INVESTIGATION OF DISSIPATIVE PROCESSES IN SUPERCONDUCTORS IN A MIXED STATE AND IN A REACTOR-RADIATION FIELD

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We investigate dissipative processes in superconductors in the mixed state. We investigate the influence of reactor radiation on these processes, and also the shift of the critical temperature T_c due to neutron irradiation and a temperature T = 4.2°K.

IF an elastic filament made of a superconductor of the second kind in the mixed state is made to execute torsional oscillations in a transverse magnetic field, then the Abrikosov vortices[1] produced in the filament on going through H_{c1} should, tending to become oriented along the field, increase the elastic torque produced by the suspension, since the vortices are pinned to a certain degree on the inhomogeneities of the crystal lattice. On the other hand, as they break away at certain twisting angles from the inhomogeneities on which they are pinned, the Abrikosov vortices moving relative to the sample should greatly increase the damping of the axial torsional vibrations in which the superconducting sample participates.

An experiment aimed at investigating phenomena of this type was organized by us, using as the samples filaments of superconductors of the second kind, including niobium, vanadium, and the alloy Ta + 5% Nb.

The instrument is shown in Fig. 1. One end of filament 1, made of a superconductor of the second kind (length 10 cm, diameter 0.020 cm), was fastened to the bottom of the Dewar 2, and the other end was attached to a straight sufficiently-thick glass rod 3, which carried on its upper end a disc 4 with moment of inertia I = 220.25 g-cm^2. The upper part of the suspension system was at room temperature. This entire system was

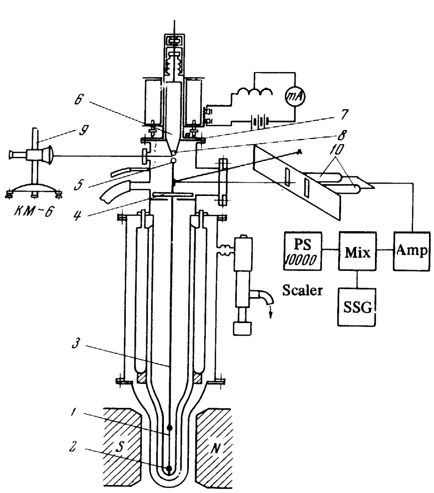

FIG. 1. Diagram of instrument (the symbols are explained in the text).

terminated from above by a spherical magnetic pole piece 5, which was attracted by an electromagnet 6, rigidly fastened to the cover of the Dewar 7. The core of the electromagnet 8 also had a spherical pole piece The distance between the two spherical magnetic pole pieces could be varied and controlled with the aid of a cathetometer 9. However, the tension of the filament could change somewhat from experiment to experiment, and this undoubtedly affected the measurement of the logarithmic damping decrement of the oscillations of the described system.

That part of the Dewar which contained the superconducting filament was filled with liquid helium and placed in a magnetic field, the force lines of which were perpendicular to the filament. The system was set to oscillate axially, thereby twisting the superconducting filament. To this end, a force couple was applied to the disc 4. This couple was produced by interaction of an external high-frequency field (f = 200 kHz) with the field of the eddy currents which were generated in copper circuits glued to the disc. The logarithmic damping decrement of the oscillations was determined from the time of travel of a light spot[2], reflected from an oscillating mirror, between two photomultipliers 10 located at a fixed distance from each other.

To study the influence of the neutron irradiation on the mechanical properties of the superconductors, we mounted a similar setup on one of the horizontal channels of the IRT-2000 reactor of the Physics Institute of the Georgian Academy of Sciences. A neutron flux of 4×10^9 neut/cm^2-sec, of which 4×10^8 neut/cm^2-sec had an energy larger than 1 MeV, was incident on the lower part of the metallic Dewar, in which the sample immersed in the liquid helium was located. The magnetic seal was applied in a direction perpendicular to the neutron flux. The sample was irradiated at a temperature 4.2°K.

The suspension system was made to oscillate in the setup by the force couple that is produced by two ferromagnetic strips glued to the disc, and an electromagnet. The moment of inertia of the suspension system was of the order of 200 g-cm^2.

