Drag of crystal lattice by moving Abrikosov fluxoids

J. G. Chigvinadze

Physics Institute, Georgian Academy of Sciences
(Submitted April 24, 1974)
Zh. Eksp. Teor. Fiz. 67, 2361–2364 (December 1974)

It is shown experimentally that moving Abrikosov vortices drag the crystal lattice. This results in resonant vibration of a niobium plate fixed at one end. The resonance frequency increases strongly in fields $H > H_{c1}$.

The motion of Abrikosov vortices in single-crystal superconducting materials was investigated mainly by two methods. The first of them, the so-called current method, was proposed in 1964 by Kim and co-workers[1]. The second, mechanical method was proposed relatively recently by myself[2]. The mechanical procedure is much more sensitive than the current procedure[3], and it should therefore be given preference over other methods in the study of small dissipations.

The mechanical procedure, was used to investigate experimentally the motion of pinned vortices dragged by a moving crystal, and the motion of three vortices relative to the crystal lattice. The present paper reports an investigation of the possibility of dragging of the crystal lattice by moving Abrikosov vortices.

To assess this possibility, the following experiments were performed:

If a superconducting plate 1 (see Fig. 1) is secured at one end (quarter-wave vibrator) and its surface is acted upon by a constant external magnetic field H and by a weak constant (or alternating) field h (applied with the aid of Helmholtz coils), then the field h will displace the Abrikosov vortices that permeate the plate. A mirror 2, which together with scale 3 was used to register the motion of the plate, was fastened to a niobium plate (length l = 15 mm, width b = 2 mm, and thickness c = 70 μ, niobium purity 99.998%).

The experiments were first performed with a constant h. As already noted above, the constant field h tries to rotate the vortices relative to the field H. It turned out that the weak magnetic field h drags the superconducting sample both in the presence and in the absence of vortices[4], see Fig. 2. As seen from the plots in this figure, in both cases the sample rotation angle φ is directly proportional to the field h. With increasing external magnetic field H, the dragging effect first increases, reaches a maximum, and then decreases (Fig. 3). These facts can be understood by recalling that the magnetic moment of the sample is determined mainly by the field H, while the torque that rotates (bends) the plate is determined by the product of the magnetic moment by the field h. In addition, the bending of the sample depends on its elastic properties and on the pinning of the vortices by the inhomogeneities of the crystal. In this connection, the plot of Fig. 3, while retaining the character of the dependence of the magnetic moment on the field, has a maximum that is shifted into the region $H > H_{c1}$. The decrease of the angle of rotation beyond the maximum may be due to the increase of the effective rigidity of the system, but this experiment does not reveal this change unambiguously. These experiments only indicate that the Abrikosov vortices are capable of dragging the crystal lattice when they move.

If this dragging does indeed exist, then it should also be observed in the case when a alternating field h is applied rather than a constant field h, i.e., oscillating vortices should also drag the crystal lattice with them, and when the frequency of the alternating field is changed one should observe a resonance at an alternating-field frequency equal to the natural frequency of the resonator (and also at the harmonics). On the other hand, such an experiment makes it possible to measure directly the effective rigidity of the system following appearance of Abrikosov vortices.

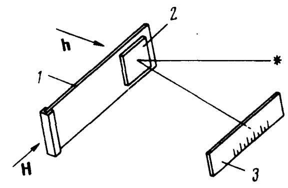

FIG. 1

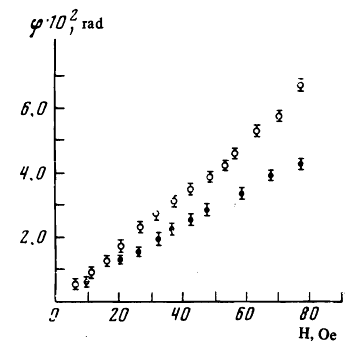

FIG. 2

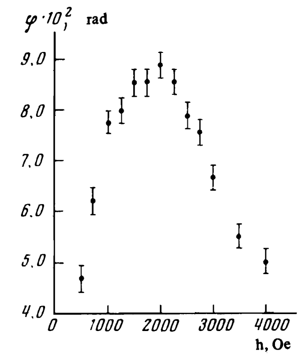

FIG. 3

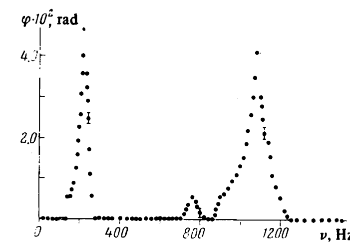

FIG. 4

FIG. 1. Experimental setup: 1—sample, 2—mirror, 3—scale, *—light source.

FIG. 2. Dependence of the sample rotation angle φ on the intensity of the constant field **h** applied perpendicular to the vortices (●—H = 500 Oe, ○—H = 2500 Oe > H_{c1}).

FIG. 3. Dependence of the sample rotation angle φ on the intensity of the magnetic field H applied along the plate.

FIG. 4. Dependence of the sample oscillation amplitude on the frequency of the alternating field, T = 4.2°K, H = 3250 Oe.

The result of such an experiment is shown in Fig. 4. In the frequency range from 20 to 20,000 Hz there are observed (in addition to several weak peaks) two frequencies at which a strong resonant dragging of the crystal by the moving vortices takes place, namely a relatively low frequency ν_L, equal to the natural frequency of the resonator, and a frequency ν_U, which is larger than ν_L by 4.5–10 times (depending on H), see Fig. 5. As seen from the diagram, the frequency ratio ν_U/ν_L decreases from 8 at $H \approx H_{c1}$ to 4.5 at $H \approx$ 3500 Oe, and then increases to 10 at $H \approx$ 4000 Oe.

