Observation of Magnetic Flux Generated Spontaneously During a
Rapid Quench of Superconducting Films

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Abstract

We report observations of spontaneous formation of magnetic flux lines during a rapid quench of YBa$_2$Cu$_3$O$_{7-\delta}$ films through $T_c$. This effect is predicted according to the Kibble-Zurek mechanism of creation of topological defects of the order parameter during a symmetry-breaking phase transition. Our previous experiment, at a quench rate of 20K/sec, gave null results. In the present experiment, the quench rate was increased to $>10^8$ K/sec. Within experimental resolution, the dependence of the measured flux on the cooling rate is consistent with the prediction.

A certain class of grand unified theories describes the early universe in terms of a series of symmetry breaking phase transitions. In that context, Kibble [1] predicted that if a system having a complex order parameter is quenched through a phase transition into an ordered state, topological defects will be created. This is due to the evolution of uncorrelated regions of the newly formed phase, each region having different values of the order parameter. The defects appear in between several coalesced regions of this kind. Zurek [2] developed this idea to predict the initial density of defects as a function of quench rate and suggested specific experiments on condensed matter systems to test this scenario. The natural candidates for such tests are superfluids and superconductors, in which the topological defects are quantized vortex lines. Superconductors have an added degree of complexity, due to the presence of the gauge field $A$ which evolves with time. Results of various experiments done so far are not unambiguous; spontaneously generated vortices were observed in superfluid $^3$He [4, 5] but not in $^4$He [6]. Experiments with homogeneous superconductors have so far shown null results [7]. Other related systems are liquid crystals undergoing an isotropic-nematic transition [8, 9] (in this case the topological defects are disclinations). Experiments done with superconducting rings [10] were done in a regime where usual thermal fluctuations dominate, rather than Zurek’s mechanism. Experiments using Josephson junctions [11, 12] gave results broadly consistent with the Zurek scenario. However, these are intrinsically
inhomogeneous systems which do not fall into the class of systems directly comparable with this theory. Here, we report the results of a new, improved experiment with superconducting films [7].

We used 300nm thick c-axis oriented YBa$_2$Cu$_3$O$_7$ films with $T_c \simeq 90$K, grown on a SrTiO$_3$ substrate and patterned into a disc, 6mm in diameter. The basic experimental setup is described in Ref. 7. Briefly, the sample is placed atop the sensing coil of a HTSC SQUID magnetometer, at a distance of 1mm. In our arrangement the SQUID remains at a temperature of 77K, and is not affected by the temperature of the sample which can be heated and cooled independently. To avoid spurious magnetic fields generated by electrical current used in resistive heating, the film is heated above $T_c$ using a light source and cools by exchanging heat with its environment. The system is carefully shielded from the earth’s magnetic field, with a residual magnetic field of less than 0.05 mG. Additional small coil adjacent to the sample was used to test the field dependence of the results. Instead of $\sim 1$ sec long illumination from a quartz lamp used to heat the sample in our previous work [7], the light source in the present experiment is a pulsed YAG laser [13]. Single pulses, $10^{-8}$ sec long, were used to heat the film. After passing through a diffuser, the laser pulse passes through the substrate and illuminates homogenously a 9mm diameter area of the film, larger than our sample. At a laser wavelength of 1.06 $\mu$m, the SrTiO$_3$ substrate is transparent and practically all the light is absorbed in the film. Hence, only the film heats up, while the substrate remains near the base temperature of 77K. The 1mm thick substrate has a heat capacity about $10^3$ larger than that of the film. Therefore, an energy of $\sim$ mJ is sufficient to heat the film above $T_c$, rather than a $\sim$ J used previously [7]. The heat from the film escapes into the substrate, which acts as a heat sink. This strongly reduced thermal mass which is cooled allows us to achieve cooling rates in excess of $10^8$ K/sec, 7 orders of magnitude faster than previously [7]. The cooling rate at $T_c$ can be varied by changing the amount of energy delivered by the laser pulse (see Fig. 1). As the figure shows, increasing this energy reduces the cooling rate. The cooling rate was determined by monitoring the time dependence of the film resistance following a laser pulse. Because heat flow into the substrate takes place in a
direction normal to the plane of the film, the temperature of the sample is approximately the same along its lateral dimensions. Measurement of the net flux is done continuously during the heating-cooling cycle.

