Effect of anomalously high oscillations of ultrasound velocity in a pure metal in a weak magnetic field

A. G. Shepelev, O. P. Ledenev, and G. D. Filimonov

Physico-technical Institute, Ukrainian Academy of Sciences

(Submitted June 26, 1975)
Pis'ma Zh. Eksp. Teor. Fiz. **22**, No. 3, 148–152 (August 5, 1975)

We have observed experimentally, for the first time, very large oscillations of the velocity of longitudinal ultrasound, $\Delta s/s \approx 0.6\times 10^{-1}$, in the normal state of a metal at low temperature. The oscillations occur at $\omega\tau\sim 1$ following variation of either the magnitude of the magnetic field or of its orientation in the plane **H⊥k**.

There have been many theoretical and experimental studies of the velocity of ultrasound (US) in a magnetic field. The largest known oscillations of the velocity are $\Delta s/s \sim 10^{-4}-10^{-3}$ (see the investigations of magnetoacoustic ("Pippard"),[1] quantum,[2] and giant quantum oscillations[3] in fields ~1, 70, and 150 kOe, respectively).

We report here the results of experiments in which we observed oscillations $\Delta s/s \approx 0.6\times 10^{-1}$ in the normal state of gallium in a field ≈50 Oe.

1. The effect is so large, that the time variation of the position of the US pulse passing through the sample is observed directly on the screen of the oscilloscope in the setup for the investigation of US absorption.[4] This has made it possible to carry out the measurements at frequencies 30–90 MHz by introducing only slight complications in the apparatus. The signal from the receiver output was fed simultaneously to the pulse selector, the oscilloscope, and a stroboscopic attachment S1-21 operating jointly with the S1-19B oscilloscope. The use of the latter with rigid synchronization of the entire system has made it possible to measure the change of the position of the US pulse passing through the sample relative to the sounding signal. The measurement accuracy, using a sweep of 300 nsec, is not worse than ± 6 nsec, corresponding at a sample length 2 cm to velocity change $\Delta s/s = \pm 1\times 10^{-3}$. The use of a pulse selector and of a PDS-021 x-y recorder makes it possible, when measuring the US velocity, to maintain at the receiver output a constant pulse amplitude with accuracy ± 0.03 dB. This has eliminated

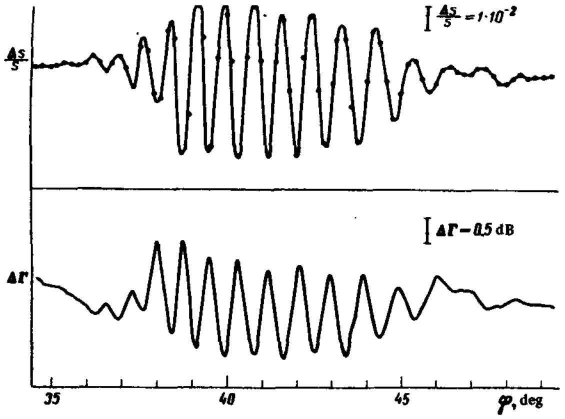

FIG. 1. Oscillations of the velocity $\Delta s/s$ and of the absorption $\Delta\Gamma$ of longitudinal US of frequency 70 MHz. vs. the orientation of H = 48.6 Oe in the plane of the axes a and c of single-crystal gallium at $T = 0.4$ °K, k ∥ b, and k ⊥ H.

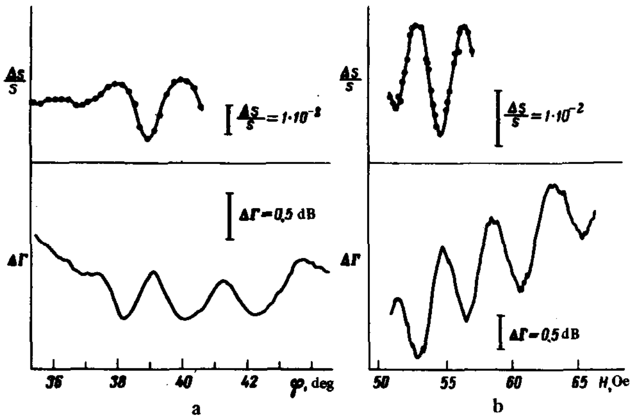

FIG. 3. Oscillations of $\Delta s/s$ and $\Delta\Gamma$ of longitudinal US of frequency 30 MHz at k ∥ b, k ⊥ H, and $T = 0.375$ °K as functions of the orientation of H = 56.6 Oe (a) and of the value of H at an angle 38.1° between H and a(b).

the errors due to the change of the US absorption in the magnetic field. The velocity measurements were made at a level $\frac{1}{3}$ from the base of the pulse and did not depend on the rise time of the pulse used for the measurements.

