Anisotropy of vortex lattice disordering in intrinsic 2H-NbSe2

S.W. MacMaster, P. Tyson, and T.J. Wark
Advanced Lab, Physics Department, Rowan University, Glassboro, New Jersey

We observed the unique behavior of flux-line lattice (FLL) disordering in 2H-NbSe2 as the magnetic field is varied by angle in relation to the c-axis. As the magnetic field is tilted with respect to the c-axis but kept at perpendicular to the current vector so that the Lorentz force is constant at a constant magnetic fields, the peak effect uniquely occurs at all angles. Thus the upper critical field \( H_{c2} \) varies as to \( \theta \) resulting in a unique angular responsive upper critical field, \( H_{c2\theta} \). The results indicate the existence of a unique peak effect critical field \( H_{p\theta} \) which through observation closely tracks the anisotropy of the upper critical field \( H_{c2\theta} \) whose proportionality function \( C(T, \theta) \) varies both with temperature below critical, \( T < T_c \), and as the angle \( \theta \) increases away from the c-axis.

Introduction

In an applied magnetic field at temperatures below critical a Type-II superconductor will enter the mixed-state where, within cores of normal state material, magnetic field lines are not excluded but remain constrained to these flux filaments [1]. The flux within these cores is generated by a vortex of persistent current circulating around the cores with a sense of rotation opposite to that of the diamagnetic surface current. This circulating current is the result electron pairs, *Cooper Pairs*, whose quantum state are bosons in contrast to a single electron which is a fermion. The arrangement of the mixed-state *Meissner* effect cores and associates electron pairs is known as *Abrikosov Vortex Lattice* after its discoverer.

Present only in an applied magnetic field between the lower and upper critical magnetic fields, Abrikosov Vortices arrange themselves in a regular periodic hexagonal array usually known as the *fluxon lattice* or *flux-line lattice* (FLL). The dimension of the cores has been demonstrated to be small, \( r_0 = 300 \, \text{Å} \) and fixed with geometric arrangements demonstrated experimentally by Essmann and Trauble [1] and imaged using Scanning Tunneling Microscopy by Harold Hess et. al. Core densities are both proportional and quantized by the magnitude of the magnetic field and by the temperature of the material varying as to vortex separation \( a_0 \) by \( a_0 = (\Phi_0 / H)^{1/2} \), where \( \Phi_0 \) quantum magnetic flux, \( \Phi_0 = \hbar c / 2e \), and \( H \) is the magnetic field [2]. As the temperature and/or the magnetic field is increased, the normal cores are packed more closely. Above the critical temperature, or critical magnetic field, the material will behave as a normal conductor. However, between the lower critical field \( H_{c1} \) and the upper critical field \( H_{c2} \) below the critical temperature, the material is in the mixed state with superconducting properties.

When a vortex moves, regardless of the mechanism, it carries its magnetic flux, \( \Phi_0 \), with it. The moving magnetic flux induces an electric field, and thus an associated voltage drop transverse to the motion of the vortex. An applied current to a system in the mixed-state will produce a force on the vortices according to the Lorentz model. The Lorentz...
force, and as a result, the vortex motion, is perpendicular to the direction of both the applied current and the magnetic field. If the vortices move due to applied driving force, dissipation in the mixed-state will be observed.

The movement of vortices and cores requires work to drive them through the material. As far as the cores are concerned the material is like a viscous medium with a constant current force and constant magnetic force acting on the FLL and cores. As a consequence of this Lorentz force, the vortex motion and resultant velocity $v_0$ of the vortices will be at an angle $\alpha$ with the direction of the transport current $v_i$. The greater the viscous drag the more nearly the vortices move to right angles $\alpha=90^\circ$. If $\alpha<90^\circ$, a resulting Hall effect current will be observed (see Figure 1).

![Diagram](image)

Fig 1When $\alpha=90^\circ$ the vortex motion is parallel to the Lorentz force and no Hall effect will be observed. When $\alpha<90^\circ$ there will be a Hall effect.

