Doppler-shifted cyclotron resonance and doppleron-phonon resonance in molybdenum

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We investigated theoretically and experimentally resonance absorption of transverse ultrasound waves in molybdenum single crystals in a magnetic field parallel to the wave vector of the sound. In addition to several series of Doppler-shifted acoustic cyclotron resonance, we observed a resonant absorption maximum due to excitation of a doppleron in the metal.

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1. The propagation of ultrasound waves in pure single crystals of metals in a magnetic field at low temperatures is accompanied by a number of effects in which the sound interacts resonantly with the conduction electrons. They come into play when the electron mean free path greatly exceeds the length of the sound wave, and the cyclotron frequency Ω exceeds the frequency ν of the collisions between the electrons and the scatterers.

We have investigated the effects of resonant absorption of ultrasound waves of two types. The first manifests itself in the form of an abrupt increase of the absorption at magnetic-field values H such that the condition of the Doppler-shifted cyclotron resonance (DSCR) is satisfied,[1] namely, $\omega - \mathbf{q}\cdot\mathbf{v} = N\Omega$, where ω is the frequency, $\mathbf{q}$ is the wave vector of the sound, $\mathbf{v}$ is the electron velocity, the bar denotes averaging over the cyclotron period, and N is the number of the resonance allowed by the symmetry of the crystal relative to the directions of the vectors $\mathbf{q}$ and $\mathbf{H}$. The second type is produced by the excitation of an intrinsic electromagnetic wave (a doppleron) in the metal by transverse sound.[2] In this case the increase of the ultrasound wave absorption should take place when the doppleron wavelength coincides with the sound wavelength.[3,4]

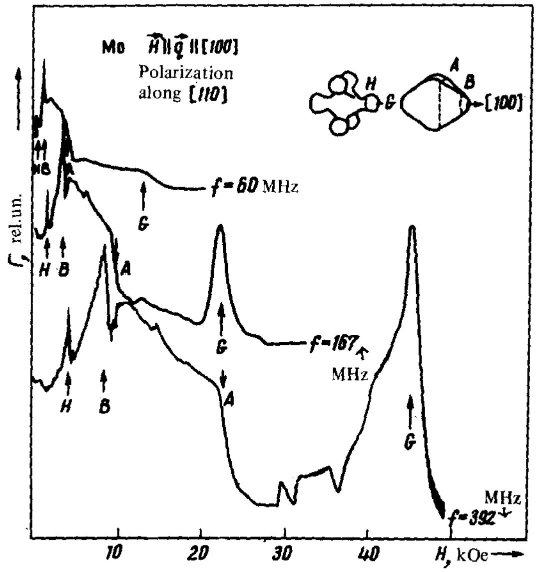
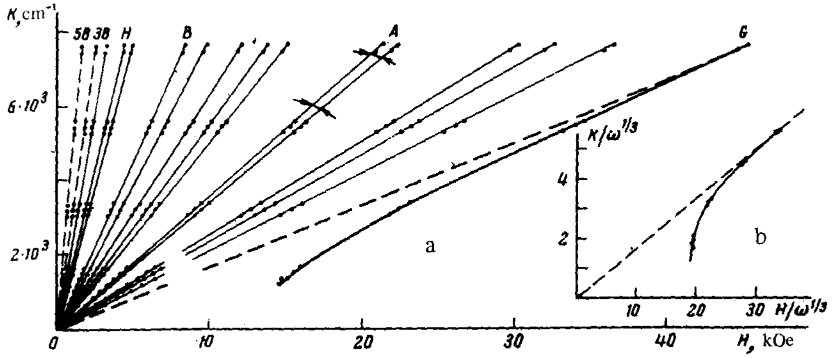


FIG. 1.

The experiment was performed on samples cut from single-crystal molybdenum ingots with room to helium resistivity ratio on the order of 6×10^4. The transverse ultrasound waves of frequency 30—400 MHz were excited by a lithium-niobate converter. The ultrasound damping was measured by a standard pulse procedure at temperatures from 1.7 to 4.2°K. The magnetic field was produced by a superconducting (up to 60 kOe) or copper (up to 5 kOe) solenoid. The geometry of the experiment was such that **H** was parallel to **q** and to the principal crystallographic directions in the molybdenum.

2. A theoretical analysis for such a geometry shows that in the absence of a magnetic field the ultrasound absorption (Γ) has a collisionless character, $\Gamma = \omega s/v$ (s is the speed of sound). In weak fields, the dependence of the smooth



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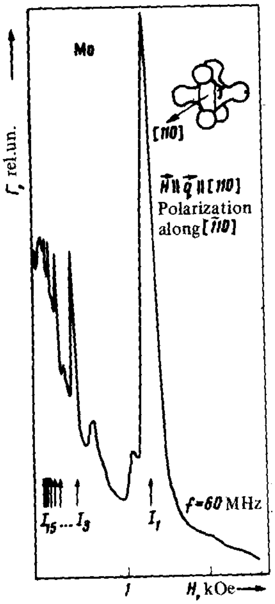

FIG. 3.

part of Γ on H is negligible. With increasing field, the collisionless absorption of the transverse ultrasound wave by the ith group of electrons gives way to weak collision damping when $\Omega > qv_{i\,\max}$. In strong fields, therefore, at $\Omega > qv_{\max}$, the total absorption decreases rapidly to a value $\Gamma \approx \nu s^2/v^2$. This picture has been qualitatively confirmed in experiment.

