Temperature dependence of the damping of helicons in indium

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It was found experimentally that the damping of helicons can be a monotonic or a nonmonotonic function of the temperature. The nonmonotonic dependence was attributed to the activation of the Landau damping because of an increase in the mean free path of electrons l at low temperatures. The collision and the Landau damping mechanisms were separated experimentally and investigated. The collision damping was found to vary with temperature as T^4. The dependence of the Landau damping on l in In differed basically from the corresponding dependence in an isotropic metal.

If the Doppler-shifted cyclotron resonance is absent ($kR < 1$, k is the wave vector and R is the cyclotron radius) and there are no open orbits, the damping of helicons is governed mainly by two mechanisms: collision and collisionless (the latter is known as the Landau damping[1]). In the local limit ($kl \ll 1$, where l is the mean free path of electrons) the damping of helicons is governed by the scattering of electrons on phonons and static imperfections in the crystal lattice. The collisionless (Landau) damping increases in importance with increasing mean free path and this is due to the absorption of energy by the electrons moving in phase with the wave. In the nonlocal limit ($kl \gg 1$) the Landau damping is governed only by the wavelength, the value of the magnetic field, and the geometry of the experiment.[2] There is an intermediate range of values of kl in which the Landau damping depends on the mean free path.[3-5] The purpose of the present investigation was to separate experimentally and to study the collision and the Landau components of the total damping of helicons in this intermediate range.

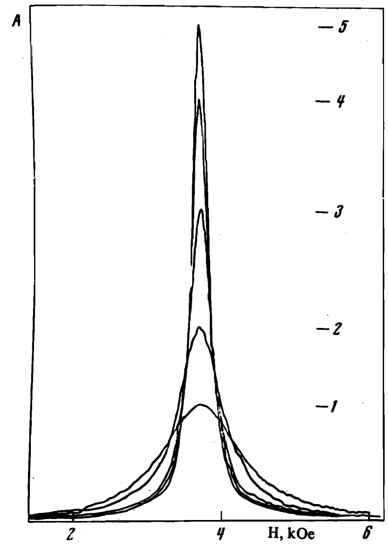

FIG. 1

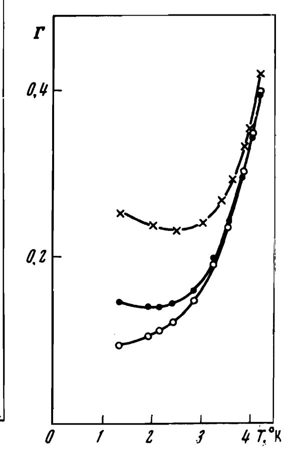

FIG. 2

FIG. 1. Typical experimental records of helicon resonances plotted as a function of the magnetic field at various temperatures (°K): 1–4.22; 2–3.57; 3–2.84; 4–2.14; 5–1.34; f = 181 Hz, $H_0 \approx 3.7$ kOe, $d \approx 0.7$ mm (thickness of the sample).

FIG. 2. Typical temperature dependences of the helicon damping in sample In4 obtained for different orientations of the external magnetic field relative to **k** at different frequencies: ○–180 Hz, $H_0 \parallel [001]$; ●–180 Hz, $H_0 \parallel I$ (Fig. 4); ×–1616 Hz, $H_0 \parallel I$.

EXPERIMENTAL CONDITIONS AND METHOD

An important condition, which determined whether the experiments could be carried out at all, was the availability of indium of very high purity whose resistivity varied by a factor of 2–2.5 on cooling from 4.2 to 3.4°K (superconducting transition temperature). The ratio of the resistances measured at room temperature and at 3.4°K was 7×10^4. The samples were grown in demountable polished glass molds using the method described in[6]. The samples were disks ≈ 0.7 mm thick and of ≈ 10 mm diameter.

As in earlier investigations,[7] we used the crossed coil method, which was very convenient in the 80–5000 Hz range in which the experiments were carried out. The measurements were made in magnetic field of 3–12 kOe at temperatures of 1.3–4.2°K. Under these conditions the relevant parameters were: $R \sim 10^{-3}$ cm, $\lambda \approx 0.14$ and 0.047 cm (λ is the wavelength), and $l \lesssim 0.1$ cm. We measured the Q factor of helicon resonances in metal plates and this factor was related to the total damping of helicons by $\Gamma = 1/Q$.

