Vortex-antivortex annihilation in underdoped $YBa_2Cu_3O_{6.354}$

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Abstract

Locally applied magnetic fields can be used to create vortex-antivortex pairs in superconducting films and thin crystals. These pairs typically annihilate on some timescale which depends on temperature. We use a 21μm diameter field coil integrated onto a scanning Superconducting QUantum Interference Device (SQUID) to create and observe vortex-antivortex pairs. We present measurements of the distribution of annihilation times as a function of temperature, which should allow us to determine the pinning forces for vortices in these highly underdoped samples of $YBa_2Cu_3O_{6.354}$.

Key words: vortex pinning; cuprate; scanning SQUID

1. Introduction

We have previously demonstrated the use of locally applied magnetic fields to manipulate single vortices and to create vortex-antivortex pairs in superconductors [1]. In this paper we report the result of measurements of the lifetime of vortex pairs created with this technique, and observations of several ways in which the pairs annihilate.

2. Apparatus

We use a scanning SQUID microscope with a susceptometer SQUID [2] to create and image vortex-antivortex pairs. The SQUID is fabricated with a commercial niobium process [3] using an IBM susceptometer design [4] modified for scanning. The pickup loop is 8μm by 8μm with a concentric octagonal field coil of diameter 21μm. By running a current through the field coil, a local magnetic field can be applied to the sample in the region measured with the pickup loop. The SQUID is mounted on a piezoelectric scanner with a scan range of about 70μm by 70μm at 4.2K. The SQUID is aligned so that the pickup loop and field coil are within a height of 2μm above the sample surface.

The sample is a very underdoped, single crystal of $YBa_2Cu_3O_{6.354}$ [5], with approximate dimensions 1mm by 1mm and 4μm thick along the *c*-axis. T_c for this sample is about 12K.

3. Measurements

After cooling the sample in zero field and scanning to make sure the field of view is free of vortices, we park the SQUID in the centre of the scan area and run a current I_{fc} through the field coil for 10s (with 4s ramp up and 4s ramp down). We then scan again to see if a vortex-antivortex pair has been created. If not, the current ramp is repeated with a larger I_{fc}. Typical currents required to create a pair in this sample are 15-23mA, depending on the location and the height above the sample.

When a sufficient I_{fc} has been applied, a vortex pair is created at some location around the field coil. One

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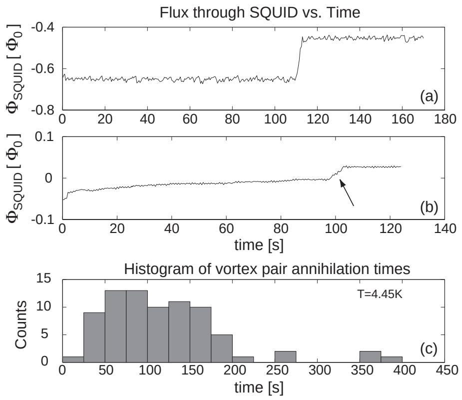

Fig. 1. (a) Annihilation event: The pickup loop of the scanning SQUID is placed over one member of a vortex-antivortex pair. The flux through the pickup loop changes abruptly to the background flux level whe the pair annihilates. (b) As in (a), but the annihilation event (indicated with an arrow) is preceded by gradual changes in flux which may be associated with the vortex moving through intermediate pinning sites. (c) Histogram of vortex pair lifetimes obtained from a sequence of flux vs. time graphs as in (a).

vortex will be just inside the field coil, the other just outside, and they will have opposite flux, one into the sample, the other out of the sample, as determined by the direction of the field induced by the current in the field coil. We then wait for the pair to annihilate.

To measure pair lifetimes, we create a pair and immediately park the SQUID over one member, then record the flux measured by the SQUID as a function of time and detect the pair annihilation event as a rapid jump in the flux signal to the background flux level (i.e. the flux with no pair). Fig. 1 shows two examples, (a) and (b), obtained at different sites in the sample. This measurement is repeated many times and the resulting data used to build a histogram of pair lifetimes for the given temperature, T_{ref} (Fig. 1(c)).

To measure pair lifetimes at other temperatures while ensuring the same initial conditions, we create the pairs at the *same* initial temperature, T_{ref}, position the SQUID and begin the flux vs. time measurement, then quickly heat to the desired measurement temperature T_{meas} and watch for the annihilation event.

4. Results & Discussion

A simple model consisting of vortices with opposite flux separated by a uniform potential barrier annihilating by thermal activation over the barrier would lead to a pair lifetime $\tau(T) = \tau_0 \exp(U/k_B T)$ where U is the barrier height. None of the sites we measured exhibited pair annihilation behaviour simple enough to be appropriately described by this model. Most sites were much more complicated, and the vortices appeared to either hop or creep through a sequence of intermediate pinning sites before finally annihilating (e.g. Fig. 1(b)). This is not unexpected since the coherence length sets the scale on which pinning occurs, and in this material it is much smaller than the separation at which we can create the vortices in a pair.

At those sites where intermediate pinning was not a problem we could measure pair lifetime histograms as a function of temperature and found that the characteristic $\tau(T)$ does sharply decrease as T increases. However, we sometimes measured pairs which persisted for a very long time. These pairs did not fit into the thermal activation picture.

We note the possibility that a single crystal may be thick enough to allow a U-shaped tube of flux inside the sample instead of a pair of vortices which penetrate all the way through. Because a scanning SQUID only images the surface flux, we would be unable to distinguish such configurations. Additional theoretical work is required to address this possibility and to model the motion through intermediate pinning sites.

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