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Hot spot in type-II superconductors: dynamics and instabilities

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Abstract

The relaxation dynamics of a quenched normal spot in type-II superconductor is considered analytically and numerically. Various instabilities accompanying recovery of superconductivity are considered. Relaxation of the normal spot starts with appearance of a microscopic instability triggering the creation of the vortex clusters.

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1. Introduction

Fast symmetry-breaking phase transitions are an important subject of research in several areas of physics. In the framework of the cosmological models Kibble [1] stressed that quenching of the more symmetric phase results generally in spontaneous generation of the topological defects on its way to a new vacuum, where the symmetry is broken. Zurek [2] captured the general feature of the rapid cooling pointing out the similarity between the cosmological phase transition and some specific experimental phenomena in solid state physics, in particular, in superconductors.

Recently experiments were carried out on several systems including nematic liquid crystals undergoing a transition from the isotropic to the nematic state and liquid ^{4}He crossing the λ-point as a result of a rapid drop in pressure, and liquid ^{3}He undergoing a superfluid phase transition when the quantizied vortices are formed during thermal quench following a local exothermic neutron-induced nuclear reaction [3–5]. Superconductor, as a well-understood and experimentally accessible system, can serve as an ideal testing ground for basic results and ideas of string formation. Vortices and anti-vortices here play a role of the topological defects in the Kibble–Zurek (KZ) scenario.

In addition studying the relaxation dynamics in superconductors allows one to test the KZ mechanism in a system with local gauge symmetry (in contrast to the helium systems, which possess only the global gauge invariance). The KZ scenario is supported by recent experiments which probe a spontaneously generated magnetic flux in the quenched metallic superconducting ring and in the high temperature superconductor (HTS) film undergoing a homogeneous quench through the critical temperature in zero magnetic field [6,7]. It should be noted though that there is a problem to

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detect significant number of topological defects in these experiments. It might be due to vortex/anti-vortex thermal dynamics, forcing the majority of created vortices and anti-vortices either to escape from the sample or else to annihilate very quickly, leaving just few pinned vortices and anti-vortices to contribute to the experimentally measurable magnetic flux. In order to study the instability of the quenched normal state accompanying by vortex generation and avoid the problems related to the vortex/anti-vortex dynamics it has been proposed to consider the recovery of superconductivity in a hot spot normal domain containing magnetic flux [8,9]. In these experiments superconductivity is suppressed locally by the heat generated by a laser. After the laser is switched off this hot spot relaxes splitting into the vortex structures that can be either stable or unstable [10].

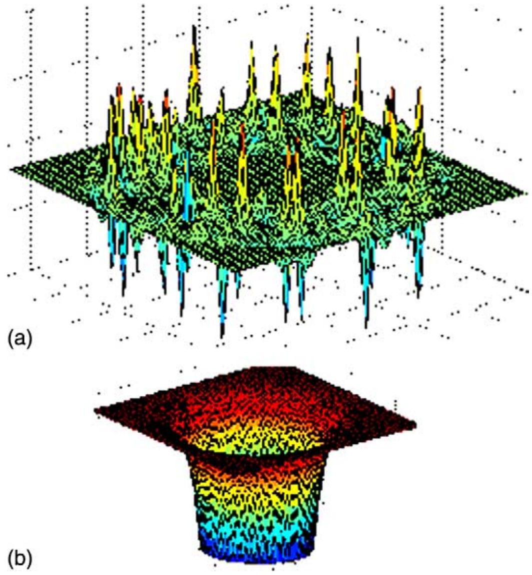

Fig. 1. (a) Onset of vortices in the superconducting ring and (b) spontaneously generated magnetic flux inside the ring.

2. The uniform quench

According to the KZ scenario of the symmetry-breaking phase transition undergoing homogeneous quench in the whole sample, the temperature $T(t)$ of a system depends only on one controllable parameter t_Q

$$T(t) = (1 - t/t_Q)T_c. \quad (1)$$

When the uniform sample, in which superconductivity was initially destroyed by the uniform heat impact, undergoes a quench, its normal electronic state becomes unstable. In this case fluctuations of the phase of the order parameter create a set of closed current loops with both signs of the topological charge defined as circulation of the phase around zero of the order parameter

$$p_i = (2\pi)^{-1} \oint \nabla\chi \, \mathrm{d}l = \pm 1$$

which in fact is the topological charge of the spontaneously generated vortices/anti-vortices [11] (Fig. 1).