When the intensity of the alternating field is in-

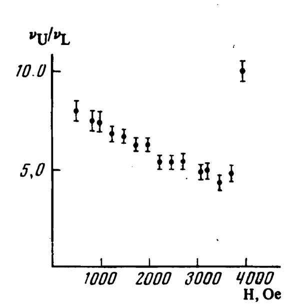

FIG. 5

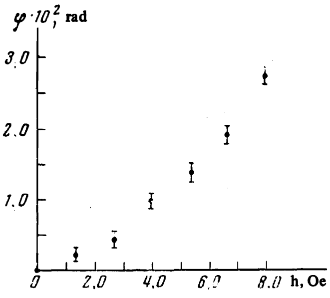

FIG. 6

FIG. 5. Dependence of the frequency ratio ν_U/ν_L on the magnetic field intensity H.

FIG. 6. Dependence of the sample oscillation amplitude on the intensity of the alternating field h; T = 4.2°K, H = 3500 Oe.

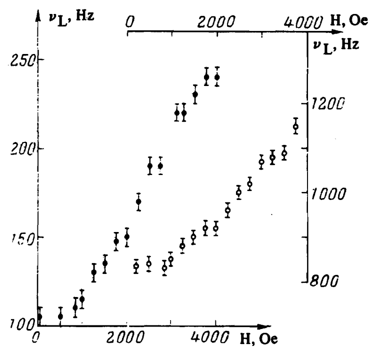

FIG. 7

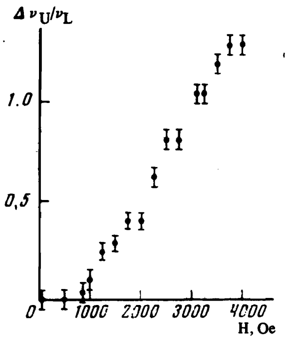

FIG. 8

FIG. 7. Dependence of the resonant frequencies on the magnetic field intensity (●—ν_L, left-hand and lower scale; ○—ν_U, right-hand and upper scales).

FIG. 8. Dependence of the change of the resonant frequency on the intensity of the constant magnetic field H.

creased, the force acting on the superconductor at resonance increases, and the crystal oscillation amplitude increases accordingly (Fig. 6).

It should be noted that the dragging of the crystal lattice is observed also without Abrikosov vortices below H_{c1}. In this case, the resonant frequency ν_L = 105 Hz is equal to the natural frequency ν_0 of the resonator, $\nu_U = 8\nu_L$, and no shift of the resonant frequencies ν_L and ν_U is observed with increasing field H. On going to the mixed state $H > H_{c1}$, both resonant frequencies increase strongly (Fig. 7). This increase of the resonant frequency might be attributed to the increase of the effective elastic modulus of the system following the appearance of the Abrikosov vortices.

The natural frequency of the resonator is calculated in our case from the formula

$$\nu_0 = A \frac{c}{l^2} \left(\frac{E}{\rho} \right)^{1/2},$$

where A is a constant (A = 0.162 for the first harmonic), c is the sample thickness, l is its length, ρ is its density, and E is Young's modulus (for our sample $E = 4 \times 10^{11}$ dyn/cm^2 in the absence of a magnetic field).

The quantity $\Delta\nu_L/\nu_0$ as a function of the magnetic field in the mixed state is shown in Fig. 8. For a field H = 3000 Oe, the frequency ν_L increases in comparison with ν_0 by a factor of two, i.e., the effective modulus is increased four times. Of course, such a large increase of the lattice modulus as a result of the presence of Abrikosov vertices should not be taken literally. A possible cause of the increase of the effective modulus is the quasielastic interaction of the magnetic moment of the oscillating sample with the field.

The observed phenomenon can be used to study the motion and the pinning of vortices in type-II superconductors and to investigate the loss mechanisms in these materials.

It should be noted that analogous dragging of the crystal lattice by charge dislocations set in motion by an electric field was observed by Sproull[5] in 1960 (deviation of the crystal in a constant electric field) and by Driyaev and Melik-Shakhnozarov in 1966[6] (in an alternating electric field).

In conclusion, the author is grateful to A. F. Andreev and Yu. G. Mamaladze for a discussion of the work.

1 C. F. Hempstead and Y. B. Kim, Phys. Rev. Lett., 12, 145 (1964). A. R. Strnad, C. F. Hempstead, and Y. B. Kim, Phys. Rev. Lett., 13, 794 (1964). Y. B. Kim, C. F. Hempstead, and A. R. Strnad, Phys. Rev., 139A, 1163 (1965).

2 J. G. Chigvinadze, Zh. Eksp. Teor. Fiz. 63, 2144 (1972) [Sov. Phys.-JETP 36, 1132 (1973)].

3 J. G. Chigvinadze, Zh. Eksp. Teor. Fiz. 65, 1923 (1973) [Sov. Phys.-JETP 38, 960 (1974)].

4 J. G. Chigvinadze, Fiz. Tverd. Tela 16, No. 7 (1974) [Sov. Phys.-Solid State 16, No. 7 (1975)].

5 R. L. Sproull, Phil. Mag., 5, 815 (1960).

6 D. G. Driyaev and V. A. Melik-Shakhnazarov, Fiz. Tverd. Tela 8, 3280 (1966) [Sov. Phys.-Solid State 8, 2623 (1967)].

Translated by J. G. Adashko
261