Internal avalanches in a pile of superconducting vortices

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Using an array of miniature Hall probes, we monitored the spatiotemporal variation of the internal magnetic induction in a superconducting niobium sample during a slow sweep of external magnetic field. We found that a sizable fraction of the increase in the local vortex population occurs in abrupt jumps. The size distribution of these avalanches presents a power-law collapse on a limited range. In contrast, at low temperatures and low fields, huge avalanches with a typical size occur and the system does not display a well-defined macroscopic critical current.

Magnetic field penetrates type II superconductors as a population of quantized flux lines called vortices due to the associated currents whirling around them. In the absence of disorder, the repulsive force between vortices leads to the formation of a regular lattice. Vortex movement as a result of the Lorentz force produced by an applied current produces dissipation and destroys superconductivity. Thus, it has a significant technological importance. The interaction between the vortex lattice and the crystal defects which pin vortices down creates a wealth of physical phenomena including thermodynamic phase transitions. While current-driven movement of vortices has been intensely explored during the past decade, out-of-equilibrium properties of vortex matter in absence of applied current have been subject to few studies.

As Bean showed many years ago, the distribution of vortices entering a superconducting sample is inhomogeneous. A finite gradient in vortex density builds up to create a driving force inward balanced by the pinning forces opposing vortex movement. The slope of this pile of vortices—originally compared by de Gennes to a sandpile—is proportional to the local magnitude of the critical current. Recently, the dynamic properties of such a pile has attracted new attention. This interest has emerged in the context of the introduction of the concept of self-organized criticality (SOC) a decade ago and covers a number of different marginally stable systems assumed to present a comparable dynamic response when driven to the threshold of instability. Apart from this, the list includes magnetic domains presenting Barkhausen noise, microfractures, earthquakes and other complex systems. In the case of a type II superconductor in the Bean state, addition of vortices by a slow increase in the external magnetic field—analogous to the introduction of new grains to a sandpile—is expected to produce vortex avalanches of all sizes and maintain a constant gradient in flux density. Such a SOC type of behavior has been reproduced numerically and the existence of these vortex avalanches has been experimentally established by Field and co-workers who recorded the voltage pulses produced by sudden changes of the flux density in a superconducting tube during a slow ramping of magnetic field. They detected avalanches of various magnitudes with a distribution exhibiting a power-law collapse over one decade. However, their experimental set-up only resolved avalanches occurring due to sudden exit of flux lines. In analogy with early sandpile experiments monitoring only grains falling off the system, this configuration could not detect internal events occurring within the sample. Direct observation of internal avalanches in sandpiles was an important experimental refinement which paved the way to demonstrating the limited relevance of SOC to real granular matter.

In this letter, we present a study of spatiotemporal profile of local magnetic induction in a superconductor during a slow ramp of an external magnetic field. By directly monitoring the population of vortices in a given area of the sample, we found that a sizeable fraction of the increase in the flux density occurs as abrupt jumps and the distribution of size and duration of these avalanches present a power-law behavior on a limited range. On the other hand, at low temperatures and fields, the same sample presents a different regime associated with huge avalanches. According to our results, the dynamic behavior of superconducting vortices is more complex than what is expected by recent simulations predicting SOC-type response with universal exponents.

The 0.8 × 0.8 mm² sample studied in our work was a granular film of niobium 20 µm thick. A 8×8 matrix of Hall probes was used to measure local magnetization. Each element of this matrix was a GaAlAs/GaAs heterojunction(µ = 170m²/Vs and n= 1.7×10¹¹m⁻² at 4 K) monitoring the magnetic field within its area (20 × 5 µm²). In principle, this configuration yields a two-dimensional profile of the magnetic field, but in our experiment we only processed data provided by two array-like rows of the matrix. Using a set of Burr-Brown INA128 preamplifiers we achieved a resolution of 5·10⁻⁷ T/√Hz in measuring magnetic inductions of the order of 0.1T. High-speed acquisition was performed using a...
16-bit 100kHz A/D converter.

