

# Metastability and switching in the vortex state of $2H\text{-NbSe}_2$

S. S. Banerjee, N. G. Patil, S. Ramakrishnan, and A. K. Grover

Tata Institute of Fundamental Research, Mumbai-400005, India

S. Bhattacharya<sup>a)</sup>

Tata Institute of Fundamental Research, Mumbai-400005, India and NEC Research Institute,  
4 Independence Way, Princeton, New Jersey 08540

G. Ravikumar, P. K. Mishra, T. V. Chandrasekhar Rao, and V. C. Sahni

TPPED, Bhabha Atomic Research Center, Mumbai-400085, India

M. J. Higgins

NEC Research Institute, 4 Independence Way, Princeton, New Jersey 08540

(Received 30 June 1998; accepted for publication 20 October 1998)

History-dependent metastable states with different bulk properties are formed in the vortex state of the type-II superconductor  $2H\text{-NbSe}_2$ . Magnetic measurements demonstrate the difference between the shielding responses of a field- and a zero-field-cooled state, and provide a procedure for switching the system from one state to the other. © 1999 American Institute of Physics.  
[S0003-6951(98)05051-7]

In a pure field cooled (FC) sample of a type-II superconductor, the magnetization ( $M$ ) response is expected to be completely reversible in both isothermal ( $M$  vs  $H$ ) measurement and isofield ( $M$  vs  $T$ ) measurements. However, in a realistic sample, due to the inevitable presence of flux pinning, the static [direct current (dc)] magnetization value of the field cooled (FC) state is different from that of the zero-field cooled (ZFC) state. But the ac susceptibility ( $\chi'$ ) response is found to be nearly path independent. This is due to the belief that the critical current density [ $J_c(H)$ ] in a single component superconductor is uniquely defined for a given  $H$ . As per a simple description in terms of Bean's<sup>1</sup> critical state model, one can write<sup>2</sup>  $\chi'$  as  $\chi' \approx -1 + [\alpha h_{ac}/J_c]$ , where  $\alpha$  is a size and geometry dependent factor and  $h_{ac}$  is the amplitude of the alternating current (ac) field. Hence, a uniquely defined  $J_c(H, T)$  results in a path independent  $\chi'(H, T)$  value. Recently, using transport measurements Henderson *et al.*<sup>3</sup> demonstrated that the  $J_c(H, T)$  in a weakly pinned crystal of a low  $T_c$  superconductor (namely, hexagonal  $2H\text{-NbSe}_2$ ) displays the inequality, i.e.,  $J_c^{\text{FC}} > J_c^{\text{ZFC}}$ . In Larkin—Ovchinnikov<sup>4,5</sup> description of weakly pinned superconductors, the vortex state is described in terms of a Larkin<sup>4</sup> volume  $V_c$  within which the flux lines are collectively pinned. In this description of the pinned FLL,  $J_c$  relates inversely to  $V_c$  as  $J_c \propto V_c^{-1/2}$ . Hence, the observation  $J_c^{\text{FC}} > J_c^{\text{ZFC}}$  implies that  $V_c^{\text{FC}} < V_c^{\text{ZFC}}$ , i.e., the more strongly pinned vortex state is more spatially disordered. Henderson *et al.*<sup>3</sup> also noted that one can transform the disordered FC vortex state to an ordered ZFC like state by depinning the vortices with the passage of a large current. It is of interest to explore whether the above stated behavior of  $J_c$  is unique to the transport current measurements or it is a generic characteristic of  $J_c$ , related to the behavior and properties of FLL created in presence of quenched random disorder. In this letter, we report the results of ac and dc magnetization measurements on FC and ZFC states in a single crystal of

$2H\text{-NbSe}_2$ , which belongs to the same batch of crystals as used by Henderson *et al.*<sup>3</sup> These results lead us to the possibility of utilizing them to situations which require bistable states with easy switching from one state to the other.