In a uniform field and a zero temperature gradient the vortices are considered solidified as a vortex crystal. At currents greater than the critical current, the vortex lattice will move uniformly retaining its geometry, collective creep as modeled by Larkin-Ovchinnikov [10], [11]. However, some vortices may become pinned at crystal defect sites resulting in amorphous deformations of the vortex crystal transforming it into a vortex glass phase. Pinning at defects suppresses vortex motion. Defects are purposefully introduced or implanted to increase vortex pinning. Although not the subject of this paper, increased pinning results in an increase of the critical current. And, as a result of randomly spaced defects whether natural or implanted, the ordered vortex pattern becomes disordered but remains solid, the vortex glass phase. Conversely, a rather perfect specimen has a very small critical current, perhaps a few tens of milliamps per mm$^2$, when it is in the mixed-state [1]. We will only be addressing the dynamics of the weakly pinned vortex system of an intrinsic Niobium Diselenide ($\text{NbSe}_2$) crystal herein [3].

Of interest are the critical current density $J_c$ and critical magnetic fields, below which the vortices are stationary with the material in the mixed-state, above which the vortices are in motion resulting in the dissipation of the mixed-state and transition to the normal state. It has been observed that near the critical current, which is the threshold for detectable vortex motion, the vortices move in a disordered fashion called the vortex liquid phase [2].

At a fixed temperature and fixed current below critical this phase should be encountered twice [4]. Since resistance is a measure of the average vortex velocity, its increase or decrease with increasing field or temperature signals a more mobile or a more sluggish vortex lattice [5], that is more or less viscosity. At a magnetic field below the lower critical field $H_{c1}$ the material is in the superconducting state just as a type-I superconductor. As the field increases to $H_{c1}$ the resistance starts to increase indicating a vortex phase transition or reentrant liquid phase with the material transitioning into the
mixed-state. As the field increases the resistance increases until just before reaching the normal state at the upper critical field $H_{c2}$ the resistance suddenly dips. This dip, when experimentally analyzed, equates to a sharp peak in the critical current and is known as the *peak effect.*

The peak effect phenomenon is the occurrence of an anomalous enhancement of the critical current density $J_c$, i.e., the pinning force per flux line, at high fields near the normal-state phase boundary, the $H_{c2}$, in low-$T_c$ systems [6],[7]. Although the exact cause of the peak effect is uncertain, it is widely regarded as a result of rapid softening of the lattice and the reentrant plastic phase, that is, some anomalous induced pinning from a moving solid phase to the liquid phase.

In an anisotropic material's lower and upper critical fields will be different at different field orientations [9]. As such, vortex dynamics will likewise vary with field orientation as well. One might expect an increase in pinning when the magnetic field and driving current are parallel to the material's lattice planes a or b-axis but mutually perpendicular. Assuming an isotropic a-b plane, we shall herein address anisotropy as magnetic field is rotated in an angular tilt direction $\theta$ with respect to the c-axis.

The *Lawrence-Doniach* model for superconductivity in layered compounds (layered crystals) can be pictured as weakly coupled stacked array of thin superconducting material [12]. At a fixed temperature below the critical temperature $T_c$, the anisotropic upper critical field, $H_{c2\perp}$, behaves according to *Ginzburg-Landau* limit:

$$H_{c2\perp} = 1/[\sin^2(\theta) + (m/M)\cos^2(\theta)]^{1/2} H_{c2\perp}$$

where $H_{c2\perp}$ is the upper critical field in the perpendicular to the c-axis in direction parallel the lattice layers, $\theta$ is the angle translation from the c-axis direction rotating perpendicular to the current (in Prober, sin$\theta$ and cos$\theta$ are reversed due to his designation of the rotation axis where $\theta=0^\circ$ is parallel to the crystal lattice a-b plane) and $m/M$ is the effective mass ratio which will be derived from known or measured $H_{c2||}$ and $H_{c2\perp}$ by the relationship:

$$H_{c2||} = (M/m)^{1/2} H_{c2\perp}$$

which is a special case of equation (1). As $H_{c2\perp}$ is a function of temperature, the mass ratio $m/M$ will also vary with temperature however, we would expect this variation to be small in the narrow temperature region of $T < T_c$ in which we shall investigate. Thus, we shall assume the mass ratio to be constant in our discussion.

