Anisotropic Origin of the Bending Instability of the Flux-Antiflux Interface in Type-II Superconductors

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The physical nature of the macroturbulence in vortex matter in YBCO superconductors is investigated by means of a magneto-optic study of the instability in a single crystal prepared especially for this purpose. The instability develops near those sample edges where the oppositely directed flow of vortices and antivortices, guided by twin boundaries, is characterized by the discontinuity of the tangential component of the hydrodynamic velocity. This fact indicates that the macroturbulence is analogous to the instability of fluid flow at a surface of a tangential velocity discontinuity in classical hydrodynamics and is related to the anisotropic flux motion in the superconductor.

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One of the most interesting and unexpected phenomenon in vortex matter in type-II superconductors was discovered about ten years ago [1–3]. Using the magneto-optical (MO) imaging technique, the turbulent instability of the vortex-antivortex interface has been observed in $YBa_2Cu_3O_{7-\delta}$ single crystals. When the magnetic flux is trapped in the superconductor and a moderate field of opposite direction is subsequently applied, a boundary of zero flux density will separate regions containing flux and antiflux. In some temperature and magnetic field ranges such flux-antiflux distribution can display unstable behavior characterized by an irregular time-dependent propagation of the boundary, where fingerlike patterns often develop. This behavior differs strongly from the predictions of the critical state model, or creep model, where only quasistatic, or slow and regular processes of flux redistribution can occur [4,5].

The nature of this intriguing phenomenon remained unclear for a long time. Actually, only a few attempts to interpret the macroturbulent instability have been made. The physical origin of the macroturbulence was discussed by Vlasko-Vlasov *et al.* [6]. They drew attention to the fact that the annihilation of a vortex-antivortex pair may be accompanied by the formation of spatial domains free of vortices (Meissner holes). The presence of such domains may cause instability due to high currents which have to flow in the vicinity of such a Meissner hole. Yet, the authors of Ref. [6] did not describe a precise physical instability mechanism. In Ref. [7] the problem was formulated in terms of the hydrodynamic flow of vortex matter accompanied by a thermal wave generated by the local release of heat due to vortex-antivortex annihilation. However, as pointed out in Ref. [8], this mechanism is probably irrelevant.

It is essential that the macroturbulence is observed only in $YBa_2Cu_3O_{7-\delta}$ single crystals placed in a magnetic field parallel to the crystallographic c axis so that the velocity vector of the moving magnetic flux lies in the ab plane. Specifically, the $YBa_2Cu_3O_{7-\delta}$ material is characterized by a pronounced anisotropy of its microstructure and of the physical properties in the ab plane due to the existence of twin boundaries. In particular, the twin boundaries cause an anisotropic flow of the Abrikosov vortices under the action of the Lorentz force. According to a number of observations, the vortices move preferably along the twins, an effect often referred to as flux guided motion [9,10]. The examination of the vortex-antivortex flow under conditions of the guiding effect prompted the authors of Ref. [8] to attribute the macroturbulent instability to the ab-plane anisotropy. They assumed an analogy in the physical nature of the macroturbulence with a kind of turbulence in the hydrodynamics of usual fluids. According to a classic paper of Helmholtz, the flow of two fluids becomes unstable near their interface and turbulence develops if there exists a discontinuity of the tangential components of their velocities (see, for example,

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Ref. [11]). Such a tangential discontinuity is present at the vortex-antivortex interface in twinned superconductors if the twin boundaries are inclined at an angle $0 < \theta < \pi/2$ with respect to the direction of the Lorentz force. Indeed, the anisotropy gives rise to vortex motion with a velocity component normal to the Lorentz force. The vortices and antivortices are forced to move towards each other along the interface where the tangential component of the flux flow velocity is discontinuous. Note that the role of anisotropy in the development of different kinds of instabilities in superconductors was considered also by Gurevich [12,13]. However, he did not study the problem of the stability of the vortex-antivortex system.

