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AC susceptibility and anisotropic flux pinning in unconventional superconductor UPt_3

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AC susceptibility measurements have been carried-out on single-crystalline samples of UPt_3 doped with 11% boron. The low-amplitude susceptibility is nearly independent on the ac field amplitude and, hence, it is related to the low-frequency complex conductivity. At large ac field, strong nonlinearities characterize the electrodynamic response. The critical state model is, however, not sufficient for analysis of the results. A reactive component of the conductivity must be included for a consistent description of the susceptibility. The strong anisotropy of the ac response observed at low fields is also present for fields near the upper critical field, H_{c2}.

1. INTRODUCTION

Superconductivity of UPt_3 is interesting, in particular due to its complex H-T diagram, as observed by ultrasound attenuation, specific heat [1], and dilatometry studies [2]. The conclusions about the presence of internal phase transition lines follow from the observation of different anomalies in the properties studied as a function of temperature or magnetic field. If the flux pinning is considered, one could expect a change of slope or a discontinuity in the temperature- or field-dependence of the critical current density at the crossing of the internal phase-transition lines. There are indications from studies of the current-voltage characteristics on whiskers of UPt_3 [3] and from magnetocaloric effects [4] that there are features in the field- and temperature dependences which could be assigned to the internal phase-transition lines. AC susceptibility studies at large fields offer a chance for gaining additional information about the flux pinning in the superconducting state.

2. RESULTS AND DISCUSSION

The specific heat, resistivity, low-field ac susceptibility and dc magnetization measurements on the same samples have been reported elsewhere [5]. Figures 1 and 2 give examples of the ac susceptibility curves registered in different ac fields as a function of temperature or dc field, for H//b. We use the definition of the superconducting phases following the work of van Dijk et al. [2]. In fig. 1 (a) (for a field of 2 kOe) the line between states A and B is crossed. In fig. 1 (b) (for H=6 kOe) the applied field corresponds approximately to the field at the line separating states B and C. For the temperature sweep at 8 kOe, in fig. 2 (b), only the response of the state C should be observed. There is

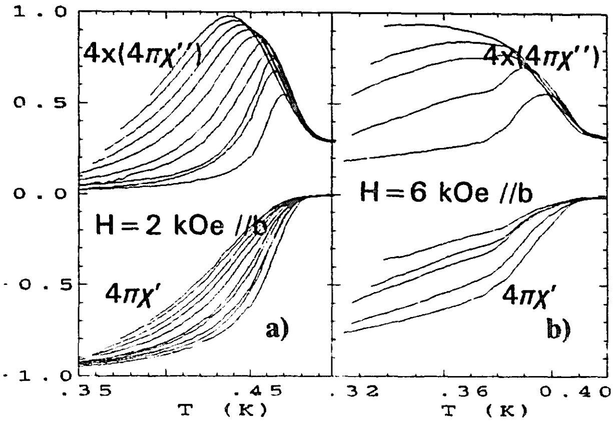

Figure 1. The ac susceptibility in a dc field of 2 kOe (a) and 6 kOe (b). The ac field amplitudes range between 0.25 and 4 Oe, for curves from right to left, respectively.

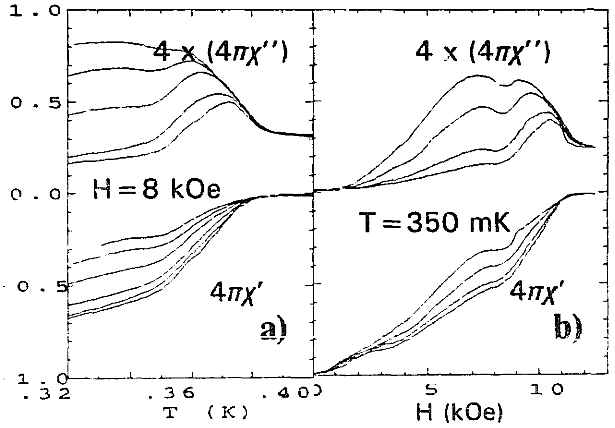

Figure 2. Temperature- (a) and field-dependences (b) of the ac susceptibility for H//b, measured in different ac field amplitudes, from 0.25 to 2 Oe, for curves from right to left, respectively.

a difference between the shape of the curves in a field of 2 kOe and those at larger fields: a change