We have measured (i) the ac permeability  $\mu'(H, T)$  (defined as  $B/H = 1 + \chi'$ ) using a home built ac susceptometer and (ii) the dc magnetization [ $M(H, T)$ ] using a standard Quantum Design Inc. SQUID magnetometer on a platelet-shaped single crystal of hexagonal  $2H\text{-NbSe}_2$  of dimensions  $2 \times 1.5 \times 0.3 \text{ mm}^3$ . This crystal has zero field superconducting transition temperature  $T_c(0)$  of  $\sim 6 \text{ K}$ ,<sup>6</sup> and was grown using nominally pure niobium metal, with 200 ppm of Fe. This level of Fe impurity suppresses the  $T_c(0)$  value of  $2H\text{-NbSe}_2$  from  $\sim 7$  to  $6 \text{ K}$ , however, pure  $2H\text{-NbSe}_2$  crystals remain weakly pinned and all intrinsic superconducting parameters in it scale with corresponding  $T_c(0)$  values. Though most of the ac magnetization measurements were made at 211 Hz, the observed behavior is independent of frequency in the range of  $10\text{--}10^3 \text{ Hz}$ .

Figure 1 presents the  $\mu'(H)$  data at 5.1 K for FLL states prepared in the ZFC and in FC manner. The information about the field dependence of  $J_c$  can be extracted from the  $\mu'$  (or  $\chi'$ ) data. In Fig. 1, the  $\mu'$  curves for both ZFC and FC states show an anomalous peak at  $H = H_p$ , illustrating the existence of the well known *peak effect* (PE)<sup>7,8</sup> phenomenon in  $J_c$  vs  $H$  below the upper critical field,  $H_{c2}$ . Note that  $\mu'(H)$  values in FC state are smaller than those in the ZFC state in the field interval  $1 \text{ kOe} < H < H_p$  and this confirms the observation of Henderson *et al.*<sup>3</sup> that  $J_c^{\text{FC}}(H) > J_c^{\text{ZFC}}(H)$ , from the low field end ( $\sim 1 \text{ kOe}$ ) upto the field value corresponding to the peak position of the PE region.

The ac magnetization measurements can also effectively exemplify that the disordered FC state with higher  $J_c$  heals into the more ordered ZFC state with lower  $J_c$ . The  $\mu'$  values in Fig. 1 were obtained with  $h_{ac}$  of 0.5 Oe [root mean square (rms)]. If the vortex state produced in the FC state is momentarily subjected to a larger  $h_{ac}$  of about 5 Oe (rms) and ac measurements subsequently made with smaller  $h_{ac}$  of 0.5 Oe (rms), the  $\mu'$  values are seen to switch over to the

<sup>a)</sup>Present and permanent address: NEC Research Institute, 4 Independence Way, Princeton, New Jersey 08540.

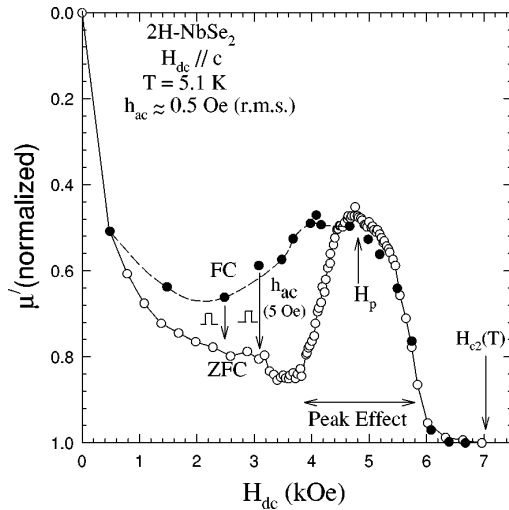


FIG. 1. Variation of in-phase ac [ $f=211$  Hz,  $h_{ac}=0.5$  Oe (rms)] permittivity [ $\mu' (=B/H)$ ] with external dc field  $H_{dc}$  ( $\parallel c$ ) at 5.1 K in a crystal of  $2H\text{-NbSe}_2$  for vortex states prepared in zero field cooled (ZFC) and field cooled (FC) states.

corresponding values of the ZFC state. This transformation process from FC to ZFC state is illustrated by arrows in Fig. 1. The larger  $h_{ac}$  of 5 Oe cannot unpin the entire FC vortex state. However, it presumably shakes the disordered FC state, which rearranges to the more weakly pinned (i.e., relatively more ordered) ZFC state.

