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A low field study of the flux line lattice in $CeRu_2$

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Abstract

The flux line lattice in $CeRu_2$ has been studied by small-angle neutron scattering. The scattering potential is found to be well described in terms of a linear superposition of single flux-line profiles, while an increase in the mosaic spread of the diffraction peaks at low fields is consistent with the theory of weak collective pinning. The pinning parameter deduced from the data gives the correct onset field of a peak in the critical current observed at higher field.

Keywords: Flux line lattice; $CeRu_2$; Superconductivity

Many single crystals of $CeRu_2$ show a very pronounced peak in their irreversible magnetisation and critical current in the superconducting mixed state as a function of field [1]. In the most conservative explanation, the phenomena is due solely to the field evolution of the pinning forces and elastic constants of the flux line lattice (FLL). Knowledge of the degree of order of the FLL is then a pre-requisite to test this hypothesis and small-angle neutron scattering is ideally suited to measure this.

In the following we report new small-angle neutron scattering results in low fields ($\mu_0 H < 0.4$ T), obtained with the D22 instrument at the ILL, which compliment previous measurements at higher fields [2]. The experiments were carried out on a single crystal of nearly cylindrical geometry, with the magnetic field perpendicular to the crystal length, parallel to a crystalline [2 1 1] axis ($CeRu_2$ is cubic), and almost parallel to the incident neutron beam.

Neutron scattering from the FLL occurs in addition to other small-angle scattering, mostly of metallurgical origin. This 'background' scattering can be determined from measurements above $T_c = 6.2$ K, and for our sample was found to be consistent with scattering from dislocations ($d\sigma/d\Omega \propto 1/q^3$) and point defects ($d\sigma/d\Omega \propto 1/q^4$), although to fit the background well it is necessary to consider these factors multiplied by angular terms to account for a small anisotropy (q is the scattering wavevector). An anisotropic contribution to the metallurgical scattering has been reported for different $CeRu_2$ samples [3], where it was found to be more pronounced in a sample with a high residual electrical resistivity. The inset in Fig. 1 shows the scattering due to the FLL averaged over small inclinations ($\leq \pm 1.3°$) of the sample and field ($\mu_0 H = 0.14$ T) to the incident neutron beam. Two FLLs occur simultaneously in our specimen. The reciprocal lattice vector of the principal lattice is aligned parallel to a [1 −1 0] crystal direction, while the reciprocal lattice vector of a weaker lattice lies perpendicular to the length of the sample (both vectors are perpendicular to H). The relative fraction (76 : 24) of the sample volume occupied by the two lattices does not change as a function of the applied field, although the weaker lattice

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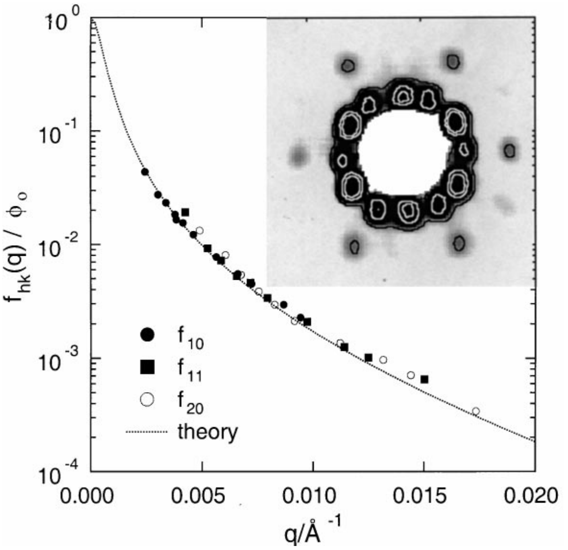

Fig. 1. The form factors f_{hk} determined from the integrated reflectivities for the first three Bragg reflections. The solid line is calculated as outlined in [6] for a Ginzberg Landau parameter, $\kappa = 23$. The coherence length is taken to be 79 Å, consistent with the upper critical field $B_{c2} = 5.3$ T at 2 K. The image is that seen on the detector due to diffraction from the FLL at 0.14 T summed over a range of 'rocking' angles. Two orientations of the FLL about the direct beam are visible as well as higher order diffraction peaks.