We thoroughly studied the magnetization features of our sample which proved to present strong pinning features associated with a hysteretic magnetization below $T_c$ (9.1 K). Moreover, the direct measurement of the spatial variation of the magnetic field permitted to establish the presence of a Bean-type profile in the sample. As seen in Fig. 1, the penetration of magnetic field in the sample is not uniform and the magnetic induction decreases almost linearly inward. Pinning forces opposing the uniform distribution of vortices create a field gradient ($8 \times 10^{-3}$ T m$^{-1}$ at $T = 4.8$ K and $H = 1500$ Oe). The critical current is thus estimated to be $10^8$ A m$^{-2}$.

To explore the criticality of this vortexpile, we studied the time-dependence of the local field in response to a gradual increase in the external magnetic field. Fig. 2 presents the local magnetic induction as monitored by one Hall sensor during a slow ramp (1.1 Oe/s) of the external field beginning at $H = 1500$ Oe. The temperature was kept constant at 4.8 K. As seen in the figure, the magnetic induction- that is, the vortex population- increases steadily during this ramp. However, by magnifying portions of the $B(t)$ curve, it is readily observed that this increase is not smooth and contains many abrupt jumps of many different scales. By converting the magnitude of local induction to flux density, one finds that during the 128 s duration of the field ramp, 1125 new vortices enter to the area covered by the Hall sensor which already contained about 6750 vortices. Our data shows that the addition of these new vortices leads to frequent sudden rearrangements. We checked that no such abrupt jumps occur in the normal state (for temperatures higher than $T_c$ or for fields exceeding $H_{c2}$). In analogy with sandpiles, the term avalanche is used to designate these abrupt changes in vortex arrangement. Note that— contrary to periodic magnetothermal instabilities observed at very fast field ramps— these avalanches occur aperiodically at millisecond timescales and are not related with any temperature instability of the sample. In order to determine the statistical distribution of avalanche size and durations, we analyzed the data from four field ramps starting at $H = 0.15T$ identical to the one presented in Fig. 2. Our sensitivity permitted to resolve abrupt jumps as small as 0.08 G (0.16 φ$_0$). We found some variation in the ratio of avalanche activity in the output of different sensors presumably due to inhomogeneous distribution of defects in the sample. Typically, between 40 to 70 percent of the increase in the vortex population occurs by such detectable jump. We recall that in the pioneer experiment of Field and co-workers, which was sensitive to avalanches containing at least 50 vortices, only 3% of the increase in the vortex population was resolved as detectable avalanches. Hence, our work, by lowering the proportion of the increase in flux density which may be attributed to fluidlike movement of the vortices, highlights the granular nature of the vortex matter.

![FIG. 1. The static profile of the magnetic induction in the sample at various fields as seen by the array of Hall probes.](image1)

![FIG. 2. The local field recorded by the first Hall captor as a function of time. The external field was ramped at a rate of 1.1 Oe/s starting at H = 1500 Oe. Upper frames are magnifications of selected areas of lower frames.](image2)
of these avalanches. A power-law distribution $P(s) = s^{-\tau}$ with an exponent $\tau = -2.1$ fits the size distribution of smaller avalanches. This exponent should be compared with those reported by the previous experiment (-1.4 to -2.2 [6]) and simulations (-1.6 [8]). However, the range of validity for this behavior is less than one decade. Its lower bound meets the instrumental noise (0.08 G). The size of the largest avalanche detected was about 1.1G which is associated with the sudden entry of 5 vortices to the detection area. However as seen in the figure, there is a downward deviation from the power-law behavior for avalanches larger than 0.7G. The absence of large avalanches (also reported in [6]) is statistically significant and is yet to be explained. We also studied the duration of avalanches and found that their distribution follows a power-law ($\tau = -3$) on a limited range covering less than one decade. The longest avalanche lasted 26 ms.

**FIG. 3.** Histogram of avalanches detected by a single probe (solid circles) and those detected in the response of the entire array (columns) during field ramps identical to the one presented in Fig. 2. The straight line represents a power law with an exponent of -2.1.

