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QUANTUM OSCILLATIONS OF VELOCITY AND DAMPING OF HELICONS IN INDIUM

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Measurements of the dependence of the surface impedance Z = R + iX of single-crystal indium plates on the magnetic field H revealed quantum oscillations of the impedance, with an amplitude that increased strongly when standing plasma waves (helicons) were excited in the plate[1)]. In the experiments, which were performed at helium temperatures, we used a modulation procedure employed by us earlier [2] to measure the dependence of the derivatives $\partial R/\partial H$ and $\partial X/\partial H$ on H. The samples were placed in the coil of the tank circuit of an oscillator (the samples and their mounting in the instrument are described in [3]). Besides recording the derivatives, the apparatus could record X(H) by plotting a signal proportional to the changes of the oscillation frequency f. For a weakly-damped wave, the impedance of an unbounded plate of thickness d is [4]

$$Z = \frac{4\pi\omega\mu}{c^2 k}\,\frac{\gamma kd - i\xi}{\xi^2 + (\gamma kd)^2}. \tag{1}$$

Here k is the real part of the wave vector and is connected with the phase velocity of the wave, $v_{ph} = \omega/k$, $\gamma \ll 1$ is the wave damping coefficient, μ is the magnetic permeability, $\xi = kd - n\pi$, and n is an odd number (the number of the resonance). Expression (1) is valid if $\xi \ll 1$ and $\gamma kd \ll 1$. The dependence of Z on the magnetic field can be obtained with the helicon dispersion law, which was investigated in detail in [3]. The experimental plot of f(H) (Fig. 1) can be made to represent the function -X(H) by drawing the abscissa axis symmetrically relative to the extrema of f(H) and by neglecting the variation of the additional term in the expression for the plate impedance connected with the high-frequency field component that attenuates near the surface.

The helicon velocity oscillations are determined by the quantum oscillations of the susceptibility χ^{osc} (the de Haas - van Alphen effect), since the oscillations of the Hall components of the conductivity tensor are negligibly small [5]. The helicon absorption oscillations are $k\ell$ times larger than the ordinary dc resistance oscillations (the Shubnikov - de Haas effect) and become giant oscillations if $(k\ell/\sqrt{N})h\Omega/k_B T)^{1/2} \gg 1$ [6]. Here $\ell \sim 0.5$ mm is the electron mean free path, $N = H/\Delta H$ the number of the Landau level, ΔH the period of the oscillations, Ω the cyclotron frequency, and k_B the Boltzmann constant. In our experiments $(k\ell/\sqrt{N})(h\Omega/k_B T)^{1/2} \sim 5$. The oscillating variations of the velocity, $\Delta v_{ph} \sim \Delta k$ and of the

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1) A similar increase in the amplitude of the quantum oscillations of the helicon velocity in aluminum was observed in [1] with the aid of the crossed-coil procedure.

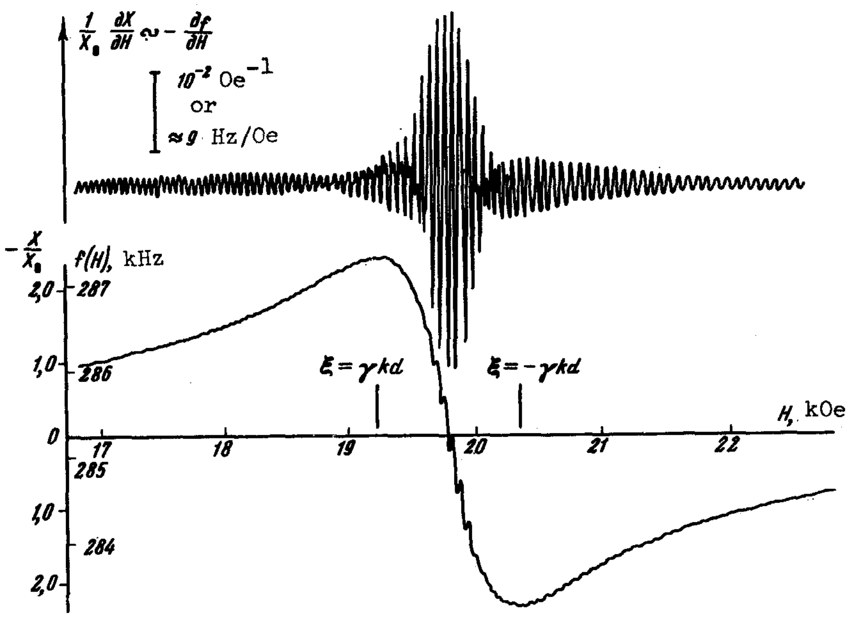

Fig. 1. Experimental curves obtained for indium single crystals 0.29 mm thick (sample 3_1). $X_0 = X(H_c)$ was determined from the frequency shift in the superconducting transition in field H_c. T = 1.4°K; $\vec{H} \parallel [100]$; $\vec{k} \parallel [110]$; n = 9