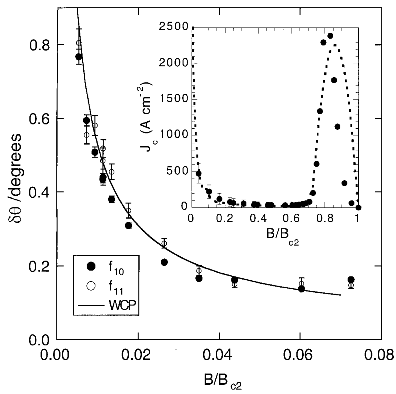

Fig. 2. The FWHM of the mosaic spread of the FLL ($\delta\theta$) is shown as a function of applied field for diffraction from the lowest two order Bragg reflections. The line is a calculation for the WCP theory. The insert shows the critical current, J_c, for our sample at 2.5 K, deduced from magnetisation measurements. The dashed line is a calculation of J_c for the WCP parameter $n\alpha^2/\xi^3 = 0.15$ consistent with the neutron scattering data.

is progressively obscured by the stronger lattice at small diffraction angles.

The normalised integrated diffracted intensity, $R(q)$, is given by

$$R(q) = \frac{\gamma^2}{16\phi_0^2 \sin(2\vartheta)} \frac{\lambda^3 t}{S_0^2} |f(q)|^2$$

$$\text{with } q = 2\pi \sqrt{\frac{2}{\sqrt{3}}} \sqrt{\frac{B}{\phi_0}} \sqrt{(h^2 + k^2 + h \times k)}$$

where S_0 is the unit-cell area of the FLL, θ the Bragg angle, ϕ_0 the flux quantum, t the mean sample thickness, and $\gamma = 1.91$. The integers h and k correspond to successively higher order reflections, while q can also be continuously varied simply by growing the FLL in different applied fields, $B \approx \mu_0 H_{app}$. For a perfectly ordered FLL, the magnetic form factor, $f(q)$, is just the Fourier transform of the field distribution normalised to a single flux line. In Fig. 1, we show $f(q)$ determined from our experiment. The experimental points lie close to a common curve for different order reflections which indicate that the field profile about each flux line does not evolve significantly with the applied field (and is close to the form calculated for isolated vortices). Furthermore, there is no evidence for any reduction in the intensity of the higher order peaks that would occur if the lattice was significantly disordered.

From the widths of the diffraction peaks on the detector and the widths of the rocking curves, combined with the instrumental resolution, it is possible to quantify the degree to which the FLL is ordered [4]. The most significant trend is found for the tilt mosaic spread, $\delta\theta$, shown in Fig. 2. ($\delta\theta$ is equivalent to an angular spread in the inclinations of the flux lines away from the mean field direction). If $\delta\theta$ is related to a longitudinal correlation length via $L \propto 1/(q\ \delta\theta)$, then our experiment shows that $L \propto (B/B_{c2})^{1/3}$ for $0.005\ \text{T} < B < 0.015\ \text{T}$. This law is exactly that expected for weak collective pinning (WCP) at these fields when the radial correlation length normalised to the lattice spacing is constant (shear limited) [5]. The quality of the fit and the fact that the constant of proportionality agrees with the value deduced at high fields [2] give convincing evidence for WCP. The constant of proportionality determines the magnitude of the parameter $n\alpha^2/\xi^3 \approx 0.15$ where n is the concentration of (point) defects, α is their pinning strength (the volume over which the order parameter would be suppressed for an equivalent loss of energy), and ξ is the superconducting coherence length. This same value determines the onset field for the peak effect (see Fig. 2). Furthermore for $n\alpha^2/\xi^3 = 0.15$, the optimum value of the normalised radial correlation length would cease to be shear limited from above about 0.3 T until the onset of the peak effect, which might account for the different dependence of the FLL order on the field history at low and high fields [2]. The height of the peak in J_c is sensitive to the value assumed for the limiting shear stress of the FLL; a value which gives 10–13 flux lines per bundle is required, compared to a ‘standard’ value of $C_{66}/60$ assumed at low fields (C_{66} is the elastic shear modulus). Calculation also indicates that thermal fluctuations in the FLL positions should be important for fields within a few percent of B_{c2}. This could explain why the observed pinning force appears to vanish more rapidly than linearly with field very close to B_{c2}.

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