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ACOUSTIC WAVE EXCITATION IN METALS BY FAST CHARGED PARTICLES AND GAMMA QUANTA

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Excitation of acoustic waves in metals by beams of fast electrons, positrons, or gamma rays is investigated. It is demonstrated that secondary electrons play a significant role in the formation of the acoustic signal in metals. The energy dependence of the acoustic signal is studied for thin and thick metallic plates for the cases of electron and photon beams. The dependence of the amplitude of the acoustic signal on the atomic number is demonstrated.

THE study of the excitation of acoustic oscillations in metals is of interest for the clarification of a number of physical problems.

In a series of theoretical researches,[1-4] it has been shown that the effect of Cerenkov radiation of phonons should develop when a supersonic electron moves in a metal. Experiments have recently been carried out in which acoustic oscillations have been discovered in metals under the action of a beam of fast electrons. The investigations were carried out over a wide range of energies $E_0 = 1.5–1000$ MeV and number of electrons in the pulse, $N_e = 10^6–10^{15}$. The experiments were performed both on apparatus with total absorption of the energy of the electron beam,[5,6] and on apparatus with a thin absorber, where the energy loss of the electron was much less than its initial value.[7] An important conclusion of[6,7] has been that the amplitude of the acoustic signal U and the total number of electrons in the pulse N_e are linearly related.

In our previous work[7] it was also established that the amplitude of the acoustic signal in thin absorbers, does not depend on the energy in the energy range $E_0 = 80–225$ MeV. For fixed initial energy E_0, the amplitude of the acoustic signal for thin plates of different thickness was shown to be proportional to the thickness of the plate h.[7] However, it has not been possible to draw any significant conclusions relative to the mechanism of excitation of the ultrasonic waves in metals on the basis of these preliminary experiments. The present research is devoted to a study of several problems of the excitation of acoustic waves in metals.

THE EXPERIMENTAL SETUP

A block diagram of the experimental apparatus is shown in Fig. 1. A beam of electrons (positrons) from the linear accelerator 8 is incident on a plate of the metal under study 1, on the surface of which is attached a piezodetector 2, which consists of sixteen plates of crystalline Rochelle salt of area 3.4 cm^2. The resonance frequency of the detector was located at the frequency f = 65 kHz. The electrical signal from the transducer was amplified by a transistor resonance preamplifier 3 with an amplification of 50 and, after a cathode follower, was fed to a matched attenuator 4 with an attenuation coefficient up to 10^3. After the attenuator, the signal was amplified in a final transistor amplifier 5 and applied to the vertical plates of the oscilloscope 6, the driving sweep of which was triggered by the synchronous pulse of the accelerator 7. The total gain of the system is $\sim 10^6$, and the bandwidth is ~1 kHz. The mean current of the electron beam was measured by a Faraday cylinder, and a secondary emission monitor calibrated against the Faraday cylinder. The duration of the current pulse was of the order of 1 μsec at a level of 0.2 the maximum amplitude.

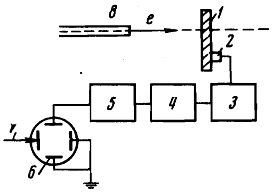

FIG. 1. Block diagram of the experimental setup for the study of the excitation of acoustic waves in metals.

A beam of bremsstrahlung radiation was formed by the electron beam with $E_0 = 620$ MeV on a tantalum target of thickness 5.3×10^{-2} cm, and the total energy of the photons of the bremsstrahlung was measured by means of a Wilson quantameter. After passage through a series of collimators, the beam of bremsstrahlung had a mean transverse dimension of ~1.5 cm on the surface of the plate under study. All the experiments were carried out on the linear accelerator of the Physico-technical Institute of the Ukrainian Academy of Sciences which possesses the necessary magnetic spectrometers, which are used both for the purpose of measurement of the energy and spectral distribution of the electrons of the beam, and for the ridding the photon beam of conversion electrons and the accompanying positrons. The spectral width for the given energy of the electrons (positrons) of the beam was no worse than 3% for the direct electron (positron) beam.[8]

EXPERIMENTAL RESULTS

Preliminary experiments[6,7] have shown that the phenomenon of excitation of ultrasonic waves is a coherent one, i.e., $U \sim N_e$. This result is obtained upon satisfaction of the following conditions: the pulse duration of the electron beam $t_u \ll T = 1/f$ which is the period of the investigated acoustic oscillations of the metal, the mean diameter of the beam $d < \lambda$—the wavelength of the acoustic radiation. To verify the satisfaction of the second condition, an experiment was performed on the violation of the coherence condition. This experiment was performed at $E_0 = 20$ MeV for a fixed number of particles in the packet N_e, but for different transverse diameters of the beam d, monitored by means of glass size detectors. Since the velocity of transverse (and flexure) waves for lead is the smallest of the metals at our disposal, the wavelength $\lambda \approx 0.3$ cm is also sufficiently small, so that the condition $d < \lambda$ could be satisfied. Figure 2 shows the dependence of the amplitude of the acoustic signal incident upon a plate with $h = 0.2$ m on the transverse dimension of the electron beam. Upon decrease of d by a factor of 3, the signal amplitude changes by a factor of almost 12. Thus, in conducting acoustic measurements on beams of charged particles, it is necessary to control the relative dimension of the beam d/λ, so that one must keep $d/\lambda \leq 1$ to obtain maximum of the signal.

