SIMULTANEOUS OBSERVATION OF FISHTAIL EFFECT AND PEAK EFFECT IN 2H-NbSe$_2$

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We report on the discovery of the simultaneous observation of Fishtail Effect (FE) and Peak Effect (PE) via the study of angular dependence of dc magnetization hysteresis loops in a clean crystal of 2H-NbSe$_2$. These result clarify and establish the occurrence of the reentrant characteristics in order to disorder transformation in an isothermal scan close to zero field superconducting transition temperature of 2H-NbSe$_2$. The ubiquitous FE arises from coalescence of two anomalous variations in current density $J_c$, one of which is related to the collapse of the rigidity FLL close to $H_{c2}$ and another one located at very low fields presumably corresponds to the pinning induced order to disorder transformation. When the two effects get well separated, an ordered state of FLL exists in the intermediate field region.

The vortex state of type II superconductors conceived by Abrikosov[1] encompasses the translational symmetry and such an ideal flux line lattice (FLL) is expected to move with arbitrarily small transport current under the influence of Lorentz force. The chemical impurities and structural imperfections in the underlying atomic lattice in any real sample provide the sources for preferentially pinning the flux lines at the expense of destroying the perfect translational symmetry of the FLL and thereby impart a critical current density ($J_c$) to the vortex array. $J_c$ of any superconducting specimen is expected to monotonically decrease while approaching the superconducting to normal phase boundary as the field increases (at fixed $T$) or as the temperature increases (at fixed $H$). However, experimentally one encounters the phenomenon of anomalous maximum in $J_c$ with increase in $H$ (or $T$) in all varieties of superconducting samples. This anomalous maximum in $J_c$ is referred to either as Peak Effect (PE) or as Fishtail Effect (FE). The basis of the latter nomenclature namely, FE, is the characteristic shape of the isothermal dc magnetization hysteresis loop of a pinned type-II superconductor.

As the concept of pinning relates inversely to the notion of perfect periodicity in the underlying symmetry of FLL, it is now generally accepted that the anomalous maximum in $J_c$ elucidates the occurrence of order to disorder transformation in the FLL as a consequence of competition and interplay between the elastic energy, pinning energy and thermal fluctuations. The advent of high $T_c$ superconductors focused widespread attention on the issue of thermal melting of the pure Abrikosov FLL. In recent years, convincing data have been collated in favor of first order nature of melting of FLL in very pure and nearly stoichiometric single crystals of High $T_c$ cuprates. In the well studied YBa$_2$Cu$_3$O$_7$ system, there are evidences that a sharp PE exists in juxtaposition to the FLL, melting transition and this coincidence supports a widely held view that a sharp PE located at the edge of depinning transition of FLL is a fingerprint of collapse of the elastic moduli of the FLL. In slightly off-stoichiometric single crystals of YBa$_2$Cu$_3$O$_7$, the maximum in $J_c$ has been reported to evolve continuously from a narrow peak lying close to $H_{c2}$ (i.e., the usual Peak Effect) to a broad hump extending over a large field region located far away from $H_{c2}$ (i.e., the Fishtail Effect) as the effective pinning increases as a consequence of either the increase in quenched random disorder or the decrease in temperature. Thus, notionally, the PE and the FE may be treated as distinct and mutually exclusive features in dc magnetization hysteresis data though intimately related. In the context of single crystals of Bismuth Cuprate system, in which there have been reports of only the fishtail type of anomalous maximum in $J_c$, it was demonstrated from $\mu$SR studies that the spatial order of FLL undergoes a sharp change at a field value coincident with the onset of fishtail anomaly in dc magnetization hysteresis data. Another $\mu$SR study in the same Bismuth Cuprate system in different ($H$, $T$) region had established that the spatial order of the FLL undergoes a sudden reduction at ($H$, $T$) values where melting of FLL was anticipated. Thus, both peak effect and fishtail effect could be associated with the notion of occurrence of order to disorder transforma-
tion which is either first order or second order. There have been numerous reports in high Tc superconductors wherein different phase boundaries across which vortex state undergoes order to disorder transformations corresponding to onset and peak position of fishtail effect have been drawn in the (H, T) space. Some of these phase boundaries match with those phase boundaries drawn from other transport and thermodynamic measurements whereas some others appear to approach them at multi-critical points (see, for instance, Fig.4 in [3] and Fig.4 in [18]).

