Experimental Evidence for Flux-Lattice Melting

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A low-frequency torsional oscillator has been used to search for flux-lattice melting in an untwinned single crystal of $YBa_2Cu_3O_{7-\delta}$. The damping of the oscillator was measured as a function of temperature, for applied magnetic fields in the range $0.1 \le H \le 2.3$ T. A remarkably sharp damping peak has been located. It is suggested that the temperature of the peak corresponds to the melting point of the Abrikosov flux lattice.

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Phase transitions of assemblies of vortices in high-T_c superconductors are of much current interest. A number of such transitions have been considered theoretically [1-3], including melting of the flux lattice [4]. The first report [5] of a vortex phase boundary, in $YBa_2Cu_3O_{7-\delta}$, identified it with flux-lattice melting, but phase boundaries inferred from subsequent experiments [6-8] depart from theoretical predictions for such melting and have been interpreted in terms of melting of a pinned vortex glass [1]. Over and above this uncertainty as to the character of the solid vortex phase, Brandt, Esquinazi, and Weiss [9] have argued that all such boundaries can be explained by using the concept of thermally activated depinning, without invoking a phase transition of any sort. Further experiments have provided quantitative support for their approach [10,11]. A comprehensive account of this controversial area has been provided by Xu and Suenaga [12].

In view of the complications known to be associated with pinning, it is surprising that there have been no reports of vortex transitions in the cleanest available high-T_c material, namely, untwinned single-crystal $YBa_2Cu_3O_{7-\delta}$. In this Letter we describe a mechanical experiment using such a sample. It will be demonstrated that the absence of pinning in the temperature range of interest allows one to probe a new physical regime in which thermally activated depinning plays no significant role. Nonetheless, a sharp vortex transition is still observed, and evidence will be presented suggesting that it corresponds to flux-lattice melting.

All the crystals of $YBa_2Cu_3O_{7-\delta}$ that have been used previously for phase boundary studies have been twinned. In a recent torque magnetometry investigation [13], an untwinned single-crystal sample exhibited no magnetic irreversibility larger than the experimental uncertainty ($<1\%$) in a field of 1 T and in the temperature range 80 K $< T < T_c$. To our knowledge, this is the most reversible magnetic behavior that has yet been reported in single-crystal $YBa_2Cu_3O_{7-\delta}$. The same sample was used in the present study. In addition, a very-low-frequency torsional-oscillator method has been developed. The experimental setup is shown in Fig. 1. The sample is in the form of a thin flat plate of dimensions $0.02\times0.17\times0.17$ mm^3. The magnetic field is produced by a conventional electromagnet, and applied along the **c** axis of the crystal. The frequency of angular motion ($=1.1\times10^{-1}$ Hz) is determined by the torsional constant k of the tungsten suspension ($=3.5$ dyn cm/rad) and the moment of inertia I of the system ($=7.1$ g cm^2). In a single measurement, the temperature and field are held constant and the suspension is given an initial angular displacement of $\sim0.1°$ from its equilibrium position. It is then released and the resulting (lightly) damped oscillations monitored with an analog optoelectronic system. Assuming a damping torque of the form $\eta\, d\theta/dt$, the damped oscillations are given by

$$\theta(t) = \theta_0 e^{-(\eta/2I)t}\cos(\omega t + \delta)\,. \quad (1)$$

The output of the detection system is sampled every $\frac{1}{10}$ s for 50 s and the resulting 500 data points fitted by the above solution with a least-squares program, providing

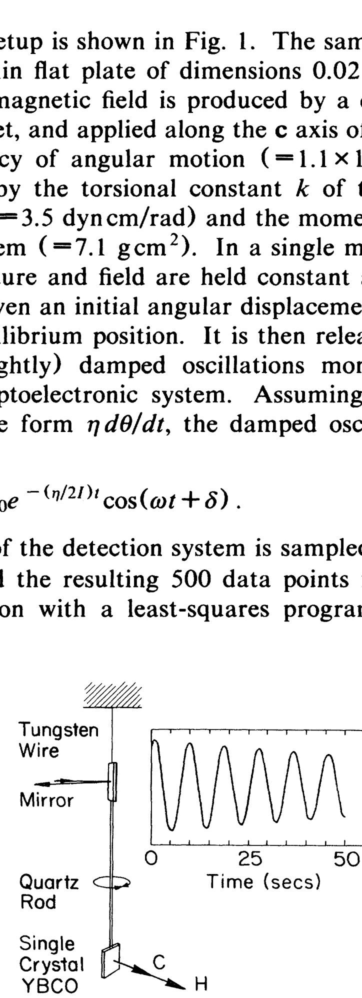

FIG. 1. Experimental arrangement used to search for flux-lattice melting in an untwinned single crystal of $YBa_2Cu_3O_{7-\delta}$ (YBCO). Small angular oscillations of the suspension are monitored optically. Below T_c, and in the presence of a magnetic field, the oscillations are damped by dissipation in the sample. The panel shows the resulting decay of oscillations having an initial amplitude of 0.14° in a magnetic field of 2.3 T and at a temperature of 85.05 K.

