Anomalous propagation of ultrasound at Doppler-shifted cyclotron resonances

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Electrons on helical orbits lead to anomalous propagation of ultrasonic waves for $\vec{q} \parallel \vec{B}$ when the conditions for Doppler-shifted cyclotron resonance are satisfied. This phenomenon makes it much easier to identify the bands of electrons on the Fermi surface responsible for the resonances.

Recently we reported that open-orbit electrons not only absorb energy resonantly from ultrasonic waves, but they also serve to propagate the ultrasonic field at the Fermi velocity.[1] We have now observed similar effects for electrons on helical orbits drifting along the direction of propagation when the magnetic field $\vec{B}$ is parallel to the propagation vector $\vec{q}$.

When the pitch of the helical orbit matches the ultrasonic wavelength λ, Doppler-shifted cyclotron resonance (DSCR) absorption of energy from the wave occurs.[2] The condition for resonance is

$$\omega_c = \omega(\bar{v}_z/v_s - 1), \qquad (1)$$

where $\omega_c = eB/m_c$, m_c is the electron cyclotron mass, ω is the ultrasonic frequency, $\bar{v}_z$ is the electron drift velocity along $\vec{B}$, and v_s is the ultrasonic velocity. For most electrons in a typical metal, $\bar{v}_z/v_s \gg 1$ so the last term in Eq. (1) will be neglected.

Since $m_c\bar{v}_z = -(\hbar/2\pi)(\partial S/\partial k_z)$, where $S(k_z)$ is the cross-sectional area of the Fermi surface in the k_z plane, the resonance condition can also be written

$$B = (\hbar q/2\pi e)(\partial S/\partial k_z). \qquad (2)$$

Resonant bands of electrons will occur for extremal values of $\partial S/\partial k_z$; thus DSCR can, in principle, be used to measure a geometrical property of the Fermi surface.[3]

In practice, however, DSCR experimental data are so complex that it is difficult, if not impossible, in many cases to deduce unambiguously the shapes of Fermi surfaces, For example, Fig. 1(a) shows the attenuation of 34-MHz shear waves in copper with $\vec{q}$ along [110], polarized along [101]. It is difficult to distinguish the DSCR peaks (or, possibly, dips) from possible magnetoacoustic oscillations. However, by observing the spread of the ultrasonic wave packet using a gated coherent detector[1] (GCD), we can clearly pick out the resonances for electrons on extended orbits along $\vec{q}$.

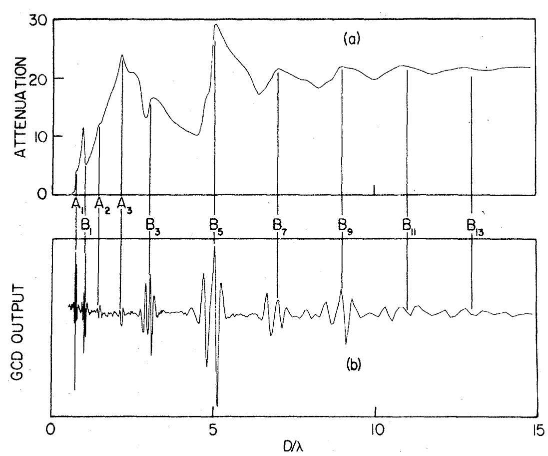

FIG. 1. (a) Attenuation of 34.54-MHz slow shear waves in copper for $\vec{q} \parallel \vec{B} \parallel$ [110] as a function of D/λ, where $D = \hbar|\partial S/\partial k_z|/eB$ and is the pitch of the helical orbits for electrons which cause the fundamental DSCR labeled B_1. (b) Output of the coherent detector, gated 0.58 μsec before the arrival of the ultrasonic wave packet. The detector output is proportional to the amplitude of the anomalous signal and to the cosine of its phase.

Figure 1(b) shows the output of the GCD, which is triggered 0.58 μsec before the expected arrival of the ultrasonic wave packet. The resonant electrons transport the sound field across the specimen in advance of the wave packet and cause output signals from the GCD at the field values for DSCR. Two series are present: those labeled A_n arise from the maximum in $\partial S/\partial k_z$ near $k_z = 0.635$, while those labeled B_n come from the broad minimum near $k_z = 0.425$, as shown in Fig. 2.[4] Note that resonances occur for $D/\lambda = 1$, 2, and 3 for the A series, but only for the odd harmonics up to about $n = 13$ for the B series.

