The plasma echo in bismuth

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(Submitted 5 September 1979)
Pis'ma Zh. Eksp. Teor. Fiz. **31**, No. 1, 3–6 (5 January 1980)

An experiment in which the plasma echo was observed in bismuth is described and the results are discussed.

PACS numbers: 72.30. + q

It was shown[1] that a third-order transverse plasma echo can be observed in a metal with a spherical Fermi surface, if a group of electrons is specularly reflected from the metal surface. In Ref. 2 an arbitrary Fermi surface was examined and a conclusion reached that in the case of anisotropic spectrum a second-order transverse echo with respect to the wave field can occur. The second-order longitudinal echo was examined earlier.[3]

Experimental observation of an echo presupposes that the field surge is brought out to the metal surface, which sets the condition for the frequencies $\omega = 2\omega'$, where ω and ω' are the frequencies of the reference waves. The echo signal is obtained at the difference frequency that coincides with one of the reference frequencies, and this leads to additional experimental difficulties. When the magnetic field is applied, the field coordinate is determined by the frequencies of the incident waves and by the magnetic field, which simplifies considerably the formulation of the experiment. In the magnetically active plasma, the echo can occur at both the sum and the difference frequencies, depending on the wave polarization. The theory of echo in a magnetically active plasma layer was formulated in Ref. 4.

In this paper we derive an expression for the echo coordinate for an ellipsoidal Fermi surface in the presence of a magnetic field and describe an experiment in which the plasma echo in bismuth was observed.

Let us assume that there are two parallel planes in an infinite metal, which are separated from each other by a distance L. We assume that the electromagnetic fields with frequencies ω and ω' are localized near these planes and are uniform on them. The external magnetic field is perpendicular to the planes. To determine the echo coordinate, we must solve the kinetic equation with an accuracy to quadratic terms of the fields. To reduce the particles with an elliptic Fermi surface to the particles with an isotropic mass, we perform the following transformations:

$$\mathbf{E} = m_c \hat{\mu}^{-1} \mathbf{E}^* ; \qquad \mathbf{H} = \frac{1}{m_c} \hat{\mu} \mathbf{H}^* ; \qquad \mathbf{r} = \frac{1}{m_c} \hat{\mu} \mathbf{r}^*$$

$$\mathbf{V} = \frac{1}{m_c} \hat{\mu} \mathbf{V}^* ; \quad v_F^* = v \ \text{ reference point,} \tag{1}$$

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where m_c is the cyclotron mass along the magnetic field. The matrix $\hat{\mu}$ in the system of principal axes of the ellipsoid is

$$\hat{\mu} = \begin{pmatrix} \sqrt{m_2 m_3} & 0 & 0 \\ 0 & \sqrt{m_1 m_3} & 0 \\ 0 & 0 & \sqrt{m_1 m_2} \end{pmatrix}$$

Solving the kinetic equation for a section at some distance from the skin-layer in a coordinate system $z \| H^*$, $x \perp N^*$, we obtain a second-order correction for the distribution function

$$f^{(2)} = \sum_{p,p'=-\infty}^{p,p'=\infty} C_{pp'}(v, v_z) \exp\{(i/v_z)(\omega_p \pm \omega_{p'})(z - ay - z^e_{pp'})\}$$

$$\times \exp\{(i/v_z)(\omega_p \pm \omega'_{p'})\, a \cos\phi (v/\Omega) + i(p - p')\phi - i\omega_e t\}, \quad (2)$$

where

$$\omega_p = \omega + p\Omega, \qquad \omega'_{p'} = \omega' + p'\Omega, \qquad a = \mathrm{tg}(\widehat{N^* z})$$

$$z^e_{pp'} = \{\omega'_{p'}/(\omega_p \pm \omega_{p'})\}\,|L^*|, \qquad L^* \| H,$$

where ω_e is the echo frequency, Ω is the cyclotron frequency, and v, v_2, and ϕ are the cylindrical coordinates in the velocity space. The echo occurs on the surface $z = \alpha y + z^e_{pp'}$, where p and p' are arbitrary integers. Performing a transformation that is inverse to Eq. (1), we obtain the echo coordinate. Since r and H can be transformed identically and $L^* \| H^*$, $|L^*| = |L|$. Therefore, the equation for the echo coordinate remains the same as in the plasma,[4] except p and p' are arbitrary integers.