helicon damping lead to small oscillations of the impedance

$$\Delta Z = \frac{\partial Z}{\partial \mu}\Delta\mu + \frac{\partial Z}{\partial k}\Delta k + \frac{\partial Z}{\partial \gamma}\Delta\gamma.$$

Differentiating (1) and separating the imaginary and real parts, we get

$$\Delta X = 4\pi\omega\mu c^{-2} d(A_1\Delta k/k + A_2\Delta\gamma)$$

and

$$\Delta R = 4\pi\omega c^{-2}\mu d(-A_2\Delta k/k + A_1\Delta\gamma),$$

where

$$A_1 = \frac{\xi^2 - (\gamma kd)^2}{[\xi^2 + (\gamma kd)^2]^2}$$

and

$$A_2 = \frac{2\xi\gamma kd}{[\xi^2 + (\gamma kd)^2]^2}.$$

We have neglected here terms of order γ and assumed that $\Delta\mu/\mu = 2\Delta k/k$. The functions A_1 and A_2 describe the change of the amplitude of the quantum oscillations of the impedance near the helicon resonance. It is easy to see that the maximum of the amplitude of the quantum oscillations connected with the helicon velocity oscillations is observed for X at $\xi = 0$ (see Fig. 1), and for R at $\xi = \pm\gamma kd/\sqrt{3}$ (see Fig. 2). To the contrary, the helicon absorption oscillations determine, in the main, ΔX at $\xi \approx \pm\gamma kd$ and ΔR at $\xi \approx 0$. In all other cases interference of the two types of oscillations takes place. We note that at T = 1.4°K the amplitude of the impedance oscillations does not vanish anywhere on the curves of Figs. 1 and 2. This is evidence of the presence of a phse shift between the helicon velocity and absorption oscillations. From the experimental curves shown in Fig. 1 it is possible to estimate the relative amplitude of the quantum oscillations of the helicon velocity $\Delta v_{ph}/v_{ph} = \Delta k/k \approx 0.5 \times 10^{-3}$, using the value $\gamma = 0.014$ determined from the width of the resonance. We note that the small value of $\Delta k/k$ makes it possible to neglect the effects of magnetic interactions [7], which are appreciable when $4\pi\chi^{osc} \sim 1$. Comparing the values of ΔX for $\xi = 0$ and $\xi = \pm\gamma kd$, we obtain for the relative amplitude of the absorption oscillations the value $\Delta\gamma/\gamma \approx 20\Delta k/k \approx 1\%$. The ratio of the absorption and velocity amplitudes, other conditions being equal, should increase in proportion to n, owing to the presence of the additional factor $k\ell$ in the expression for $\Delta\gamma$ [6]. This agrees with the experimental data if account is taken of the increase of the helicon damping in the case of large numbers. For example, when n = 15, $\gamma = 0.018$, and $\Delta\gamma/\gamma \approx 30\Delta k/k$ (see Fig. 2).

The observed quantum oscillations are due to those sections of the Fermi surface of indium, which have the form of tubes elongated along the {110} direction (β-tubes in the third energy band). The magnitude of the periods of the oscillations $\Delta(1/H)$ and their anisotropy agree fully with the known experimental data [8]. In fact, the observed helicon absorption oscillations are giant quantum oscillations of the Landau damping due to the electrons of the third band. Comparison of the numerical values of $\Delta\gamma/\gamma$ with the theoretical estimates is made difficult by the fact that the contribution of the electrons of the third band to the total damping of the helicons is unknown. According to the theory [9, 10] the amplitude of the helicon velocity and absorption oscillations should vanish if the corresponding electron trajectories lie in the phase plane of the wave, i.e., if $\vec{k}$ is parallel to the axis of the tube. Experiment confirms these considerations. When $\vec{k} \parallel [110]$ and $\vec{H} \parallel [100]$ the oscillations are due just to the sections of the tubes located along $[1\bar{1}0]$, and not along [110]. This was established from the dependence of $\Delta(1/H)$ on the orientation of $\vec{H}$, which

