Intrinsic Pinning in the High Field C-Phase of $UPt_3$

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Abstract

We report on the a.c. magnetic response of superconducting $UPt_3$ in a d.c. magnetic field. At low fields ($H < H^*$), the in-phase susceptibility shows a sharp drop at $T_c$ followed by a gradual decrease with decreasing temperature, while the out-of-phase component shows a large peak at $T_c$ followed by an unusual broad peak. As the B-C phase line is crossed ($H > H^*$), however, both the in-phase and out-of-phase susceptibilities resemble the zero-field Meissner curves. These features are only observed for relatively large a.c. excitation fields. We interpret these results in terms of a vortex pinning force which, while comparatively small in the A/B-phases, becomes large enough to effectively prevent vortex motion in the C-phase.

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Thermal and acoustic transport measurements \[1\] of the multi-phase heavy fermion superconductor $UPt_3$ have proven invaluable in deciphering the structure of the zero-field superconducting gap. In particular, the ability of thermal conductivity and ultrasonic attenuation experiments to couple to the excitation spectrum while ignoring the superconducting fraction enables one to measure the momentum space distribution of quasiparticles and thus of the gap itself. Similar studies of the high-field C-phase, however, are greatly complicated by vortex contributions to the electron and phonon scattering rates, and the intrinsic structure and behavior of this phase remain largely unknown. While not usually viewed as such, an a.c. magnetic susceptibility, $\chi'(H_{dc}, T) + i \chi''(T, H_{dc})$, measurement for fields $H_{dc} > H_{c1}$ may be regarded as a transport experiment: the real component, $\chi'$, probes the ability of vortex supercurrents to shield the bulk while the imaginary component, $\chi''$, measures the electrical dissipation due to the motion of normal state quasiparticles (from vortex cores or regions of vanishing gap) in the a.c. magnetic field, much as sound attenuation measures the dissipation due to quasiparticle motion due to the moving lattice. In this paper we present in-field magnetic susceptibility data on $UPt_3$ in the superconducting state that demonstrate a qualitative difference in the properties of the high field C-phase and the two low-field phases. Our data are consistent with a scenario where the vortex pinning in the C-phase is sharply higher than that in the low-field regime. These results, consisting of both field and temperature sweeps, may also help elucidate behavior previously noted \[2\] in the literature.

