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CYCLOTRON WAVES IN BISMUTH

V. S. Edel'man
Institute of Physics Problems, USSR Academy of Sciences
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The study of cyclotron waves (CW) in metals has attracted many workers of late. Their interest is stimulated by the fact that the CW spectrum depends on the Fermi-liquid interaction of the conduction electrons [1, 2]. CW were observed experimentally in alkali metals [1, 3] and in bismuth [4]. The influence of the anisotropy of the Fermi surface of bismuth on the spectrum of the CW in it is also investigated in [4].

We are interested in "ordinary" CW, in which the field $\vec{E}$ is parallel to the external magnetic field $\vec{H}$. At symmetrical field directions (e.g., when $\vec{H}$ is parallel to C_1 or C_2, the bisector or binary axis of the crystal, respectively), when $\vec{K} \perp \vec{H}$, the CW spectrum is given by the equation $\sigma_{zz} + (ic^2/4\pi\omega)k^2 = 0$, where the component σ_{zz} of the conductivity tensor (without allowance for collisions) is of the form [5]

$$\sigma_{zz} = \Sigma \frac{e^2}{2\pi^2 \hbar^3} \int_{-p_z}^{p_z} dp_z \frac{m}{\Omega} \sum_{n=-\infty}^{\infty} \frac{v_z^{-n}(-\psi)\, v_z^{n}(\psi)}{in - i\omega/\Omega}; \quad (1)$$

here

$$\psi = \int^{\phi} \frac{kv(\phi)}{\Omega} d\phi, \qquad \phi = \Omega t$$

$v_z^n(\psi)$ is the Fourier component of the function $v_z(\phi)e^{i\psi}$; v is the electron velocity, Ω and m its cyclotron frequency and effective mass, p_z the maximum value of the momentum along the magnetic field, and $\vec{k}$ and ω the wave vector and angular frequency of the wave; the first summation is over all sections of the Fermi surface. In a strong magnetic field when $\omega/\Omega >> 1$, the inequality Im $\sigma_{zz} > 0$ is satisfied and the propagation of undamped waves is impossible. At field values such that $\omega/\Omega \approx 1$ for any one of the carrier groups, an important role is assumed by the terms with n = 1, and

$$\sigma_{zz} \approx \sigma_{zz}^0 - \frac{ie^2}{2\pi^2 \hbar^3} \int_{-p_z}^{p_z} dp_z \frac{m\omega}{\Omega^2} \frac{P(\psi^2)}{1 - (\omega/\Omega)^2}, \quad (2)$$

where the polynomial $P(\psi^2) > 0$; its form depends on the shape of the Fermi surface in the H direction, and σ_{zz}^0 is a slowly varying function of $\vec{k}$ and $\vec{H}$, containing all the remaining terms. Its magnitude differs little from the value of σ_{zz} when $H \to \infty$. It follows from (2) that when $1 >> 1 - (\omega/\Omega)^2 > 0$ we have Im $\sigma_{zz} < 0$, which leads to a possibility of propagation of undamped waves. In the general case, with the field directed at an angle to the symmetry axis of the resonating Fermi surface (type I waves), $P(\psi^2)$ begins with the constant, and the zero value of k is reached not at resonance but at a larger value of the field (at the so-called dielectric anomaly), and k increases with decreasing field; waves with small values of k do not exist near resonance. On the other hand if the field is parallel to the symmetry axis of the resonating Fermi surface (type II waves), the $P(\psi^2)$ begins with the quadratic term; when $\psi^2 << 1$ and $1 - (\omega/\Omega)^2 >> 0$ this corresponds to the wave spectrum $k^2 \sim 1 - (\omega/\Omega)^2$. Calculations performed in [1] show that for type II waves, at specified values of H and ω, CW with several values of k can exist simultaneously; this is apparently possible also for type I waves, since the difference between these two cases occurs only at small values of k.

The CW spectrum was determined by observing, using a frequency-modulation method and varying the field H, oscillations induced in the surface resistance by standing waves propagating along a normal to the surface in plane-parallel single crystals of bismuth [5]. The field H was set parallel to the high-frequency current I in a strip resonator. The investigated samples had a normal parallel to the trigonal axis accurate to 1 - 2°. The preparation of the samples is described in [5].

