Correlations beyond the horizon

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We have imaged spontaneously created arrays of vortices (magnetic flux quanta), generated in a superconducting film quenched through its transition temperature at rates around $10^9 K/s$. Spontaneous appearance of vortices is predicted by Kibble-Zurek and by Hindmarsh-Rajantie models of phase transitions under non-equilibrium conditions. Differentiating between these models requires a measurement of the internal correlations within the emerging vortex array. In addition to short range correlations predicted by Kibble and Zurek, we found unexpected long range correlations which are not described by any of the existing models.

Any physical system undergoing a phase transition within a finite time interval is necessarily driven out of equilibrium. One model that describes the dynamics of such phase transitions is the Kibble-Zurek scenario. The model was first suggested by Kibble [1,2] for cosmological phase transitions which occurred in the early universe. Kibble proposed that fast cooldown of the universe, through a critical temperature $T_c$, leads to formation of initially isolated domains of a new ordered phase. The typical size of a domain, $\xi$, inside which the emerging order is coherent, is a product of the speed of light and time needed to complete the phase transition. Consequently, different domains are uncorrelated due to causality. As these disjoint domains coalesce, the mismatch of the order parameter between different regions leads to the appearance of topological defects. The domain size determines both the typical distance and the correlation length between topological defects. Zurek [3] proposed terrestrial tests of this model by examining analogous situations in condensed matter systems having the same symmetry of the order parameter. The analogous "speed of light" in condensed matter systems is the velocity of propagation of the order-parameter. Since, some aspects of the Kibble-Zurek (KZ) model has been tested in a variety of physical systems, including liquid helium [4,5], liquid crystals [6], superconductors [7,8] and Josephson junctions [9,10]. Thus, the Kibble-Zurek model is a universal theory of defect formation whose applications range from phase transitions in grand unified theories of high-energy physics to phase transitions observed in different condensed-matter systems. An alternative mechanism of spontaneous vortex formation in superconductors was proposed by Hindmarsh and Rajantie [11,12] (HR). According to this mechanism, thermal fluctuations of the magnetic field freeze inside the superconductor during the transition, creating domains of magnetic flux with the same polarity and characteristic size. In contrast, the KZ model predicts only short range correlations, with neighboring defects having different topological charge. In a superconductor, where the topological defects are vortices carrying a quantum of magnetic flux, this means that adjacent vortices should have a different polarity. The presence of spontaneously generated topological defects was observed in several experiments. Regarding the more sensitive testing of correlations predicted by these models, there is only one experiment on liquid crystals in which an array of topological defects was actually imaged. However, the amount of data was insufficient to detect correlations beyond nearest neighbours. The objective of our experiment is to decide between these two models by imaging spontaneously formed arrays of vortices in a superconductor and measuring their correlations.

Investigating the spatial distribution of the vortex array requires a technique capable of imaging a relatively large area with a micrometer resolution. Furthermore, the statistical nature of the problem requires accumulating many such images. The only practical method to achieve both these goals is Magneto-Optical (MO) imaging. Resolving single vortices however requires pushing the technique to its limits, and until now only one group has achieved this goal [13]. We have developed a high resolution Magneto-Optical system specifically for this experiment. Our system is described in detail elsewhere[14]. Briefly, having the magneto-optical indicator as close as possible to the superconductor’s surface and a cryogenic design suppressing vibrations allowed us to achieve the best spatial resolution (0.8μm) demonstrated so far by this technique [14]. The superconductor sample consists of a 200nm thick Niobium film deposited on a sapphire substrate. The film was prepared by DC magnetron sputtering and it is superconducting below 8.9K. The film is patterned into small squares of 200μm across, to ensure homogeneous illumination by the heating laser pulse and avoid thermoelectric currents inside the sample. On top of the Nb film, we deposited a 40nm layer of EuSe which serves as the Magneto-Optic sensor. Due to the huge magneto optical Kerr effect in EuSe the polarization plane of linearly polarized light is rotated if local magnetic field is present. By mapping this rotation at each point of the image, we get an image of the magnetic field directly above the surface of the superconductor. The typical lateral size of a vortex in a Nb film is about 100nm [15], so the images of individual vortices are diffraction limited. In our setup, observation of individual vortices is possible over a large field of view.
(100 × 100μm²) using relatively short integration time (10s), allowing us to acquire hundreds of images during an experimental run.