In Figs. 2(a) and 2(b), we show the temperature evolution of the  $\mu'$  response for a FLL prepared in the ZFC (○) and FC (—) states in  $H_{dc}=5$  kOe (approximately the field value corresponding to peak position of PE at 5.1 K in Fig. 1). In Fig. 2(a), the sample has been first cooled to 4.2 K in zero field, a dc field of 5 kOe is then applied and magnetic shielding response measured in  $h_{ac}$  of 0.5 Oe (rms), while warming up to the normal state [ZFC (I) ○]. In the second cycle(II), the crystal is cooled down to 4.2 K in the same dc field and ac response is measured with  $h_{ac}$  of 0.5 Oe (rms) while warming [FCW (II) —] up to the normal state. In the third cycle(III), the specimen is cooled down once again in the same dc field to 4.2 K and the ac response is measured in  $h_{ac}$  of 0.5 Oe up to 4.35 K. At 4.35 K,  $h_{ac}$  is momentarily increased to a value of about 4 Oe (rms) and ac response measurements carried out once again with lower  $h_{ac}$  value of 0.5 Oe (rms), while warming up to the normal state (FC→ZFC).

The following features are noteworthy in Fig. 2(a). First, we observe that  $J_c^{FC} > J_c^{ZFC}$  [using Eq. (1)] for  $T < T_p$ . At the peak temperature  $T_p$  of PE, the relatively well ordered FLL of ZFC state presumably gets completely disordered and approaches the “frozen in disordered state” of FC mode. There are now also evidences from structural studies that PE signifies loss of spatial order in FLL.<sup>9</sup> (We shall not dwell more on the consequences of this physical facet in this letter as it has been described elsewhere.<sup>10</sup>) Second, the disordered FLL in a field of 5 kOe (FC state) transforms to an ordered ZFC like state with a small ac driving force of 4 Oe (rms). Such a transformation cannot be reversed by either warming the sample up to the PE region or cooling it down towards 0 K (data not being shown here). Third, it appears that there exists a threshold value of  $h_{ac}$ , up to which the disordered FC state does not show any sign of healing (on the time scale of