The sample is a single crystal cube of dimensions $1.4 \; mm^3$ cut from a polycrystalline ingot prepared in ultra-high vacuum. The a.c. susceptibility was measured at low frequencies (17 to 25 Hz) using a lock-in amplifier (a Stanford Research SR-850). As the coils were uncompensated, a field-dependent/temperature-independent susceptibility has been subtracted from the data (field and temperature sweeps), as determined by the condition that $\chi'(T > T_c) = 0$. The data are normalized by assuming that $\chi'$ drops by $1/4\pi$ on entering the superconducting state in zero d.c. field as measured by a run taken before the superconducting magnet was energized (and thus in the absence of a residual d.c. field,
which may be as large as 400 Oe in the case of the data of Figs. 1 and 3). Susceptibility data are given in c.g.s. units throughout. The maximum possible phase error (which would result in a mixing of the true in- and -out-of-phase results) is estimated at about 1 degree from the magnitude of the out-of-phase signal in the normal state. (This estimate is also consistent with the quoted absolute phase accuracy of the lock-in amplifier). Correcting the data for such a maximal phase error does not alter any of our conclusions. Also, data taken at several different frequencies show that both $\chi'$ and $\chi''$ scale linearly with frequency, as opposed to the quadratic scaling of $\chi''$ expected if it were simply due to, e.g., capacitive crosstalk of the in-phase component (with one factor of frequency entering due to the linear growth of the in-phase component while another comes in due to the capacitive coupling itself). Self-heating effects due to the a.c. field are believed to be small for a number of reasons. Firstly, as noted above, no frequency dependence was observed, eliminating eddy currents in the sample or mount as a heating source. Indeed, heating in the normal state is very small since $T_c$ did not appreciably change as a function of excitation. Finally, even if heating is present, it would not lead to the observed a.c. field amplitude dependence we observe. We will return to this point below. As a check on the experiment, we note that we have recently measured a different sample from a separate growth with a different shape using compensated coils and new electronics (a Linear Research LR-700). These results are in excellent agreement with those presented here. A number of experimental parameters can affect the susceptibility, including temperature, d.c. field, frequency and amplitude of the a.c. field, the directions along which the magnetic fields are applied, and the time period over which the typically metastable vortex state is measured. As mentioned, at the frequencies used in this work, no anomalous $\Phi\Phi\Phi_\text{us}$ frequency dependence was seen. Also, temperature sweeps at half the rate of the data shown here gave identical results, indicating that we are not simply measuring the time (rather than temperature) dependence of the susceptibility [3]. Furthermore, the field directions were fixed, $H_{dc}||\hat{a}$ and $H_{ac}||\hat{b}$ (and thus $H_{dc} \perp H_{ac}$). An important qualitative dependence on the magnitude of $H_{dc}$ was observed, however.
In Fig. 1 we show $\chi'(T)$ at various fixed $H_{dc}$ for $H_{ac} \approx 50e$. These data, like all the temperature sweeps shown, were taken by warming above $T_c$ and then slowly cooling in field. The first thing to note is that the susceptibility falls on entering the superconducting state. This is in obvious contrast to an idealized (clean) type II material for which the slope of the magnetization, $M(T,H)$, is positive at $H_{c2}$, and is typical of a material with significant vortex pinning.

Qualitatively, this follows from the fact that the susceptibility is a direct measure of the derivative, $4\pi\chi = dM/dH_{ac} = d(B - H_{ac})/dH_{ac}$, of the (time dependent) magnetization induced by the small a.c. field. In the presence of pinning, the oscillations of $B$ in time are much smaller than those of $H_{ac}$: the vortex lattice cannot "follow" the external field variations, and the flux is at least partially frozen into the sample. In the limit of very strong pinning, $dB/dH_{ac} = 0$ and the susceptibility is $-1/4\pi$, as in the Meissner state. Thus the drop in $\chi'$ near $T_c$ is qualitatively indicative of the strength of the pinning in the superconducting state.

The data in Fig. 1 may be naturally divided into two regimes: for low fields ($H_{dc} < 5$ kOe), the in-phase susceptibility falls sharply below $T_c$ to a value significantly less negative than $-1/4\pi$ (indicating relatively weak pinning), has a weak shallow minimum, and then approaches the Meissner value in a roughly linear fashion. For larger d.c. fields, the value characteristic of very strong pinning is obtained within a small temperature range below $T_c$. The question naturally arises as to whether the distinct change evident for $H_{dc} \approx 5$ kOe is correlated with the multiple superconducting phases known to exist in the H-T plane of $UPt_3$.

We show in Fig. 2a the second critical field as defined by the onset of the initial, sharp drop in $\chi'$ for the data of Fig. 1 (equivalent results are obtained if one uses the imaginary susceptibility). A definite "kink" is noted at $H_{dc} \approx 5$ kOe. Numerous experiments have shown that this feature arises from a tetracritical point at which three superconducting phases (A,B, and C, as shown schematically in Fig. 2a) and the normal state meet. The in-phase susceptibility data of Fig. 1 therefore imply that the vortex lattice pinning is
significantly stronger in the high field C-phase than in the low-field/low-temperature B-phase \[5\]. Note that this enhanced pinning is "intrinsic" in the sense that the sample purity, shape, and so on are unchanged at the B-C phase boundary. The strong correlation between the feature in \(H_r\) and the pinning strength is graphically displayed in Fig. 2b, where we plot the magnitude of the sharp drop in \(\chi'\) near \(T_c\) as a function of field: a precipitous change is noted in the vicinity of the B-C phase boundary.