experimental values for ω and η. With the sample maintained above the transition temperature, a small background damping was observed, corresponding to an η value of $(1.0\pm0.1)\times10^{-2}$ g cm^2/s. There are a number of contributions to this background, including the viscosity of the exchange gas required to establish thermal equilibrium between the freely suspended sample and the adjacent thermometry. Above the transition temperature, the background was found to be independent of temperature, oscillation amplitude, and field, to the uncertainty indicated. Below T_c, the damping increased by up to a factor of 10 when a magnetic field was applied. In this Letter, we use the term "dissipation" to denote the increase of η above the background value, divided by the volume of the sample.

The observed dissipation is plotted as a function of temperature for three different fields in Fig. 2. In each case, as the temperature is increased there is a slow fall in the dissipation, followed by a rapid rise to a sharp peak. The typical behavior of the frequency ($=\omega/2\pi$) of the oscillator is shown in Fig. 3. The straight line in this figure is a fit to the data in the region above 86 K where a linear variation with temperature is observed. A sharp peak can be resolved just below this temperature. The temperature of the peak in the frequency was found to coincide with that in the dissipation for all values of the applied magnetic field.

A total of five single crystals were examined. All were in the form of thin flat plates, and all had T_c values in excess of 90 K. Two of them were twinned, and these exhibited no dissipation above the uncertainty of our measurement. The data for one of the untwinned crystals have already been presented. Of the two others, one exhibited $\sim\frac{1}{6}$th and the other only $\sim\frac{1}{10}$th of the dissipation shown in Fig. 2. Nonetheless, the same peak structures were observed. The locations of the 2.3-T peaks were specifically checked and found to lie in the temperature interval from 85.1 to 85.4 K for all three untwinned crystals. The crystal with the highest dissipation was selected for detailed study because it was not possible to resolve the lower-field peaks in the others.

The data reported above establish that our experiment is probing a novel physical regime. The sharp peak in the frequency is a completely new result. However, the overall increase of frequency with increasing temperature is of more significance for our present discussion. In previous experiments, the frequency was *always* observed to decrease monotonically as the temperature was increased [5,10,11]. The effective "stiffness" of an oscillator decreases when vortices become unpinned from the sample, and a decrease in frequency with increasing temperature is a direct consequence of thermal depinning. In our experiment, by contrast, the frequency *increases* over essentially the whole temperature range. This can also be well understood, although on completely different physical grounds; it is due to a decrease in the anisotropic equilibrium magnetization of the sample, which turns out to increase the effective stiffness of the suspension [14]. Thus, both the *sign* and the *magnitude* of the slope of the straight line in Fig. 3 provide direct evidence that our experiment probes a new physical regime, one in which thermally activated vortex depinning plays a negligible role in the temperature range of interest. There is a further remarkable distinction between our work and a previous vibrating-reed experiment on a twinned $YBa_2Cu_3O_{7-\delta}$ sample [5]. Using a similar displacement amplitude, the dissipated power per unit volume in our experiment is a factor of 10^6 larger.

A number of lines of evidence suggest that the striking

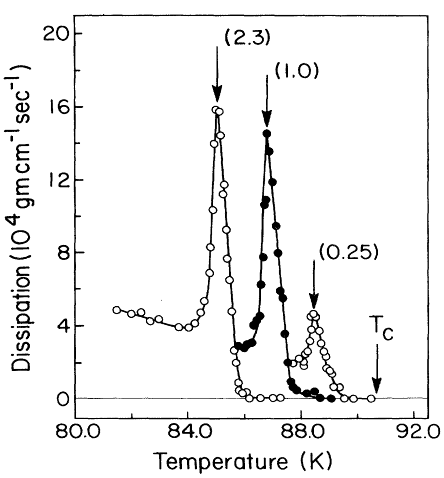

FIG. 2. The dissipation (defined in the text) plotted as a function of temperature in three different magnetic fields. The lines are drawn to guide the eye. In each case, the sharp peak in the dissipation is labeled with the magnetic field (in T) used to obtain that data set. T_c indicates the transition temperature of the sample, as measured in a previous experiment [13].