We investigated first the internal friction of the vanadium and of the Ta + 5% Nb alloy in a superconducting state without a magnetic field. As seen from Fig. 2, below T_c the logarithmic damping decrement of the oscillations of the suspension system in the case of

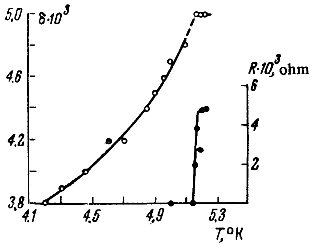

FIG. 2

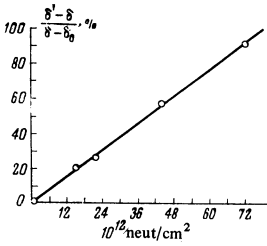

FIG. 3

FIG. 2. Dependence of the logarithmic damping decrement of the oscillations of the suspension system on the temperature for vanadium in the absence of a magnetic field. The dependence of the resistance on the temperature (dark circles) is also shown.

FIG. 3. Dependence of the logarithmic damping decrement of the oscillations on the integral dose of neutron irradiation (δ – logarithmic damping decrement prior to irradiation, δ' – after irradiation, δ_0 – logarithmic damping decrement due to friction of the suspension system against the gaseous helium).

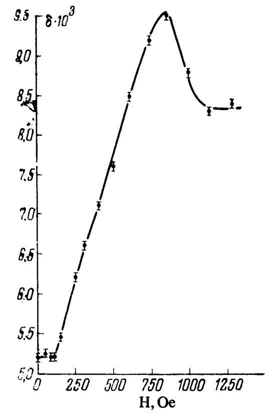

FIG. 4

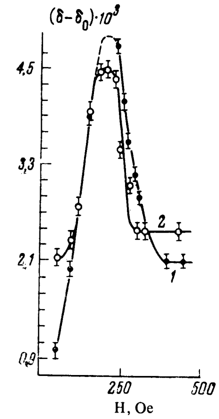

FIG. 5

FIG. 4. Dependence of the logarithmic damping decrement of the oscillations on the applied magnetic field; T = 2.55° K.

FIG. 5. Dependence of the logarithmic damping decrement of the oscillations on the applied magnetic field in a sample before and after irradiation with neutrons: curve 1 – non-irradiated sample, curve 2 – sample after irradiation with an integral dose 7.2×10^{13} neut/cm²; T = 4.2° K (δ_0 – logarithmic decrement of the damping due to the friction of the suspension system against the gaseous helium).

a vanadium wire depends strongly on the temperature[1)]. A similar curve was obtained also for the Ta + 5% Nb alloy.

Mason and Bommel have shown[3] that in the case of metals at sufficiently low temperatures (below 20°K) the main role in the dissipation of the lattice-vibration energy is played by the interaction between the lattice and the free electrons. When the metal goes over into the superconducting state, the number of normal electrons in the superconductor decreases with decreasing temperature, owing to the pairing of the electrons into Cooper pairs that do not interact with the lattice. This is indeed the cause of the decrease of the internal friction in the case of oscillations of superconducting lattices.

The investigation of the influence of neutron irradiation on the internal friction of the superconductors revealed that the internal friction (the logarithmic damping decrement) increases linearly with increasing irradiation dose. It increases by approximately 100% at integral doses 7×10^{13} neut/cm² (see Fig. 3). We know of no cases of low-temperature irradiation of the metals in which the radiation damage leads to a noticeable increase of the internal friction and to a decrease of the elastic constants of the metals in the normal state. Usually the opposite takes place.

As expected, at low values of the magnetic field intensity the logarithmic damping decrement remained unchanged in the interval from zero to H_{c1}. The oscillation period of the supsension system is T = 4.55 sec at H = 0. As to the behavior of the logarithmic damping decrement at $H > H_{c1}$, it experienced characteristic changes shown for the case of Ta + 5% Nb at T = 2.55°K in Fig. 4. As seen from the figure, the damping first remains independent of the magnetic field, then begins to increase approximately linearly, reaching a maximum, after which it decreases. A similar picture of the initial part of the curve was obtained for pure niobium in magnetic fields not exceeding 4000 Oe. Control measurements of the influx of the magnetic field on the logarithmic damping decrement of the suspension system, carried out at room temperature (T = 300°K) on pure niobium, show that the logarithmic damping decrement is completely independent of the field up to 4000 Oe.

