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Muon spin rotation evidence for loss of order in the flux line lattice in the peak effect region in 2H-NbSe$_2$

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Abstract

Muon spin rotation (μSR) technique has been used for measuring the magnetic field distributions inside the superconductor 2H-NbSe$_2$, close to its $T_c(H)$ line. In this region, the material is known to exhibit a 'peak effect'. Our results show a sharp change in the field profiles in the peak effect region, indicating a phase transition in the flux line lattice (FLL). We argue that this transition is associated with a loss of order in the FLL. © 1998 Elsevier Science B.V.

Keywords: Muon spin rotation; Flux line lattice; 2H-NbSe^2

The discovery of high temperature superconductivity in cuprates has refocussed attention on the nature of the mixed state of type-II superconductors in general. This has been due to the richness in the character of the mixed state, not recognised earlier. Specifically, the possibilities of transitions from a flux lattice to a flux liquid due to thermal fluctuations, and the occurrence of glassy phases due to quenched pinning disorder, have culminated in an intense theoretical as well as experimental activity. A transition involving loss of order in the flux line lattice (FLL) should be detectable in a microscopic study of the structure of the flux assembly. In addition, the concomitant changes in the rigidity of the flux assembly could produce changes in the effective pinning response and hence in the current carrying capacity. Indeed, the occurrence of the ubiquitous peak effect (PE) (namely, a sharp peak in the critical current density as a function of temperature/field) is often cited as a signature in support of this expectation. However, a direct microscopic structural evidence of a transition in the FLL is yet to be observed in the peak effect regime. Here, using muon spin rotation (μSR) measurements, we identify a transi-

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tion in the FLL in 2H-$NbSe_2$, and show that this transition overlaps the peak effect seen in magnetisation studies, thereby providing a link between the two phenomena.

The anisotropic superconductor 2H-$NbSe_2$ ($\gamma \approx 3$; $T_c \approx 7$ K) has been a subject of a number of investigations in recent years [1–3], because of the weakly pinned characteristic of its FLL. In high quality single-crystal samples of this superconductor, the ratio of depinning current J_c (the critical current) to the theoretical depairing current J_o, i.e., J_c/J_o, is $\sim 10^{-6}$. This is orders of magnitude smaller than that observed in most other systems. Such a low value of J_c/J_o indicates a very weakly pinned FLL, making it one of the cleanest systems available for studying transformations in a disorder-free FLL. It is also known that 2H-$NbSe_2$ exhibits a robust PE just below H_{c_2} [3], in the form of an abrupt increase in J_c as a function of T or H, and unravelling the behaviour of FLL near the PE region is of particular interest.

It has been argued on many occasions that the PE arises from the softening/melting of the underlying FLL [3–5]. The basis for this argument lies in Pippard's hypothesis [6], which associates the increase in J_c with a rapid decrease of the rigidity of FLL. A more comprehensive explanation of the PE as arising from the softening of all the elastic moduli of the FLL was subsequently presented [7]. It is suggested that, as the normal state is approached, the FLL may lose its rigidity more rapidly than the reduction in pinning strength, resulting in the breakdown of the collective pinning regime and a crossover to stronger pinning of the individual vortices to inhomogeneities. This would yield an anomalous increase in the critical current density (i.e., the PE) [8]. Experimentally, PE temperature $T_{\mathrm{peak}}(H)$ can be identified with the position of a negative peak in the in-phase ac magnetic susceptibility (i.e., an anomalous maximum in the diamagnetic screening response as a consequence of peaking of the critical current density) in the presence of superposed dc fields [2]. Fig. 1 shows the real part of low frequency ac susceptibility [9] (χ'), recorded as a function of temperature with a superposed dc field of 20 mT, in a single crystal sample of 2H-$NbSe_2$. This crystal, and the others used in the studies being reported in this letter, have been grown by vapour transport method [10] and have a $T_c(0)$ of ~ 7 K. The onset of PE (marked with an arrow in the inset of Fig. 1) can be clearly noted at $T \approx 6.77$ K ($H = 20$ mT), just below $T_c(H)$. Further, the PE region (i.e., the anomalous variation in χ') extends up to $T \approx 6.85$ K, and thereafter the ac susceptibility rapidly decreases in the usual way till $T_c(H)$ is reached.