The characteristic growth time of the topologically defect is $t_Z = \sqrt{t_{GL} t_Q}$, where t_{GL} is the microscopic Ginzburg–Landau (GL) time. It can be estimated from the time-dependent GL equation with $T(t)$ in the form of Eq. (1). The total density of topological defects is estimated as $n_0 \approx \xi^{-2} = \xi_0^{-2} t_z/t_Q = \xi_0^{-2}\sqrt{t_{GL}/t_Q}$, while the net vorticity, i.e. the difference between numbers of vortices and anti-vortices is

$$\Delta N \approx \sqrt{R/2\pi\xi} \propto \xi_0^{-1/2}(t_G/t_Q)^{1/8} \quad (2)$$

Hindmarsh and Rajantie [12] presented additional mechanism of fluctuations of the magnetic field in the gauge system leading to creation of the spontaneously generated vortices forming the vortex or the anti-vortex domains. Vorticity for this mechanism is estimated as $\Delta N \approx \sqrt{e^2 RT}$ and does not depend on the cooling rate. In any case, the net vorticity is very small and apparently cannot be increased by raising the cooling rate. The results of the numerical simulations are presented in Fig. 2.

The net flux slightly depends on cooling rate. This dependence is even smaller than in the Zurek theory (see Eq. (2)). The small number of the generated vortices/anti-vortices is caused by the intensive vortex–anti-vortex annihilation (Fig. 1a) when thermally activated vortices washes out the fluxoids generated by the conventional Kibble–Zurek mechanisms. This result is in a good agreement with experiment [13] where spontane-

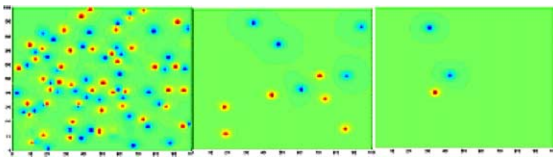

Fig. 2. Spontaneously generated vortices and anti-vortices in superconducting plate for various cooling times $t_Q/t_G = 5 \times 10^2, 5 \times 10^4, 5 \times 10^5$.

ously generation of vortices and anti-vortices is detected in thin films rings of the amorphous superconductor Mo_3Si. These rings are exceptionally susceptible to thermally activated vortex process due to very large magnetic penetration length which makes vortex–anti-vortex annihilation more essential and nucleation of vortices not too energetically costly at temperatures relate vilely far from T_c.

3. Micro-instability of a hot spot with confined magnetic flux

The process starts with the laser heat impact, locally suppressing the superconducting state and creating a large normal domain that confines the magnetic flux [9]. The normal domain undergoes rapid relaxation from the moment the laser heating is turned off. We start with the simplified set of TDGL equations

$$\Gamma \frac{\partial \psi}{\partial t} = [1 - \Theta(r,t)]\psi - |\psi|^2\psi - (\mathrm{i}\nabla + A)^2\psi,$$
$$\frac{\partial A}{\partial t} = -\nabla \times \nabla \times A - \frac{\mathrm{i}}{2\kappa^2}(\psi^*\nabla\psi - \psi\nabla\psi^*) - \frac{1}{\kappa^2}|\psi|^2 A, \tag{3}$$

where $\Theta(r,t) = T(r,t)/T_c$ is the inhomogeneous temperature, completed with the temperature diffusion equation

$$\frac{\partial \Theta}{\partial t} = D\nabla^2\Theta + \varepsilon\left(\frac{\partial A}{\partial t}\right)^2 - \gamma(\Theta - \Theta_0). \tag{4}$$

These equations determine the relaxation dynamics of the hot spot. In the case of the azimuthally symmetric hot spot, with conserved topological charge (magnetic flux), the temperature front (TF) defined by $T = T_c$ and the order parameter front (OPF) defined by $\psi \to 0$, are quite different. TF is persistently accelerated (curve 2), while OPF slows down and is eventually stopped (Fig. 3).

