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Translated by Scott A. Stewart

Kinetics of formation of Abrikosov vortices in type-II superconductors

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(Submitted 1 February 1980)
Zh. Eksp. Teor. Fiz. 78, 2337–2342 (June 1980)

Data obtained by mechanically vibrating a superconductor sample in a magnetic field indicate that the Abrikosov fluxoids penetrate the sample in jumps. The number of vortices entering the sample in each jump is so high that even if they were distributed over the entire sample surface prior to penetration they would fill several surface layers with total thickness on the order of the penetration depth, and so densely that the distance between them would be of the order of the coherence length. This suggests that a surface barrier of such an assembly of "protovortices" is small compared with the insurmountably high barrier for a single vortex.

PACS numbers: 74.30.Ci, 74.60. — w

This communication is devoted to an experimental investigation of the kinetics of the penetration of Abrikosov vortices into a type-II superconductor and to their departure from the sample when the external magnetic field is increased and decreased.

A mechanical procedure was used for the investigation—we observed the vibrations of a superconductor suspended on a thin elastic filament in a vortex-producing magnetic field perpendicular to the sample axis.[1] By measuring the frequency of the oscillations of the suspension system we could asses the number of fluxoids that penetrate through the superconducting sample, since their tendency to become oriented along the magnetic field contributes a definite increment to the torsional momentum of the suspension.

A diagram of the setup used by us to observe the kinetics of vortex creation and destruction is shown in Fig. 1. The superconducting sample *1* (2.4 mm dia, $l = 1.5$ mm) was secured to a straightened glass rod *2* that carried on its upper end a light disk *3* of duraluminum with a moment of inertial $I = 2.25$ g·cm^2. The rod *2* was suspended on a thin elastic phosphor-bronze filament *4* (40 μm dia, $l = 100$ mm) and executed axial-torsional oscillations that were registered with the aid of a light beam reflected from mirror *5* and a scale *6*. The entire low-temperature part of the setup was filled with liquid helium and placed between Helmholtz coils *7* that produced a magnetic field up to 400 Oe directed perpendicular to the sample axis. This system is light enough for precise registration of the dependence of the frequency Ω on the field intensity H produced when Abrikosov vortices appear in the superconductor.

We used cylindrical samples of thermodynamically reversible single-crystal $Ta_{70}Nb_{30}$.[2] The samples were spark-cut from the original single crystal, and then carefully polished electrically to obtain crystals with mirror-finish surfaces (roughness dimension < 1 μm).

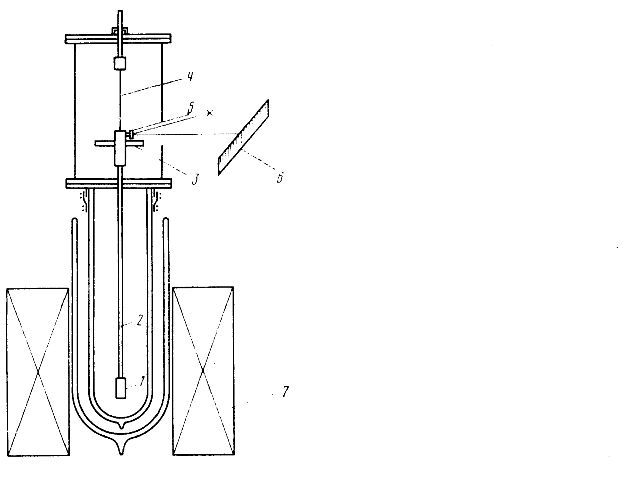

FIG. 1. Diagram of setup: 1—sample, 2—sample-holding rod, 3—disk, 4—suspension filament, 6—scale, 7—Helmholtz coils.

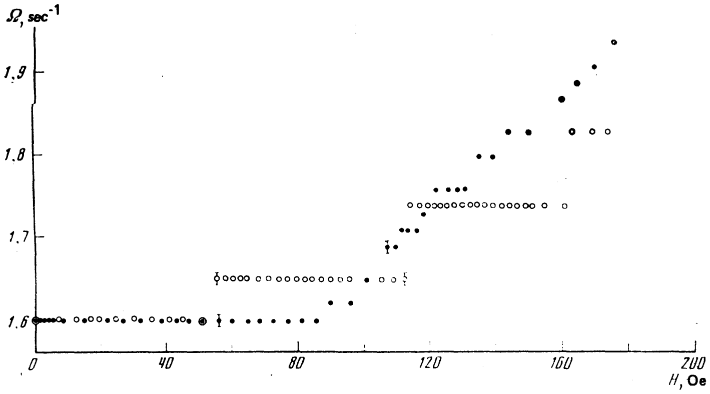

FIG. 2. Dependence of the suspension-system oscillation frequency on the intensity of the external magnetic field for an electrically polished sample. The dark and light circles correspond to measurements with increasing and decreasing magnetic field, field, respectively.