To what extent avalanches detected by a single probe are local events? In order to answer to this question, we compared them with the response of an entire row of Hall probes during identical ramps. Columns in Fig. 3 represent the occurrence of avalanches found in the output of an entire row of sensors. An avalanche of size $s$ confined to an area covered by only $n$ probes would produce a jump equal to $ns/8$ in the output of the entire row. Therefore, only global avalanches would be detected with their correct magnitude in this output. As seen in the figure, the size collapse of the jumps detected by an entire row closely follows the distribution of those found by a single captor. However, there is a deficit of large and an excess of small avalanches in the response of the entire row which gives an indication of limited spatial extension. A direct way to explore the spatial extent of these avalanches is to search for correlations in the events recorded by different probes. We found that the occurrence of an avalanche at one area of the sample makes it highly likely to detect a quasi-simultaneous avalanche on another place 50 $\mu$m away. Moreover, there is a detectable finite delay between the two detections of the same incident. This is seen in Fig. 4 which compares the output of the first two captors. The inset displays the difference in the amplitude of the jumps with the shift in their temporal occurrence. The right-left asymmetry of the data indicates that avalanches detected by captor B which is farther to the edge occur with an average delay of the about 0.8 ms after those occurring quasi-simultaneously at the site of captor A closer to the edge. Thus, as one would naïvely expect, the apparition of avalanches at a “higher altitude” on the vortexpile often precedes their passage “downward”. Assuming a diffusive regime, the diffusion coefficient for avalanches can therefore be estimated to be $3 \times 10^{-6} m^2 s^{-1}$. The smaller up-down asymmetry detected in the inset of Fig. 3 suggests that avalanches often grow in size when passing from captor A “downward” to captor B.

**FIG. 4.** Main frame: Comparison of magnetic induction recorded by two captors 50 $\mu$m apart. Most avalanches occur quasi-simultaneously at both points. Inset: Each symbol represents an event detected quasi-simultaneously on both probes. Difference in size between the two events is plotted versus the difference in temporal occurrence. The right-left asymmetry of the distribution indicates that observation of an event on the captor situated closer to the edge usually preceded its detection on the other one.

Finally, we found that below 3.4 K and for fields close to the lower critical field, our sample displayed a quite different behavior. Huge “catastrophic” avalanches associated with sudden movement of thousands of vortices were observed (see the upper inset in Fig. 5). To rule out a thermal origin for them, we checked that the existence...
of these avalanches did not depend on the speed of the field ramp. They presented a characteristic size and were observed in both upward and downward sweeps but with different threshold fields. They share all these features with vortex avalanches observed at very low temperatures in YBa$_2$Cu$_3$CO$_7$ by Zieve et al. [17] which remain unexplained.

![Graph of magnetic induction as a function of magnetic field](image)

**FIG. 5.** Main frame: Temperature dependence of upper (filled circles) and lower (filled squares) critical fields of the niobium sample. Catastrophic avalanches were seen only in the marked area below 3K. Upper inset shows the local magnetic induction at $T=1.2$ K as a function of increasing (decreasing) external field with catastrophic avalanches observed in the field window marked by upward (downward) arrows. Lower inset, compares the gradient in magnetic induction as a function of external field for two different temperatures.

It is instructive to compare the gradient in magnetic induction, in the two different regimes. This gradient — i.e. the critical current density — is readily available as $\delta B$, the difference between the responses of two adjacent probes. As seen in the inset, at $T=3.4$ K, $\delta B$, after attaining a maximum just above $H_{c1}$ decreases monotonously with increasing magnetic field. In contrast, at $T=1.2$ K and in the field range of catastrophic avalanches, it does not display a smooth behavior suggesting the absence of a well-defined single critical current. Our results suggest that in presence of strong pinning, when vortices are far apart and densities and thermal activation is weak, the system does not build up a critical state. This situation may be compared with real sandpiles where the occurrence of huge quasi-periodic avalanches was attributed to the absence of a single “critical” slope [10]. The presence of this type of avalanches in a sample which displays a wide distribution of avalanche scales at higher temperatures is enlightening. It indicates that the relevant parameter in the passage between the two type of behaviors in not the density of pinning centers as suggested by recent theoretical suggestions [5,8]. Hence, the catastrophic avalanches reported here and in ref. [17] still lack a satisfactory explanation. We note that in a model proposed by Gil and Sornette [19], both large-avalanche and SOC behaviors may emerge in the same system according to the outcome of the competition between diffusive relaxation and instability growth rates.

In conclusion, we determined the size distribution of internal avalanches of vortices during a slow ramp of external magnetic field. A single sample of niobium in the strong pinning limit displayed two different types of behavior. At temperatures above 3 K, avalanches of different sizes were observed and the system is constantly kept in a critical state. In contrast, at low temperatures and low fields, the occurrence of huge avalanches with characteristic size is associated with the absence of criticality.

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