EXPERIMENTAL RESULTS

Typical helicon resonance records, obtained at a fixed frequency, are shown in Fig. 1 as a function of the magnetic field. We can see that the Q factor of these resonances and, consequently, the helicon damping, vary strongly with the temperature. The various types of the temperature dependences of the helicon damping, obtained for various orientations of the magnetic field $\mathbf{H}_0$ relative to the wave vector **k** and the crystal axes, are given in Fig. 2. The nonmonotonic dependences cannot be explained simply by the collision damping mechanism. We have to assume that the collision damping, whose contribution to the total effect decreases with increasing mean free path, competes with the Landau damping whose contribution increases with this path. It is known that under certain conditions the Landau damping may be absent in a metal with an arbitrary closed Fermi surface.[2,5] If these conditions are realized, we can study pure collision damping.

COLLISION DAMPING

In these measurements we used a grown sample whose normal to the surface coincided with the [001] axis within 1°. It was found that the helicon damping in magnetic fields directed along the normal to the surface depended on the temperature in the range 1.3–4.2°K in accordance with the law T^4 (Fig. 3). In this range the helicon damping was independent of the wavelength (this was evidence of the absence of the Landau damping[2]).

Next, we carried out measurements on a sample

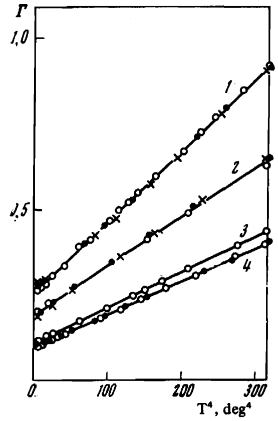

FIG. 3. Dependence of the helicon damping on T^4: O–f = 180 Hz, $\lambda \approx 1.4$ mm, $H_0 \approx 3.7$ kOe; ●–f = 1616 Hz, $\lambda \approx 0.47$ mm, $H_0 \approx 3.7$ kOe; ×–f = 460 Hz, $\lambda \approx 1.4$ mm, $H_0 \approx 11$ kOe. Curve 1 represents the sample In1, $\mathbf{k} \parallel \mathbf{H}_0 \parallel [100]$; curve 2 represents sample In2, $\mathbf{k} \parallel \mathbf{H}_0 \parallel [001]$; curve 3 represents sample In3, $\mathbf{k} \parallel \mathbf{H}_0 \parallel [001]$; curve 4 represents sample In4 (the orientation is given in Fig. 4), $\theta = -20°$. The ordinate scale is given for $H_0 \approx 3.7$ kOe.

whose normal was directed along the [100] axis and which was subjected to a magnetic field parallel to the normal. In this geometry the Landau damping due to the electrons in the third zone could be active but it was not found at the wavelengths and mean free paths applicable to our experiments. Once again we observed the T^4 law and the absence of the dependence on the wavelength (Fig. 3).

It is known that in the case of a metal with an arbitrary Fermi surface there are certain irrational directions of the wave vector and the magnetic field for which a minimum or the complete absence of the Landau damping should be observed.[5] This makes it possible to determine the temperature dependence of the collision damping for an irrational direction of the field $\mathbf{H}_0$.

We grew a sample whose normal was inclined by 30° with respect to [001] axis and the inclination was in the direction of [$\bar{1}$10] (Fig. 4). The anisotropy of the helicon damping, found by rotation of $\mathbf{H}_0$ in the (110) plane at different wavelengths and temperatures, is shown in Fig. 4. At angles of inclination of the field $-20° < \theta < -30°$ [the helicon damping was found to be independent of the wavelength at all temperatures. This corresponded to a minimum of the Landau damping. Similar minima were observed in[8,9] and investigated theoretically in detail in[5].

We recorded the temperature dependence of helicon damping in the region of minimum of the Landau mechanism ($-20° < \theta < -30°$) and found that the damping obeyed the T^4 law. The results are presented in Fig. 3.