With the above-mentioned physical picture in mind, a simple hydrodynamic model was developed that takes into account the specific features of vortex and antivortex motion in anisotropic superconductors [8]. To describe the anisotropic flux motion, a linear relationship between the Lorentz force and the vortex velocity with a symmetric tensor of viscosity was used. The ratio $\varepsilon < 1$ of the principal values of this tensor can be used to characterize the anisotropy. The analysis of the behavior of the vortex-antivortex system has shown that under certain conditions the flat interface separating the regions occupied by vortices and antivortices becomes unstable. The anisotropic power law for the current-voltage characteristics was exploited in Ref. [14] for the analysis of the macroturbulent instability,

$$J_X = \frac{1}{\epsilon} J_c \left(\left| \frac{E_X}{E_0} \right| \right)^{1/m} \mathrm{sgn}\left(\frac{E_X}{E_0} \right),$$

$$J_Y = J_c \left(\left| \frac{E_Y}{E_0} \right| \right)^{1/m} \mathrm{sgn}\left(\frac{E_Y}{E_0} \right).$$

Here $J_{X,Y}$ and $E_{X,Y}$ are the current density and electric field components, J_c is the critical current density defined as the value of J_Y at $E_Y = E_0$ ($E_0 = 1\ \mu$V/cm is the usual criterion), $\epsilon < 1$ is the parameter of the current anisotropy, and X and Y directions correspond to those along and across the twin boundaries (principal axes of the anisotropy). Typically, the parameter m for YBCO single crystals is 10–20 or larger at temperatures $T < 50$–60 K. As it follows from Ref. [14], the instability occurs if $m^2 \epsilon^m < \varepsilon_c \ll 1$. As a result, the macroturbulent instability can arise even for relatively low *current anisotropy*, $\epsilon \sim 0.3$–0.5. The model developed in Refs. [8,14] allows one to describe the main features of the macroturbulent instability.

Thus, our previous studies [8,14] led us to conclude that the macroturbulent instability arises due to the tangential discontinuity of the hydrodynamic velocity at the vortex-antivortex interface resulting from the guiding effect. Nevertheless, a certain dissatisfaction persisted since an experimental investigation of this physical picture has not been performed. In Ref. [3] an attempt was made to detect the effects of the sample properties (such as sample structure, size and geometry, current carrying capability) on the macroturbulent behavior of the vortex matter. Unfortunately, this study did not reveal direct correlations between the macroturbulence and these properties. A subsequent experimental study allowed us to conclude that the increase of the twin boundary density results in an extension of the temperature window in which the instability is observed [8]. This result, although being in favor of the anisotropic origin of the macroturbulence, is insufficient as solid proof. This motivates the present study devoted to the experimental investigation of the possible nature of the instability. The main idea of this paper is to study the behavior of the flux-antiflux interface in a crystal cut out in such a way that the anisotropy effects would be present mainly near some edges of the sample and absent near others. To realize such an experiment, the sample was shaped into a triangular plate with one edge cut parallel to the twin boundaries. Hence, flux guiding and macroturbulence are not expected for the interface running along this edge, but should be present for the other edges.

The $YBa_2Cu_3O_{7-\delta}$ single crystals were grown using a technique described in Ref. [15]. The crystals were synthesized from CuO, Y_2O_3, and $BaCO_3$ powders of purity 99.99%. Powders containing the metallic elements Cu:Ba:Y in the ratio 73:24.5:1.5 were mixed and annealed in flowing oxygen at 1130 K for 4 days. The crystals were grown in a gold crucible, in the temperature range of 1130–1250 K, in the presence of a temperature gradient of 2–4 K/cm with the rate of temperature decrease of about 4 K/h. This method allows us to produce crystals with dimensions up to 5×5 mm^2 parallel to the ab plane and about 10–20 μm along the c axis. The crystals were saturated with oxygen at a temperature of 700 K in an oxygen flow at ambient pressure for 4 days. Then, several crystals having large domains with aligned twin boundaries were chosen. After a selection of such domains, we prepared two samples and shaped them by laser cutting [16] into a nearly right-angled triangular plate. The polarized light microscope image of one of the samples is shown in Fig. 1. The size of the sample along the hypotenuse is about 1.1 mm. The crystallographic ab plane coincides with the sample plane. It is clearly seen that the twin boundaries are directed along the hypotenuse. The twin spacing is approximately 2 μm. The critical temperature of the samples is 91 K and the width of the transition is about 0.3 K.