Achieving as high a cooling rate as possible is extremely important in order to enter the regime where the Zurek scenario applies. To observe the effect, the system needs to be out of equilibrium over a temperature interval wider than the critical regime near $T_c$. Due to the anisotropy of the superconducting properties of YBCO, our films are effectively 2D near $T_c$. We therefore expect that quantized vortices will develop only perpendicular to the film surface. The 2D Ginzburg-Landau model yields a $10^{-2}$K as the width of the critical regime [14] (the 2D-XY model gives an even smaller value). At quench rates between $10^7$-$10^8$K/sec the system remains out of equilibrium over an interval of 0.1-0.2K of $T_c$. Thus, the condition for observing this effect are satisfied in our case. Because the coherence length of HTSC is small, the predicted initial flux-line density $n_i$ generated in the film by a thermal quench is very large according to this scenario, $n_i = 10^{11} - 10^{12} cm^{-2}$. This includes both vortices and antivortices, with the lower value corresponding to G-L model, and the larger to 2D-XY model. In our experiment we measure directly the difference between the number of vortices and antivortices, namely the net flux. If the picture of regions having a well defined phase, and with the choice of a minimal phase gradient between the regions (the geodesic rule [15]) is correct, than the net rms flux should scale as $n_{net} \sim (L)^{1/2}(n_i)^{1/4}$, where $L$ is the length of the sample perimeter. In terms of the quench rate $dT/dt$, $n_{net} \sim (dT/dt)^{1/8}$. We point out that this weak dependence leads to a predicted $n_{net}$ which increases only by 20% while the quench rate increases by an order of magnitude. In the range of our experiment, the net flux density is predicted to be $\sim 10^2 \phi_0/cm^2$. The noise level of our magnetometer is equivalent to a flux noise of $\sim 5 \phi_0$, referred to the film. Thus, the effect should be observable. It should be noted that our measuring system can detect only the net flux "frozen" in the film, due to the fact that the film’s total cooling time is of the order of 1µsec, while the SQUID system responds on a time scale of about 10 µsec. Flux will be "frozen" in the film if the pinning site density is much larger than the flux density. The pinning
site density in similar films was estimated in Ref. 17 (and in references therein) as 1-6×10^10 cm$^{-2}$ ≫ $n_{net}$. Since pinning in YBCO films is very strong at temperatures below the critical regime, we conclude that the net flux generated during the quench should remain inside the film.

In a typical experiment, the SQUID’s output is recorded vs. time as the sample cools following a thermal quench. Such measurements were performed both on superconducting samples and on a control sample. The control sample is a similar film of underdoped YBCO, having $T_c$ of 60K, which is not superconducting in our temperature range. Indeed, net flux was observed with the superconducting film while no flux was seen in the control experiment. Fig. 2 shows data from 100 such measurements. According to the Zurek scenario, the rms of spontaneously generated flux should increase in amplitude with the cooling rate while the sign of the net flux should be random from one quench to the next. Fig. 2 clearly shows that this indeed is the case. Further, the signal obtained with superconducting film is much larger than the control signal. A typical distribution of flux from such measurements is plotted in Fig. 3. It can be seen that the distribution of the signal is symmetric about zero flux, as expected from this scenario. In order to check for the effect of any residual field, our measurements were repeated under different fields up to 10mG, about 10^8 times larger than our residual field. The inset in Fig. 3 shows that the magnetic field has no significant influence on our results.

The net flux was deduced by deconvoluting the noise from the measured signal. The net flux distribution width vs. the cooling rate is shown in Fig. 4. The solid line shows the $(dT/dt)^{1/8}$ dependence predicted by Zurek [2, 3], with a prefactor given by Rudaz et al. [15]. To agree quantitatively with the data, the theoretical prediction was scaled down by a factor of 4. It is seen that the data are consistent with this prediction. The consistency of our results with the $(dT/dt)^{1/8}$ dependence further implies that the geodesic rule is valid in a non-equilibrium regime. The validity of this rule was not considered obvious [17]. Extrapolating the data shown in Fig. 4 down to a cooling rate of 20K/sec, that of ref. [7], gives a predicted
flux density of $\sim 6 \phi_0/\text{cm}^2$ for that experiment. This value is very close to the noise level, and thus explains the null result obtained [7]. Finally, we carried out several checks to see how the magnitude of a signal is influenced by temperature gradients. The presence of temperature gradients is important with respect to the homogeneous approximation [3, 18]. We estimate our maximum temperature gradient as $\nabla T \sim 1 \text{ K/cm}$ parallel to the film surface, similar to the spread of $T_c$ across the film. Under these conditions, the homogeneous approximation is valid in our experiment. In these additional experiments, we created intentional temperature gradients in order to check whether the scaling factor between theory and experiment cited here is a result of such gradients present in our film. We found that this was not the case [19].

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FIGURES

FIG. 1. Temperature cycle of the film after a laser pulse. The energy of the pulse is 7.1 mJ (closed symbols) and 3.1 mJ (open symbols). The horizontal line is $T_c$ for our sample. Note that the cooling rate through $T_c$ is slower for the high energy pulse.

FIG. 2. Typical sequence of 100 consecutive magnetometer readings each following a separate quench. Open symbols- control sample, closed symbols-superconducting film. The lines connect successive data points.

FIG. 3. Typical histogram of spontaneous flux from several hundred quenches. The solid line is Gaussian fit. The inset shows that the distribution width does not depend on the external field.

FIG. 4. Dependence of the distribution of spontaneous flux vs. the cooling rate. The solid line is the prediction of ref. [2],[15] scaled to fit the data.
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Measurement Number

SQUID Signal (mV)
Signal Distribution ($\phi_o$) vs. Cooling Rate (K/sec)