The field dependence of the oscillation frequency was measured in the interval from zero to $4H_{c1}$, where H_{c1} is the first critical field, ≈50 Oe for our samples (if the field is perpendicular to the sample axis).

Figure 2 shows one of the obtained plots of the dependence of the system oscillation frequency Ω on intensity H of the external magnetic field. The dark circles show results obtained with increasing magnetic field, and the light ones with decreasing field. In different runs the field was increased jumpwise (and remained constant during the course of the successive frequency measurement), and in others smoothly. There is no substantial difference between the results obtained in the two procedures. It is seen from this figure that:

1) the change of frequency begins above H_{c1}, namely at an external field intensity $H = 90$ Oe ($H_{c1} = 49.5$ Oe);

2) the oscillation frequency Ω varies with the magnetic field jumpwise from $H = 90$ to $H = 160$ Oe, followed by a smooth increase of Ω with the field;

3) with decreasing field the frequency begins to decrease jumpwise immediately, and the succeeding jumps exceed by several times those produced when the field is increased; the departure of the vortices ends with the last jump at $H = H_{c1}$.

To interpret these data we must examine the situation that arises when $H > H_{c1}$ and the presence of Abrikosov fluxoids in the sample is thermodynamically favored,[3] but their penetration into the sample is hindered by the surface energy barrier theoretically investigated by Bean and Livingston,[4] De Gennes,[5] Galaĭko,[6] Petukhov and Chechetkin,[7] and Shmidt and Mkrtchyan.[8]

It is known that vortices do not penetrate into well polished samples up to fields $H_s \approx H_{cm}$, where H_{cm} is the thermodynamical critical field (see e.g., the experimental paper of De Blois and De Sorbo[9]). $H_s < H_{cm}$ only for samples with rough surfaces, the shift $H_s - H_{c1}$ depends on the degree of roughness, and H_s ranges from values greatly exceeding H_{c1} (as was observed, for example, by Campbell, Evetts, and Dew-Hughes,[10] who obtained $H_s = 220$ Oe at $H_{c1} = 160$ Oe and $H_{cm} = 900$ Oe) up to H_{c1} in the case of a rough surface.

Our relatively well polished surfaces have a shift $H_s - H_{c1} = 40$ Oe, and although H_s is quite small compared with H_{cm} (which equals 600 Oe), the influence of the surface barrier manifests itself quite noticeably.

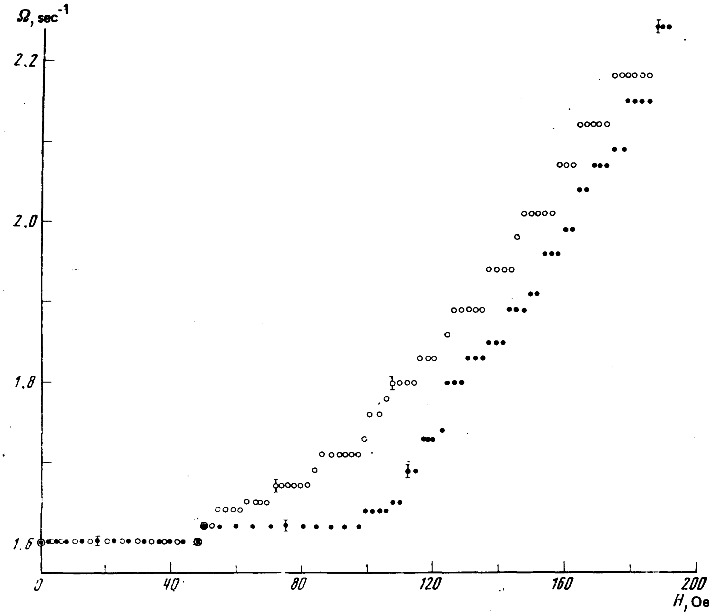

FIG. 3. Dependence of the suspension-system oscillation frequency on the intensity of the external magnetic field for a sample with surface defects. The dark and light ci circles correspond to measurements with increasing and decreasing magnetic field, field, respectively.

Production of microroughnesses on the sample surfaces by abrasion decreases H_s to H_{c1} and makes the jumps more frequent (Fig. 3). The sizes of the jumps, however, remain of the same order as in the polished samples. This is apparently evidence that the experimental curve is very close to the equilibrium curve (more frequent shifts of the same order mean a faster growth of the number of vortices).

With increasing field, the jumps on Fig. 2 demonstrate clearly (both in the interval $H_{c1} < H < H_s$) and at $H > H_s$) that the number of vortices lags the equilibrium value and that they penetrate into the sample in large groups. With decreasing field the jumps demonstrate the clustering of the metastable vortices as well as their jumpwise vanishing.