The data in Fig. 3, measured concurrently with the \(\chi'\) results of Fig. 1, show \(\chi''(T)\) for various values of \(H_{dc}\). Three regimes might be posited: for low fields, a large, sharp, peak is seen near \(T_c\). However, at intermediate \(H_{dc}\), the peak is followed by a broad second peak extending to the lowest temperatures measured (100mK). Finally, for \(H_{dc}\) larger than the critical "kink" field of \(\approx 5\) kOe, the data once again resemble the low field results, with a sharp peak near \(T_c\) followed by a monotonic drop. In interpreting these results, we recall that the out-of-phase susceptibility, \(\chi''\), is a measure of the dissipation caused by the movement of vortex core quasiparticles under the influence of the a.c magnetic field. If pinning is very strong, the vortices do not move, and \(\chi'' = 0\). Therefore, the data in Fig. 3 are in qualitative accord with the in-phase behavior seen in Fig. 1: vortices are more weakly pinned in the B-phase than in the C-phase.

All of our data show a pronounced peak in \(\chi''\) slightly below \(T_c\) coincident with the sudden drop in \(\chi'\). We note that the observation of such a peak is also seen in some conventional superconductors under the general heading of the "peak effect," about which a sizable body of literature exists. In this work we mention only that a very sharp peak in \(\chi''\) is also found in a "true" zero-field run, i.e., one done before the magnet had been ramped, and thus the peak is not solely due to the presence of a vortex lattice. More interesting from our standpoint is the unexpected presence of a second peak in \(\chi''\).

The susceptibility was also found to be a strong function of the strength of the a.c. magnetic field. In Fig. 4 we show \(\chi(T)\) for two \(H_{dc}\) bracketing the field at the tetracritical point, for various \(H_{ac}\). At low excitations, the aforementioned features in \(\chi'\) and \(\chi''\) as a function of \(H_{dc}\) are absent; the in-phase susceptibility drops at \(T_c\) to the strong pinning
value both above and below the tetracritical point and the out-of-phase component exhibits low dissipation in all three phases. Somewhat similar effects have previously been noted in $UPt_3$. These data emphasize the fact that the phenomena presented here are non-linear in the sense that they are observed only when vortices are strongly perturbed about there pinning sites. One may also see from Fig. 4 that there is a clear saturation effect: the curves appear to be reaching an asymptotic shape with increasing a.c. field amplitude. We note that this is not what would be expected from self-heating, which would shift the curves along the temperature axis.

Data taken as a function of field allow us to relate the our results to previous work. Tenya et al. measured the static magnetization, $M$, of $UPt_3$ as a function of field for the field along $\hat{c}$ (orthogonal to our experiment). They found a feature in $M$ close to $H_{c2}$, taking the form of a peak or a dip depending on the field history of the sample. The feature appears to exist only in the C-phase. We have performed a limited number of field sweeps measuring $\chi(H)$ at fixed $T$, taken by ramping up the field above $H_{c2}$ and then stopping at each measurement field on ramping down.

The data at 350mK in Fig. 5 show a sharp drop at about 5 kOe. Cuts of temperature sweep data are in relatively good agreement with the field sweep data. Comparing the two, we observe that the drop in 5 kOe results from the sharp drop in $\chi'$ at the B-C-phase boundary seen in Figs. 1 and 2a. It is tempting to conclude that the feature seen in the a.c. susceptibility field sweep shown in Fig. 5 is associated with the d.c. magnetization anomaly observed near $H_{c2}$ by Tenya et al.. However, magnetization computed in this manner is distinct from that measured in a d.c. experiment, probing as it does a non-linear response as the field rises and falls. Furthermore, the d.c. field direction in the experiment of Tenya et al. is perpendicular to ours. Thus more work is required to ascertain whether the features in $M(H)$ observed by Tenya et al. are related to the sharp changes in pinning observed in this work. A field dependence of $\chi'$ similar to that of Fig. 5 has also been seen in the heavy fermion superconductor $UPd_2Al_3$. Whether this is a signature of a sharp change in vortex pinning (perhaps at a phase line analogous to the B-C line observed here) remains a
subject of future work.