It should be noted that the behavior of the logarithmic damping decrement curve as a function of the magnetic field in strong fields is very sensitive to the state of the sample. In some cases the decrement decreased beyond the maximum to practically its initial value characteristic of H = 0. Naturally, we attribute these changes of the internal friction in the magnetic field to the occurrence of Abrikosov vortices which, trying to remain parallel to the magnetic field, move relative to the crystal lattice and cause thereby dissipation of the oscillation energy of the suspension system.

When the sample is irradiated, the $\delta(H)$ curve begins to deform (curve 1 changes accordingly into curve 2 of Fig. 5). The irradiation, first, decreases the height of the peak of the internal friction and, second, it shifts the right side of the curve towards lower fields. The nonzero slope of the attenuation curve in the region of small magnetic fields (see Fig. 5) is due to the fact that the residual magnetic field on the electromagnet mounted on the reactor exceeded the first critical field H_{c1}. By measuring the logarithmic decrement as a function of the temperature near T_c at maximum irradiation doses 9×10^{13} neut/cm², we observed a shift of the critical temperature T_c towards lower temperatures. If we determine the change of T_c from the shift of the kink on the logarithmic-decrement curve, then ΔT_c = 0.03°K (see Fig. 6). Although we have no data on the behavior of the logarithmic decrement at higher temperatures (above 4.5°K), the fact that the electric resistance of the irradiated Ta + 5° Nb sample has a plateau at the same level as the non-irradiated one immediately after passing through T_c shows that irradiation generates a very small amount of defects (since their ap-

1)The ordinates of Fig. 2 represent the total logarithmic damping decrement of the entire system.

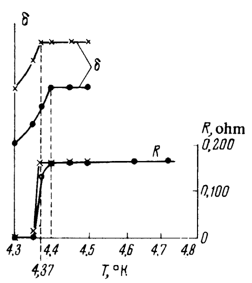

FIG. 6

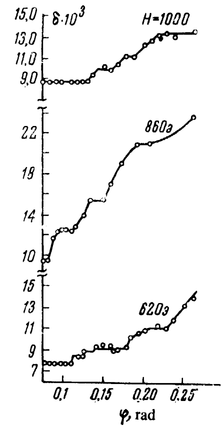

FIG. 7

FIG. 6. Dependence of the logarithmic damping decrement of the oscillations on the temperature: O—before and X—after irradiation with neutrons (9×10^{13} neut/cm^2).

FIG. 7. Dependence of the logarithmic damping decrement of the oscillations on the oscillation amplitude φ in different magnetic fields and at T = 2.55° K.

pearance does not influence the electric resistance in the normal metal).

The regularities connected with the amplitude effects are of interest. It turns out that the plot of the logarithmic damping decrement against the torsion angle, plotted at a constant field at a constant temperature, has a section parallel to the abscissa axis (see, for example, the upper curve of Fig. 7). It is clear that on this section the deformation of the vortex lines is purely elastic. With increasing magnetic field, this section becomes shorter. At a magnetic field corresponding to the maximum on the curve, the linear section has a minimal length, thus evidencing the effect of the slipping of the vortices, i.e., their breaking away from the pinning centers (see Fig. 7). In all probability, the slipping coefficient of the vortices changes with changing field, experiencing an extremum in magnetic fields corresponding to the maximum damping.

It is of interest also to consider the amplitude dependences of the logarithmic damping decrement at large amplitudes. These dependences can be approximated more readily by steplike curves than by smooth ones.

An estimate of the vortex-defect binding energy, determined from the amplitude plots, yield for one vortex $E \sim 8 \times 10^{-16}$ J, which is in good agreement with the published data [4].

We observe a striking analogy between the velocity dependence of the logarithmic damping decrement of the disc (immersed in rotating helium II and rotating together with the helium [5]) and the logarithmic damping decrement of a pendulum suspended on a superconducting filament placed in a magnetic field. In the case of helium II such a dependence is due to the presence of Onsager-Feynman vortex filaments, which pass through the helium parallel to the rotation axis and are pinned to the disc.

We believe that the method proposed by us for determining the dissipative processes in superconductors can find use in the determination of the binding energy of the vortices with the crystal-lattice defects and with impurities in superconductors of the second kind during the operating regime of the latter.

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