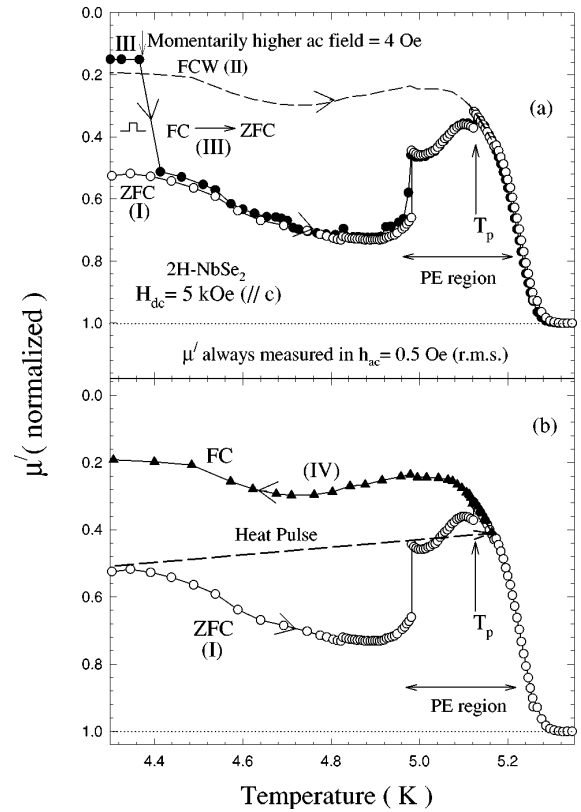


FIG. 2. Temperature variation of  $\mu'$  measured in  $h_{ac}$  of 0.5 Oe (rms) in a crystal of  $2H\text{-NbSe}_2$  for vortex states prepared in ZFC and FC states for  $H_{dc}(\parallel c) = 5$  kOe. For detailed description of cycles I, II, III in panel (a), see the text. It is to be noted that  $\mu'$  is always measured in same value of  $h_{ac}$  of 0.5 Oe (rms). In cycle III, a momentarily increase in  $h_{ac}$  value from 0.5 Oe (rms) to 4 Oe (rms) results in  $\mu'$  values switching from FC branch to ZFC branch. In panel (b), if a heat pulse increases the sample temperature from an initial  $T \ll T_p$  to a higher temperature such that  $T_p(H) < T < T_c$  and the sample is thereafter slowly cooled, the  $\mu'$  values follow the FC path (IV), which is akin to the cycle II (FCW) in panel (a).

duration of our experiment, i.e., several hours) towards the more ordered ZFC like state. For example, in the temperature interval 4.2–4.8 K, an application of  $h_{ac}$  of less than 2.75 Oe (rms) to FC state did not produce any change in its  $\mu'$  value. The existence of such a threshold height of an ac pulse implies that a finite energy barrier separates the FC state from the ZFC state; when this barrier is overcome by the threshold ac amplitude, the system makes a transformation from the FC state to the ZFC state.

If we subject a ZFC lattice to a heat pulse such that the specimen temperature momentarily exceeds the superconducting transition temperature  $T_c(H)$ , the sample will get cooled down in field and the resulting vortex state would be a FC state. To further explore this idea, we subjected a vortex state prepared in ZFC state to cool down cycles [see Fig. 2(b)] from different chosen temperatures lying below the  $T_c(H)$ . If a vortex state on the ZFC curve is cooled down from a temperature value lying below the onset temperature of PE, the cool down  $\mu'(T)$  curve retraces its warm-up path. However, if a cool down cycle is initiated from a temperature value lying in the PE region, the cool down  $\mu'(T)$  curve does not reach the ZFC  $\mu'(T)$  curve, instead the cool down  $\mu'(T)$  values overlap with the FC like  $\mu'(T)$  curve. This is illustrated in Fig. 2(b) by the solid triangle data points. Thus, if a heat pulse is applied to a FLL in ZFC state at  $T \ll T_c(H)$ , such that the sample temperature momentarily en-

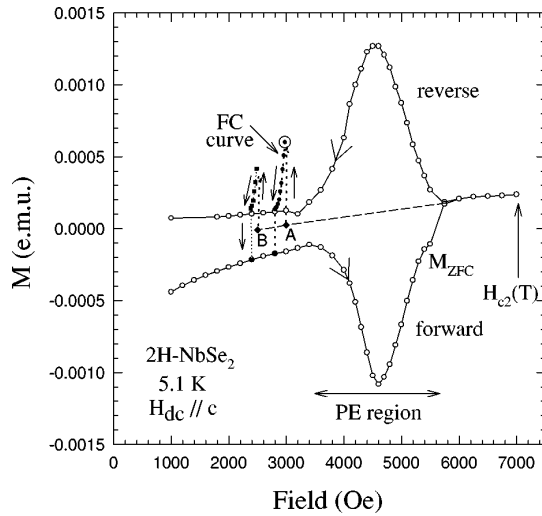


FIG. 3. A portion of dc magnetization hysteresis loop at 5.1 K in a crystal of 2H-NbSe<sub>2</sub> for  $H_{dc} \parallel c$ . Data points A and B identify the field cool magnetization values. When field is reversed from  $H_A$  (or  $H_B$ ), the magnetization values follow the dotted FC curve.

ters the PE region, the sample would eventually cool down to a FC like state [at  $T \ll T_c(H)$ ]. Now a momentary ac pulse of amplitude  $\geq 4$  Oe (rms) would transform this FC state to the ZFC state [at  $T \ll T_c(H)$ , i.e., without any change in sample temperature]. The  $\mu'(T)$  values of FC and ZFC differ significantly, so the transformation from the ZFC to the FC state via a heat pulse and changeover back to a ZFC like state with an ac pulse in a predictive manner has the **characteristics of a binary device**.