Considering that different phases of vortex matter and transformation amongst them are a consequence of competition and interplay between elastic energy, pinning energy and thermal fluctuations, it is of interest to explore the presence of such characteristics in the vortex states of conventional low temperature superconductors in the appropriate (H,T) region. Amongst the low temperature superconductors, the clean single crystals of 2H-NbSe2 system having Tc(0) ≈ 7 K are in current focus [21], from the point of view of pristine physics issues of vortex matter [3] because of (i) their very weak pinning nature, (ii) their relatively large Ginzburg number value (Gc1 ∼ 10^{-4}) [4] and (iii) the existence of a robust PE in them [18]. We present here new results pertaining to the discovery of simultaneous presence of fishtail effect and peak effect in a clean crystal of 2H-NbSe2 at low fields (in H < 1 kOe where the FLL lattice constant a0 > 2000 Å) and in the high temperature (T/Tc(0) > 0.95) region. We believe that these results are the first of their kind. They pertain to a vortex array in its di-nascent stage and the fluctuation effects are very strong due to the close proximity to Tc(0). These results have lead us to construct phase boundaries in (H,T) space which have the potential to clarify complex issues emerging from studies related to PE/FE/FLL melting in high Tc cuprates [3][5]. One specific issue that the simultaneous observation of PE and PE aims to resolve is the reentrant characteristic of order-disorder phase boundary of FLL [3][11][12][22] as the interaction gets progressively enhanced (with increasing field) while thermal fluctuations (T) and quenched random disorder remain fixed.

For our present study we chose a single crystal of 2H-NbSe2 (Tc(0)~7.2K with a ΔTc~50 mK). The sample dimensions are 5 X 2 X 1 mm3 and Jc values in it lie below 1000 A/cm2. It is our belief that the present sample has a level of purity which lies in between those of the crystals A and B, used by us in our earlier studies [4]. We measured its ac magnetization screening response using a high sensitivity ac-susceptometer [23] and dc-magnetization using a standard Quantum Design SQUID magnetometer with a specially designed home made sample holder which allows an angular variation of 0° to 180° between the field H and the ab-plane of the single crystal.

Fig.1 shows the temperature dependence of the diamagnetic screening response (χ′(T)) for the FLL created at different Hdc (||c) values. From a generalized Critical State Model relation [24] : 

\[ \chi' \approx 1 + \frac{\alpha \beta_{ac}}{J_c}, \]  

where α is a geometry and size dependent factor and \( J_c \) is the (H,T) dependent critical current density. From this relationship, it can be deduced that PE phenomenon (i.e., peak in Jc) should manifest itself as an anomalous increase in the diamagnetic screening response (χ′(T)) for a given Hdc. In Fig. 1, we have marked with arrows the peak temperatures Tp of the PE in χ′(T) behavior at various Hdc. It can be seen that Tp values increase with decreasing Hdc down to 200 Oe. Further more, another noteworthy feature in χ′(T) data is that, the PE starts to broaden substantially about Tp value as one moves to lower fields (from 100 Oe to 50 Oe). To reveal the possible connection between the phenomenon of broadening of PE and the behavior of FLL at low fields it may be pertinent to point out here that, in the field range from 100 Oe to 50 Oe where the PE starts to broaden, the values of a0 vary from 4800 Å to about 6800 Å. Recalling that λc vary from 4550 Å, in 2H-NbSe2 in the (H,T) region under consideration [21], the vortex array is in the dilute limit (a0 > λ) for H < 100 Oe and the flux lines are only weakly interacting, with the result the FLL is in a state which is easily susceptible to thermal fluctuations and pinning effects. The inset in Fig.1 shows the PE curve which has been determined by picking out the field - temperature values at which the peak in PE occurs in χ′(T) data. The noteworthy features of PE are: (i) at high fields (H > 200 Oe) the PE curve tracks the Hc2(T) curve, such that both of them have a slope of 5 ± kOe/K, however at lower fields (H < 100 Oe) the PE curve bends away from the Hc2(T) curve, (ii) the progressive increase in the size of the error bars on the data points indicates the commencement of process of broadening out of PE phenomenon, while approaching Tc(0). Our previous studies [5] had revealed that increased effective pinning broadened out the PE, we thus surmise that an interplay between pinning and thermal fluctuation effects at low H - high T determines the broadening feature in PE in Fig.1. This prompts to investigate the features of PE and its broadening through isothermal magnetization M(H) hysteresis loop measurements, where we study the progression of flux line lattice of varying a0 under the influence of fixed thermal energy. To perform these isothermal M(H) measurements, we chose particularly those temperatures (close to Tc(0)), where the PE broadened and the PE curve seems to bend away from Hc2(T) (see Fig.1).