From our previous experiments [7], we know that extremely high cooling rates are essential for spontaneous generation of a measurable amount of vortices. No less important, fast cooling to low temperatures (far below \( T_c \)) traps the vortices on pinning centers, preventing mutual annihilation of a vortex and an anti-vortex. High cooling rates are achieved in the following way: first, the superconducting film is heated above \( T_c \) by a short laser pulse. The 200nm thick film is deposited on a sapphire substrate, which is transparent at the wavelength of the laser. Hence, only the film heats up, while the 1mm thick substrate remains near the base temperature. At the end of the heating pulse, the heat from the film escapes via ballistic phonons into the cold substrate, which has a thermal mass of \( \sim 1000 \) larger than that of the film and acts as a heat sink during the cooldown. At low temperatures involved (below 14K), phonon scattering is small enough so that the heat transfer from the film into the substrate is ballistic. The timescale of the heat transfer is much shorter than the length of the laser pulse. Therefore, the cooling rate depends only on the decay time of the laser pulse. We used pulse shaping techniques to change the decay time. In this way two cooling rates of 4 \( \times 10^8 \) and 2 \( \times 10^8 \)K/s were achieved. The cooling rates were measured using GeAu thin film resistive bolometer. The conductivity of the GeAu film, which is temperature dependent, was measured vs. time during the laser pulse. Finally, at these cooling rates, the mean inter-vortex spacing predicted by the models is larger than our optical resolution, so that we should be able to observe the entire vortex array.

Typical images of spontaneously generated vortex arrays are shown in Fig.1. During these measurements, the system was carefully shielded from external magnetic fields, and the measured asymmetry between the density of positive and negative vortices is less than 1%. It is clear that the vortex arrays appear random. On average, the two cooling rates we could use, 4 \( \times 10^8 \) and 2 \( \times 10^9 \)K/s, produced a density of vortices of 6 \( \times 10^5 \)cm\(^{-2}\) and 1.3 \( \times 10^8 \)cm\(^{-2}\) respectively. Those densities are almost 2 orders of magnitude lower than expected from the KZ model. This discrepancy was already noticed in our earlier experiments [7]. However, the scaling of the density with the cooling rate is consistent with the KZ model (proportional to the square root of the cooling rate). One potential reason for the low density could be the mutual annihilation of nearby vortices having opposite polarities. The closer vortices are to each other, the stronger the attractive force between them. Vortices are prevented from mutually annihilating by pinning forces, which however do not depend on the distance. Therefore a critical distance between vortices with opposite polarity exists, below which pairs of vortices will overcome the pinning force, merge and annihilate. We determined this critical distance by repeating the experiment under various external magnetic fields (Fig. 2). When the density of the vortices due to external field is such that the distance between them is less than critical, all the vortices having an opposite polarity should annihilate. This critical length turns to be 1μm or less, significantly smaller than the scale of short range correlations. Hence, annihilation should not affect any of the correlations observed in our experiment.

We used images like Fig.1 to determine the correlations between the vortices. In order to increase the statistical ensemble, the correlation function was averaged over 170 such images, with 12,000 vortices in total. We first show the density-density correlation function, irrespective of the vortex polarity. This function is defined as
\[
D(r - r') = < \rho(r) \rho(r') >
\]
where \( \rho(r) \) is the local vortex density. The value of \( \rho(r) \) is taken to be 1 at the location of a vortex regardless of its polarity and 0 elsewhere. According to the KZ model, if a vortex is created at some vertex between different domains, the probability to find another vortex at the nearest neighbour vertex is higher by 33% than the average. Consequently, \( D(r) \) should show a peak at the characteristic nearest neighbour distance. The correlation function calculated from
our data is presented in Fig.3. There is indeed a peak at \( r \approx 3 \mu m \), a strong evidence for the short range correlations predicted by the KZ model. Beyond the peak, the correlation function decays towards a constant value. The nearest neighbour distance is also the best estimation for a typical domain size \( \xi \).

Next we calculate the correlation function taking into account the polarity of each vortex. The vortex-vortex correlation function is defined as \( G(r - r') = \langle n(r)n(r') \rangle \), with \( n(r) = 1 \) at the location of a positive vortex, \(-1\) at the location of negative vortex and 0 elsewhere. The KZ model predicts that nearest neighbor vortices should have opposite polarities. This should manifest itself as a negative peak in \( G(r) \), which according to theory \[16\] should decay exponentially to zero \( (G(r) \propto r^2 \exp(-r^2/\xi^2)) \). In the KZ model, \( \xi \) is the only length scale, and both the decay length of the correlations and the characteristic distance between vortices should be \( \approx \xi \). In contrast, in the HR model neighboring vortices should have the same polarity and so the peak in the correlation function should be positive.