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from smooth susceptibility curves towards a kind of double-structure curve emerges in $\chi'(T)$ and $\chi''(T)$ at larger ac fields. This double structure is absent for H//c (not shown), where the registered curves resemble those measured at low fields for H//b, as in fig. 1 (a). The common feature of the data is that the maxima in $\chi''(T)$ are small at low excitation fields, they increase to the value which is expected in the critical state model ($4\pi\chi'' \approx 0.2$) when H_{ac} increases, and they possibly increase further towards a flux-flow-like behaviour at larger ac field amplitudes ($4\pi\chi'' \approx 0.4$). One can not use the critical state model for the analysis of the experimental susceptibility results on UPt_3. However, at low excitation fields, the dependence of the susceptibility on H_{ac} is very small and one can use the linear theory as an approximate approach to the analysis of the results. The complex conductivity has been determined, $\sigma = \sigma_r + i\sigma_i$, and subsequently the reactive and dissipative penetration depths $\lambda^2 = c^2/4\pi\omega\sigma_i$ and $\delta^2 = c^2/2\pi\omega\sigma_r$, by using the method described by us previously [5]. No clear signature was found of internal phase transition lines in plots of λ or δ as functions of H or T. At fields $H < H_{c2}/2$, the same functional dependence on $\lambda(H)$ is observed as reported for low fields, $\lambda \sim H^{1/2}$, supporting the idea that the reactive component of the complex conductivity finds its origin in the interaction between vortices and the ac current [5], a mechanism described by Campbell. There is, however, a feature in the susceptibility curves which marks a change in the $\chi(T)$ or $\chi(H)$ dependences near the critical temperature $T_c(H)$ and which divides the H-T plane in regions of small and large dissipation. In the plot of χ'' vs. χ' in fig. 3 (a), this feature is marked by an arrow. At calculating λ and δ from the data of fig. 3 (a), it is observed that this feature corresponds to a change in character of the $\lambda(\delta)$ dependence from a nearly linear relationship to a power-law behaviour with a value of the exponent of about 4, near H_{c2} (fig. 3 b). If the characteristic fields which correspond to the position of the arrows in fig. 3 are drawn on H-T diagram, they form lines parallel to the $H_{c2}(T)$ curve. One finds that this diagram is not related to the expected H-T diagram.

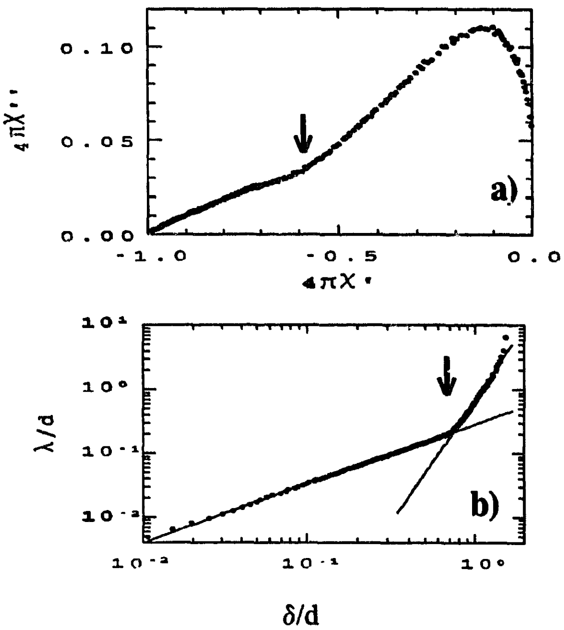

Figure 3. (a) - The χ'' vs. χ' plot which is obtained at low temperatures (near 300 mK) when it is measured as a function of magnetic field for H//b. (b) - The penetration depths calculated from the results of fig. (a), in a plot of λ/d vs. δ/d.

3. CONCLUSION

A large anisotropy of the ac susceptibility of UPt_3 has been established. The field- and temperature-dependence of the penetration depth is concistent with Campbell's penetration depth, which is supposed to be relevant in the presence of an interaction of the current with pinned vortices. Near $T_c(H)$, a strongly nonlinear response is observed which leads to an appearently broad transition region, in similarity to the behaviour of another heavy-fermion superconductor URu_2Si_2 [6]. The results should be attributed to one of the unconventional scenarios: the formation of an inhomogeneous superconducting state arising from a coupling between superconductivity and structural modulations or antiferromagnetism [5] or the presence of quasiparticles excitations in a superconductor with gap nodes.

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