The T^4 law was observed in all those cases when the contribution of the Landau damping was slight because of the smallness of kl. This was found in the measurements corresponding to the lowest values of $k = \pi/d$ (d is the thickness of the sample) at "high" temperatures ($T = 3$–$4.2°$K). The negligible contribution of the Landau damping was confirmed by the weak dependence of the damping on the wavelength (Fig. 4). It was interesting to note that the temperature dependences of the helicon damping obtained for different directions of the magnetic field in the region where they obeyed the T^4 law could be made to coincide by multiplication by a constant factor. Thus, the collision damping could be described by the formula

$$\Gamma_c = H_0^{-1}(C_1 + T^4)C_2(\theta), \qquad (1)$$

where the angle θ defines the direction of the magnetic field and C_1 is independent of θ.

LANDAU DAMPING

The total helicon damping Γ can be represented by the sum of the collision Γ_c and the Landau (collisionless) Γ_L components:

$$\Gamma = \Gamma_c + \Gamma_L.$$

We used the dependence $\Gamma_c(T)$ in the form given by Eq. (1). The coefficients C_1 and C_2 were deduced from the temperature dependence corresponding to the minimum Landau damping (Fig. 3) and from the damping anisotropy recorded at 4.2°K for longer wavelengths (Fig. 4).

The temperature dependence of the Landau damping was deduced from the function

$$\Gamma / \Gamma_c = 1 + \Gamma_L / \Gamma_c.$$

The experimental temperature dependences of this function are plotted in Fig. 5 for several directions of the magnetic field. At low values of kl, i.e., at long wavelengths and "high" temperatures the total damping was governed by the collision mechanism so that $\Gamma/\Gamma_c \approx 1$ (this point is discussed at the end of the preceding section). The contribution of the Landau damping increased with increasing kl (decreasing temperature and wavelength) and it could exceed the contribution of the collision damping. The temperature dependence of the Landau damping was a function of the direction of the magnetic field and the orientation of the sample. In particular, in some cases the temperature dependence of the Landau damping was nonmonotonic (Fig. 6). This dependence was observed for the first time and, as will be shown later, it is only possible in a metal with a nonellipsoidal Fermi surface.

DISCUSSION OF RESULTS

1. The collision damping of helicons in a metal with a closed Fermi surface can be represented in the form

$$\Gamma_c = \frac{(\tau_{eff})^{-1}}{H_0 \cos\theta}\Phi \sim \rho_{xx}, \ \rho_{yy}, \qquad (1')$$

where $(\tau_{eff})^{-1}$ is the effective frequency of collisions of electrons with static lattice defects and with phonons (the frequency is averaged out over all the Fermi surface); Φ is a function which depends on the shape of the Fermi surface and on the directions of the vectors $\mathbf{H}_0$ and $\mathbf{k}$ relative to the crystal axes; ρ_{xx} and ρ_{yy} are the diagonal components of the magnetoresistance tensor. Thus, the temperature dependence of the collision damping ob-

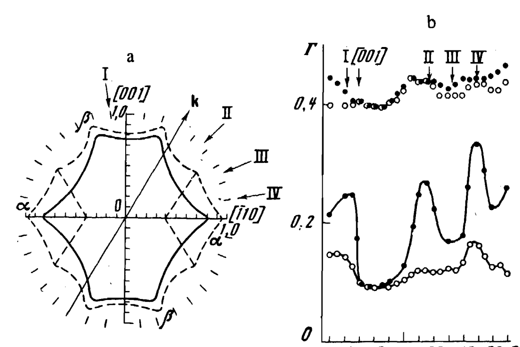

FIG. 4. Orientation of sample In4 (a) and dependences of the helicon damping on the angle between the external magnetic field $\mathbf{H}_0$ and the vector $\mathbf{k}$: O–f = 181 Hz, $\lambda \approx 1.4$ mm; ●–f = 1616 Hz, $\lambda \approx 0.47$ mm. The upper two curves correspond to T = 4.2°K and the lower two curves to T = 1.35°K.

