Vortex avalanches in the non-centrosymmetric superconductor Li$_2$Pt$_3$B

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We investigated the vortex dynamics in the non-centrosymmetric superconductor Li$_2$Pt$_3$B in the temperature range 0.1 K – 2.8 K. Two different logarithmic creep regimes in the decay of the remanent magnetization from the Bean critical state have been observed. In the first regime, the creep rate is extraordinarily small, indicating the existence of a new, very effective pinning mechanism. At a certain time a vortex avalanche occurs that increases the logarithmic creep rate by a factor of about 5 to 10 depending on the temperature. This may indicate that certain barriers against flux motion are present and they can be opened under increased pressure exerted by the vortices. A possible mechanism based on the barrier effect of twin boundaries is briefly discussed.

The occurrence of superconductivity in compounds with non-centrosymmetric crystal structures has attracted considerable attention recently. Besides various other systems, superconductivity has also been reported in the ternary boride compounds Li$_2$Pd$_3$B and Li$_2$Pt$_3$B which have superconducting critical temperatures of 7-8 K and 2.4 K, respectively [1, 2]. These two isomorphous compounds crystallize in a structure consisting of distorted boron centered octahedra of BPd$_6$ or BPt$_6$ in an approximately cubic arrangement with an interpenetrating lithium formation [3]. Both substructures, and hence the composite crystal structure, lack inversion symmetry. Several unusual properties appear in non-centrosymmetric superconductors depending upon various factors, in particular the specific form of the spin-orbit coupling in such systems as well as the pairing symmetry [4, 5, 6]. In contrast to the strongly correlated non-centrosymmetric heavy fermion superconductors CePt$_3$Si$_2$ [7], CeRhS$_3$ [8], and U$_2$ [9] for which superconductivity is associated with a magnetic quantum phase transition, there is no evidence of magnetic order or strong electron correlations in either Li$_2$Pd$_3$B or Li$_2$Pt$_3$B. Measurements of the London penetration depth suggest that Li$_2$Pd$_3$B has a full quasiparticle gap in the superconducting phase, while for Li$_2$Pt$_3$B, the data indicate line nodes in the energy gap [10]. NMR measurements [11] suggest that Li$_2$Pd$_3$B is a spin singlet, s-wave superconductor. In contrast, in Li$_2$Pt$_3$B, the spin susceptibility measured by the Knight shift remains unchanged across the superconducting transition temperature, and the spin-lattice relaxation rate $1/T_1$ shows no coherence peak below $T_c$, decreasing as $T^3$ with decreasing temperature, consistent with gap line nodes. In this letter, we investigate a further intriguing property of the unconventional superconductor Li$_2$Pt$_3$B, observed in the vortex dynamics. We demonstrate that the behavior of the flux creep is very unusual, displaying at short times extremely small creep rates followed by a faster avalanche-like escape of magnetic flux.

Samples of Li$_2$Pt$_3$B used in this experiment were synthesized in an arc furnace utilizing a two-step process similar to that outlined in the work of Badica et al. [2]. An initial binary sample of BPt$_3$B was grown using Pt of purity 99.99% and B of purity 99.999%. In the final step of sample growth, an excess amount of Li was added in order to account for losses during arc melting, giving a Li to BPt$_3$B ratio of 2.2:1. The crystal structure was verified via powder X-ray diffraction measurements. No impurity or binary phases were detected.

Prior to the magnetic relaxation measurements, the Li$_2$Pt$_3$B sample was characterized by means of measurements of electrical resistivity $\rho$, magnetization $M$, and specific heat $C$. All three measurements yielded a value of the superconducting critical temperature $T_c = 3.0$ K. This value is significantly higher than the values reported in the literature, the highest of which is $T_c = 2.4$ K [2]. Evidently, the value of $T_c$ is rather sensitive to the composition of the sample, which could be a further indication that Cooper pairing is unconventional in this compound.