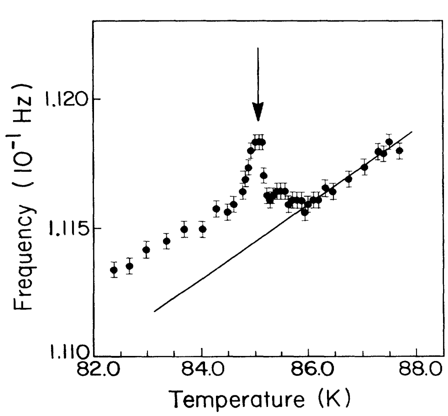

FIG. 3. Variation of the frequency with temperature in a field of 2.3 T, obtained by fitting the decaying oscillation data by Eq. (1). The straight solid line is a linear fit to the data for temperatures above 86 K. The arrow indicates the location of the peak in the dissipation data obtained in the same field.

coincident peaks in the dissipation and frequency plots are associated with the fundamental process of flux-lattice melting. In the first place, the peak temperatures were found to be independent (to 0.1 K) of the amplitude and frequency of the sample motion, over the complete range accessible to us [15]. This observation, together with the (untwinned crystal) reproducibility, justifies an association of the peaks with some intrinsic phase boundary in $YBa_2Cu_3O_{7-\delta}$.

A clue as to the physical origin of the peaks is provided by the magnitude of the observed dissipation. It is a factor of $\sim 10^4$ larger than would be anticipated [16] if the vortex assembly were moving *uniformly* with respect to the sample and dissipating energy via the Bardeen-Stephen mechanism [17]. Since this is thought to be the principal microscopic mechanism for energy dissipation in the vortex state, the observed dissipation implies that the motion of the vortex assembly cannot be uniform. We offer the conjecture that the microscopic origin of the dissipation is the motion of dislocations in the flux lattice. When a dislocation moves, individual vortices are obliged to execute rapid local motions. There is an established general theory for the mechanical dissipation expected as a result of *dislocation-mediated* lattice melting [18]. This is based on the Kosterlitz-Thouless approach, and so can only strictly apply to two-dimensional systems. Nonetheless, there is growing evidence that other aspects of Kosterlitz-Thouless theory may be applicable, at least approximately, to the quasi-two-dimensional high-T_c materials [19–21]. As will be discussed elsewhere [22], dislocation-mediated lattice-melting theory appears to provide an excellent description of the temperature dependence of the dissipation observed in the present experiment. In particular, the sharp peaks emerge as a direct consequence of the fact that the density of dislocations is only appreciable in the immediate vicinity of the melting point [18]. The otherwise puzzling absence of dissipation in the twinned crystals also finds a natural explanation, since twin boundaries will serve to prevent any extensive dislocation motion.

In order to further test the melting hypothesis, the observed phase boundary was fitted by an equation of the form

$$H = H_0(1 - T/T_c)^\beta, \tag{2}$$

where H_0, T_c, and the exponent β were treated as fitting parameters. Resistive phase boundary work in samples with pinning provides [7,8] values for the exponent β of $\sim \frac{4}{3}$, markedly different from the value of 2 expected [4,23] for the lattice-melting phase boundary close to T_c. As shown in Fig. 4, our data are fitted by Eq. (2) very well and the exponent agrees with the value expected for flux-lattice melting. This is the first report of such a parabolic phase boundary in high-T_c materials, although it should be noted that Suenaga *et al.* recently reported [24] good agreement with lattice-melting predictions for the magnetization-determined phase boundary in two low-T_c superconductors.

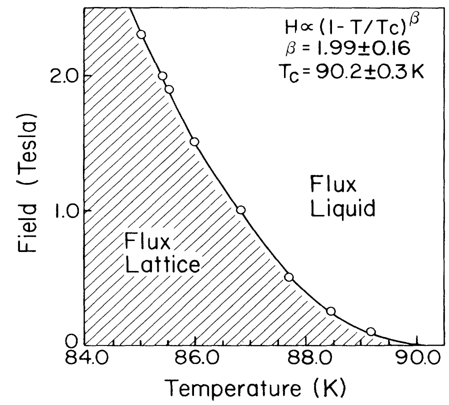

FIG. 4. Relationship between the temperature of the dissipation peak and the field. The solid curve through the data is a fit by Eq. (2), with the parameters shown in the figure. As discussed in the text, the parabolic form of this curve provides strong evidence for the phase assignments indicated.

In conclusion, a vortex phase boundary has been located in an untwinned single crystal of $YBa_2Cu_3O_{7-\delta}$ which has a sharpness comparable to that of the superconducting phase transition itself. Evidence has been presented suggesting that this boundary may be associated with melting of the Abrikosov flux lattice.

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[14] It may be easily shown that the frequency shift $\Delta\nu$ due to the (anisotropic) sample magnetization is given by $\Delta\nu = -(\nu/2k)d\tau/d\theta$, where τ is the *equilibrium* torque in the vortex state and k is the torsional constant of the suspension. Direct measurement of the quantities on the right-hand side of this expression yields a change in frequency which agrees within 10% with that given by the straight line in Fig. 3. Note also that $d\tau/d\theta$ itself depends on the angle of the field to the **c** axis. In fact, for angles greater than 75°, $d\tau/d\theta$ changes sign [13]. The above expression then implies that for such angles the slope of the line in Fig. 3 should become *negative*. This prediction is also born out experimentally [see D. E. Farrell, J. P. Rice, D. M. Ginsberg, and M. Stan (unpublished)].
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