Direct Observation of Rectified Motion of Vortices in a Niobium Superconductor

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Using Lorentz microscopy to directly image vortices, we investigate vortex motion control and rectification in a niobium superconductor. We directly observe a net motion of vortices along microfabricated channels with a spatially asymmetric potential, even though the vortices were driven by an oscillatory field. By observing the individual motion of vortices, we clarify elementary processes involved in this rectification. To further demonstrate the ability to control the motion of vortices, we created a tiny vortex “racetrack” to monitor the motion of vortices in a closed circuit channel.

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Brownian motors are attracting considerable attention because these can be used to control the motion of tiny particles [1], even in the absence of dc drives. The idea that oscillating forces (or random forces, e.g., thermal fluctuations) could generate a net motion along one direction has inspired a novel generation of devices in a wide range of fields, from microfluidics to electron devices operating either in the ballistic or tunneling regimes [1]. Regarding vortex matter in superconductors, vortex motion control is being explored in a variety of systems [2–8]. For many device applications, including SQUIDs, vortex motion causes noise that degrades their performance. Thus, it is advantageous to selectively remove undesirable vortices and precisely control their motion.

Theoretical studies have proposed different ways to rectify the motion of vortices in a superconductor [2–6]. Most cases consider a spatially asymmetric potential in the sample, and an externally applied ac drive. An asymmetry of the pinning force (critical current) with regard to a reversal of the dc driving current in superconducting foils with a series of asymmetric surface microgrooves was observed in Ref. [9]. Recently, a remarkable reversible (i.e., the direction of net dc motion could also be controlled) rectifier was obtained in Ref. [8] using a hybrid magnetic-superconducting system. However, none of the experiments done so far could monitor the individual motion of vortices. A microscopic understanding of the vortex dynamics in this asymmetric system requires the use of direct imaging techniques.

The aim of this study is to investigate the microscopic individual motion of vortices in superconducting ratchets by direct imaging via Lorentz microscopy [10]. An advantage of our method is that it allows the possibility of finding ways to improve the performance of this device based on the knowledge obtained by the direct observation of the individual vortices moving inside the fabricated potential.
Vortices were driven by changing the applied magnetic field $H(t)$ as shown in Fig. 1(c): oscillating $H$, with a fixed amplitude, $\Delta H$, and a constant ramping rate, $dH/dt$, of $\sim 0.2$ Oe/s in a temporally symmetric manner. The motion of the vortices was monitored using video (30 frames/s) by Lorentz microscopy using the 1 MV field emission electron microscope [15].

The samples were Niobium (Nb) thin films. In the middle of the sample, an internal hole was produced by chemical etching. Then, the sample was cut and the hole was connected to the outside so that vortices smoothly entered from an edge of the hole into a central part of the film with increasing $H$. Several irradiated areas with uniform thickness of $\sim 100$ nm, near the hole (with vortices flowing dominantly in the direction parallel to the channels in the irradiated pattern) were chosen for observation, as shown in Fig. 1(d).

Figures 2(a) and 2(b) show Lorentz image snapshots of vortices taken at 15 Oe and 6.9 K. From these figures, three different regions can be recognized. One is a pin-free region on the right side (slightly up) of the field of the view. The second region is a channel formed by a series of arrow-shaped wedged cages which are directed toward the southeast direction. The leftmost channel is directed northwest. As an initial state, each irradiated defect must be filled with one vortex so that the irradiated pattern works as a spatially asymmetric potential. Thus, the initial state was prepared via field cooling: the temperature was decreased to below $T_c = 9.2$ K, with $H = 100$ Oe, which is above the first matching field (67 Oe). Then $H$ was decreased to 15 Oe, with the pinned vortices (trapped in the periodic array of defects) remaining fixed. At 15 Oe, 832 vortices were pinned at the irradiated defects, and about 333 vortices were distributed both inside the channel and outside the irradiated region, inside a $40 \times 40 \, \mu$m$^2$ square. Corresponding magnetic field densities $B$ were 33 G for the irradiated area and 6 G nearby it, respectively. In this situation, with increasing $H$ above 15 Oe, vortices were
driven inward owing to a field gradient, $dB/dx$, created by a gradient of vortex density outside the irradiated area.

Figures 2(c) and 2(d) show snapshots of moving vortices when increasing $H$ from 25 to 30 Oe. Figures 2(e)–2(g) were taken when decreasing $H$ to 30, 20, and 15 Oe, respectively. Outside the pinning (red) region, the number of unpinned vortices increased or decreased with increasing or decreasing $H$. This occurred because vortices were smoothly pushed inward (outward) from (to) the edge of the sample with increasing (decreasing) $H$. Therefore, no net motion of vortices occurred outside the potential during an $H$ cycle, as was naturally expected for the pin-free region. In short, $\langle dB/dx \rangle = 0$ was satisfied around this region in an $H$ cycle.

The situation was rather different inside the arrow-shaped channels. When $H$ increased, a steady penetration of vortices from the bottom cage toward the upper cages was observed in the upward (leftmost in Figs. 2(b)–2(d)) channel. Vortices behaved in a different way in the downward channel: Vortices first penetrated through the potential energy cage no. 7 [marked in Fig. 1(a)] eventually reaching cage no. 5; 15 vortices were found in cage no. 5, as shown in Figs. 2(d) and 2(e). In addition, when increasing $H$, vortices outside the irradiated area reached its top side, and some penetrated into the downward channel through cage no. 1, toward cage no. 2. Indeed, four vortices are visible in cage no. 2 in Figs. 2(d) and 2(e). However, it is noteworthy that the number of vortices remained fixed in cages no. 3 and no. 4, with increasing $H$.

