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A neutron study of the flux lattice in the superconductor CeRu2

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Abstract

Small-angle neutron diffraction measurements from the flux lattice in a single crystal of the cubic Laves' phase superconductor, $CeRu_2$, are reported. The mixed state is described in terms of aligned rigid bundles of vortices. The bundle diameters decrease above $\frac{1}{2}H_{c2}$ (consistent with collective weak pinning theory) and become comparable with the penetration length at a field at which a 'peak effect' is seen in magnetisation measurements. A clear memory of field histories that pass through the 'peak effect' region is also found; however, some of the induced disorder can be removed by subsequently cycling the field.

1. Introduction

In all high quality samples of $CeRu_2$ studied to date, a sharp transition from an apparently highly reversible superconducting state just below an applied field H^* ($H_{c1} \ll H^* < H_{c2}$) to a magnetically hysteretic state above H^* has been seen (Fig. 1). Physically, this transition differs from the general body of observations relating to 'classical peak effects' studied extensively since the 1960s in two ways: (I) The state just below H^* is much more reversible (at least for the time scales measured) than for the classical cases for which the critical current remains everywhere at least a few percent of its value at the peak height. (II) For $CeRu_2$ there is no 'peak effect' region for $H < 0.8$ T, which rules out a 'scaling law behaviour' found empirically for the 'classical cases'.

To help identify the origin of the above phenomena, we report our small-angle neutron diffraction study of the flux line lattice (FLL), carried out at the Institut Laue Langevin and Oak Ridge National Laboratory.

2. Experiment

The sample was a long cylindrical single crystal grown by the Czochralski technique. The magnetic field was applied along a [1 1 1] crystal direction, perpendicular to the axis of the cylinder, and nearly parallel to the neutron beam. The cryostat, sample and magnetic field could be rotated together to bring each of the principal reciprocal lattice points of the FLL into the plane of a multi-detector. All the measurements reported here were taken at a temperature of 1.8 K for which $H^* = 3.8$ T and $H_{c2} = 5.5$ T. The FLL was always found to be triangular, with a reciprocal lattice vector parallel to the [1–10] crystal direction and a lattice spacing consistent with the applied field. Our measurements were performed for two distinct field histories, which effect the perfection of the

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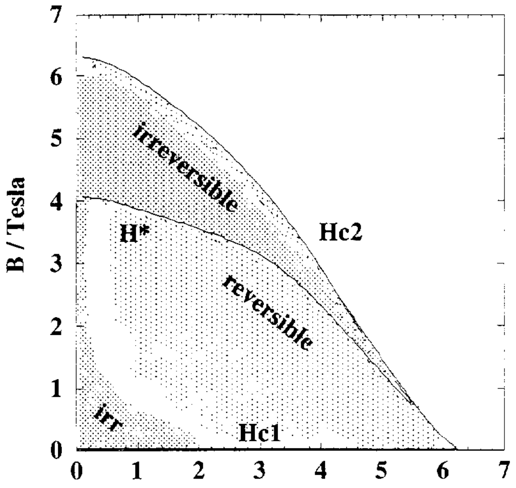

Fig. 1. A schematic phase diagram of $CeRu_2$ showing the regions of reversible and irreversible behaviour, after Ref. [1,2].

FLL; (i) field cooled (FC), in which the sample temperature was lowered over a period of 2 min from 7 K to 1.8 K at constant field and (ii) zero field cooled (ZFC), for which the sample was cooled to 1.8 K in zero field and then the field applied. It was found that an equivalent state to (ii) was obtained if the field was cycled up or down by more than 0.5 T after procedure (i).

The diffracted spot profiles and the rocking curve widths are determined by the various resolution functions of the instruments, together with the degree of perfection of the FLL [3]. With sufficient resolution it is possible to deduce the degree of rotational order of the FLL about the applied field, and the correlation lengths of the FLL perpendicular (W, assumed isotropic for $CeRu_2$) and parallel (L) to the field. For the ZFC lattice where the spots are much better defined, we deduce that the mixed state consists of long cigar-shaped bundles of parallel flux lines, with no measurable rotational disorder, and $L > 10$ μm. W as a function of field is shown in Fig. 2, where it is compared to a model for weak collective pinning [4, 5]. The fit contains a single variable parameter, which in our case is found to be $n\alpha^2/\xi_0^3 \approx 0.2$, where n is the concentration of pins and α is a volume characteristic of the range of the pin flux line interaction (ξ_0 is the superconducting coherence length). One might expect that $\alpha \approx \xi_0^3$, which would imply that the pin spacing is close to coincidence with that of the FLL at fields close to H_{c2}.

For field histories that traverse the irreversible region (i.e. $H > 1$ T) the FC lattice consists of much more finely divided blocks than for the ZFC lattice; both W and L are smaller. This is clear evidence of memory of the passage through the irreversible region.