Fig.4 shows the vortex-vortex correlation function. The correlation function was multiplied by \( r \) to emphasize long range behavior. The nearest neighbour peak is negative, which indicates that the KZ scenario is the dominant mechanism of vortex formation. The solid line is a fit to the theory of \[16\] with \( \xi = 3 \). It indeed appears that the nearest neighbour distance (the peak in Fig.3) and the decay length of the short range correlation (Fig.4) are the same. However, at distances beyond the peak the theoretical correlation function decays to zero, while the experimental correlations do not. Surprisingly, the data show an oscillatory behavior which decays as \( \propto r^{-\alpha} \), with \( \alpha = 1 \pm 0.5 \). This oscillatory behavior is well outside the error margins. Such oscillations, if any, are within the noise in Fig.3. Hence the oscillations in Fig.4 represent long range correlations in the polarity of vortices rather than in their density. We found that the wavelength of these oscillations decreases weakly with increasing cooling rate as well as with applied magnetic field. One possibility is that these long range correlations result from some local inhomogeneities in the sample. To check this possibility, we repeated the experiments at several different locations on the film. We found that the correlations were independent of the location. Further, local variations in the local properties such as the value of \( T_c \) could potentially modulate the density of vortices which however is constant (fig. 3), but not the polarity of vortices which is what we see.

Long range correlations were predicted in the HR model \[11, 12\]. However, these correlations should decay as \( r^{-4} \), instead of \( r^{-1} \) which we observe and the predicted domain size is on a \( mm \) scale, 2 orders of magnitude larger than the few \( \mu m \) which we see. In cosmology, the size of a domain is determined by the speed of light. The analogous speed in superconductors is the propagation velocity of the order parameter \[3\]. Close to \( T_c \),
FIG. 4. First moment of the vortex-vortex correlation function $G(r)$. The negative peak at short distance reflects vortex-antivortex correlations predicted by KZ model. The blue line is a fit to theory of [16].

This speed is about $10^3 m/sec$. This speed determines the nearest neighbour distance, the only correlation length in the KZ model. However, vortices are also coupled to electromagnetic field, which propagates with speed $c$. Such coupling may perhaps be linked with the longer range correlations, which are currently a puzzle.

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[1] T.W.B. Kibble, 1976, J. Phys. A 9, 1387.
[2] A. C. Davis, and T.W.B. Kibble 2005, Contemporary Physics 46, 313.
[3] W.H. Zurek, 1985, Nature 317, 505.
[4] C. Bauerle, Y.M. Bunkov, C. N. Fisher, H. Godfrin, and G. R. Pickett, 1996, Nature 382, 332.
[5] V. M. H. Ruutu, V. B. Eltsov, A. J. Gill, T. W. B. Kibble, M. Krusius, Yu. G. Marhlin, B. Plaçaís, G. E. Volovik, and Wen Xu, 1996, Nature 382, 334.
[6] R. Ray, and A. M. Srivastava, 2004, Phys. Rev. D 69, 103525.
[7] A. Maniv, E. Polturak, and G. Koren, 2003, Phys. Rev. Lett. 91, 197001.
[8] J. R. Kirtley, C. C. Tsuei, and F. Tafuri, 2003, Phys. Rev. Lett. 90, 257001.
[9] R. Monaco, J. Mygind, and R. J. Rivers, 2002, Phys. Rev. Lett. 89, 080603.
[10] R. Carmi, E. Polturak, and G. Koren, 2000, Phys. Rev. Lett. 84, 4966.
[11] M. B. Hindmarsh, and A. Rajantie, 2000, Phys. Rev. Lett. 85, 4660.
[12] A. Rajantie, 2009, Phys. Rev. D 79, 043515.
[13] P. E. Goa, H. Hauglin, A. F. Olsen, M. Baziljevich, and T. H. Johansen, 2003, Rev. Sci. Instrum. 74, 141.
[14] D. Golubchik, G. Koren, E. Polturak, and S. Lipson, 2009, Optics Express 17, 16160.
[15] A. Gauzzi, J. Le Coche, G. Lamura, B. J. Jönsson, V. A. Gasparov, F. R. Ladan, B. Plaçaís, P. A. Pronst, D. Pavuna, and J. Bok, 2000, Rev. Sci. Instrum. 71, 2147.
[16] F. Liu, and G. F. Mazenko, 1992, Phys. Rev. B 46, 5963.