The upper critical field $H_{c2\perp}$ can be calculated using the anisotropic Ginzburg-Landau theory as a function of field orientation by determining the temperature dependent coherence length $\xi(T)$ where:

$$\xi(T) = \xi(0) (T_c/(T_c - T))$$

which leads to a solution for $H_{c2\perp}$:

$$H_{c2\perp}(T) = \phi_0 / 2\pi \xi(T) = \phi_0 / [2\pi \xi(0) (T_c/(T_c - T))^2]$$
Solving for $\xi^2(0)$ we can set-up a ratio between the upper critical fields $H_{c2\perp}(T)$ and temperature resulting in:

$$H_{c2\perp}(T_4) = H_{c2\perp}(T_1) \left[\frac{(T_c - T_2)}{(T_c - T_1)}\right]^2$$  \hspace{1cm} (5)

Where we calculate an unknown upper critical field at a temperature from a known upper critical field. Or, if available, we can measure either $H_{c2||}$ and apply equation (2), $H_{c2||} = (M/m)^{1/2} H_{c2\perp}$.

Also, since the advent of high-$T_c$ superconductors, much of the experimental work has focused on the characteristics of the dense vortex phase, high $H_{c2}$, for which a different type of critical current density anomaly, termed the *fishtail effect* or second magnetization peak, has been witnessed [6]. The name fishtail effect relates to the characteristic shape of the isothermal dc magnetization hysteresis loop. We wish to demonstrate the transition to the liquid phase, its relationship to the angle of the applied magnetic field, magnetic hysteresics and the peak effect with a decreasing and increasing magnetic field using a low-$T_c$ weakly pinning material.

**Experimental**

Intrinsic Niobium Diselenide (NbSe$_2$) layered crystalline material with a charge density wave (CDW) transition at 33K, and a superconducting transition at 7.2K (see Table 1). The c-axis lattice spacing of NbSe$_2$ is on the order of 6.3Å and it has a melting point $>1300^\circ$C. It is easily cleavable, creating atomically flat regions at least several hundred nanometers wide.

| Table 1: Anisotropic superconducting parameters for 2H-NbSe$_2$ [11] |
|-------------------|-------------------|-------------------|
| Parameter         | $H_{||}$ c         | $H_{\perp}$ c     |
| $k$               | 9                 | 30                |
| $x$               | 77 Å              | 23 Å              |
| $l$               | 690 Å             | 2300 Å            |
| $J_c$ (1T, 4.2K)  | 1 – 30 A/cm$^2$   | 10 – 200 A/cm$^2$ |
| $H_{c2}$ (4.2K)   | 2.3T              | 7.0T              |

In our experiment we attached four (4) leads to a 0.75mm x 4.45mm x 0.06mm sample of intrinsic Niobium Diselenide (NbSe$_2$). Two (2) leads were attached at either end of the sample for current injection while two (2) leads were attached 3.05mm apart to measure induced voltage and thus, we can determine resistance due to vortex motion.

The sample was mounted onto a sapphire slide and attached to a rotating sample holder. Placed in a Quantum Design Physical Property Measurement System (PPMS), the sample temperature was maintained at 6.0K or 6.5K in the cryostat for each experimental series. We measured AC transport at 19Hz as the sample was rotated through $360^\circ$ with the axis of rotation being the drive current direction while applying drive currents of 5mA, 10mA and 15mA for each applied field varying between 0.2T and 0.8T by 0.2T increments. This rotation allowed us to measure differences while maintaining a
constant Lorentz force. Lastly, the sample was held with $H \parallel c$ at fixed temperature 6.0K varying the magnetic field between 0T and 2.5T at fixed currents.

**Discussion of Results**

Figures 2a and 1b show the magnetic field dependence of the sample resistance at different drive currents for the case of $H \parallel c$ at a fixed temperature, $T = 6.0K$. When the sample is in a field above $H_{c2}$, the upper critical field, the resistance $R$ measurement flattens indicating the sample is in the normal state where the $I$-$V$ relationship is linear. As the magnetic field is reduced below $H_{c2}$ a dramatic rapid decrease in resistance $R$ is observed. The sample enters the mixed-phase, where a nonlinear dynamic resistance dominates the vortex motion. In Figure 1b a dip in resistance is measured when the magnetic field is just below $H_{c2}$ corresponding to the “peak effect”. This value we call peak field $H_p$ as we subsequently are quantitatively able to measure and model it.