At present, we are not aware of any quantitative theoretical work with which to interpret our results on the sharp change in pinning in the C-phase. To gain some qualitative understanding of what strong pinning may imply about the Abrikosov lattice, we recall that a vortex is strongly pinned at a site where the superconducting condensation energy is small, since this minimizes the energy gained by the system due to the vanishing order parameter in the vortex core. Thus if, for example, the superconducting order parameter remains non-zero throughout the vortex lattice, we would expect relatively weak pinning. Qualitatively, this is exactly what is predicted by some particularly successful theories of the multiple phases of $UPt_3$ [8]. The order parameters of the three phases within these theories are different linear combinations of two symmetry-allowed functions. In the B-phase, both components contribute to the order parameter, resulting in two vortex lattices spatially separated from each other. The condensation energy, calculated as the sum of the condensation energies of the individual lattices, is everywhere non-zero over the sample. In the C-phase, however, only one function is believed to contribute, leading to a conventional vortex lattice. This is exactly the scenario envisioned above and results in stronger pinning in the C-phase than in the B-phase. Quantitative calculations are required before the data presented here can be taken as strong evidence for the exotic inter-penetrating lattice scenario discussed here. Given the highly developed nature of the theories, we hope that the amplitude and temperature dependence of a.c. measurements may provide quantitative information on the exotic order parameters in $UPt_3$.

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FIGURES

FIG. 1. In-phase a.c. susceptibility as a function of temperature for various d.c. fields with $H_{ac}=5$ Oe. The zero-field abscissa ranges from 0.51 K to 0.35 K with the minimum and maximum temperature decreasing by 0.01 K for each successive field (the exception being the 17 T data which extends from 0.11 K to 0.27 K). The drop in $\chi'$ near $T_c$ increases suddenly around $H=5$ kOe, indicating strong pinning in the C-phase. Note also the similarity of the high field (17 kOe) data with the zero field result.

FIG. 2. (a) Phase diagram for $UPt_3$ showing multiple superconducting phases. The internal phase lines are based on data from similar samples and are schematic only. (b) Drop of $\chi'$ near $T_c$ as a function of field showing the sudden change as the tetracritical point field is crossed.

FIG. 3. Out-of-phase a.c. susceptibility as a function of temperature for various d.c. fields. The temperature ranges are the same as in Fig. 1. Two peaks are seen at low d.c. fields, with the broad peak at lower temperature suppressed for $H_{dc}>5$ kOe.

FIG. 4. Real and imaginary susceptibility as a function of a.c. field for d.c. fields above and below the tetracritical point at 5 kOe. The a.c. fields range from 0.2 (lower curves) to 4.8 Oe (upper curves) in steps of 1.15 Oe. The effects indicative of stronger pinning in the C-phase are only evident at large $H_{ac}$.

FIG. 5. $\chi'(H)$ at $T=350$ mK as measured in a field sweep (solid points) and from isothermal cuts of the data of Fig. 1. The sharp drop at $H \approx 5$ kOe is correlated with the change in $\Delta\chi'$ noted in Fig. 2(b).
The figure shows a series of curves labeled as $4\pi\chi'$ plotted against temperature $T$ (K). The curves are for different magnetic fields: 0.00 kOe, 0.75, 1.50, 2.25, 3.00, 3.75, 4.50, 5.25, 6.00, 6.75, 7.50, and 17.00 kOe. A scale of 50 mK is also indicated.
$4\pi\Delta\chi'$ vs $H$ (kOe) for $T = 350$ mK.