The study of the magnetic flux penetration and the macroturbulence was carried out by the conventional magneto-optic imaging technique [17]. The image in Fig. 2 demonstrates the distribution of trapped magnetic flux after cooling the sample down to 30 K in an external transverse magnetic field $H = 1$ kOe, which was subsequently switched off. The brighter regions of the image correspond to higher values of the magnetic induction. Owing to the flux guiding effect, the penetration depth of

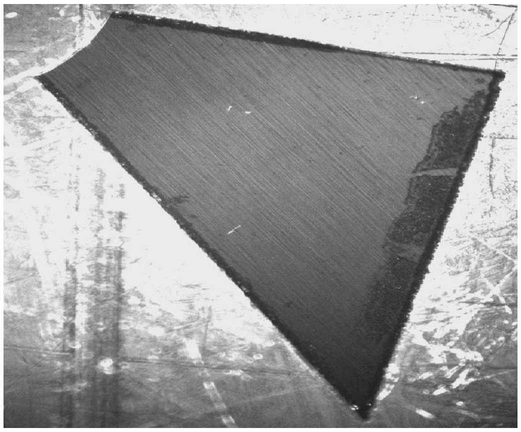

FIG. 1. Polarized light image of the sample, which reveals that it consists of essentially singly oriented twin boundaries parallel to the long side (hypotenuse).

the magnetic flux along the direction of twins is clearly seen to be higher than that across this direction. Unfortunately, we can only evaluate the critical current density along the twin boundaries as about 10^5 A/cm^2 because the sample shape is irregular.

In order to search for instability, the sample was first cooled in a transverse magnetic field H. Then the field was abruptly reversed and MO images were recorded and analyzed. Various sample temperatures and reverse fields were used. The most pronounced unstable behavior was observed at $H = 1$ kOe and $T = 30$ K and is illustrated by the series of MO images in Fig. 3. The manifestation of instability as seen through the oculars of the microscope can be described as follows. We observed a specific contrast vortex-antivortex interface (the dark lines in the images) before building up the instability. This correlates with the data in Ref. [6] as well as with the model developed in Ref. [14] and may be an indication of a role of the Meissner hole in the instability appearance. Then, a small-scale and fast "trembling" of the interface was observed. It is clearly seen from the images that the magnetic flux frozen in the central part of the sample disappears with time. Unfortunately, we are not able to illustrate this effect by static photographs. Then, a bending and irregular motion of the interface deep into the sample occurred. However, we could not observe a very distinct fingering of the interface, as found in the classic observations [1–3] of the phenomenon. On the other hand, previous studies [18] have shown that a lack of fingering is typical when the lateral dimensions of the sample are comparable to the spatial scale of the turbulent perturbations. Unfortunately, we could not produce larger samples with desirable geometry and with a single twin boundary orientation.