![Figure 2a](image-url)

**Fig 2 a) Conventional resistance curves where $H \parallel c$ the field is ramped up higher, held there, and then ramped down lower at a fixed temperature $T=6.0K$ for several currents. b) The peak effect is shown as a dip in resistance just below $H_{c2}$. Note: in all cases the lower tract represents the increasing magnetic field, the upper is the decreasing magnetic field.**

Bhattacharya and Higgins have shown the same effect is observed when the current is fixed and the temperature is varied [8], [11]. This implies that the resistance minimum, a peak effect, has a unique location in the $(H, T)$ plane. Of interest here is the lack of an observable or measurable peak effect in the lower drive currents, 1 and 2 mA in this case. This would indicate these current densities are below well $J_0$ where the Lorentz is less than the force required to move the vortex. This current dependence of the anomaly shows that it is related to pinning and the minimum itself is associated nonlinearly with the pinning properties of the FLL [11].

The cross section area of our sample is $A = 4.5 \times 10^{-8} \text{m}^2 = 4.5 \times 10^{-4} \text{cm}^2$ with a sample thickness $t = 60 \mu \text{m}$ and a length between voltage contacts $L = 3.05 \text{mm}$. Therefore, $J(2 \text{mA}) = 4.44 \text{A/cm}^2$ and $J(5 \text{mA}) = 11.1 \text{A/cm}^2$. Our concern now will focus on the $dR/dH$ at fields below and above the reentrant phase as well as the case of low current density when such a phase transition or effect is not observable. As $R$ is proportional to the exponential of the thermodynamic energy:

$$R = R_n \exp[-(U - nJ_0t dx)/(kT)]$$

(6)
where $R_n$ is a fitting parameter related to the attempt frequency of a vortex trying to escape the well, $n$ is the number of vortices in a bundle which moves, $J$ the current density, $\phi_0 = 2.07 \times 10^{-15} \text{T m}^2$ the quantized normal core magnetic flux, $t$ is the sample thickness, $dx$ is the vortex displacement, and:

$$U = \alpha \pi r_0 t B_c^2(T) / (2 \mu_0) (1 - H / H_{c2}(T))$$

(7)

where, $\alpha$ is the efficiency, $0 < \alpha < 1$, $r_0$ is the normal core radius, and $B_c(T)$ is the thermodynamic critical field $\sim 0.2T$. In the case of either side of the resistance minimum peak effect it should be shown that $n_1 \ll n_2$, with a theoretical $n_2 = 1$ on the high field side but, more realistically, a small number of vortices in a “bundle”. In the second low current density case, theoretically $n = 1$, but as before, $n$ is likely to be related to single bundles.

The first qualitative explanation of the peak effect by Pippard was that the shear modulus of the FLL softens faster than the depletion of pinning as $H$ approaches $H_{c2}$. Thus the competition between the pinning interaction and elasticity of the FLL results in an enhancement of the threshold pinning force [8]. Thus, at lower current densities, the FLL does not reenter the liquid phase but collectively slides into the normal phase as the critical field is exceeded.

It was also our original desire to measure magnetic hysteresis in this phase of the experiment. A closer look at the data could not confirm such an observation in that the separation in traces between the increasing field and decreasing field are neither significant nor is there enough data in the region of the first order peak effect to quantify such an observation. Experiments by Ling and Berger indicate hysteresis is measurable in defect-free NbSe$_2$ [5]. However, in analyzing their data it became apparent that the magnetic field was perpendicular to the c-axis in their case. Thus, they were dealing in a field direction where increased pinning is observed and a phase of pinning “memory” as described in the literature.
Figure 3 shows angular measurements of the sample as it is rotated 360° in both a fixed magnetic field and fixed temperature through several currents. H || c at both 180° and 0/360°. Obviously H_{c2||} is less than 0.6T at 6.0K since, in all cases, a peak in R indicated a moving FLL in the normal state. Similarly, at 90° and 270°, when H ^ c, H_{c2}^c is greater than 1.2T in that, at all currents tested, R is at an absolute minimum indicating the mixed-state with a pinned FLL.

Of particular interest, however, are the dips in R located at some regular angular distance on either side of H^c. We recognize this as the anisotropy of the peak effect at values of H_p^c just less than H_{c2}^c. Notice that in each field H_p^c is found at the same angle regardless of the current indicating the anomaly is only field dependent and, as we will see Figure 4, temperature dependent, again uniquely located in (H, T) phase space.
Since $H_p$ is independent of current, Figure 5 compares the dissipation measurements at two temperatures, 6.0K and 6.5K at a single current, $I=5mA$. We can clearly see that the angular separation between $H^c$ and $H_p$ gets smaller with an increasing magnetic field but is present at all fields above $H_{c2||}$. $H_{c2||}$ is clearly below 0.4T at $T=6.5K$, $I=5mA$ but is between 0.4T and 0.6T at 6.0K and 5mA. Bhattacharya and Higgins demonstrated that $H_p$ closely tracks the anisotropy of $H_{c2}$ confirming that the peak effect occurs at all angles in a way similar to how the peak effect tracks temperature [11].

