Wave resistance of indium in the intermediate state

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(Submitted April 26, 1974)
ZhETF Pis. Red. **19**, 726–729 (June 20, 1974)

An increase of the resistance of samples of ultrapure indium was observed in the intermediate state following application of a static inhomogeneous field near the surface of the sample. It is proposed that this effect is due to excitation of helicons in the structure of the layers of the normal and superconducting phase, in analogy with the manner in which the resistance to the motion of a ship is connected with excitation of waves on a water surface.

In 1967 Andreev considered a new mechanism of resistance of superconductors in the intermediate state.[1] In an uncompensated metal, helical magnetic waves (helicons) can propagate at a sufficiently large carrier mean free path. If direct current is made to flow through a sample in the intermediate state, then in the coordinate frame that moves together with the normal and superconducting phase layers, the helicons are excited by surface inhomogeneities of the constant external magnetic field. In the laboratory coordinate frame, an inhomogeneous static distribution of the electric and magnetic fields is established in the sample and is generated by the surface perturbation. To maintain such a field distribution, or, from the point of view of a moving observer, to excited helicon waves, an additional current-source energy is necessary. This means the appearance of an additional electric resistance in the sample. In analogy with the known effect in hydrodynamics, Andreev called this wave resistance. This paper reports an attempt to observe experimentally the wave resistance of pure superconductors in the intermediate state.

Single-crystal cylindrical samples of 4 mm diameter and approximate length 100 mm, made of ultrapure indium, were used in the experiments. The measurements were made on two samples of nearly equal quality and yielding identical results. The sample was placed in liquid helium, whose temperature was lowered to 1.3 °K, and was transformed to the intermediate state by a constant homogeneous magnetic field H perpendicular to the cylinder axis. The static inhomogeneous magnetic field H_1 was produced with the aid of a single-layer bifilar coil of superconducting wire wound around the sample. The length of the winding was about 65 mm. The direction of the current in the turns alternated in such a way that the perturbation had a spatial period $\lambda = 1.36$ mm along the cylinder axis (see Fig. 1). The gap between the turns and the sample surface was about 0.3 mm. An estimate shows that a direct current $I_m = 10$ A flowing through the coil produced on the sample surface, in the normal state, a perturbation amplitude $H_1 = 30$ Oe. The voltage U on the part of the sample situated inside the coil was measured with an F-118 nanovoltmeter and was plotted with an automatic recorder as a function of the current I through the sample. Examples of the current-voltage characteristics are shown in Fig. 1.

Curve 1 of Fig. 1 demonstrates simply Ohms's law in the normal state. Curve 2 has a smaller slope, in accord with the fact that the concentration of the normal phase is $C_n = 0.3 < 1$. When the static perturbation H_1 is turned on, the form of the current-voltage characteristic in the intermediate state is significantly altered. The stationary value $U(I_m)$ at small currents through the sample is established very slowly, so that the instability of the null point of the nanovoltmeter and the parasitic thermal emf in the measuring circuit do not make it possible to assess reliably the initial sections of the curves at $I \leqslant 1$ A. At currents $I \approx 3$ A, a maximum of the resistance is observed and can greatly exceed the resistance in the normal state. At larger currents, the resistance increases in such a way that the difference $\Delta U = U(I_m) - U(0)$ changes relatively little, up to currents $I = 30$ A. The magnitude of the effect $\Delta R = \Delta U/I$ depends strongly on the perturbation amplitude $H_1 \sim I_m$. At small perturbations, $\Delta R \sim I_m^2$. This fact agrees with Andreev's calculations. According to the formulas of[1], the relative increment due to the wave resistance is, apart from a numerical factor, $R_{\text{wave}}/R \approx (\Omega\tau)^2 (H_1/H)^2$. Here R is the resistance of the sample in the intermediate state at $H_1 = 0$, Ω is the cyclotron frequency in the critical field H_c, and τ is the electron relaxation time. Measurements of a helicon damping in sample 1 by the method described in[2] yielded a value $\Omega\tau \approx 3.3$ at $T = 1.3$ °K. Comparison of the slopes of curves 2 and 3 in Fig. 1 at $I = 3$ A shows that the observed increase of the resistance, $\Delta R/R \approx 10$, agrees in order of magnitude with the theoretical estimate. The measured value of ΔR depended strongly on the temperature and became smaller than the noise level of the apparatus at $T \gtrsim 2.5$ °K. It turned out that at a fixed concentration C_n