A superconductor shields itself from any change in external magnetic field by setting up currents equal to Jc(B), which in turn result in the magnetization M at a given field H. When one obtains a dc magnetization hysteresis loop, the width of the magnetization hysteresis at a given field, i.e., \( \Delta M (\Delta M(H)=M(H_+)-M(H_-)) \) may be taken as a measure of Jc. This implies that any non-monotonic variation in the behavior of Jc(H) can,
therefore, show up as an anomalous modulation in the width ($\Delta M$) of the magnetization hysteresis loop. The PE emerges thus as an anomalous bubble like anomaly superposed on the quasi reversible magnetization ($M(H)$) hysteresis loop (see PE region centered around $H_p$ in the main panel of Fig.2(a)). In isothermal dc magnetization hysteresis data at $T=6.95$ K in 2H-NbSe$_2$, we observe that there is a well formed PE (anomalous $M(H)$ hysteresis bubble) centered around $H_p \approx 1000$ Oe (cf. Fig.2(a)) and this peak field value is consistent with the $T_p(H)$ curve in Fig.1. In Fig.2(a) in the field range from 50 Oe to 250 Oe (see arrow marked $H_d$ in Fig.2(a)), there is an anomalous modulation in the width of the magnetization hysteresis loop. We can determine the $J_c$ using the relationship $J_c \propto \Delta M/d$, where $d$ is the thickness of the sample. In the inset of Fig.2(a) the behavior of $J_c$ versus $H$ at $T=6.95$ K is shown in dark square symbols on a semi-log plot. Such a $J_c(H)$ plot shows an overall linear (i.e., $J_c \propto \exp(-H)$) behavior (examine the straight line passing through the data points). It can be easily verified that in the field range of 70 Oe $\leq H \leq 250$ Oe, there is an anomalous behavior in $J_c(H)$ which brings out the deviation from the overall linear behavior. We label the center of gravity of this anomaly as $H_d$ at $\approx 100$ Oe. The development of this anomaly at $H_d$ as a function of temperature is investigated by studying the M(H) hysteresis loop (cf. main panel of Fig.2(c)) at $T=7.0$ K, where the hysteresis loop seems to be completely anomalous and irreversible in the entire field range from 0 Oe $\leq H \leq H_{c2}$. The visible differences that emerge by comparing the M(H) hysteresis loop at $T=7.0$ K and $T=6.95$ K are: (i) one cannot precisely locate the low field anomaly at $H_d$ in the M(H) loop at 7.0 K and (ii) one cannot also clearly identify from the M(H) hysteresis curve the upper PE which occurs close to $H_{c2}$. In the inset of Fig.2(c), we have put together the behavior of the $J_c(H)$ at 7.0 K and 6.95 K. The usual expectation is $J_c(H, T=7.0K) < J_c(H, T=6.95 K)$, however such an inequality is satisfied only for $H \leq H_d$. At $H > H_d$, the $J_c(H, T=7.0K) > J_c(H, T=6.95 K)$, which is a manifestation of an anomalous behavior in $J_c$ and it signals the occurrence of peak effect like feature in $J_c$ at low fields which are far from $H_{c2}$. It thus seems that the anomalous modulation in $J_c$ at $H_d$ at 6.95 K in Fig.2(a) is a fingerprint of a low field PE phenomenon and it presumably survives at 7.0 K.