The selection rule for the occurrence of harmonics of the fundamental resonance depends on the orbit symmetry.[5] The electrons causing the A series have orbits which are essentially twofold symmetric in the plane perpendicular to $\vec{B}$, which

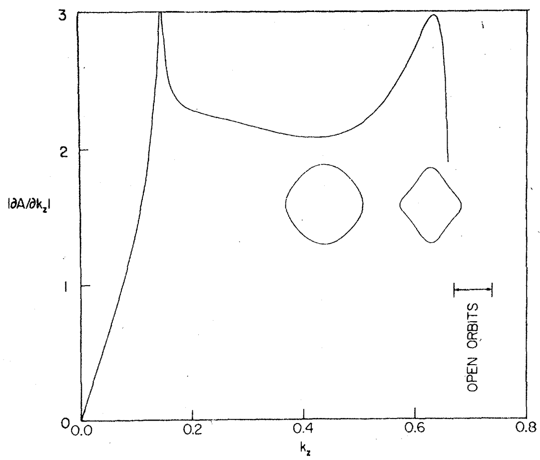

FIG. 2. Magnitude of the derivative of the cross-sectional area of the copper Fermi surface along [110]. Here and in the text k_z and $\partial S/\partial k_z$ are in units of $2\pi/a_0$, where $a_0 = 3.603 \times 10^{-8}$ cm. The resonances labeled A_n and B_n in Fig. 1 arise from the maximum near $k_z = 0.635$ and the minimum near $k_z = 0.425$, respectively. The shapes of the orbits are as indicated in the lower portion of the figure.

permits all harmonics to occur. The harmonic structure thus allows one to assign one of the resonance series to one band of electrons unambiguously.

The attenuation oscillations for $D/\lambda \geq 5$ look very much like ordinary magnetoacoustic oscillations from closed orbits. However, only extended orbits lead to appreciable wave-packet spreading,[6] so we can assign these oscillations to extended orbits undergoing DSCR. Using Eq. (2) we obtain $|\partial S/\partial k_z| = 2.89 \pm 0.03$ for the A series and $|\partial S/\partial k_z| = 2.07 \pm 0.04$ for the B series. The values calculated from the copper Fermi surface are 2.98 and 2.08, respectively. The slight discrepancy for the A series may indicate either that the "accepted" Fermi surface for copper is slightly in error near the necks, or that some averaging over k_z takes place in the resonant band.

We located the resonances by picking the field at which the envelope of the GCD output reached a maximum. Our simple theory[1] shows that the phase difference between the anomalously propagated signal and the ultrasonic wave packet is given by $(\Delta B/B_n)qx_0$, where $\Delta B = B - B_n$ is the deviation from precise resonance and x_0 is the distance in front of the wave packet. A more accurate procedure for locating the resonance, which we will implement shortly, would be to determine the field at which the phase difference is zero.

In summary, we have shown that anomalous sound propagation provides a useful method for unraveling the complex features of DSCR experiments. Resonances which were undecipherable in the attenuation data are clearly observed and easily distinguished from magnetoacoustic oscillations.

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[4] The curve in Fig. 2 is obtained from the Fermi-surface parameters of both M. R. Halse, Philos. Trans. R. Soc. Lond. A 265, 507 (1969); B. Bosacchi and P. Franzosi, Phys. Rev. B 12, 5999 (1975), since they agree within a fraction of a per cent.

[5] The rule for fourfold symmetry is deduced in Ref. 3. The arguments contained therein are easily extended to twofold symmetry.

[6] A related effect for closed orbits has been observed in ultrapure gallium (mean free path $l \approx 1$ cm) by V. D. Fil, N. G. Burma, and P. A. Bezuglyi, Pis'ma Zh. Eksp. Teor. Fiz. 23, 428 (1976) [JETP Lett. 23, 387 (1976)], and explained by E. N. Bogachek, A. S. Rozhavskii, and R. I. Shekhter, Pis'ma Zh. Eksp. Teor. Fiz. 23, 432 (1976) [JETP Lett. 23, 391 (1976)] as the result of current sheets within the specimen coupled by electrons on closed orbits. However, l in our specimen is an order of magnitude smaller so that the effect for closed orbits would be negligible.