A very pure gallium sample1) produced by the experimental plant of Rare Metals Institute was a cylindrical single crystal of 7 mm diameter and 19.6 mm length. The cylinder axis coincides with the crystallographic axis b of the gallium. X-cut quartz single crystals 0.3 mm thick and 4.5 mm in diameter are secured to the end faces of the sample and serve as the source and receiver of the longitudinal US. The US wave vector is oriented along the axis of the sample, which is in contact with the liquid helium-3 of the cryostat[6]; the temperature in the latter can range from ~0.4 to 2.2 °K. The external homogeneous magnetic field of a pair of Helmholtz coils, H ⊥ k, is oriented in the plane of the axes a and c of the gallium with accuracy ± 0.03°. The vector H can rotate in this plane with a speed of 1 revolution per hour. The field stabilization (with accuracy better than 10^{-5}) and variation of its magnitude at a rate of 0.6 Oe/min were effected by means of a stabilization and sweep system. The earth's magnetic field was cancelled out by two pairs of Helmholtz coils.

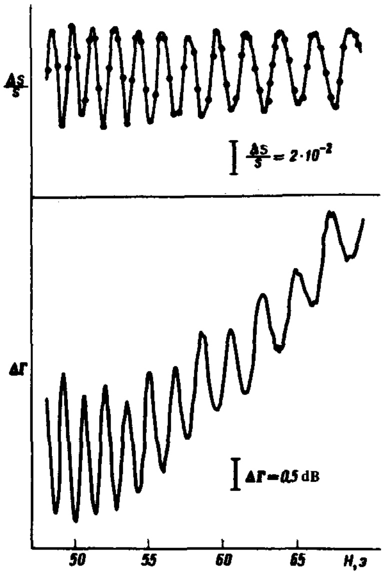

FIG. 2. Oscillations $\Delta s/s$ and $\Delta\Gamma$ of longitudinal 70-MHz sound vs. the value of H at an angle 40° between H and a, k ∥ b, k ⊥ H, and $T = 0.4$ °K.

2. At a fixed value of the field $H > H_c \approx 50$ Oe and a temperature 0.4 °K we investigated the dependence of the propagation of longitudinal US of frequency 70 MHz on the orientation of H in the plane of the axes a and c of gallium (rotation diagram).2) It was observed that appreciable oscillations of the US velocity, $\Delta s/s = 6\times10^{-2}$, take place in a definite region of the rotation diagram (Fig. 1), and accompany the absorption oscillations $\Delta\Gamma$ (recorded with the x-y recorder). The maxima of the oscillations $\Delta s/s$ correspond to minima of $\Delta\Gamma$. The oscillations have a clearly pronounced region of angles between H and a, namely 36–48° (when H ⩾ 50 Oe is rotated 360°, there are four angle regions symmetrical about the a axis) and appear in fields up to ~100 Oe. No such changes of $\Delta s/s$ were observed outside these regions, in spite of the fact that the absorption changed strongly. The observed $\Delta s/s$ oscillations occur at temperatures 0.4–2.2 °K. Deviation of the H rotation plane from the condition H ⊥ k by an angle 1–2° likewise does not lead to a vanishing of the effect.

3. At a fixed orientation of the magnetic field H, in the indicated range of angles between H and a, variation of its intensity also causes $\Delta s/s$ oscillations of the same scale (Fig. 2), accompanied by $\Delta\Gamma$ oscillations. The period of the oscillations is $\Delta(1/H) \approx 5\times10^{-4}$ Oe^{-1} at an ultrasound frequency 70 MHz.3) It should be noted that with further increase of H there occur $\Delta\Gamma$ oscillations of close amplitude (but a different period), which are not, however, accompanied by large $\Delta s/s$ oscillations.

4. The picture of the phenomenon depends strongly on the frequency (wavelength) of the US. It is seen from Fig. 3 that a decrease of the US frequency by a factor 2.3 has led to the same increase of the period of oscillations; the scale of the $\Delta s/s$ oscillations de-

creased at the same time by a factor of three. Thus, these are not quantum oscillations. In light of the existing concepts,[9] at $\omega\tau\sim 1$ (where ω is the US frequency and τ is the electron relaxation time), in strong magnetic fields ($kR \ll 1$, where R is the radius of the electron orbit in the magnetic field) there should occur only a monotonic change of the US velocity[5]. In weak fields ($kR \gtrsim 1$) the US velocity in a pure metal ($l \gtrsim R$, where l is the electron mean free path) should experience "Pippard" oscillations due to the change of kR under the influence of the field. In addition, in so pure a metal as gallium, the change of the US frequency can lead to a change of the US velocity not only because of the change of $\omega\tau$ in the "Pippard" oscillations, but also probably because of the change of the ratio ω/Ω, owing to the acoustic cyclotron resonance Ω is the cyclotron frequency.