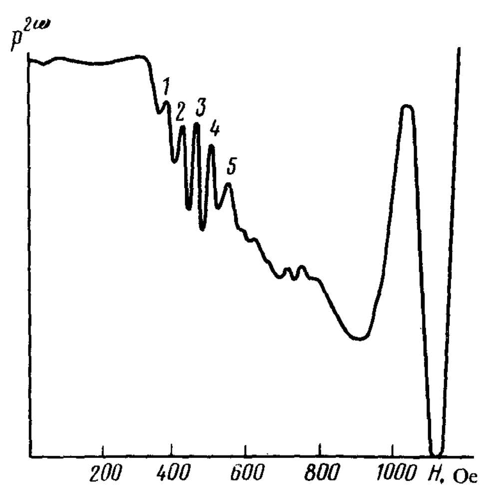

FIG. 1. Dependence of the incoming signal strength on the magnetic field.

In a real metal, the plate surfaces play the role of planes, near which the electromagnetic fields are localized. We shall examine a case in which both fields are localized on a single surface, and for the electrons that are specularly reflected from the metal surfaces we can assume that the situation is similar to that of the unbounded metal for which the distance between the field sources is $L = 2d$ (d is sample thickness). The echo signal is received on the unexposed side, i.e., the echo coordinate is $z_e = 3d$. If $\omega = \omega'$, then $p = -p' = 1$, and the echo is observed at the sum frequency which, as can be seen, produces a surge on the surface at

$$\Omega = 2\omega . \tag{3}$$

The experiment was performed as follows. A 0.2-mm-thick bismuth plate with the C_3 axis parallel to N was placed between the two cavities tuned to 9200 and 18 400 MHz. The temperature of the sample was 4.2 K. At 9200 MHz, the cavity was excited by a magnetron operating in a pulsed mode. At the high-frequency side, the signal was received at 18 400 MHz and, after clearing the peak voltmeter, it was applied to the y-coordinate of an x-y automatic recorder. A signal proportional to the magnetic field was applied to the other coordinate. The strength of the incoming signal was proportional to the square of the power of the incident wave. The obtained plot is shown in Fig. 1. In the small fields the signal is produced as a result of harmonic generation on the exposed side of the sample. The signal growth in the 1.1-kOe field is attributable to the cutoff of the Landau damping. The oscillations $\Omega \sim 2\omega$ cannot be explained in terms of the excitation of waves in the limited region of the fields,[6,7] since the transverse waves analyzed in Ref. 6 produce a much shorter period than that observed in the experiment, and the longitudinal waves, which exist in fields where $1 < \Omega/2\omega < 1.5$, produce spacings between the peaks that vary greatly with the peak number. In addition, if a sample is "x-rayed" by a small-amplitude, 18 400-MHz signal, then the oscillations will be missing in the field region of interest.

The observed picture can be explained in terms of the plasma-echo effect. The echo current at the plate surface is

$$j^e = \int_1^\infty \psi(x) \exp(i\lambda x) dx,$$

where $\psi(x)$ is a nonoscillating function and λ in our case ($\omega_e = 2\omega$) is

$$\lambda = \frac{2\omega_e d}{v_F^*} \left[\left(1 - \frac{\Omega}{2\omega}\right) + \frac{2i}{\omega\tau} \right].$$

At $\Omega/2\omega = 1$, a peak with the largest amplitude can be seen (peak 3 in Fig. 1). In case of a signal that is transmitted through the sample, the position of the following peak is determined by the condition $\Delta\lambda \approx 2\lambda$, i.e.,

$$\frac{\Delta\Omega}{2\omega} \approx \frac{\pi v_F^*}{\omega_e d}. \tag{4}$$

In the experiment $\Delta\Omega/2\omega = 0.08$, and the estimated value is 0.09, which is considered fully satisfactory, considering the approximate nature of Eq. (4).

The dependence of the echo signal on the magnetic field is similar to the dependence of the echo amplitude in the plasma on the probe coordinate, which was observed in Ref. 5. This is understandable, since both dependences are described by the same function.

The authors are very grateful to V.F. Gantmakher, V.F. Dryakhlyshin, A.P. Kopasov, Yu.A. Romanov, and E.G. Yashchin for discussions, and to N.V. Yashnikova for preparing the thin bismuth single crystals.

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