Oscillatory deviation effect in a metal in a weak magnetic field

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A deviation effect has been observed in a metal in a weak magnetic field. The effect is characterized by oscillations in sound attenuation, as predicted by Eremenko *et al.* {Zh. Eksp. Teor. Fiz. **87**, 1757 (1984) [Sov. Phys. JETP **60**, 1010 (1984)]}. The size of the noncentral cross section of the Fermi surface and the electron velocity in gallium are found. At low sound frequencies, an "inverse" deviation effect is observed.

1. The deviation effect in the interaction of conduction electrons with sound was identified a long time ago[2] and has been observed in many metals, including gallium.[3] The effect is manifested as a sharp dependence of the attenuation of sound and of the dispersion of the sound velocity on the angle (φ) by which the magnetic field $\mathbf{H}$ deviates from the direction orthogonal to the sound propagation direction $\mathbf{q}$. The deviation effect provides an effective method for finding the velocity of conduction electrons at the Fermi surface and has usually been studied in strong magnetic fields under the condition $qR \ll 1$, where $\mathbf{q}$ and λ are the wave vector and wavelength of the sound wave, $|\mathbf{q}| = 2\pi/\lambda$, and R is the Larmor radius of the electron trajectory in the magnetic field.

An attempt has recently been undertaken to carry out a thorough theoretical study of the possible existence of a deviation effect in a weak magnetic field under the condition[1,4,5] $qR \gg 1$. Eremenko *et al.*[1] have predicted a new oscillatory deviation effect, which would be manifested at such fields. This effect is interesting in that it would make it possible to find not only the electron velocity but also the dimensions of noncentral cross sections of the Fermi surface of a metal. Fal'ko *et al.*[5] have derived a theory for the oscillatory deviation effect for metals and semimetals with multiply connected Fermi surfaces. In the experimental part of Ref. 4, where the deviation effect was studied in tungsten under the condition $qR > 1$, the oscillatory effect was not observed. We felt it worthwhile to attempt to observe the oscillatory deviation effect in a metal in a weaker magnetic field.

2. In the present letter we report a study of the attenuation of sound as a function of the deviation angle in single-crystal gallium samples with an electron mean free path $l \sim 1$ cm. The latter condition made it possible to reduce the magnetic field by two orders of magnitude from that in Ref. 4. The measurements are carried out by a pulsed method in a field $H = 42.3$ Oe at a temperature $T = 1.2$ K. The sample, which is cut by an electric-erosion method from a single crystal of large dimensions, is cylindrical,

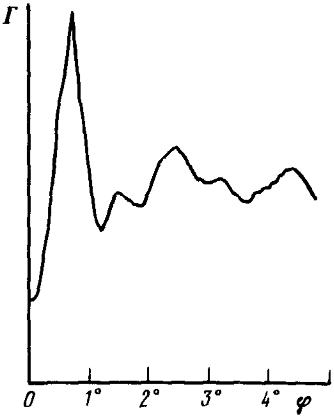

FIG. 1. Sound attenuation versus the deviation angle in gallium. $\omega/2\pi = 150$ MHz; $\mathbf{q}\|\mathbf{c}$; $\mathbf{H}\|\mathbf{a}$ with $\varphi = 0$.

with a diameter ~1 cm and a length of about 2 cm. Acoustic transducers, made of *X*-cut quartz, with a fundamental frequency of 10 MHz, are mounted on the polished flat end surfaces with the help of a silicon-organic liquid. A longitudinal ultrasonic wave propagates along the crystallographic **c** axis of the gallium. The crystallographic orientation of the sample is adjusted within ~0.1° by an x-ray technique. The geomagnetic field is cancelled by a special magnetic system. The measuring field **H** which is produced by a pair of Helmholtz coils, can be rotated in the plane perpendicular to the axis of the sample; it can also deviate from this plane by an angle up to ~6°. An auxiliary pair of Helmholtz coils makes it possible to carry out experiments at large values of φ also.