The obtained data allow us to describe the process in somewhat greater detail. We estimate for this purpose the number of vortices connected with each of the jumps. To this end we can use an expression for the energy of interaction of a single vortex with the external field in the form

$$E=\mathbf{DH}=DH-{}^1/_2DH\varphi^2, \qquad (1)$$

where D is the dipole moment of the vortex, equal to $\Phi_0 d/4\pi$, d is the average length $4R/\pi$ of the vortex, Φ_0 is the flux quantum, and φ is the angle of rotation of the sample ($\varphi \ll 1$). It follows from (1) that each vortex adds to the torsion moment of the sample an average contribution

$$f_1=\Phi_0 HR/\pi^2. \qquad (2)$$

On the other hand, the change of the torsion moment in each jump of the oscillation frequency is equal to

$$\Delta f=I\Delta(\Omega^2), \qquad (3)$$

where I is the moment of inertia of the suspension system.

Thus, change of the number of vortices in each of the jumps can be estimated from the experimental value of the jump by using the formula

$$\Delta N=\frac{\Delta f}{f_1}=\frac{\pi^2 I\Delta(\Omega^2)}{\Phi_0 HR}. \qquad (4)$$

This formula is an estimate, since the details of the vortex distribution over the sample are unknown (the distribution is assumed to be uniform) and no account is taken of the fact that contributions to the oscillation frequency are made only by pinned vortices (those freely moving over the sample contribute only to the damping of the oscillations).

To check on Eq. (4) we have reduced it with the aid of data of old measurements, made by one of us,[11] of the frequency of the oscillations of a type-II superconductor in the mixed state. The numbers of the vortices estimated from the measurements of the magnetic moment and from the equation

$$N=\pi^2 I[\Omega^2(H)-\Omega^2(H_{c1})]/\Phi_0 HR,$$

differ by not more than 20–30%.

We present now the estimates obtained with the aid of (4). With increasing field we have

$$\Delta N_1=6.2\cdot10^5,\quad \Delta N_2=9.8\cdot10^5,\quad \Delta N_3=10.7\cdot10^5,$$

and with decreasing field

$$\Delta N_1=30.3\cdot10^5,\quad \Delta N_2=23.5\cdot10^5,\quad \Delta N_3=6.0\cdot10^5.$$

We allow ourselves to advance some arguments on the basis of these results. It seems to us that an important role in the understanding of the meaning of the obtained data can be played by the following estimate. We consider the intersection of the surface of the sample by a plane perpendicular to the field and estimate the distance of the vortices present at the instant immediately preceding their penetration into the sample (and its subsequent distribution over the sample cross section). Assuming a uniform distribution of the vortices over the periphery of the sample cross section we obtain, say for the first jump (at $H=H_s$):

$$2(l+2R)/\Delta N_1=1.3\cdot10^{-6}\text{ cm}.$$

On the other hand, the coherence length for the investigated sample is $\xi\approx 4.3\times10^{-6}$ cm. Since the distances between the vortices cannot be several times smaller than the coherence length, it remains to assume that prior to the entry into the sample the vortices, being unable to surmount the surface barrier, are accumulated in several rows in a surface layer having a width of the order of λ. In our case $\lambda \approx 9.5\cdot10^{-6}$ cm and this corresponds approximately to the possibility of accomodating two or three layers, so that we can increase the estimate of the distance between vortices to a value of the order of ξ. It is known that it follows from theoretical estimates[4-8] that it is practically impossible to overcome, by thermal activation, the surface barrier calculated for a single vortex. However, vortices (it would be more accurate to call them "protovortices" or vortex embryos) that are separated from one another by a distance of the order of ξ cannot be regarded as a simple aggregate of single vortices. It is not excluded that under these conditions the barrier becomes surmountable, and it is precisely for this reason that a large number of vortices rush into the sample simultaneously. A similar accumulation of the outgoing vortices in front of the surface can take place also when the field is decreased.

In the state preceding the breaching of the superconductor by the vortices, they lower substantially the number of cooper pairs in the surface layer and weaken by the same token to Meissner current and the screening external field. This may be the cause of the lowering of the barrier (compared with the barrier for a single vortex).

These processes are similar to the jumplike change of the numbers of vortices in the case of acceleration (start) or deceleration (stop) of the rotation of vessels with helium II, or in the HeII→HeI phase transition, as observed in the experiments of Andronikashvili, Gudzhabidze, and Tsakadze,[12] Packard and Sanders,[13] and Dzh. Tsakadze and S. Tsakadze.[14] The latter have observed a jumplike self-acceleration of a decelerating rotating vessel with helium II. This self-acceleration, as shown theoretically by Kiknadze and Mamaladze,[15] is due to the transfer of angular momentum to the vessel from the vortices emerging in rows.

However, despite the undoubted analogy, there is apparently a substantial difference between the kinetics of the penetration and departure of vortices in helium II, on the one hand, and in type-II superconductors on the other. In particular, the departure of vortices from helium II (Refs. 13 and 14) is a smoother process than that investigated by us. A study of the role of pinning in similar processes is obviously one of the most important subjects of further research.

The authors thank E. L. Andronikashvili for constant interest which prompted the performance of this experiment, as well as Yu.G. Mamaladze and Z.K. Saralidze for helpful discussions that contributed to the interpretation of the results.

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Translated by J. G. Adashko