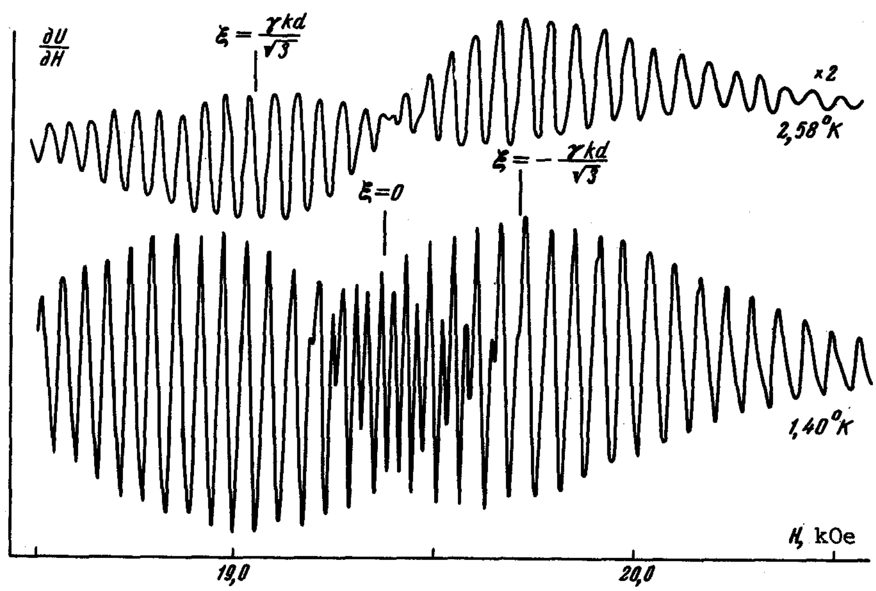

Fig. 2. Plots of oscillations of $-\partial R/\partial H \sim \partial U/\partial H$ (U - generation amplitude) in sample 3_1 at two temperatures. $H \parallel [100]$, f = 0.77 MHz, n = 15. When plotting the upper part of the curve, the sensitivity of the apparatus was doubled.

rotates in the (001) plane.

Oscillations whose period is half as large appear on the experimental curves shown in the figure at definite values of ξ. We note that under the conditions of these experiments the oscillation period $\Delta\gamma$ differs from the χ^{osc} period by a negligibly small amount. The causes of so large a relative amplitude of the second harmonic remain unclear to us. A simple calculation of the terms of order $(\Delta k)^2$ and $(\Delta\gamma)^2$ in the expansion of ΔZ gives a value ~ 0.1 for the ratio of the amplitude of the second harmonic to the first. At the same time, the higher harmonics in the periodic dependence of the susceptibility and of the conductivity on the magnetic field are decreased by a temperature coefficient $\exp(-\alpha T) \sim 0.03$ at $T = 1.4^{\circ}K$. Here α is a certain coefficient, whose value was determined from the temperature dependences of the amplitudes of the oscillations at $\vec{H} \parallel [100]$ and $\vec{k} \parallel [100]$. The value of α is the same for the oscillations Δk and $\Delta\gamma$ and corresponds to an effective mass $m^* = 0.4m_0$ (m_0 is the mass of the free electron). Other experimental data [8, 11] give at this orientation a value $m^* = 0.27m_0$. It should be noted that helicon absorption oscillations were observed at $T < 2.5^{\circ}K$ (see Fig. 2), and the amplitude of the oscillations Δk increased more slowly when the temperature was reduced below $2.5^{\circ}K$ than would follow from the theoretical relation for the de Haas - van Alphen effect [9]. The reason for the deviations lies apparently in the incomplete allowance for the factors influencing the impedance oscillation amplitude.

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QUANTUM SIZE EFFECTS IN THIN TIN FILMS

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It is shown in a number of theoretical papers [1-3] dealing with quantum effects in thin films that the thermodynamic and kinetic characteristics of the elementary excitations in the films should oscillate when the thickness is varied, with a period equal to half the de-Broglie wavelength of the excitations. It follows from the latter that these effects can be