The integrated diffracted intensity as the sample is rocked through a Bragg condition gives directly the squared modulus of the spatial variation of the magnetic field coincident with the plane spacing. For the lowest order Bragg peak, this quantity, $|\delta B|^2_{[10]}$, is plotted in Fig. 3. From the low field part of our data and the simple formula [6],

$$\langle|\delta B|^2_{[10]}\rangle = \frac{3\phi_0^2}{64\pi^4\lambda_0^4}\,e^{-8\pi^2 B\xi_0^2/\sqrt{3}\phi_0}, \quad B \geqslant \phi_0/\lambda_0^2, \tag{1}$$

we find values for the penetration length $\lambda_0 = 1400$ Å, and the coherence length, $\xi_0 = 70$ Å, (ϕ_0 is the flux quantum) in reasonable agreement with other measurements [1, 2]. For the FC lattice above 1 T the large widths of the rocking curves and spot profiles make it difficult to include all of the diffracted intensity in the tails of the Bragg peaks. This might well explain a substantial part of the difference in the integrated intensities between the FC and ZFC measurements. For ZFC the FLL is more perfect and the small deviation from Eq. (1) below H^* is most probably due to the over-simplified treatment of the vortex cores in the theory. In contrast to this small deviation, there is a clear change of behaviour at H^*, above which the scattered intensity drops much more rapidly with field. Significantly, the flux lattice still

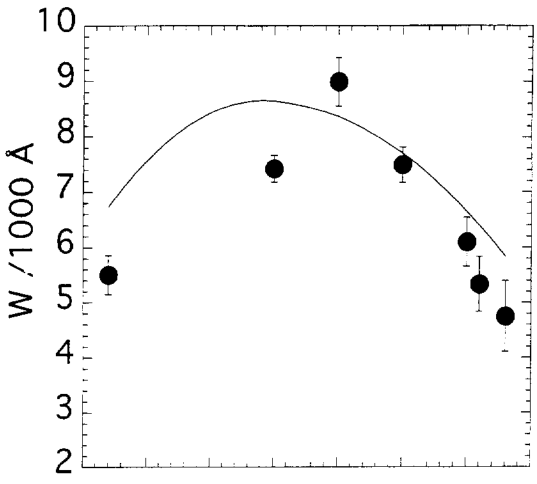

Fig. 2. The radial correlation length (W) of the flux bundles for the ZFC lattice as a function of applied field. W is defined as $2\pi/\delta\tau$, where $\delta\tau$ is the rms width of the lowest order Bragg spot in the reciprocal space. The line is a fit to a model for collective weak pinning from Ref. [4,5].

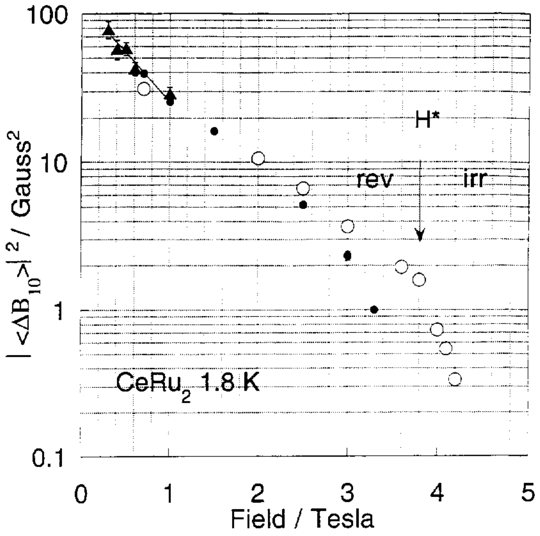

Fig. 3. The measured squared form factor for the lowest order reciprocal lattice point of the flux lattice in $CeRu_2$ at 1.8 K. The open circles are for ZFC and the solid symbols correspond to FC data (circles = ILL, triangles = ORNL). The straight line is a fit of the low field data to Eq. (1).

persists at fields immediately above H^*, although by 4.5 T (well below H_{c2}) any diffracted intensity was too small to be detected.

3. Conclusions

Our data show that the FLL in the region below H^*, is always highly fractured, and shows memory of its field history. This must clearly be reconciled with the almost perfect reversibility of the bulk magnetisation, which suggests further study is needed to understand how flux can move along the bundle boundaries and of activated processes. The improvement in the quality of the FLL on cycling the field could be similar in origin to the cases of Nb [7] and $NbSe_2$ [8], where the FLL is improved by passing currents through the specimens.

The parameters from a fit to weak collective pinning suggest that the pin spacing might be similar to the lattice spacing at high fields. A synchronisation of the flux lattice to this spacing might then be an important ingredient in driving the transition at H^*, coupled to a conventional softening of the lattice, facilitated as the bundle diameter becomes comparable to the penetration depth. The similar behaviour of $H^*(T)$ for samples of different origin then suggests, some, as yet unidentified, underlying structure might be responsible for this pinning, such as some intrinsic long-range metallurgical structure or long-wavelength magnetic order which might also evolve with temperature and field.

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