At H parallel to C_1 we observed type I waves connected with excitation of cyclotron resonance of electrons of mass $0.0162m_0$ (electrons of two ellipsoids resonate simultaneously). These CW were observed in samples 0.2 - 1 mm thick at temperatures 1.5 - 4.2°K and at a frequency close to 9.6 GHz. One of the samples (0.21 mm thick) revealed simultaneously two series of oscillations, while the others showed only one series each (Fig. 1 and Fig. 1 of [4]). In determining the absolute value of k it was assumed that each successive oscillation on Fig. 1 corresponds to unity change in the number of half-waves (and not full waves [7]) spanned by the thickness of the sample.

We were able to observe standing CW of type II only in a sample 0.2 mm thick at a temperature 0.6°K (obtained by pumping-off He^3 vapor) and at a frequency 19.1 GHz. The field H was parallel to C_2 and the waves were connected in this case with the resonance of the electo-ns of the ellipsoid whose major axis was perpendicular to the C_2 axis. A plot of the experimental results is shown in Fig. 2.

Using the ellipsoidal model of the Fermi surface, with the parameters given in [8], we calculated, accurate to terms $\sim\psi^6$, the initial section of the CW spectrum (at small values of ψ) in case I. The result is shown in Fig. 1. The assumed approximation turned out to be insufficient for the calculation of the upper branch of the spectrum (corresponding to the more frequent oscillations on Fig. 1), and no such calculation has been performed as yet.

In the calculation of the wave spectrum with H parallel to C_2, we used as the first approximation the same ellipsoidal model, but the value of Ω/ω was determined from the experimental plot, and was not calculated from the field values given by the model. The difference is quite appreciable here, since the mass of the electrons of the limiting point, $m_{lim} \approx 0.137m_0$ [9], exceeds the central-section mass $m = 0.12m_0$ used to determine the parameters of the model. Figure 2 shows the results of a comparison of experiment with calculation. The different groups of points correspond to different choices of the characteristic place on the