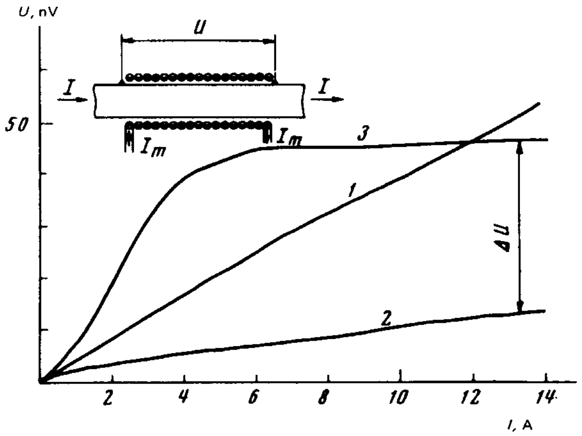

FIG. 1. Current-voltage characteristics obtained for sample 1 at $T = 1.3$ °K: 1) $H/H_c = 1.1$, 2) $H/H_c = 0.65$, $I_m = 0$; 3) $H/H_c = 0.65$; $I_m = 15$ A.

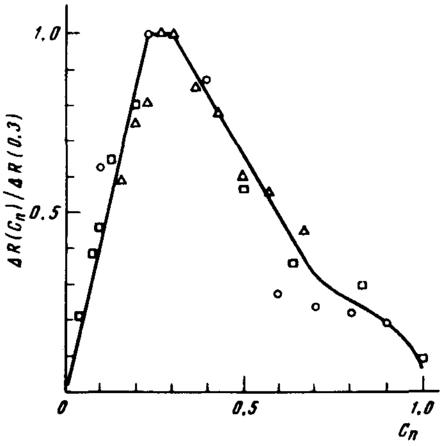

FIG. 2. Increase resistance vs concentration of the normal phase at $I_m = 15$ A and $T = 1.3$ °K: circles and triangles—sample 1 in different experiments, squares—sample 2.

and at a relative value of a perturbation $H_1/H_c = \text{const}$, we have $\Delta R \sim H_c^2/R$. This fact also agrees with the theory, if the magnetoresistance is neglected and it is assumed that $R \sim 1/\tau$ at $C_n = \text{const}$.

Unlike the maximum value of ΔR, its position and width are not described by the formulas of[1]. The reason for this discrepancy lies apparently in the geometry of the sample. Andreev[1] calculated the spectrum of helicon oscillations in a plane-parallel plate and showed that in the case of the spatially periodic perturbation H_1 the $R_{\text{wave}}(I)$ plot exhibits a number of resonance maxima of relative width $\sim 1/\Omega\tau$, at currents such that the perturbation frequency, which is Doppler shifted by the carrier drift, coincides with the frequency of the natural oscillations of the helicon mode. The frequency of the fundamental mode of the helicon oscillations in a cylinder, at full homogeneity of the fields along the cylinder axis, i.e., at $\lambda \gg d$, was measured in[2]. Using these data, we can easily show that the first maximum of ΔR should be observed at $I \approx 30$ A. The large discrepancy with the results of the experimental data can be attributed to the fact that the spectrum of the helicon oscillations in the cylinder at $\lambda < d$ shifts strongly towards lower frequencies.

We note that the conditions for the validity of the equations of macroscopic hydrodynamics of the intermediate state[1] are quite well satisfied in our experiments. The period $a \approx 0.3$ mm of the structure of the layers of the superconducting and normal phases is much smaller than λ. The absence of pinning of the layers by defects of the sample was verified simultaneously with the plotting of the current-voltage characteristics, by means of a microcontact attached to the sample between the windings of the central part of the bifilar coil. At $I_m = 0$ and $I \geqslant 1$ A, periodic oscillations of the microcontact resistance were observed, due to the uniform motion of the regular structure of the layer.[3]

Deviations from Andreev's theory were observed also in the dependence of ΔR on $C_n = 2H/H_c - 1$. Figure 2 shows the measured values of ΔR at constant I_m, relative to the value at $C_n = 0.3$. According to[1], $R_{\text{wave}} \sim C_n$, so that the decrease of ΔR at $C_n > 0.3$ remains unexplained. It is possible that the condition $I_m = \text{const}$ does not ensure a constant perturbation when the concentration of the normal phase is varied.

The authors thank A. F. Andreev, I. L. Landau, and Yu. V. Sharvin for a discussion of the results and for useful discussions, and L. M. Shpel'ter for preparing the high-grade samples.

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[3] Yu. V. Sharvin, ZhETF Pis. Red. **2**, 287 (1965) [JETP Lett. **2**, 183 (1965)].