Separation of ballistic-type and wave-type electromagnetic excitations in a metal

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(Submitted 19 May 1980; resubmitted 25 November 1980)

Pis'ma Zh. Eksp. Teor. Fiz. **33**, No. 1, 3–6 (5 January 1981)

The effects of ballistic and wave penetration of an electromagnetic field into a metal, which are caused by the Doppler-shifted cyclotron resonance of the same group of carriers at the Fermi surface, were observed and separated (using tungsten) simultaneously for the first time in our work by using an ultrasonic method. The unique features of both types of excitations, which reflect their different interactions with sound, are determined.

PACS numbers: 76.40. + b, 62.65. + k

An external electromagnetic field can cause two types of electromagnetic excitations in a metal in a magnetic field H perpendicular to its surface. The first excitation is ballistic, which is determined by the actual shape of the trajectories of an isolated group of carriers[1,2] where largest displacement is per cyclotron period along **H.** The second excitation is the wave type. We are dealing here with the wave that has been given the name "doppleron."[3] All the carriers participate in its formation; however, the dispersion law of the wave is uniquely determined by the same isolated resonance group of carriers. As the magnetic field increases (as k increases) for $\omega \ll \nu \ll \Omega$ the doppleron spectrum approaches asymptotically and finally merges with the ballistic-excitation spectrum.

$$k = \Omega / \bar{v}, \tag{1}$$

Because of this, both excitations generally cannot be easily distinguished in an experiment. (Here, ω and k are the frequency and the wave vector of the excitation, $\bar{v}$ is the average drift velocity of the resonance group of carriers along **H,** Ω is the cyclotron frequency, and ν is the collision frequency of the carriers.) For small k the doppleron spectrum

$$k^2 = \frac{4\pi i\omega}{c^2}\,\sigma_{\pm}(k) \tag{2}$$

can differ significantly from Eq. (1). [Here $\sigma_{\pm}(k)$ is the nonlocal conductivity for circularly polarized components of the field.] Consequently, two excitations with different wavelengths must coexist in the metal near the Doppler-shifted cyclotron resonance.

However, only one of these excitations is observed in experiments involving the measurement of the *rf* impedance of a metal, and the excitation cannot be fully identified at this time. The excitations cannot be separated when they are both observed at the same time. Until now, only one excitation was observed in each specific case in the

ultrasonic experiments.

At the same time, a study of the absorption of transverse ultrasound makes it possible, in principle, to prove the existence of both types of excitation in a metal. In fact, the resonance interaction of sound with an electromagnetic excitation has the form

$$k_\tau = k \tag{3}$$

(k_τ is the wave vector of the transverse wave). For the different dispersion laws (1) and (2) and a given ultrasound frequency (i.e., a given k_τ) the condition (3) is satisfied for the two types of excitations in different magnetic fields in which the individual singularities are observed in the dependence of the absorption coefficient Γ of transverse sound on H.[4,5]

We have achieved this in our work.

The experiment was performed on tungsten single crystals with a room temperature to helium temperature resistivity ratio of 1.5×10^5 at $T = 4.2$ K in the $k\,||\mathbf{k}||[001]$ geometry. We used a pulse ultrasonic spectrometer in the 5-to 700-MHz frequency range.

We used the doppleron spectrum, which was produced by energetic resonance carriers localized near the A plane of the hole octahedron in band III (Fig. 1) and which was measured in tungsten at radio frequencies.[6] This spectrum was reproduced experimentally in a broad asymptotic region in which the corresponding ballistic exci-

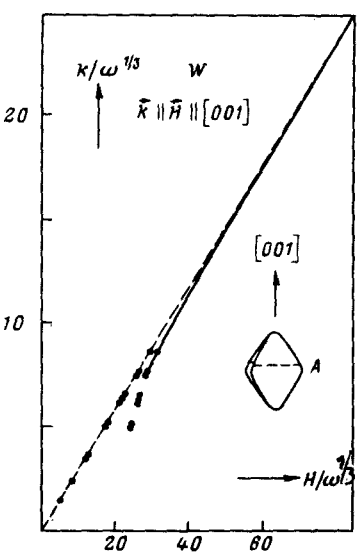

FIG. 1. Spectra of electromagnetic excitations in W attributed to the group A carriers of the hole octahedron. The solid curve is the doppleron spectrum.[6] The dashed line represents the spectrum of the ballistic excitation reconstructed from the doppleron. ● represents the data of the present magnetoacoustic experiment.

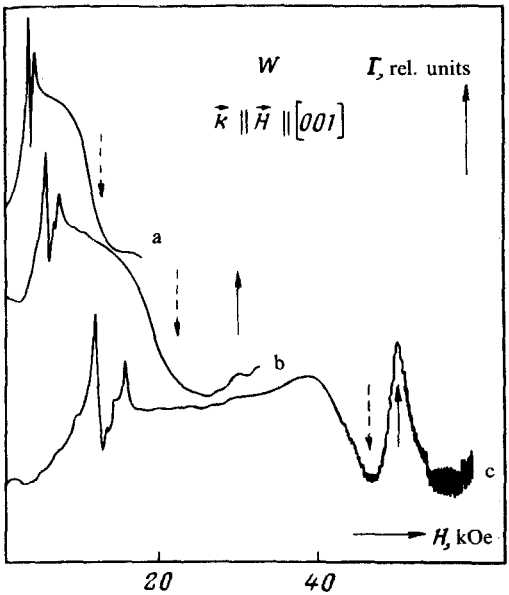

FIG. 2. A set of experimental curves: the dashed and solid arrows show the location of the resonance singularities of ballistic and wave excitations, respectively. (a) $\omega/2\pi = 160$ MHz, (b) $\omega/2\pi = 295$ MHz, (c) $\omega/2\pi = 643$ MHz.

tation coincides with the spectrum (1). This makes it possible to plot the latter with high accuracy because it has the shape of a straight line that passes through the origin in the (k, H) coordinates (Fig. 1). On the basis of the obtained data we plotted the resonance field of the ballistic excitation on the experimental $\Gamma(H)$ curve (Fig. 2).

Its location shows that the resonance caused by a ballistic-type excitation or the Doppler-shifted acoustic cyclotron resonance can be observed experimentally and has the form of a step—absorption edge[4]—which assumes the shape of an asymmetrical peak as the frequency increases. The resonance field, however, always corresponds to the edge—to an abrupt decrease of the sound absorption coefficient. It can be seen in Fig. 2 that in addition to a ballistic resonance a wave resonance or a doppleron-phonon resonance can also be observed. From the moment of its appearance at $\omega/2\pi \approx 300$ MHz the doppleron-phonon resonance has the shape of a peak (Fig. 2), which increases sharply with increasing frequency as the doppleron damping decreases and becomes a well-defined Lorentz absorption peak.[7] In both cases the line shape is in agreement with the physics of the effect.[4,7]

Thus, both types of penetrating electromagnetic excitation in a metal, which are attributable to the same group of carriers, were separated unambiguously for the first time, and the possibility of their coexistence was established experimentally. The qualitative difference in the shape of both resonance lines was demonstrated and it was shown that the wave resonance corresponds to a maximum of Γ in the examined range of magnetic fields, whereas the ballistic resonance is near the minimum of Γ. The obtained results show that the interpretation of the previous ultrasonic experiments

should be re-examined.

The authors thank V. F. Gantmakher for a discussion of the work and for his valuable advice and A. K. Dementenko for his technical assistance.

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Translated by Eugene R. Heath
Edited by S. J. Amoretty