Decrease of the contribution of surface scattering of electrons to helicon damping on going to the intermediate state

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(Submitted April 4, 1974)
ZhETF Pis. Red. **19**, 588–593 (May 5, 1974)

We investigated experimentally the decrease of helicon damping on going to the intermediate state. The results offer evidence of a decreased contribution of surface scattering of the electrons, due to the limitation on the electron motion within the limits of the normal layers.

Helicons, or helical plasma waves propagating in an uncompensated metal along a strong magnetic field, were observed experimentally by Maxfield and coworkers[1,2] in the intermediate state. It was noted in[1] that the helicon damping in a metal decreases on going over to the intermediate state. We have investigated this effect experimentally as a function of the electron mean free path l. The results offer evidence that the contribution of the surface scattering of the electrons to the helicon damping decreases on going to the intermediate state. The reasons that the greater part of the electrons, which cause the dissipation of the energy wave, oscillate in accordance with Andreev's theory[3] within thin normal layers and never collide with the surface of the sample.

The experiments were performed with single-crystal

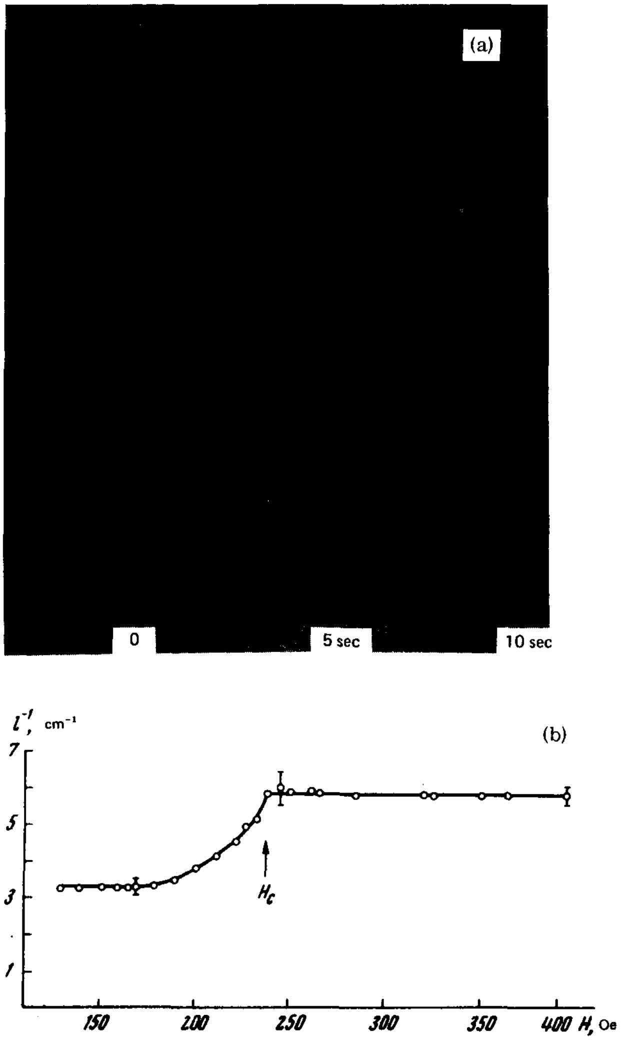

FIG. 1. a) Helicon-oscillation signals from sample 1 at $T = 1.35\,°$K; uppercurve—H= 170 Oe, lower—H=250 Oe, the ordinate scale is arbitrary and is different for the upper and lower curves. b) Damping of helicon oscillations in sample 1, expressed in reciprocal electron mean free paths $1/l$; $T = 1.35\,°$K.

samples made of very pure indium. The samples were cylinders with diameters $d=2$ and $d=4$ mm and approximate length 100 mm. The helicons were investigated by observing the free damped electromagnetic oscillations, a procedure first used by Bowers.[4] The sample was placed in a strong constant magnetic field $H=100$—4000 Oe perpendicular to the cylinder axis. To simplify the exposition, we introduce a coordinate system with x axis and with z axis along H. An additional pair of coils produced a small homogeneous magnetic field $H_1=10$—30 Oe along the y axis. Rapid switching of H_1 excited natural electromagnetic oscillations in the sample. These oscillations induced an emf in the receiving coil with axis along z. The central part of the sample was located inside the receiving coil, which was approximately 3 cm long and 1 cm in diameter. The voltage induced in the receiving coil was amplified with an infralow-frequency semiconductor amplifier with a bandwidth 0.05—20 Hz, and recorded on the screen of a long-persistence oscilloscope S1-51. Typical plots of the signals of the free helicon on oscillations in the sample are shown in Fig. 1a.