The scale of the phenomenon, generally speaking, suggests a strong electron-phonon interaction or else the possibility of collective electronic excitation. The difficulty of the analysis is determined by the complexity of the Fermi surface of the gallium, by the presence of many strongly differing dimensions of the electron orbits, and by the anisotropy of both the effective electron-phonon interaction and of the electron relaxation time. It is possible that a special role is played by groups of extended electron orbits that pass near saddle (or conical) points of the Fermi surface. Orbits with two saddle points were observed in the indicated region of the orientations of **H** in investigations of the magnetoresistance of gallium.[11] One cannot exclude the possibility of magnetic breakdown in gallium in a weak magnetic field,[12] although a discussion of this question is beyond the scope of this article.

To extend the temperature range, investigations were made of the observed phenomenon on single-crystal gallium of the same orientation and purity (6 mm thick), but of different shape, in a different cryostat with a different magnetic system. The measurements were performed at an US frequency 90 MHz, as before, using the first transmitted pulse, and at 30 MHz, using a pulse that made three passes through the sample. It turned out that the phenomenon takes place in the same interval of angles between **H** and **a** and in the same field interval (i. e., it is not connected with size effects) at temperatures 1.5–2.7 °K. At higher temperature this phenomenon is not observed, a fact that can be attributed to a decrease of the mean free path.

We note that at 1.5 °K up to fields 30 Oe, where the US absorption changes very strongly in the indicated range of angles between **H** and **a**, no large changes of the rate of $\Delta s/s$ are observed.

The authors thank B. G. Lazarev, É. A. Kaner, M. I. Kaganov, V. L. Pokrovskiĭ, V. F. Gantmakher, A. A. Slutskin, A. M. Grishin, and V. S. Édel'man for interesting discussions of the results.

[1] Oscillatory absorption of US was observed earlier[5] in gallium of this kind in the intermediate state; this can occur only in a very pure superconductor.

[2] In our communication[7], the rotation diagrams in Figs. 2 and 3 show plots of the amplitude of the US passing through the sample, $A(\phi)$, rather than $\Gamma(\phi)$.

[3] The French physicists[8] observed in gallium oscillations of the absorption $\Delta\Gamma$ under similar experimental conditions. In their opinion these are "Pippard" oscillations due to the six-hole Fermi surface.

[4] It was established in[10] that in a strong ≈ 15 kOe field the velocity of the longitudinal US in gallium increased by $\approx 3 \times 10^{-2}$.

---

[1] B. G. W. Yee and J. D. Gavenda, Phys. Rev. **175**, 805 (1968).
[2] E. P. Missell, N. S. Wisnik, C. C. Becerra, and Y. Shapira, Solid State Comm. **13**, 971 (1973).
[3] L. J. Neuringer and Y. Shapira, Phys. Rev. **165**, 751 (1968).
[4] A. G. Shepelev and G. D. Filimonov, Prib. Tekh. Eksp. No. 1, 194 (1965).
[5] A. G. Shepelev, O. P. Ledenev, and G. D. Filimonov, ZhETF Pis. Red. **14**, 428 (1971) [JETP Lett. **14**, 290 (1971)].
[6] A. G. Sepelev, Prib. Tekh. Eksp. No. 5, 237 (1971).
[7] A. G. Shepelev, O. P. Ledenev, and G. D. Filimonov, Solid State Comm. **12**, 241 (1973).
[8] C. Alquie and J. Lewiner, Phys. Rev. **B6**, 4490 (1972).
[9] S. Rodriguez, Phys. Rev. **130**, 1778 (1961); **132**, 535 (1963); I. O. Kulik, Zh. Eksp. Teor, Fiz. **47**, 107 (1964) [Sov. Phys.-JETP **20**, 73 (1965)]; V. M. Kontorovich, Zh. Eksp. Teor. Fiz. **59**, 2116 (1970); **61**, 1181 (1971) [Sov. Phys.-JETP **32**, 1146 (1971); **34** 630 (1972)].
[10] P. A. Bezuglyĭ and N. G. Burma, ZhETF Pis. Red. **10**, 523 (1969) [JETP Lett. **10**, 334 (1969)].
[11] J. R. Cook and W. R. Datars, Canad. J. Phys. **48**, 3021 (1970).
[12] J. C. Kimball and T. W. Stark, Phys. Rev. **B4**, 1786 (1971).