Following Bhattacharya and Higgins we can see that the upper critical field $H_{c2}$ is proportional to the peak critical field $H_p$, $H_{c2} \propto H_p$, and, it follows $H_{c2} = C H_p$. As there is both a n angular and temperature dependence of proportionality we can further state:

$$H_{c2\theta}(T) = C(T, \theta) H_{p\theta}(T)$$  \hspace{1cm} (8)$$

where $H_{c2\theta}$ is derived by Prober [12], and $C(T, \theta)$ is the temperature and angle dependent proportionality function. We can now rewrite the Prober equation as:

$$H_{p\theta} = 1/[\sin^2(\theta) + (m/M)\cos^2(\theta)]^{1/2}H_{c2\perp}(1/ C(T, \theta))$$  \hspace{1cm} (9)$$

At a temperature at $T_c$ and $H \parallel c$, $C(T, \theta) \equiv 1$ that is, $H_{c2||}$ and $H_{p||}$ converge.

As indicated by the data gathered, we can reasonably measure the peak critical field at angles $H_{p\theta}$ and have done so for $H \parallel c$ as well as a full 360° rotation. From the data presented in Table 1 we find the effective mass ratio $m/M = 9.263$. Using $H_{c2||} = (M/m)^{1/2} H_{c2\perp}$, we can derive $H_{c2\perp}$ using $H_{p\theta}$ measured at $T=6.0K$ in Figure 1a to be $H_{p\theta} = 0.81T$ therefore $H_{c2\perp} = 2.5T$. With $H_{c2\perp}$ we can now model the anisotropic Ginzburg-Landau equation solving for $H_{c2\theta}$ for all $\theta$ and, in Figure 6, compare this model with the measured $H_{p\theta}$’s which should all be less than but proportional to the theoretical $H_{c2\theta}$. For the case of $T=6.5K$ we calculated a perpendicular upper critical field using the equation (5) anisotropic Ginzburg-Landau limit to find $H_{c2\perp} = 1.4T$. 


![Fig 5 Dissipation vs field angle comparing the results of measurements made at T=6.0K & 6.5K at 5mA with fields varying between 0.4T and 0.6T.](image-url)
Fig 6 Peak critical field $H_{p\theta}$ extracted from data for $T = 6.0K \& 6.5K$ with theoretical curves for $H_{c2\theta}$ for each temperature. Notice how $H_{p\theta}$ typically is less than the theoretical $H_{c2\theta}$ curve taking into account for the proportionality constant $C_{T,\theta}$.

Of particular interest is the measured $H_{p\theta}(\theta=0^\circ)= 0.81T$ while $H_{p\theta}(\theta=28^\circ)= 0.8T$ indicating the measurement at $\theta = 0^\circ$ is incorrect, as it does not follow the anisotropic Ginzburg-Landau model. However a look at Figure 5 indicates a small resistance dip at $180^\circ$ which is also equal to $0^\circ$ ($H \parallel c$) in this case. This anomaly does not stand out in the literature and may require other work in understanding.

Conclusions

In conclusion, we have presented three central results. 1) The “peak effect” has a unique location in $(H,T)$ phase space yet, at the same time, is also current dependent. When the driving current is below a critical density $J_c$ the FLL does not reenter the liquid phase below the upper critical field $H_{c2}$, but collectively slides into the normal phase according to the Larkin-Ovchinnikov model. 2) As the magnetic field is tilted with respect to the c-axis but kept at perpendicular to the current vector so that the Lorentz force is constant at in constant fields, the peak effect uniquely occurs at all angles. Thus the upper critical field $H_{c2}$ varies as to $\theta$ resulting in a unique angular responsive upper critical field, $H_{c2\theta}$. 3) Most importantly, there exist a unique peak effect critical field $H_{p\theta}$ which through observation closely tracks the anisotropy of the angular upper critical field $H_{c2\theta}$ whose proportionality function $C(T,\theta)$ varies both with temperature below critical, $T < T_c$, and as the angle $\theta$ increases away from the c-axis.

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