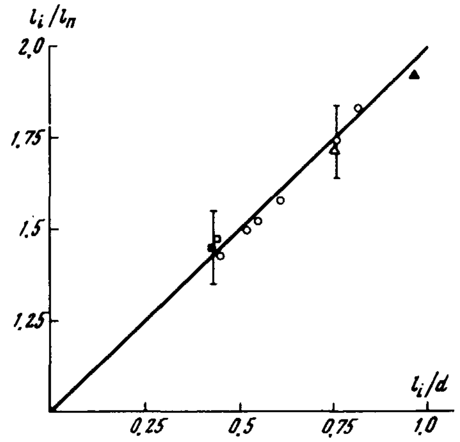

FIG. 2. Relative change of helicon damping l_i/l_n on going to the intermediate state as a function of the ratio of the mean free path l_i in the bulky metal to the sample diameter d. Symbols: ○—data obtained from sample 1, $d=4$ mm at temperatures in the range $T=1.22$—$1.98\,°$K. □—sample 2, $d=4$ mm; ■—sample 3, $d=4$ mm; ▲—sample 4, $d=2$ mm; △—deformed sample 4; all data are for $T=1.35\,°$K.

With exception of the initial section, which amounts to approximately half the period, the signal is an exponentially decreasing sinusoid of frequency ω, corresponding to the fundamental mode of the natural oscillations. The logarithmic damping decrement of the helicons propagating along H, both in the normal[5] and in the intermediate[3] state, is given in the local limit by the expression $\Delta = 2\pi(\mathrm{Im}\,\omega/\mathrm{Re}\,\omega) = \pi(\sigma_{xx}+\sigma_{yy})/\sigma_{xy}$. 1) The components of the conductivity tensors are functions of the magnetic field. For the intermediate state, these functions assume values corresponding to the critical field $H=H_c$. The local limit is reached at $l \ll d$ for the normal state and at $a \ll d$ for the intermediate state (a is the period of the layer structure of the normal and superconducting phase).

In the case of an isotropic metal we have $\Delta = 2\pi/\Omega\tau$, where $\Omega = eH/m^*c$ is the cyclotron frequency, m^* is the effective mass, and τ is the electron relaxation time. Using the averaged value $m^* = 2m$ (m is the free-electron mass) from data on cyclotron resonance in indium[6] and the experimental value of the Fermi velocity $v = 1.1\times10^8$ cm/sec[7] for the largest electron group, we have determined the reciprocal of a certain averaged mean free path $l = v\tau$ from the measured values of the logarithmic decrement Δ of the helicon oscillations, using the relation for an isotropic metal. The value of $1/l$ obtained in this manner for the rest of the investigated samples (sample 1) is shown in Fig. 1b as a function of the constant field H. The value of $1/l$ in the intermediate state was determined with the aid of the value of Ω corresponding to the critical field of indium at the given temperature.[8] The value of l corresponding to the limiting minimum value of the damping decrement of the helicons in the intermediate state at $H \lesssim (3/4)H_c$ will be designated l_i. In the normal state, within the limits of measurement errors, the quantity $l=l_n$ does not depend on the field or its direction. At the same time, the

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value of l in both the normal and in the intermediate state was strongly dependent on the temperature T, in accordance with the law $1/l(T) = 1/l_0 + \beta T^4$. The value of the coefficient β varied insignificantly from sample to sample and amounted on the average to ≈ 0.20 cm^{-1} deg^{-4} with a deviation of approximately 10%. The residual mean free path for sample 1 was $l_{0t} = 3.99$ mm.

A comparison of the results on the function $1/l(H, T)$ in the normal state with the data on the dependence of helicon damping on the field and on the temperature in those cases when nonlocal increments of the cyclotron-damping type (see, e.g.,[9]) or Landau damping (10) are noticeable, shows that in our experiments the nonlocal increments to the damping of the helicons can be neglected, in spite of violation of the strong inequality $l \ll d$. On the same basis we can state that in our experiments there was no additional damping connected with the excitation of the surface helicon modes.[11]

As seen from Fig. 1, on going to the intermediate state, the helicon damping decreases noticeably, approaching a constant value of $H \lesssim (3/4)H_c$. We measured the relative change of the helicon damping l_t/l_n for sample 1 ($d = 4$ mm) at different temperatures, for samples 2 and 3 with the same diameter but with more impurities, and for sample 4 with $d = 2$ mm. In addition, we performed measurements on sample 4 subjected to plastic deformation (slight bending). The results of these measurements are shown in Fig. 2. We see that all the experimental results are described within the limits of errors by the formula $l_t/l_n = 1 + l_t/d$. This formula coincides with Nordheim's relation, which approximates the dependence of the conductivity of thin cylindrical samples in the normal state on the ratio l/d, with accuracy $\lesssim 5\%$ (see, e.g.,[12]). The value of l_t corresponds in this case to the electron mean-free path in a bulky metal, whereas l_n is decreased as a result of electron scattering by the surface of the sample.

It should be noted in conclusion that if conditions are created under which large nonlocal helicon damping, of the cyclotron damping or Landau damping type, is observed in the normal state, then on going to the intermediate state the helicon damping should decrease even more strongly than in the present experiments, and approach their local value $1/\Omega\tau$. Thus, measurement of helicon damping in samples in the intermediate state provides a convenient method of measuring the average electron mean free path, without the complications introduced by corrections for nonlocality and scattering from the surface.

The authors are sincerely grateful to L.M. Shpel'ter for preparing the high-grade samples, and to R.K. Nikolaev and A.D. Bronnikov of the Institute of Solid State Physics for supplying the extremely pure indium.

[1)] In the corresponding formula[3] the denominator contains a superfluous number π.

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