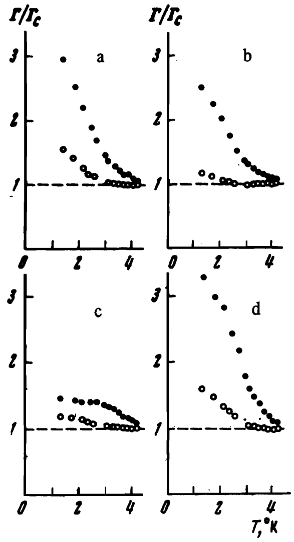

FIG. 5

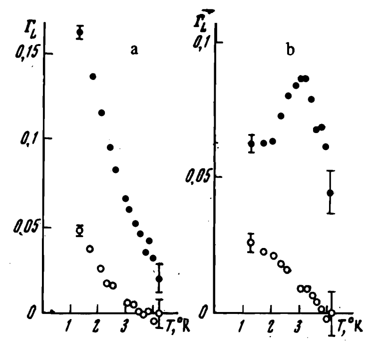

FIG. 6

FIG. 5. Dependences of the ratio of the total to the collision damping $\Gamma/\Gamma_c = 1 + \Gamma_L/\Gamma_c$ for sample In4 and different orientations of the magnetic field relative to the wave vector and the crystal axes: O—$\lambda \approx 1.4$ mm, f = 180 Hz; ●—$\lambda \approx 0.47$ mm, f = 1616 Hz. The errors correspond approximately to the dimensions of the points. a—Direction I (Fig. 4); b—direction II; c—direction III; d—direction IV.

FIG. 6. Dependences of the absolute value of the Landau damping in sample In4 obtained for H_0 parallel to the directions I (a) and III (b): O—$\lambda \approx 1.4$ mm, f = 180 Hz; ●—$\lambda \approx 0.47$ mm, f = 1616 Hz. $H_0 \approx 3.7$ kOe.

tained in our experiments indicated that ρ_{xx} and ρ_{yy} varied with temperature in accordance with the T^4 law. A similar result was obtained in[10] for the static magnetoresistance of aluminum.

The resistance of indium in the absence of a magnetic field varied in accordance with the T^5 law (Bloch law).[11,12] This indicated that the resistance and magnetoresistance of indium were governed by different effective relaxation times.

The influence of the scattering on the magnetoresistance was considered by Pippard.[13] He showed that the effective electron relaxation time is affected strongly by the scattering through small angles in a metal whose Fermi surface approaches quite closely the boundaries of the Brillouin zone at several points. There is a definite probability J of the scattering of an electron from a given orbit to an orbit in a neighboring cell (the situation is similar to that which arises in magnetic breakthrough). The effective relaxation time of electrons is proportional to $(nJ)^{-1}$ if the electron crosses n "singular" points per unit time. If the Fermi radius is p_0, we find that $n \sim v_p/p_0$, where v_p is the velocity of electrons in the p space under the action of the Lorentz force.

If the probability of scattering over a distance p, P(p), is taken in the form $ae^{-\lambda|p|}$, we find that $J \sim 4a/(v_p\lambda^2)$ in strong fields so that $\tau_{eff} \sim \tau_c/\varphi$, where $\tau_c = \lambda/2a$ is the average time between collisions and $\varphi \sim (\lambda p_0)^{-1}$ is the scattering angle. In the phonon scattering case we have $\tau_c \sim (T/T_D)^{-3}$ (T_D is the Debye temperature) and $\varphi \sim T/T_D$, so that $\tau_{eff} \sim (T/T_D)^{-4}$.

The Fermi surface of indium satisfies the requirements necessary for the operation of the mechanism described above. The probability J depends on the relationship between the scattering angle and the gap separating orbits in the p space, which can lead to an additional temperature dependence of τ_{eff}. The gap in indium is $\Delta p/p_0 \sim 10^{-2}$ and in our experiments the scattering angle was $T/T_D \gtrsim 10^{-2}$ at all the temperatures employed. Thus, the law T^4 obtained in our experiments for the collision damping of helicons can be explained by the Pippard model.