3. In the course of the experiments, it was found that an oscillatory deviation effect occurs in gallium in this magnetic field. This oscillation effect is characterized by an oscillation in the attenuation behavior $\Gamma(\varphi)$ at small values of φ. Figure 1 shows an experimental curve. The frequency of the sound wave is $\omega/2\pi = 150$ MHz. At $\varphi = 0$, the magnetic field is oriented along the **a** axis; as φ is increased, the magnetic field deviates in the **c** direction. On the experimental curve we see a sharp peak in the attenuation, followed by oscillation of $\Gamma(\varphi)$. The experimental results agree qualitatively with the behavior predicted by the theory. The value of qR in our case is 40, and

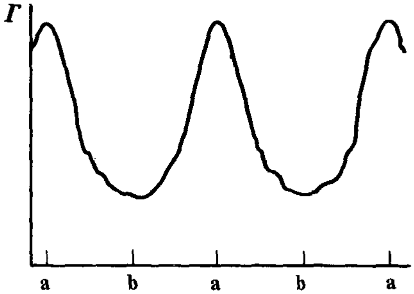

FIG. 2. Sound attenuation versus the direction of the magnetic field **H** in the plane of the **a** and **b** axes of gallium. $\omega/2\pi = 50$ MHz; $\mathbf{q}\|\mathbf{c}$.

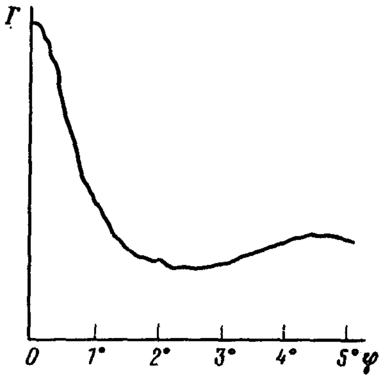

FIG. 3. Sound attenuation versus the deviation angle in gallium. $\omega/2\pi = 30$ MHz; **q**||**c**; **H**||**a** with $\varphi = 0$.

this value is responsible for the sharpness of the first attenuation peak at $\varphi = \varphi_k$. Using the relation[1] $\sin \varphi_k = S/v$, we find the electron velocity: $v \simeq 4 \times 10^7$ cm/s. This velocity agrees well with the result found from the deviation effect in gallium in strong magnetic fields[3]: $v \simeq 5 \times 10^7$ cm/s. The periodicity of the oscillatory deviation effect is described by[1]

$$\Gamma_{\rm osc} \sim \sin^2 \left[qR \left(1 - \frac{\sin \varphi_k}{\sin \varphi} \right)^{1/2} - \frac{\pi}{4} \right],$$

We then find the size of the oscillating noncentral cross section to be $p_{\rm b}/\hbar \simeq 1.4 \times 10^7$ cm^{-1}. This value agrees with studies of the Fermi surface of gallium.[6] The displacement of the cross section along the **a** direction is $p_{\rm a}/\hbar \simeq 1 \times 10^7$ cm^{-1}, where $p_{\rm a}$ and $p_{\rm b}$ are the electron quasimomenta on the Fermi surface along the **a** and **b** directions. At large deviation angles, we were able to observe oscillations of a Pippard resonance, which set in at $\varphi \gtrsim 9°$, in agreement with calculations from the expressions given in Ref. 5 using the particular dimensions of the Fermi surface of gallium. This agreement again stresses the circumstance that only oscillations of the oscillatory deviation effect are manifested at small angles in Fig. 1.

4. At sound frequencies in the interval 30–50 MHz, as **H** is rotated in the plane of **a** and **b** (i.e., with $\varphi = 0$), we observe the orientation dependence of Γ shown in Fig. 2. We wish to call attention to an "inverse" deviation effect, which is observed in the orientation **H**||**a**, i.e., when Γ reaches a maximum. Figure 3 shows the $\Gamma(\varphi)$ dependence for this orientation. We see that in the case the attenuation varies in a manner opposite that in Fig. 1. A possible explanation is that various sound attenuation mechanisms come into play; we might suggest a cyclotron resonance at **H**||**a** and a disappearance of this resonance as the orientation of **H** is changed. This effect may mask the attenuation due to the oscillatory deviation effect or the nonoscillatory effect and may be manifested as the behavior in Fig. 3. This inverse deviation effect requires a separate study, and our comment regarding its mechanism is simply tentative.

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