Single vortices observed as they enter NbSe$_2$

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Abstract

We observe single vortices as they penetrate the edge of a superconductor using a high-sensitivity magneto-optical microscope. The vortices leap across a gap near the edge, a distance that decreases with increasing applied field and sample thickness. This behaviour can be explained by the combined effect of the geometrical barrier and bulk pinning.

Key words: Vortex dynamics, edge penetration, surface barrier, magneto-optical imaging

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1. Introduction

As vortices enter a superconductor, their motion is determined by the complex interplay between several competing forces: the Lorentz force from the shielding currents tends to drag them into the sample, pinning forces resist their motion, and finally they must overcome an edge barrier (the Bean-Livingston [1] barrier and the geometrical barrier [2]).

The resulting behaviour has been studied both theoretically and experimentally. It has been found that the forces near the edges can be a source of magnetic irreversibility even in the absence of bulk pinning [2], and can control the transport current distribution ([3], [4]).

In this paper we report direct magneto-optical (MO) observations of individual vortex motion near a superconductor’s edge.

2. Method

We have used a magneto-optical microscope capable of resolving single vortices to look at the detailed flux dynamics near the edge for two samples of NbSe$_2$. The basic principle of the method is to let polarised light pass through a magneto-optical indicator film placed close to the sample surface, and then detect changes in the polarisation. The instrument is further described in [5]. For single vortex resolution the MO film must be very close to the sample, because at larger distances the single vortex field quickly becomes smeared out.

The field penetration experiments were performed on two NbSe$_2$ single crystals [6] with thickness 100 µm and 10 µm. The sample shape was approximately a rectangle with the smallest dimension ≈1 mm. The samples were initially cooled to 5 K in a residual field of 0.05 mT. After cooling, an external field $H_a$ was applied perpendicular to the plane of the sample and ramped from 0 to 1 mT.

3. Observations

Figure 1 shows snapshots of vortex penetration into the 100 µm thick sample. Individual vortices are clearly seen as they enter the sample. But we also see that near the edge of the sample a vortex free band exists, approximately 5 µm wide. When a vortex enters the sample, it jumps across the band and gets pinned. When observing the vortex entry over a wider field range,
we see that the band remains (albeit thinning a bit as the field increases) as more vortices penetrate, while the vortex density increases beyond the band. A full movie of vortex penetration during the field ramp can be found at http://www.fys.uio.no/super/results/sv.

Figure 2 shows field distributions for the thin sample. Because of larger distance between the sample and the MO film, individual flux quanta cannot be seen here. However, the gray levels still represent the actual flux density. The graphs underneath show profiles of flux density obtained from the images by averaging gray level in each pixel column.

4. Discussion

Both samples show a vortex free band near the edge. When vortices enter the sample, they move quickly through this band and get pinned some distance $x$ from the edge. The three main observations to be explained are: (i) the band is shrinking as the field increases, (ii) the band is wider for the thinner sample, (iii) there is a narrow bright band at the edge. All these observations can be explained by the combined effect of the geometrical barrier and bulk pinning [2], [7]. A physical picture of the vortex entry process is the following: there is an energy cost associated with vortex formation at a superconductor’s edge. Once the barrier due to this energy is overcome, the vortex is pushed inwards by the Meissner current. The Meissner force decays as the vortex gets deeper so at some point it is balanced by the pinning force, and the vortex stops. The pinning force is larger for the thicker sample, so qualitatively this is consistent with our observation (ii) above.

However, this simple picture can not account for the first observation, and hence a more careful analysis is required. When vortex entry is governed by both bulk pinning and the geometrical barrier, the width of the vortex free band can be found from the equation $H_a/H_0 + dj_c/H_0 \ln w/x = 1/\sqrt{x/w}$ obtained from Eq.(15) of Ref.[7] in the limit $x \ll w$, where $2w$ is the sample width, $d$ - thickness, $j_c$ is the bulk critical current density, and $H_0$ is a normalization parameter. The band width dependence $x(H_a, d)$ following from this equation is in qualitative agreement with both our observations (i) and (ii). Besides, it predicts a stronger dependence of $x$ on $H_a$ for a thinner sample, which is also the case experimentally.

Finally, the bright band of high flux density near the sample edge can be explained by a build up of partially penetrated vortices “climbing” the geometrical barrier. In fact, individual vortices constituting this band can be resolved at low fields. However, the width of this barrier is thought to be of the order of the sample thickness [2], while we observe a much lower width of the band ($\approx 3 \mu m$) that is the same for both samples.

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