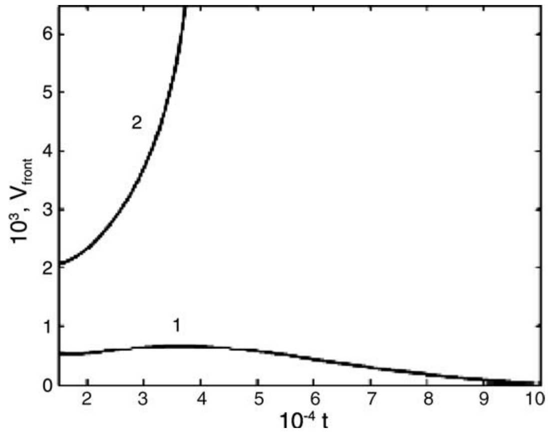

Fig. 3. Velocities of OPF (curve 1) and TF (curve 2).

Temperature in the domain between OPF and TF is lower than T_c, while the order parameter in this area is still zero (Fig. 4)

Therefore this domain (green in Fig. 4a) should loose its stability. The instability starts with small fluctuations of the order parameter that can be represented in the form

$$\psi = \left[F(r) + \sum_m (C_m(r)\cos(m\varphi) + D_m(r)\sin(m\varphi))\exp(\lambda_m t)\right]\exp(\mathrm{i}N\varphi).$$

Here η is the perturbation, N is the topological charge trapped in normal domain, λ_m are the growth rates for the mth unstable harmonic (Fig. 5).

The number of the most unstable harmonic, $m = 20$ in the present case (m is the number of vortices to be grown in the ring) is smaller than the total topological charge $N = 64$ confined inside the hot spot. Topological defects appearing at the early stage of the unstable domain evolution are washed out by the moving OPF. In the steady state point of the OPF, the front cannot suppress the vortex creation and the vortex structure emerges (Fig. 6).

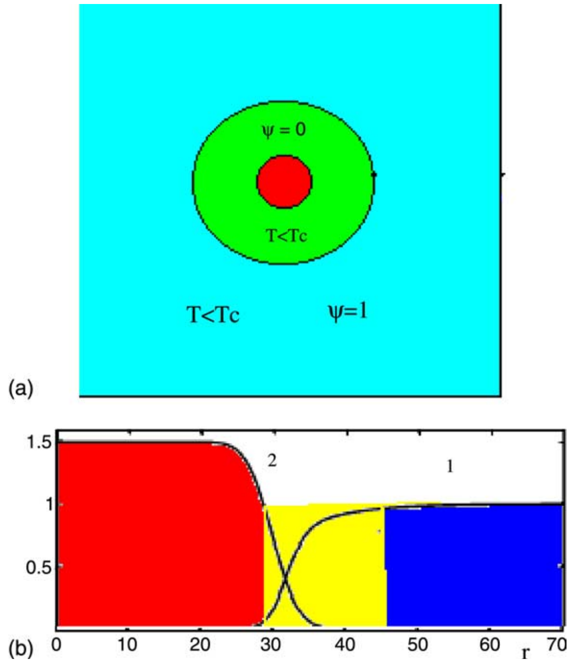

Fig. 4. (a) Unstable domain between OPF and TF and (b) spatial profiles of the OPF and TF.

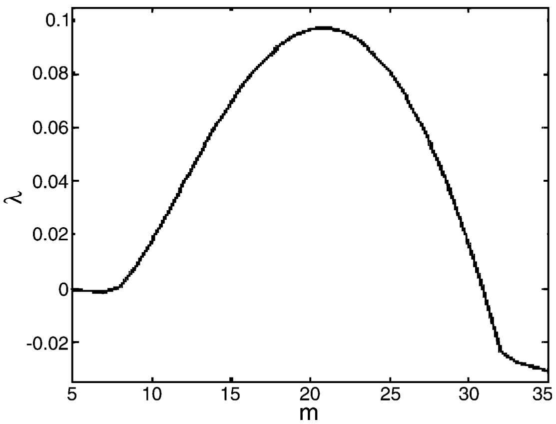

Fig. 5. Growth rate of azimutal instability for different m for the vortex ring instability.

It strongly depends on the TF velocity V_T. If the distance swept by TF for the characteristic Zurek time of the single vortex growth t_Z is of the order of several coherence lengths $V_T t_Z \approx \xi$, then a single vortex ring appears. Otherwise, a crystallite of the Abrikosov lattice forms, see Fig. 7.