When decreasing $H$, unpinned vortices in the downward channel went down through the channel and most of them were finally expelled from the bottom cage no. 7, toward the outside of the irradiated region. Notice that the number of vortices in cage no. 5 changes from 15 to 1, when $H$ was decreased by just 10 Oe, in short, from Fig. 2(e) to 2(f). Vortices did not escape through cage no. 1 in the upward direction, and also did not penetrate into cage no. 1 from the outside. Since vortices did not enter cages no. 3 and no. 4 from the bottom, when increasing $H$, and some vortices in cages no. 1 through no. 4 went down through cage no. 4 with decreasing $H$, the number of rectified vortices transported downward was nonzero in an $H$ cycle. Therefore, we obtained direct microscopic evidence for the rectification of vortices in this spatially asymmetric structure. In the upward channel, most vortices trapped in the top and the neighboring cages escaped upward toward the outside (i.e., vortex motion was rectified upward) when increasing $H$. When decreasing $H$, vortices began to go down through the lower cages toward the outside. However, several vortices were still trapped in the pockets in the upward channel, as shown in Fig. 2(h). They were pushed upwards, through the channel, when increasing $H$, and finally rectified upwards after several cycles of $H$.

The role of each cage in the downward channel is summarized as follows. Vortices penetrated and remained trapped in cages no. 1 and no. 2 with increasing $H$ and were transported downward when $H$ decreased. In this sense, cages no. 1 and no. 2 worked as a reservoir of vortices to be rectified. The rectification occurred through cages no. 3 and no. 4. Cages no. 5 through no. 7 worked as a buffer to prevent vortices from penetrating from the bottom throughout the channel, which is caused when a large difference appears in the vortex density inside and outside the channel. Here, the number of cages in each channel was limited to seven. When increasing the number of cages, we expect the rectification to mostly occur in the (longer) central part of the channel.

Similar rectified motion was observed when the amplitude $\Delta H$ of the oscillation of $H$ was varied from 5 to 25 Oe, with the minimum value of $H$ fixed at 15 Oe. Figure 3 shows the net number of vortices $N_v$ rectified downward from cage no. 3 to no. 4, versus $\Delta H$, in a single cycle of the periodically changing $H$. $N_v$ was obtained by analyzing the video. $N_v$ increases monotonically with increasing $\Delta H$, as in the low-$T$ limit of the theoretical Fig. 4 in [3]. If we had many parallel channels pointing upward, then the total number of rectified vortices would be much larger. A parallel-channels version of our device has recently been made using asymmetric pores in a silicon membrane acting as massively parallel ratchets [16]. We used extremely low frequencies, below 0.01 Hz. For example, in Fig. 1(c), a period of each cycle was 250 s. Vortices intermittently rearranged themselves throughout the cycle, until quasiequilibrium configurations were reached at both constant maximum and minimum field. The difference between these two quasiequilibrium states provides a lower limit of $N_v$. In the downward channel in Fig. 2, most vortices in cages no. 1 to no. 4 were rectified. The higher the maximum field is, the higher the vortex density in the cages (especially in no. 1 and no. 2) and the resulting $N_v$ are. In this sense, the behavior of $N_v$, observed in Fig. 3, is naturally understood.

It is noteworthy to compare our results with those in Ref. [8], which were taken under an ac driven current, at frequencies between 500 Hz and 10 kHz. As also seen in [3,17,18], when the frequency increases, the distance over which vortices move during one cycle becomes shorter. Indeed, particles moved from one pinning well to a neigh-

![Net number of rectified vortices per period vs. $\Delta H$](image_url)
Snapshots when increasing along one (or several adjacent parallel) linear 1D track(s). The vortex path can bend and take turns [3] as opposed to just moving to control the motion in 2D channels, where the vortex path is constrained by the geometry of the channel. The rectification of vortices in a closed loop is a result of the application of a periodically oscillating field {\( H(t) \)} that exerts a net force on the vortices, forcing them to move in circular paths or along conveyor belts [3,6,18]. The transport of oscillatory field-gradient-driven vortices observed in this closed loop suggests novel ways to transport vortices in the system, including cyclic vortex “conveyor belts” and pumps [3,6,18]. Also, the energy of vortices moving in circles could be extracted as a dc voltage output along a radial direction.

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FIG. 4 (color). (a) Pinning site locations (red dots) of a closed circuit channel. Characteristic lengths are the same as those in Fig. 1(a). (b), (c) Sequence of snapshots taken at 6.5 K when increasing {\( H \)} from 26 to 46 Oe. Pinned and unpinned vortices are represented by red and blue circles, respectively. The green (light blue) vortex was the first (last) rectified vortex four cycles prior to (after) these snapshots monitoring the tagged magenta vortex. The field of view in (b) and (c) is inside the blue dashed circle in (a). The arrows in (a) show the direction of the driving force exerted by the oscillating {\( H \)}. With increasing {\( H \)}, vortices were driven to the left. (d) Trajectories of three vortices in this field cycle (26 Oe \( \to \) 46 Oe). Black dots indicate the final locations of the three vortices.

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**References**