We now present an analysis of the pinning force $F_p(=J_cH)$, which brings out features not readily apparent from the M(H) hysteresis data or from the $J_c(H)$ behavior. We first determine $F_p$ using the $J_c(H)$ data extracted from the M(H) hysteresis loops, and we call it $F_p(measured)$. Next, we construct a monotonically decreasing $J_c(H)$ which is devoid of any anomalous modulation, i.e., this constructed $J_c$ gets rid of any PE like features at low fields or at high fields (a procedure to construct such a $J_c(H)$ can be seen from the semi log plot of $J_c(H)$ (in the inset of Fig.2(a)) at 6.95 K). Using this constructed $J_c$, we determine the pinning force which we call $F_p(constructed)=J_c(constructed)H$. Finally, we determine \( \Delta F_p = F_p(measured) - F_p(constructed) \). $\Delta F_p$ is a quantity which can convey signatures of anomalous changes in the intrinsic pinning force density being experienced by the flux lines. In Figs. 2(b), 2(d), 2(f), 2(h), we have plotted $\Delta F_p$ as a function of $H$. At 6.95 K (cf. Fig.2(b)), one can clearly distinguish two well resolved PE features in $\Delta F_p(H)$. One PE located at $H_d=100$ Oe, is the novel low field PE, this peak in $\Delta F_p$ at $H_d$ coincides with the field at which the anomalous non monotonic low field behavior in $J_c(H)$ is observed (cf. inset of Fig.2(a)). The other PE, is the high field PE at $H_p$, which occurs close to $H_{c2}$. At $T=7.0$ K (cf. Fig.2(d)), one can again distinguish two well resolved peak like features in $\Delta F_p$, at $H_d$ and $H_p$. It should be noted that although the M(H) hysteresis loop at 7.0K was devoid of any distinguishing features of PE at $H_d$ and $H_p$, through the present analysis we can now discern features of PE at both $H_d$ and $H_p$ in the $\Delta F_p(H)$ plot at 7.0 K. If one now compares the Fig.2(b) with Fig.2(d), it seems that though the PE at $H_d$ does not move as we change T from 6.95 K to 7.0 K, the $H_p$ has moved from $\sim 1000$ Oe at 6.95 K to $\sim 750$ Oe at 7.0 K, which is a rate of 5 kOe/K. This slope value of $dH_p/dT$ matches well with the slope of the PE curve in the inset of Fig.1, which was determined from temperature dependent ac susceptibility measurements.

From the above analysis one can conjecture that due to a motion to lower fields (close to $H_d$), of the PE at $H_p$ at the rate of 5 kOe/K as $T$ is increased, one should be able to see the emergence of a single peak from the coalescence of two well resolved PE peaks in $\Delta F_p$ (i.e., one at $H_d$ and another at $H_p$). We now show the M(H) hysteresis loop at subsequently higher temperatures. The M(H) hysteresis loop at $T=7.05$ K (cf. Fig. 2(e)), appears even more anomalous than that at 7.0 K. It is a broad, irreversible loop which results in a single broad peak in $\Delta F_p$ (cf. Fig. 2(f)). The M(H) hysteresis loop at 7.05 K now resembles so called “Fishtail Effect Anomaly”. This fishtail effect like anomaly in the M(H) hysteresis loop and in $\Delta F_p(H)$ plot persists at $T \geq 7.05$ K. Figs. 2(g) and 2(h) show M(H) hysteresis loop and the $F_p(H)$ at $T = 7.1$ K. It is to be noted that the width of the PE anomaly, (i.e., $\Delta H_d$ in Fig.2(b), Fig.2(d), Fig.2(f), Fig.2(h)) has an interesting temperature dependence, we shall discuss it at a later stage. We shall now demonstrate through a sequence of M(H) hysteresis loops obtained at various orientations with respect to the ab plane of the single crystal as to how the composite broad PE effect at 7.0 K (see Fig.2(c)) gets resolved into two anomalous maxima in $J_c$ which are centered around $H_d$ and $H_p$.