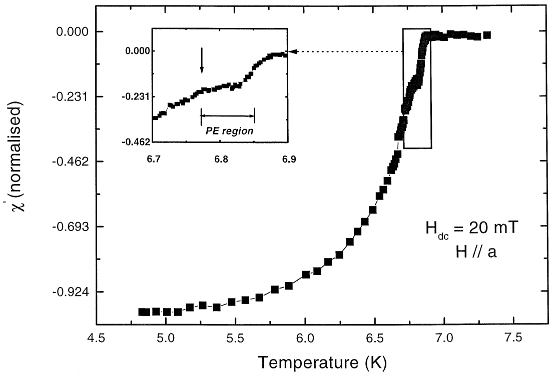

Fig. 1. Temperature dependence of the in-phase ac magnetic susceptibility χ'_{H} (T) ($f = 211$ Hz, $H_{\mathrm{ac}} = 0.05$ mT, $H_{\mathrm{dc}} = 20$ mT) for $H \| a$ in a single crystal of 2H-$NbSe_2$ [$T_c(0) \approx 7.0$ K]. The inset identifies the peak effect region and its onset at $T \approx 6.77$ K.

The present μSR investigations were aimed at probing the behaviour of FLL in the H–T plane across the PE region. The μSR technique gives a measure of the field distribution inside a type-II superconductor, and thus provides a direct evidence of any phase transitions in FLL in the form of changes in the field distribution as a function of T or H. It is thus a *microscopic probe* of the vortex lattice structure. It has been successfully used earlier [11] to demonstrate FLL melting and the associated dimensional crossover phenomenon in the high T_c superconductor $Bi_{2.15}Sr_{1.85}CaCu_2O_{8+\delta}$. In the present experiments, transverse μSR measurements were performed at the pulsed muon facility (ISIS) of the Rutherford Appleton Laboratory, UK. For our experiments, we used a mosaic consisting of about 35 small crystallites (each $\approx 2 \times 2 \times 0.5$ mm^3) of 2H-$NbSe_2$, stuck in the slurry of moisture-free Fe_2O_3, with their *ab*-planes parallel to the sample plate. Magnetic field was applied parallel to the sample plate as well as to the largest dimension of each of the crystallites (in order to minimise the demagnetisation effects). Positive muons were incident on the sample with their initial spin-polarisation

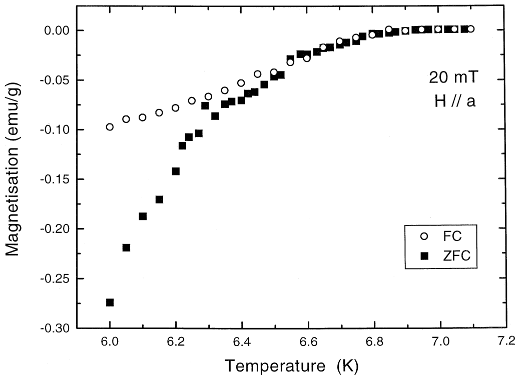

Fig. 2. Temperature dependence of the dc magnetisation (M) of a single crystal of 2H-NbSe$_2$ under 20 mT $(H \| a)$, in both zero-field-cooled and field-cooled modes. Note the near identical values of magnetisation in the two modes for $T > 6.5$ K. These measurements were made using a commercial SQUID magnetometer.

vector perpendicular to the applied field. Muon time decay spectra were recorded in the temperature region close to T_c in the zero-field-cooled (ZFC) mode as against the usual field-cooled (FC) mode [12]. However, it has been ascertained by independent dc magnetisation measurements (see Fig. 2) that the ZFC magnetisation is equal to FC magnetisation (within the experimental error) in the temperature region scanned in the μSR studies. In the ZFC mode, the sample was first cooled to a temperature $T < T_c(H)$, the magnetic field was then applied and the muon time decay spectra were recorded at various temperatures during the warming-up cycle. To assess the background contribution to these spectra, the procedure described in Ref. [12] was used. In this procedure, the sample is first cooled in zero field to a temperature well below $T_c(H)$, after which a small field is applied. Under these conditions, since most of the magnetic flux would be excluded from the interior of the superconductor, the average internal field in the sample is shifted well below the applied field, while the background signal would show up at the applied field value. This allows an assessment to be made of the background contribution to the μSR signal. Following this procedure, it was confirmed (at 5 K and in 4 mT) that the contribution to muon spectrum in our experiments is almost entirely from the superconductor, with negligible signal from the background.