The temperature dependence of the specific heat was measured using a quasi-adiabatic heat pulse method in a $^3$He refrigerator, in the temperature range of 0.6 K $\leq T \leq 20$ K, and in magnetic fields up to $H = 4$ T. The temperature dependence of the specific heat in the normal state could be described by the expression $C(T) = C_v(T) + C_l(T)$, where $C_v(T) = \gamma T$ is the electronic contribution and $C_l(T) = \beta T^3$ is the lattice term. The best fit to the data yields $\gamma = 7.0$ mJ/(mol K$^2$) for the electronic specific heat coefficient and $\Theta_D = 203$ K for the Debye temperature, in good agreement with the values $\gamma = 7.0$ mJ/(mol K$^2$) and $\Theta_D = 228$ K reported by Takeya et al. [12]. A relatively sharp jump in the specific heat, $\Delta C = 15$ mJ/(mol K), was observed at the transition into the superconducting state, yielding a ratio $\Delta C/\gamma T_c = 1.2$, larger than the value of 0.8 reported by Takeya et al. [12] but smaller than the weak coupling
BCS value of 1.43. Below $T_c$, $C_c(T)$ decreases nearly as $T^2$ upon decreasing the temperature to $T \approx 0.5 T_c$, consistent with the behavior reported previously [12] and in contrast to the exponential $T$-dependence expected for a BCS superconductor. The upper critical field, $H_{c2}$, determined from the $C(T)$ measurements, increases linearly with decreasing temperature from $T_c$ to $T = 0.6$ K and extrapolates linearly to a value of $H_{c2}(0) \approx 1.5$ T at $T = 0$ K.

We also characterized the superconducting transition of the sample by means of ac magnetic susceptibility measurements in a low ac field of $H = 3$ mOe and at a frequency of $f = 80$ Hz. This measurement was done with the sample situated inside a custom built mixing chamber of a dilution refrigerator using an inductance bridge with a SQUID as a null detector [13]. The midpoint of the superconducting transition of this sample is at $T_c = 3.07$ K and the transition width $\Delta T_c = 240$ mK. The data are displayed in Fig. 1. In the inset of Fig. 1, we show the low temperature part of the electrical resistivity, $\rho(T)$ measured using a standard four wires arrangement in a $^3$He cryostat. $\rho(T)$ which displays a sharp phase transition into the superconducting state with a width $\Delta T_c = 55$ mK, $\rho(T)$ reaches zero at $T = 3.05$ K, in very good agreement with the susceptibility data. In the normal state, the $\rho(T)$ measurement revealed typical metallic behavior.

The investigation of vortex dynamics was performed in the temperature range 0.1K - 2.8 K. Isothermal relaxation curves of the remanent magnetization $M_{rem}$ were taken after cycling the specimen in an external field H. Vortices were introduced into the sample at a slow rate in order to avoid eddy current heating. After waiting for several minutes, the magnetic field was reduced to zero and the relaxation of the metastable magnetization recorded with a digital flux counter for several hours. The sample was prepared in the form of a thin slice and the magnetic field was applied along the longest direction. At $T = 100$ mK, we determined the field corresponding to the Bean critical state for this sample to be $H = 300$ Oe. In Fig. 2, we show values of the remanent magnetization obtained after cycling the sample in a field of $H = 300$ Oe as a function of temperature. $M_{rem}$ decreases monotonically upon increasing the temperature with the experimental data well fitted by a parabola (dashed line in Fig. 2) which reaches zero at around $T \approx 3.1$ K. This is in excellent agreement with the value of $T_c$ yielded by specific heat, ac susceptibility and electrical resistivity measurements.