It had been argued by Pippard [24] and also experimentally seen that the PE peak $H_p$ always scales with $H_{c2}$. 2H-NbSe$_2$ is an anisotropic system to which anisotropic Ginzburg-Landau description applies [23]. The angular dependence of $H_{c2}$ is given by as $H_{c2} = H_{c2}(\{c,T\} (\sin^2(\theta) + e^2 \cos^2(\theta))^{-1/2})$, where $e=1/\langle\text{Anisotropy of crystal}\rangle$ and $\theta$ the angle between $H$ and the ab plane of the single crystal of NbSe$_2$. As $\theta$
changes from 90° to 0°, \( H_{c2} \) increases from the value of \( H_{c2}(c,T) \) to that of \( H_{c2}(ab,T) \), and concomitantly the value of \( J_c \) also follow suit. In Fig.3, the \( M(H) \) hysteresis loops in 2H-NbSe₂ at 7.0 K for different \( \theta \) The insets in each of the Figs. 7(a) to (f) show \( F_p \) vs \( H/H_{c2}(\theta) \). In the inset of Fig.3(a) we can see that the low field, maximum in \( F_p \) at \( H_d \) and the high field PE peak at \( H_p \) lie in juxtaposition. When the angle \( \theta \) changes from 90° towards 0°, the following features in Fig.3 are noteworthy: (i) In all the insets of Fig.3, the peak in \( F_p \) at \( H_p \) seems to occur at \( H/H_{c2}(\theta) \approx 0.7 \). (ii) The low field peak in \( F_p \) at \( H_d \) shifts to lower values of \( H/H_{c2}(\theta) \) as \( \theta \) increases (iii) The most striking feature emerging from the plots of Fig.3 is the separating out of the two anomalous modulations in \( J_p \) corresponding to a distinct double peak structure in the \( F_p(H) \) plot. The main panels of Fig. 3 show that by varying \( \theta \), the PE peak at \( H_p \) moves to higher fields (since \( H_p/H_{c2}(\theta) \approx 0.7 \)), and as the \( H_p \) value moves sufficiently far away, the novel low field anomalous modulation in \( J_p \) at \( H_d \) gets identified distinctly as an independent feature. If we attempt to fit the observed \( H_{c2}(\theta) \) behavior to the above stated Ginzburg-Landau relationship, we get a value of \( \epsilon \) as \( <0.5 \), or an anisotropy of about 2 for 2H-NbSe₂, which is a satisfactory value for NbSe₂ for \( H < 2 \) kOe [28]. Thus our anisotropy study of the \( M(H) \) hysteresis loop elucidates the fact that, PE could be composed of an anomalous modulation in \( J_p \) centered at low field \( H_d \) and the usual PE peak at \( H_p \).

We now summarize our discussion and propose a schematic for the low \( H \) and high \( T \) parts of the vortex phase diagram. In the inset of Fig.1(a), we had presented a phase diagram which comprised the PE phase boundary \( T_p(H) \) across which the FLL disorders into an amorphous phase. However, this phase diagram is incomplete as it does not give us any indication of changes in the vortex matter occurring at field values such as at \( H_d \) and \( \Delta H_d \), which we can observe from the isothermal \( M(H) \) hysteresis loops. Returning to Fig.2, we consider the behavior of the width \( \Delta H_d \) of the low field PE centered at \( H_d \). Shown in Fig.4, is a shaded region which is obtained by combining the \( H_p \) curve, to the \( H_{c2}^{upper} \) curve (see main panel of Fig.4). This new phase boundary across, designated as \( H_{ord} \) in the inset of Fig.4, has a reentrant nature, i.e., in fixed \( T \) scan, the order-disorder boundary shall be encountered twice. Such a reentrant characteristic is reminiscent of reentrant nature of the FLL melting curve of a pure (pinning free) Abrikosov state, first proposed by D. R. Nelson [13]. Between this newly constructed reentrant \( H_{ord}(T) \) line and the \( H_{irr}(T) \) line, the vortex matter can be designated as the “pinned liquid phase”, following the nomenclature in the literature on vortex state studies [13].

In conclusion we may state that 2H-NbSe₂, seems to be an appropriate system, whose intrinsic parameters, make the phase boundaries, across which the various phases of vortex matter exists, become accessible to within experimental limits. Though the present set of results are the first preliminary steps in characterizing the different phases of vortex matter, the experimental and theoretical investigations in this field are wide open to enormous possibilities and opportunities.

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Fig. 1 (S. S. Banerjee et al)
Fig. 2 (S.S. Banerjee et al)
Fig. 3 (S. S. Banerjee et al)

Field (Oe)
Fig 4. (S. S. Banerjee et al)

Schematic plot for 2H-NbSe$_2$

Fixed $T$ scan

Ordered Solid

Ordered Solid

Unpinned Amorphous phase

Pinned Amorphous phase

Field (KOe)

Reduced Temperature (K)