3. Figure 1 shows typical plots of $\Gamma(H)$ for the geometry $\mathbf{q} \parallel \mathbf{H} \parallel [100]$. A high-power absorption peak is observed on the strong-field side, and is due to the excitation of the doppleron wave. Its amplitude increases rapidly with increasing sound frequency. Estimates show that $\Gamma_{\max} \sim \omega^2 H^4$ at the maximum. With increasing ω, the maximum shifts towards larger values of H. From the position of the maximum it is possible to reconstruct the doppleron spectrum (Fig. 2(b)). In strong fields, the doppleron clings to the straight line corresponding to the DSCR of the electrons with a maximum displacement along H within the cyclotron period $(2\pi\hbar)^{-1}(\partial S/\partial P_H)_{\text{ext}} = 0.915$ Å^{-1}. It appears that this doppleron mode is formed by the electrons from the vicinity of the limiting point G on the "cone" of the electronic "jack" of the Fermi surface of the molybdenum.

With decreasing ω, the doppleron spectrum deviates more and more from a straight line, the amplitude of the doppleron-phonon resonance decreases, and at frequencies below 50 MHz it is already practically indistinguishable from the background of the collision absorption. The reason is the abrupt increase of the natural damping of the doppleron $\text{Im}q \approx \nu\Omega^3/q^3v^4$ at small q. We note that at the location where it is produced, the doppleron-phonon resonance has an asymmetrical shape. It is similar to a step, because a low and broad peak is superimposed on the monotonic part of Γ that decreases with increasing H. It is curiou that the doppleron-phonon resonance is not accompanied on the weak-field side by a corresponding DSCR of the intrinsic damping of the sound wave. This indicates that the DSCR of the electrons of the limiting point G is too weak to produce a noticeable singularity of the direct absorption of the ultrasound by the electrons, although it is strong enough to produce a doppleron mode.

4. For the case of weak magnetic fields, Fig. 1 shows peaks of DSCR absorption of ultrasound by electrons with smaller extremal displacements along **H** within the cyclotron period. They appear against a background of relatively large collisionless absorption. With increasing ω, their maximum shifts linearly towards larger H. As seen from Fig. 2, at least 10 individual DSCR branches are observed. We shall not discuss here the absorption picture in detail. The identification of the branches and a detailed comparison of the theory with experiment will be the subject of a separate communication. We call attention to the following circumstances: The largest peaks are due to absorption of ultrasound by electrons of the almost-parabolic neighborhood of the limiting point B of the hole octahedron, $(2\pi\hbar)^{-1}(\partial S/\partial P_H)_{\text{ext}} = 0.169$ Å^{-1}, and by the electrons of the H section, $(2\pi\hbar)^{-1}(\partial S/\partial P_H)_{\text{ext}} = 0.89$ Å^{-1}. The values of $(\partial S/\partial P_H)_{\text{ext}}$ determined from the slopes of the DSCR branches agree with those measured earlier in molybdenum by means of the radio-frequency size effect.[5] We note that the carriers of section A of the hole octahedron with the maximum displacement led in the experiment of[5] to large size-effect oscillations. Our present measurements show (see Fig. 1) that the amplitude of their DSCR is small. The point is that the section $A(P_H \approx 0.2P_F)$ is close to the central section $(P_H = 0)$ of the hole octahedron and the components of the deformation potential (which are proportional to P_H) are small for this group of carriers.

Figure 3 shows a plot of the DSCR at $\mathbf{q} \parallel \mathbf{H} \parallel [110]$. We see here a series of intense pulses (up to 15 harmonics). It corresponds to the section I on the body of the electron jack. For this section we have $(2\pi\hbar)^{-1}(\partial S/\partial P_H)_{\text{ext}} = 0.216$ Å^{-1}. The DSCR appears not in the form of single peaks but in the form of series because the trajectories of electron motion in the plane perpendicular to H are not circles. Under DSCR conditions, the number N is precisely the result of the Fourier expansion of the transverse velocity components of the electrons. From a comparison of Figs. 1 and 3 it is seen that the amplitude of the multiple DSCR from section I decrease with increasing number much more slowly than for other groups of resonant electrons. The reason is the almost rectangular shape of the section I. In accordance with the conclusions of the theory, only odd harmonics of DSCR are observed in both geometries.

No doppleron modes were observed in the vicinity of the described DSCR in the present experiment. The apparent reason is that they should exist (in contrast to the G doppleron) in the region of strong collisionless absorption. They are difficult to observe because the doppleron spectra cling to the DSCR lines and higher sound frequencies are needed to be able to register them.

5. Thus, magnetoacoustic investigations provide a sufficiently complete picture of DSCR in metals. They serve as a constructive procedure for the study of the spectrum of doppleron excitations. In contrast to the investigations of the doppleron-phonon resonance with the aid of the radio-frequency effect,[4] in acoustic experiments the resonance appears in pure form, and not in the form of small changes of the amplitudes of doppleron oscillations of the surface impedance. Nor do we encounter in the analysis of the experimental data the

problem peculiar to the size effect, that of separating the doppleron from the Gantmakher-Kaner effect. At the same time, different doppleron modes manifest themselves differently in the two procedures, so that magnetoacoustic and size-effect experiments complement each other.

In conclusion, the authors are grateful to Professor É. A. Kaner for useful discussions.

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