A typical decay of the remanent magnetization from the critical Bean state at $T = 400$ mK is shown in Fig.
3. In this case, the creep was recorded for about 18000 s. At that time, the sample was heated above $T_c$ in order to obtain the total value of the remanent magnetization as a sum of the amount decayed in the first 18000 s plus the quantity expelled on crossing $T_c$. This value is then used to normalize the creep rate. In the inset, the same data are displayed on an expanded scale. We can clearly distinguish two different logarithmic creep regimes. For $50 \text{s} < t < 2400 \text{s}$ we observe a clear logarithmic relaxation law, with an extremely low relaxation rate, $S = \partial \ln M / \partial \ln t = 8.3 \times 10^{-4}$. At around $t = 2400 \text{s}$, a sudden, strong increase of the relaxation rate occurs, following also a logarithmic law, but with a rate about a factor of four larger, $S = 3.1 \times 10^{-3}$. Indeed, an avalanche-like escape of vortices has suddenly occurred around $t = 2400 \text{s}$, indicating that the relaxation process is rather complex. Vortices escaping the sample apparently need a considerable amount of time to overcome a certain barrier. We observed this type of regime change at all temperatures (see Fig. 4), except for relaxations below $T = 400 \text{ mK}$ and above $T = 2 \text{ K}$. To our knowledge, this phenomenon of avalanches in the slow decay of vortices toward equilibrium has never been observed before in any superconductor, conventional or unconventional. This unexpected result points to new vortex physics in this non-centrosymmetric superconductor. The normalized relaxation rates corresponding to the creep before the avalanches occur are depicted in Fig. 5. In the upper panel, the rates are given in a double logarithmic plot while, on the lower one, in linear scales. These rates are even lower by a factor of five than the very weak creep rates observed in PrOs$_4$Sb$_2$[14], a superconductor that violates time reversal symmetry. As discussed by Sigrist and Agterberg [15], the lack of time reversal symmetry in such superconductors allows for the formation of flux flow barriers formed by fractional vortices on domain walls of the superconductor, that can prevent the motion of normal vortices.

A possible explanation for the extremely slow motion of flux lines in Li$_2$Pt$_3$B has recently been given by Iniotakis et al. [16]. In many cases for non-centrosymmetric materials, the absence of an inversion center allows for the twinning of the crystal. These authors have shown theoretically, that a phase that violates time reversal symmetry can also be realized at interfaces separating crystalline twin domains of opposite spin-orbit coupling. In this case, flux lines with fractional flux quanta could exist on such interfaces and turn twin boundaries into strong barriers impeding flux creep. Within this model, vortex avalanches could be expected when such a fence opens due to excessive pressure of normal vortices. This is possible, if the vortex density increases to a level such that fractional vortices can no longer exist and the vortex pinning mechanism of twin boundaries fails. In the frame of this scenario, we can interpret the temperature window in which the avalanche effect has been observed in the following way. At temperatures below $T = 400 \text{ mK}$, vortices move so slowly that the time necessary to build up the

![FIG. 4: Sequence of isothermal relaxation curves. Two relaxations regimes can be observed at intermediate temperatures as explained in the text.](image)

![FIG. 5: The temperature dependence of the initial decay rate $S = \partial \ln M / \partial \ln t$ in a double logarithmic (upper panel) and a linear plot (lower panel).](image)
necessary vortex density to break a barrier exceeds the observation time. For temperatures above $T = 2\, \text{K}$, on the other hand, the overall density of vortices is strongly reduced (see Fig. 2), so that it becomes more difficult to reach the density required for demolishing barriers.

In conclusion, we have observed in Li$_2$Pt$_3$B strong avalanches in the relaxation of the remanent magnetization. Prior to the avalanches, vortices move toward equilibrium for several hours with an extraordinary slow creep rate, indicating that a new type of pinning is effective in this non-centrosymmetric superconductor. This type of pinning is different from the conventional pinning by defects, since it is effective only at low density of vortices. If the density of vortices leaving the sample increases close to the barrier keeping them from moving, an avalanche occurs followed by creep rates that are about 5 to 10 times faster. This creep behavior has never been observed up to now. A possible mechanism has been proposed by Iniotakis et al., based on the role of twin boundaries in non-centrosymmetric superconductors [16].

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