That the transformation from more disordered (FC) to more ordered (ZFC) vortex state and vice versa really occurs by a gentle intervention of a small driving force, like, the addition and removal of a small fraction of total number of vortices to a pinned vortex lattice as alluded to above, can be seen from a novel feature in the isothermal dc magnetization hysteresis data recorded in the same sample.

Figure 3 shows a portion of the dc magnetization hysteresis loop encompassing the PE region in 2H-NbSe<sub>2</sub> sample for ( $H_{dc} \parallel c$ ) at 5.1 K. The forward and reverse legs define the envelope (loop) of magnetization hysteresis. The width ( $\Delta M$ ) of the magnetization hysteresis loop at a given  $H$  conventionally measures  $J_c(H)$ , i.e.,  $\Delta M [= M(H \uparrow) - M(H \downarrow)] \propto J_c(H)$ . The anomalous opening of the hysteresis bubble prior to its complete collapse identifies the PE region. The data points A and B mark the field cool magnetization values [ $M_{FC}(H_A)$  and  $M_{FC}(H_B)$ ] at two chosen fields lying prior to the PE region. The dotted curves show that as soon as the applied field is reduced from A or B by about a few Oe, the measured magnetization values exceed the envelope of magnetization hysteresis. As the external field values are reduced further, the dotted FC curves fall back onto the envelope curve. The observed phenomenon can be viewed as the progressive shrinkage of hysteresis width, which is defined as [ $M_{FC}(H \downarrow) - M_{FC}(H_A)$ ]. The difference,  $M_{FC}(H) - M_{FC}(H_A)$ , at the encircled data point in Fig. 3 is presumably a measure of the current density  $J_c(H_A)$ . On reversal from  $H_A$ , initially the currents of density  $J_c^{FC}(H_A)$  are induced. Since  $J_c^{FC}(H_A) > J_c^{ZFC}(H_A)$ , the initial magnetization value exceeds the envelope curve, thus, effectively yielding a larger  $\Delta M$ , consistent with a larger  $J_c$ . However, as the external field is

progressively decreased further, the disordered FC state starts to get transformed into a more ordered ZFC like state, which can sustain only smaller  $J_c$ . The process of transformation from disordered FC to ordered ZFC state presumably gets over at the merger point of FC curve with the envelope hysteresis curve. Thus, we find that the FC state at a given  $H$  transforms into a ZFC like state by changing ( $\Delta H$ ) the external dc field  $H$  by only a small fraction of its value ( $\Delta H/H \sim 5 \times 10^{-2}$ ). In the ac magnetization experiment of Fig. 2(b), the same transformation could be brought about by even a smaller driving force ( $h_{ac}/H \approx 10^{-3}$ ). It may be worthwhile to state here that if instead of momentarily exposing the FC state to higher  $h_{ac}$  value [as in Fig. 2(a)], one decreases (or increases) the dc field by about 100 Oe in the experiment of Fig. 2(a) (as done in Fig. 3), the smaller  $\mu'(T)$  value of FC state indeed switches over to the larger  $\mu'(T)$  value of more ordered ZFC like state (data not being shown here).

The above results demonstrate that metastable states with widely different bulk screening response can be obtained in the vortex state of a type-II superconductor. The origin of this metastability is the presence of pinning centers.<sup>11</sup> The two states are robust against thermal fluctuations. Furthermore, the system can be switched predictably from one state to the other, through the use of a small ac or dc field in one case or by a heat pulse in the other. Thus, the weakly pinned type-II superconducting system provides a basis, in principle, of a binary device which can be used, for example, as a magnetic memory cell.

We would like to acknowledge Professor S. S. Jha for his suggestion and encouragement to explore the device potential of the work presented above. We thank Dr. Mahesh Chandran for a careful reading of the manuscript.

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