The measured muon time decay spectrum contains information about the field distribution inside the superconductor. To obtain the probability distributions of these internal fields (i.e., $\rho(B)$ vs. B) we computed the Fourier transforms of the muon spectra, using the maximum entropy technique [13]. Expectedly, the field distributions obtained were nearly symmetric with the peaks close to the applied field values. Fig. 3 shows the $\rho(B)$ vs. B curves (in an applied field of 20 mT) at two temperatures, one below the onset of the PE (viz., at 6.68 K) and the other at 6.80 K in the PE region itself. Note that the curve for 6.68 K shows features characteristic of a three dimensional (3D) ordered vortex lattice, notably a gradually falling 'tail' at higher fields, coming from vortex core regions. (The singularities exhibited by the probability distribution for a perfect FLL are expected to be smeared in a real superconductor [14] and are therefore not seen [11].) In comparison, the curve for 6.80 K shows a higher 'mean value', consistent with increased flux penetration (lower magnetisation) as $T_c(H)$ is approached. Moreover, the latter curve shows a substantial shift of probability distribution towards the low field region even as the high field tail stays unchanged. This last feature is consistent with the simulation studies relating to the field distributions inside an imperfect flux line lattice. It was shown [14] that when a random perturbation displaces the flux lines from their regular positions, there is a shift of probability

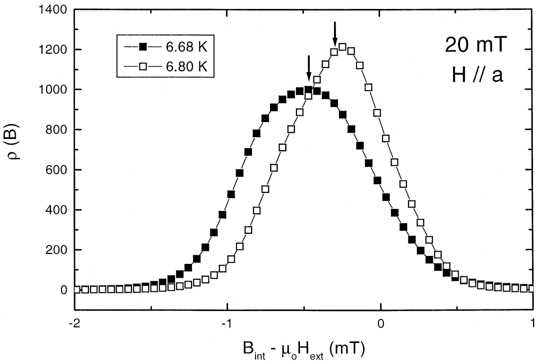

Fig. 3. The probability distributions of the internal magnetic fields in 2H-NbSe$_2$, showing significantly different line shapes across the peak effect region ($\mu_0 H_{ext} = 20$ mT). The arrows indicate the respective mean values. Note that the curve for $T = 6.68$ K shows asymmetric features characteristic of an ordered vortex lattice, whereas the other curve ($T = 6.80$ K) shows a substantial shift of spectral density towards the low field region.

distribution towards the low field region, with the high field tail intact, identical to what is seen in the present data. Thus, our muon measurement provides a clear evidence of an enhanced spatial randomisation of the FLL, on the high temperature side of the transition.

In order to quantify this inference, we have computed various moments of the field distributions using the expression for ith moment:

$$\langle \Delta B^i \rangle = \frac{1}{N} \sum_j p_j(B) \big(B_j - \langle B \rangle \big)^i , \tag{1}$$

where $\langle B \rangle = (1/N) \sum_j p_j(B) B_j$ is the first moment (mean value), while $N = \sum_j p_j(B)$. For evaluating the changes in the field distribution as a function of temperature, we used a dimensionless parameter α, defined [11] as,

$$\alpha = \left[\frac{\langle (\Delta B)^3 \rangle^{1/3}}{\langle (\Delta B)^2 \rangle^{1/2}} \right] . \tag{2}$$