2. The Landau damping of helicons in a metal with an arbitrary closed Fermi surface ($\mathbf{H}_0$ and $\mathbf{k}$ are assumed to be located in a reflection plane and the damping is due to one sheet of the Fermi surface) is given by

$$\Gamma_L(k,T) \sim \frac{1}{H_0}\int_{-p_{zm}}^{p_{zm}} \frac{k^2 l(p_z,T)A^2(p_z)}{1+(k_z l(p_z,T))^2 B^2(p_z)}\,dp_z,$$

$$A(p_z) \sim \left(\frac{\mathbf{k}}{k}\left\langle\frac{\mathbf{v}}{v_F}P_y\right\rangle\right), \quad P_y = p_y - \langle p_y\rangle, \quad v_F B(p_z) = \langle v_z\rangle, \qquad (2)$$

where the averages are taken over an orbit, $\mathbf{v}$ is the electron velocity, the z axis is directed along $\mathbf{H}_0$, and the y axis lies in a reflection plane. In the case of plane orbits we have $A(p_z) = 0$ if the plane of an orbit of momentum p_z is perpendicular to the wave vector in the real (coordinate) space in the "guiding center" system.[5] Irrespective of the nature of the functions in Eq. (2), we can go to the limit

$$\Gamma_L \to 0 \text{ when } kl \to 0. \qquad (3)$$

This is the local limit corresponding to the absence of the Landau (collisionless) damping. In the nonlocal limit, we obtain

$$\Gamma_L \to kA^2(p_z^0)/H_0, \quad kl \to \infty, \qquad (4)$$

where p_z^0 is the value of p_z at which $B(p_z)$ vanishes. In this limit the Landau damping is governed by a narrow belt of electrons with momenta p_z^0 (these are the resonance electrons moving in phase with the wave). At intermediate values of kl the Landau damping includes a contribution of the nonresonance electrons located near p_z^0 in a belt $\sim 1/kl$ wide. In this range of kl the damping depends on the nature of the functions in the integral (2).

We shall now consider some specific cases.

1) If $A(p_z^0) \neq 0$, the Landau damping is absent at low values of kl corresponding to Eq. (3) and it tends to the limit (4) with increasing kl. The dependence of the damping on kl can be monotonic. Such a situation occurs, for example, in metals with a spherical Fermi surfaces if $\mathbf{H}_0 \nparallel \mathbf{k}$.[4]

2) If $A(p_z) \equiv 0$, the Landau damping is absent at all values of kl. This corresponds to the minimum Landau damping.[5]

3) In a metal with an arbitrary closed Fermi surface there may be a situation when $A(p_z^0) = 0$ but $A(p_z) \not\equiv 0$. The resonance electrons with the momenta p_z^0 make no contribution to the damping and the Landau damping is absent in the local and nonlocal limits. At intermediate values of kl the Landau damping is due to the nonresonance electrons and can be large. In this case the dependence of the Landau damping on kl is nonmonotonic.

These cases explain qualitatively our temperature dependences of the Landau damping.

We shall use the geometrical construction suggested in[9] to find the direction of the magnetic field $\mathbf{H}_0$ for which minima of the Landau damping are possible. If $\mathbf{H}_0$ is perpendicular to the line $\alpha\alpha$ (Fig. 4) the value of $A(p_z)$ vanishes in a wide belt of orbits passing through the dish-like indentations in the Fermi surface. In this case the Landau damping is absent at all temperatures and wavelengths used in our study. If $\mathbf{H}_0$ is perpendicular to the line $\beta\beta$, we find that $A(p_z) = 0$ for the orbits with $p_z = 0$. This direction of the magnetic field corresponds to the nonmonotonic temperature dependence of the Landau damping. Along all other directions the Landau damping increases monotonically with decreasing temperature.

3. It is evident from Eq. (2) that in case of an arbitrary value of kl the Landau damping cannot be represented as a function of some effective mean free path. This damping depends on the nature of the function $l(p_z, T)$. The expression (2) is the integral equation relative to $l(p_z, T)$ for known function $A(p_z)$ and $B(p_z)$, which are governed by the energy spectrum of electrons.

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