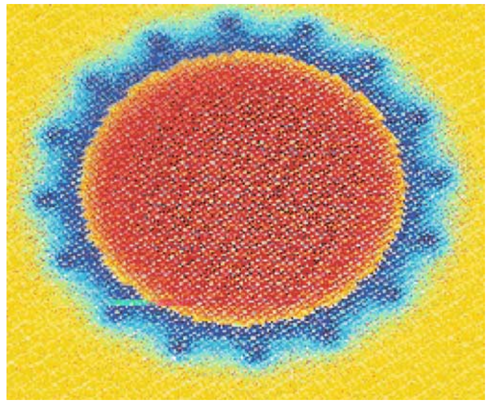

Fig. 6. Fluctuations on the initial stage of instability.

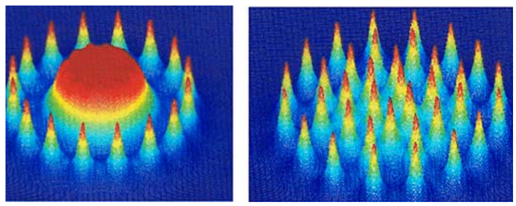

Fig. 7. Single vortex ring and cluster of the Abrikosov lattice.

The vortex structure in the ring regime releases only part of the topological charge confined in the hot spot. After the vortex ring creation, the velocity of OPF suddenly increases. The OPF moves, washing out the growing vortices and pressing the rest of the magnetic flux inside the hot spot. Then OPF is slowing down and its velocity again drops to zero. The second vortex ring is emerging, while the rest of the topological charge remains in the hot spot. The process repeats itself many times until complete relaxation of the hot spot is achieved (Fig. 8).

If the feedback term $\varepsilon(\partial A/\partial t)^2$ in the temperature diffusion equation (4) becomes important, then the vortex ring emerging from the unstable normal domain demonstrates "turbulent" behavior. The geometrically perfect ring is transformed into a broken shape figure (Fig. 9).

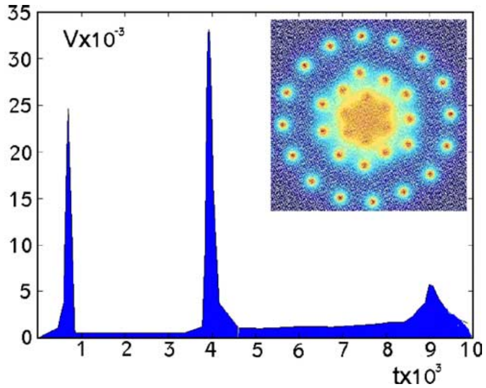

Fig. 8. OPF velocity and emerging vortex rings.

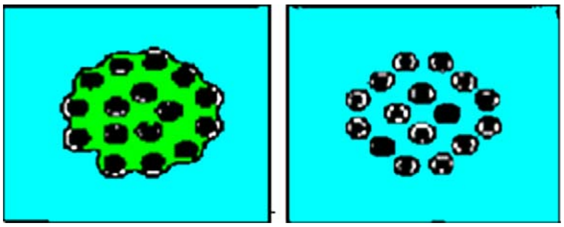

Fig. 9. Creation of a turbulent Abrikosov vortex domain as a result of a large self-heating parameter ($\varepsilon = 10^4$) and non-turbulent domain for a small self-heating parameter ($\varepsilon = 10^2$).

4. Summary

Recovery of the superconductivity in the hot spot starts when the temperature front separates from the front of the order parameter. The temperature front accelerates, while the front of the order parameter velocity decreases approaching zero. The normal domain appearing between these two fronts is unstable with respect to disintegration into a set of single vortices. On the other hand, these well separated vortices can be ‘‘washed out’’ by the order parameter front. When the front of the order parameter is stopped the vortices emerge from the unstable domain. If the size of the normal domain is of order of several coherence lengths, then only part of the topological charge confined inside the hot spot is released. It results in creation of the ring of Abrikosov vortices, while the rest remains in the central-spot area where the temperature still exceeds the critical. The front of the order parameter accelerates after that and the process repeat itself. If the hot spot is quenched quickly, then the Abrikosov vortex crystallite grows over the entire unstable domain. It should be noted that the only parameter determining the type of the vortex structure is $\chi = 4\pi\sigma D/c^2$ [9], where σ, D are the conductivity and diffusion coefficient of the superconducting materials in its normal state.

Self-heating of the moving vortices affects their velocities and leads to formation of a turbulent, non-regular vortex cluster.

Acknowledgements

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