The images (a)–(d) in Fig. 3, obtained at 0.1, 0.2, 0.3 and 10 s after the field reversal, show the consecutive stages of the development of the instability. The key point here is to observe the significant difference in the interface geometry and its motion away from the sample edges as functions of time. First, one notes that except for the

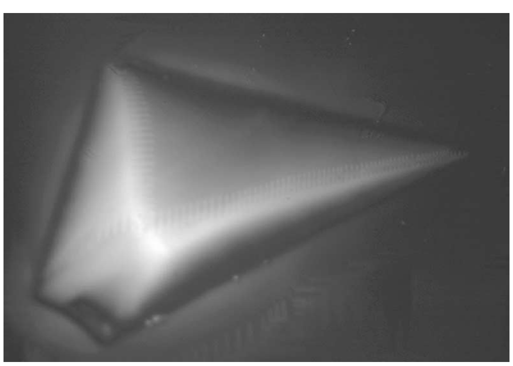

FIG. 2. MO image of the trapped magnetic flux. $T = 30$ K.

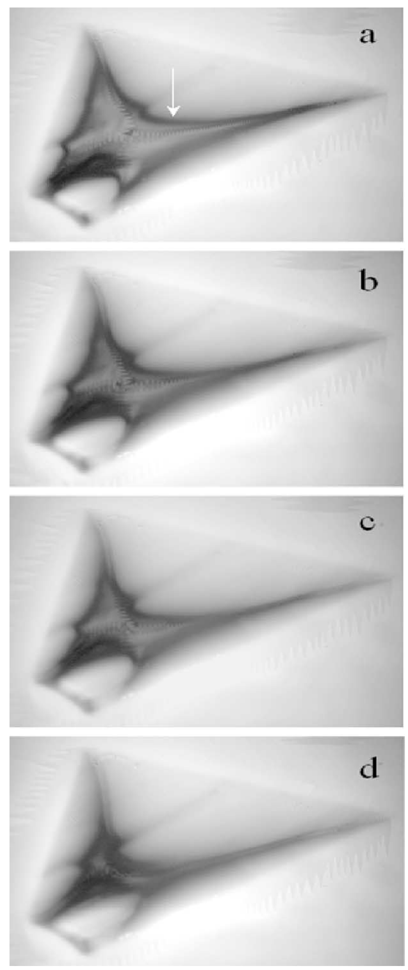

FIG. 3. Evolution of the magnetic flux distribution under the condition of the development of instability. Images (a)–(d) were obtained in 0.1, 0.2, 0.3, 10 s after the reverse of the external magnetic field, respectively. $T = 30$ K, $H = 1$ kOe. The flux-antiflux interface is the dark line, e.g., as pointed out by the white arrow.

hypotenuse, the interface elsewhere is very sharply defined, a usual feature of turbulent behavior. Second, along the hypotenuse the interface remains essentially static whereas substantial motion takes place elsewhere, e.g., for the interface along the upper cathetus, where the velocity is estimated to 3 mm/s at the initial stage of the development of the instability. Note that the fast change of the interface position occurs after the field reversal, when the critical profile has been established, and can be interpreted as the development of the instability only. Unstable motion appears clearly also from the short edge in the lower left part of the crystal. Also along the left cathetus the interface moves, although with a slightly smaller velocity. We conclude therefore that we experimentally found that the instability giving rise to the bending flux-antiflux interface occurs only along edges oriented with some angle $\theta \neq 0, \pi/2$ with respect to the twin boundaries, i.e., where the guiding effect leads to the tangential discontinuity of the hydrodynamic vortex velocity. By performing MO imaging at different temperatures we found that the instability exists in the present sample in the temperature window of $15 < T < 45$ K. The effect is reproducible after several cycling magnetic field and temperature.

Thus, the present study can be considered as a good experimental confirmation for the possible ascertainment of the physical nature of the instability in type-II superconductors [1–3]. The specific anisotropy for $YBa_2Cu_3O_{7-\delta}$ superconductors provides the guiding effect in the vortex motion. As a result, the discontinuity of the tangential component of the flux-line velocities appears at the vortex-antivortex interface. This leads to the development of the turbulence similar to the case of the classical dynamics of fluids. In principle, the presence of large current densities at Meissner holes may facilitate the instability development. The critical current density across a twin boundary is smaller than parallel to the boundary. So, the current flow lines of the large Meissner currents in the holes are bent. This effect supports the vortex motion along the twin boundary and gives rise to the enhancement of the discontinuity of the tangential component of the flux velocity. So, the existence of the large Meissner currents at the interface is favorable for the instability development which was confirmed by MO experiments. In the general case the discontinuity of the tangential component of the flux-antiflux velocity can arise not only due to the guiding effect but owing to other reasons. The existence of macroscopic defects and the nonideal shape of a specimen can also distort the vortex trajectories that result in the tangential discontinuity of the hydrodynamic velocity of vortex and antivortex motion near the interface.