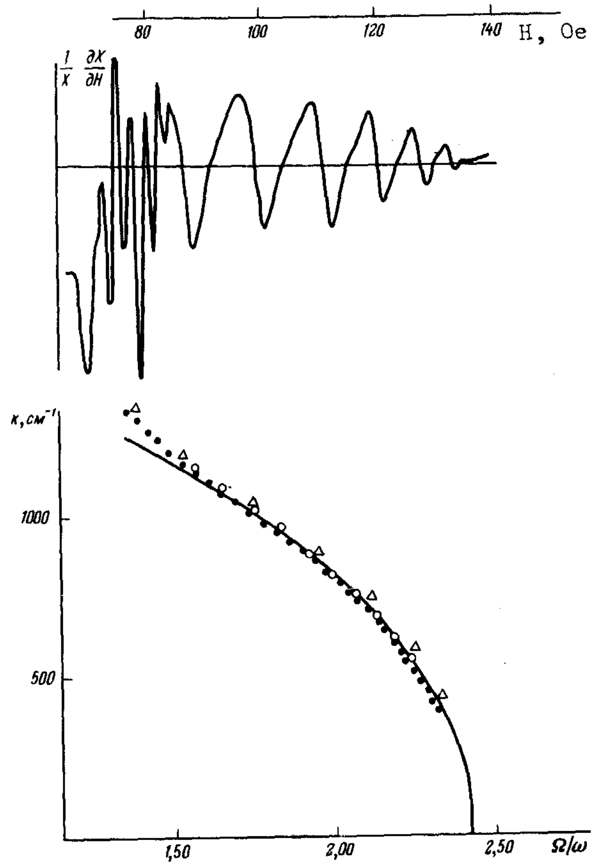

Fig. 1

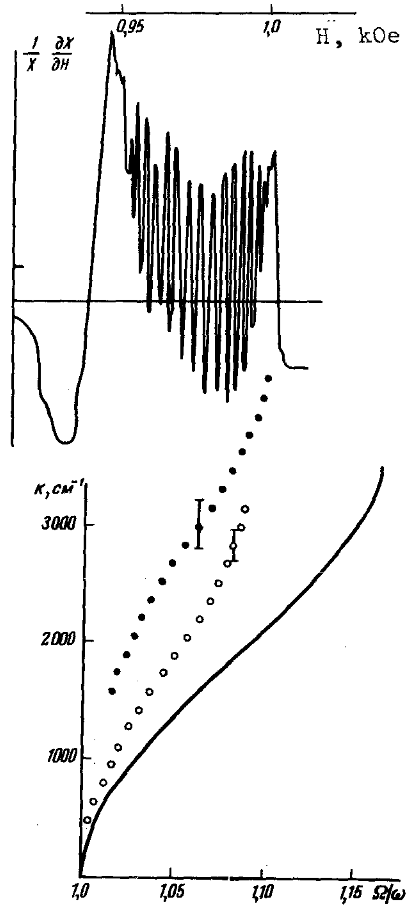

Fig. 2

Fig.1. CW spectrum for $\vec{k}||C_3$, $\vec{H}||C_1$, $\vec{E}||\vec{H}$. Top - experimental plot for sample thickness D = 0.21 mm, frequency f = 9.80 GHz. Bottom - comparison of experiments with calculation: ● - D = 1.00 mm, f = 9.60 GHz; o - D = 0.47 mm, f = 9.51 GHz; Δ - D = 0.21 mm, f = 9.80 GHz. Solid curve - calculated. The measurement error does not exceed the dimensions of the points.

Fig. 2. CW spectrum for $\vec{k}||C_3$, $\vec{H}||C_2$, $\vec{E}||\vec{H}$. Top - experimental plot for sample thickness D = 0.20 mm, frequency f = 19.1 GHs. Bottom - comparison with calculation: ● - the location of the resonance $\Omega/\omega = 1$ is taken to be the zero of the derivative (effective mass $m = 0.138m_0$); o - the location of the resonance Ω/ω is taken to be the maximum of the derivative ($m = 0.139m_0$). Solid curve - calculated. The bars show the measurement errors.

experimental plot, capable of corresponding to the condition of exact resonance. The absolute value of k was determined by extrapolating the initial section near resnance in accordance with the formula $k^2 \propto 1 - (\omega/\Omega)^2$.

According to Fig. 2, there is an appreciable quantitative discrepancy between the measured and calculated values of k, unlike the case shown in Fig. 1, in the region of fields in which wave propagation is possible. The reson lies primarily in the deviation of the electron spectrum from quadratic [9], but this question calls for further research.

We were unable to observe CW connected with resonance on the hole surface. According to estimates, when k is parallel to C_3 the width of the region of existence of these CW, ΔH/H, does not exceed about 0.5% and it is obviously impossible to observe the CW at the hole values $\omega\tau \sim 200 - 300$ possessed by the better of the samples at 0.6°K and 19 GHz.

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POSSIBLE METHOD OF OBTAINING ULTRACOLD NEUTRONS BY REFLECTION FROM MOVING MIRRORS

A. V. Antonov, D. E. Vul', and M. V. Kazarnovskii
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When neutrons with velocity smaller than a certain limit $v_{lim} \simeq 5 - 6$ m/sec are normally incident from vacuum on a medium with appreciable positive coherent scattering length, they experience specular reflection [1 - 4]. We shall call such neutrons ultracold neutrons (UCN).

Research with UCN is of considerable interest [5, 9]. However, their fraction in neutron fluxes from moderators is extremely small. We discuss below the possibility of obtaining UCN by decelerating faster neutrons by a series of successive reflections from suitably moving mirrors. We shall show that in the case of a pulsed source it is possible to increase appreciably the yield of UCN from neutron fluxes by this method.

Neutrons are specularly reflected from a medium when the neutron-velocity component $v_\perp^{rel}$ normal to the surface, relative to the "mirror," does not exceed v_{lim}.

Let $\vec{v}$ and $\vec{u}$ be respectively the velocities of the neutron and the mirror, and let $\vec{n}$ be the unit vector of the outward normal to the reflecting surface of the medium. Then $v_\perp^{rel} = \vec{n}\cdot\vec{v} - \vec{n}\cdot\vec{u}$ and it can be readily verified that the neutron velocity after reflection is

$$\vec{v}' = \vec{v} + 2\vec{n}(\vec{n}\cdot\vec{u} - \vec{n}\cdot\vec{v}).$$

Inasmuch as $v_\perp^{rel} < v_{lim}$, the maximum decrease in velocity equals $2v_{lim}$. Thus, by causing the neutron to be reflected successively from a properly moving mirror (or system of mirrors), it is possible to reduce gradually its velocity to an arbitrarily low value. We note that the minimal number of reflections n_{min} necessary to decelerate completely a neutron having a velocity v is equal to $v/2v_{lim}$; in particular, if $v \simeq 2000$ m/sec, then $n_{min} \sim 10^2$.

Because the number of reflection may greatly exceed this value under real conditions, it is very important to determine the maximum number of possible specular neutron reflections from such mirrors without a noticeable loss of intensity. Unfortunately no reliable theoretical estimates of this number have been obtained as yet. In the experiment of Shapiro et al.