It was shown earlier [11] that this parameter is a measure of the asymmetry of the field distribution, the variation of which reflects underlying changes in the vortex structure. We have estimated α at various temperatures for an applied field of 20 mT, and the results are shown in the main panel of Fig. 4. We find that α exhibits a sharp change in magnitude with a change in sign, at $T \approx 6.75$ K, signifying a phase transition in the FLL in the PE region. As stated above, concomitant changes in the internal field distributions across this transition imply an abrupt reduction in the spatial order in FLL as the PE sets in, with the higher temperature phase being more disordered. In the inset of Fig. 4, we have plotted the corresponding variation of the second moment of the field distribution as a function of temperature. Knowing that for a static array of 3D flux lines, the second moment is a measure of the superconducting penetration depth [15], we conclude from the inset of Fig. 4 that the penetration depth varies smoothly in the temperature region of interest, with no discontinuity across the PE region. Using the second moment value of the field distribution at 6.68 K and in 20 mT, we have estimated the penetration depth to be 5570 Å, which would give $\lambda(0)$ to be 2300 Å using the expressions, $\langle (\Delta B)^2 \rangle = 0.00371 \phi_0^2 \lambda^{-4}$ and $\lambda(t) = \lambda(0)/(1-t^4)^{1/2}$. Such a value of $\lambda(0)$ is consistent with the in-plane penetration depth values reported in the literature [3]. Further, our observation about the second moment suggests that, in the phase transition seen in the present μSR studies, only a change in flux line arrangement is involved, while mechanisms such as a dimensional crossover seen [11] in a Josephson coupled layered superconductor $Bi_{2.15}Sr_{1.85}CaCu_2O_{8+\delta}$ (i.e., a reduction in the correlations between the positions of vortex cores in the adjacent layers, which manifest as a discontinuity in the penetration depth) are ruled out.

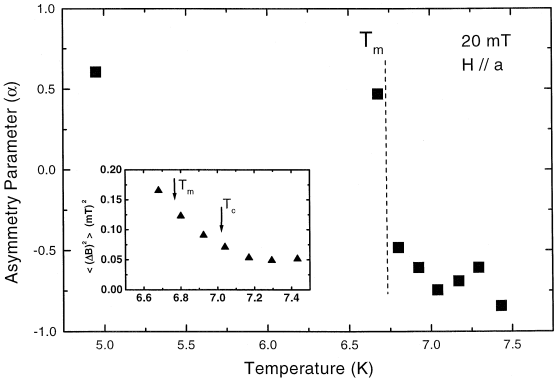

Fig. 4. A plot of the line shape asymmetry parameter α as a function of temperature for $\mu_0 H_{ext} = 20$ mT. $\alpha = [\langle (\Delta B)^3 \rangle^{1/3} / \langle (\Delta B)^2 \rangle^{1/2}]$, where $\langle (\Delta B)^i \rangle$ is the ith moment of the magnetic field distribution. The vertical dotted line indicates an abrupt change in the value of α at T_m. The inset shows a smooth variation of the corresponding second moment values across T_m, thereby confirming that the penetration depth does not show any discontinuity across this transition.

Within the resolution of our experimental setup (here the temperature stability was within ~ 40 mK), the locus of the transition in H–T plane seen in our μSR experiments overlaps the PE region. We thus conclude that the nature of the transition in FLL, which manifests in the form of a PE in 2H-$NbSe_2$, corresponds to a sharp loss of spatial order of the flux line lattice. This loss of order may be driven by thermal fluctuations that soften the lattice at the incipient melting transition. Alternatively, this may be also caused by quenched disorder that triggers a sharp onset of plastic deformation or fragmentation of the lattice aided by thermal fluctuations [3]. In either case, the PE or an enhancement of the critical current is caused by this underlying loss of order of the FLL. Indeed, if we identify our $T_m = 6.75$ K with the FLL melting, we can estimate the Lindermann number c_L using the expression [16–18] $\beta_m(T) = \beta_m(c_L^4/G_i)H_{c_2}(0)(1-T/T_c)^2$. Using [3,18] $H_{c_2}(0) \approx 10.6$ T, $\beta_m = 5.6$ and the Ginzburg number $G_i \approx 3 \times 10^{-4}$, which comes out to be about 0.1. This value agrees with other estimates for c_L obtained via the Lindemann melting criterion [2,11], implying that the PE occurs in the same part in the (H,T) phase space where FLL melting is expected.

In conclusion, we have presented μSR evidence of a discontinuous transition in the FLL of 2H-NbSe$_2$, associated with a sharp reduction in order in the FLL. Supportive magnetisation studies reveal that this transition overlaps with, and is the cause of, the peak effect phenomenon.

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