is the level spacing inside the core). This would predict a resonance that increases with field, unless ω_{pin} is assumed to decrease very strongly with B. On general grounds, however, a resonance that is determined by a pinning frequency should be very broad because of the random distribution of pins. The sharpness of our peaks argues against a pinning-frequency interpretation. Moreover, it is unclear why ω_{pin} should vary with temperature as shown in Fig. 4.

Our present conclusion is that the observed peaks represent a mode that is intrinsic to the vortex system. As discussed above, the systematic shift of the peak as ω increases from 30 to 50 GHz provides clear evidence that we are observing a *resonance* in the absorption. Further, the temperature dependence in Fig. 4 and the energy scales involved indicate that the excitation involves a cyclotron mode coupled to a collective excitation in the vortex lattice. As discussed above, a low-lying, anticyclotronic mode, with a dispersion similar to that in Fig. 2, comes out naturally from such hybridization [5,7]. The most interesting feature is the sharp change in behavior of both the resonant energy and the linewidth as the vortex transition line is crossed. The cusplike maximum displayed by B_0 suggests that the resonant mode is sensitive to both the correlation length and the elastic modulus of the lattice. On the high-temperature side of the transition, the linewidth narrows rather abruptly before increasing again with T. The narrowness of the resonance line (equivalent to lifetimes of 10–20 ps) is in itself a puzzle. At our highest temperature 30 K, the ratio $\hbar\gamma_0/k_B T \sim 0.15$, i.e., the observed width is only 15% of the width expected from thermal broadening, suggesting that the mode is only weakly coupled to the phonon bath.

To our knowledge, an excitation mode in the vortex state with features reported here has not been anticipated in any model. Its existence poses a challenge to our understanding of the vortex state in the cuprates. Further, there exist few techniques to measure lifetimes in the vortex state directly. It may be possible to glean this information from the linewidth. Thus, aside from the intrinsic interest of understanding the origin of these resonances, there is some promise that the excitation will serve as a powerful diagnostic of the vortex state.

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[1] D. A. Bonn *et al.*, Phys. Rev. B **47**, 11 314 (1993).
[2] Y. Matsuda, N. P. Ong, Y. F. Yan, J. M. Harris, and J. B. Peterson, Phys. Rev. B **49**, 4380 (1994).
[3] K. Karrai *et al.*, Phys. Rev. Lett. **69**, 355 (1992).
[4] H. Safar, P. L. Gammel, D. J. Bishop, D. B. Mitzi, and A. Kapitulnik, Phys. Rev. Lett. **68**, 2672 (1992).
[5] Let u_1 and u_2 represent two normal modes of the system with propagators $-\omega^2 + \Omega_1^2$ and $-\omega^2 + \Omega_2^2$, respectively, in zero field. A field couples the two modes via the equations $(-\omega^2 + \Omega_1^2)u_1 - i\omega\omega_c u_2 = 0$ and $i\omega\omega_c u_1 + (-\omega^2 + \Omega_2^2)u_2 = 0$. One of the coupled modes, $\omega \sim \Omega_1\Omega_2/\omega_c$, is anticyclotronic.
[6] Ch. Sikorski and U. Merkt, Phys. Rev. Lett. **62**, 2164 (1989); P. A. Maksym and Tapash Chakraborty, Phys. Rev. Lett. **65**, 108 (1990).
[7] B. G. A. Normand, P. B. Littlewood, and A. J. Millis, Phys. Rev. B **46**, 3920 (1992).
[8] E. Choi, H. T. S. Lihn, H. D. Drew, and T. C. Hsu (to be published).
[9] Theodore C. Hsu, Phys. Rev. B **46**, 3680 (1992); Physica (Amsterdam) **213C**, 305 (1993).