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[1] V. K. Vlasko-Vlasov, V. I. Nikitenko, A. A. Polyanskii, G. Crabtree, U. Welp, and B.W. Veal, Physica (Amsterdam) **222C**, 361 (1994).
[2] M.V. Indenbom, Th. Schuster, M. R. Koblischka, A. Forkl, H. Kronmüller, L. A. Dorosinskii, V. K. Vlasko-Vlasov, A. A. Polyanskii, R. L. Prozorov, and V. I. Nikitenko, Physica (Amsterdam) **209C**, 259 (1993).
[3] T. Frello, M. Baziljevich, T. Johansen, N. Andersen, T. Wolf, and M. Koblischka, Phys. Rev. B **59**, R6639 (1999).
[4] C. Bean, Phys. Rev. Lett. **8**, 250 (1962).
[5] Y. Yeshurun, A. Malozemoff, and A. Shaulov, Rev. Mod. Phys. **68**, 911 (1996).
[6] V. K. Vlasko-Vlasov, U. Welp, G.W. Crabtree, D. Gunter, V.V. Kabanov, V. I. Nikitenko, and L. M. Paulius, Phys. Rev. B **58**, 3446 (1998).
[7] F. Bass, B. Shapiro, I. Shapiro, and M. Shvartser, Phys. Rev. B **58**, 2878 (1998).
[8] L. M. Fisher, P. E. Goa, M. Baziljevich, T. H. Johansen, A. L. Rakhmanov, and V. A. Yampol'skii, Phys. Rev. Lett. **87**, 247005 (2001).
[9] A. K. Niessen and C. H. Weijsenfeld, J. Appl. Phys. **40**, 384 (1969).
[10] H. Pastoriza, S. Candia, and G. Nieva, Phys. Rev. Lett. **83**, 1026 (1999).
[11] L. Landau and E. Lifshits, *Fluid Mechanics* (Butterworth-Heinemann, Oxford, 1987).
[12] A. Gurevich, Phys. Rev. Lett. **65**, 3197 (1990).
[13] A. Gurevich, Phys. Rev. B **46**, 3638 (1992).
[14] A. L. Rakhmanov, L. M. Fisher, A. A. Levchenko, V. A. Yampol'skii, M. Baziljevich, and T. H. Johansen, Pis'ma Zh. Eksp. Teor. Fiz. **76**, 349 (2002) [JETP Lett. **76**, 291 (2002)].
[15] M. A. Obolenskii *et al.*, Fiz. Nizk. Temp. **16**, 1103 (1990) [Sov. J. Low Temp. Phys. **16**, 639 (1990)].
[16] A. G. Sivakov, A. P. Zhuravel, O. G. Turutanov, and I. M. Dmitrenko, Appl. Surf. Sci. **106**, 390 (1996).
[17] L. A. Dorosinskiĭ, M.V. Indenbom, V. I. Nikitenko, Yu. A. Ossip'yan, A. A. Polyanskii, and V. K. Vlasko-Vlasov, Physica (Amsterdam) **203C**, 149 (1992).
[18] T. H. Johansen *et al.* (unpublished). It was previously observed that when strongly turbulent YBCO crystals of a large size (~5 mm) were divided into smaller pieces, the fingering of the flux-antiflux boundary stopped, demonstrating a clear size effect in the phenomenon.