As was shown previously,[7] upon satisfaction of the condition $d/\lambda \leq 1$, any change in the transverse dimensions of the beam over wide limits does not change the amplitude of the acoustic signal.

To explain the role of secondary electron ionization (the δ electrons) in the formation of the acoustic signal, we carried out experiments on thin, $h \ll t_0$, and thick, $h \gg t_0$, metallic plates (here t_0 is the radiation unit of length). The results of these experiments are shown in Figs. 3 and 4. Figure 4 shows the dependence of the amplitude of the acoustic signal on the energy of the primary electrons for thin aluminum plates for the thickness $h = 0.2$ cm. Since the energy of the electrons E_0 in this experiment is less than critical for aluminum ($E_c = 40$ MeV), we must assume the ionization losses to be the chief form of loss. Here the total number of electrons in the energy range from 10 to 36 MeV does not change, since $N_\delta \propto \beta^{-2}$, while the relative velocity $\beta \approx 1$ for $E_0 \geq 10$ MeV, so that constancy of the amplitude of the acoustic signal becomes natural in this case. Figure 4 shows the dependence of the amplitude of the acoustic signal for a thick aluminum plate ($\sim 0.56\ t_0$). Here the amplitude of the acoustic signal changes in proportion to the change in the energy of the beam of electrons in the energy range $E_0 = 5$–40 MeV.

To clarify the role of shower particles in the formation of the signal, experiments were carried out on the excitation of acoustic waves in lead plates of thickness $8.8\ t_0$ by a beam of electrons or positrons with E_0 – 620 MeV and a beam of bremsstrahlung with $E_{\gamma\max} = 620$ MeV.

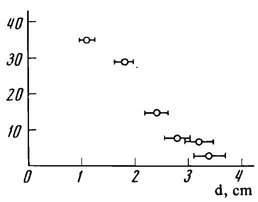

FIG. 2. Dependence of the amplitude of the acoustic signal (in relative units) on the diameter of the electron beam at the target.

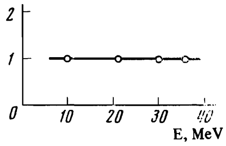

FIG. 3. Dependence of the amplitude of the acoustic signal (in relative units) on the energy of the electrons for a thin aluminum plate (h = 0.2 cm).

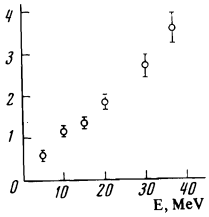

FIG. 4. Dependence of the amplitude of the acoustic signal (in relative units) on the energy of the electrons for a thick aluminum plate (h = 5.0 cm).

Figure 5 shows the dependence of the amplitude of the acoustic signal on the total number of electrons (or positrons) in the pulse. It follows from this figure that the connection between the signal amplitude U and the total number of particles in the pulse can be expressed by the dependence $U \sim N_e$.

Some deviation (5–8%) is found in the amplitude of the acoustic signal excited by the electrons and positrons. The reason for this difference is that the coherent acoustic radiation of the medium in the case of thick absorbers is possibly formed by the excess charge. The excess charge represents the difference between the total number of electrons and positrons in the shower, so that the shower becomes negatively charged because of the annihilation in flight of the positrons, and the involvement in the shower cascade of Compton and δ electrons.[9] Since the multiplicity of secondary shower particles for one primary particle with energy $E_0 = 620$ MeV amounts to ~20, then, in the case of collision of primary positrons with the target (the plate), the value of the excess decreases by about 5%, which also explains the difference noted in Fig. 5.

It follows from this experiment that the quantity $F = E_A/E_0N_e^2 \approx 10^{-18}$, where E_A, the energy of the acoustic signal, is identical with the same quantity obtained in the work of Beron et al.[6] From the data of Perry,[5] obtained for a mean kinetic energy of the electrons ~1.5 MeV, one can obtain the value $F \approx 10^{-18}$.

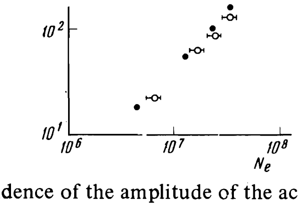

FIG. 5. Dependence of the amplitude of the acoustic signal (in relative units) on the number of electrons (black circles) and positrons (white circles) in a pulse for a lead plate of thickness 5.0 cm (E_0 = 620 MeV).

This allows us to assume that the mechanism of energy transfer from the primary beam to the acoustic vibrations of the metallic lattice remains constant in the experiments on thick plates over a wide range of energies $E_0 = 1.5-1000$ MeV. Since the data of other authors[5,6] and the present work refer to aluminum, copper, and lead, respectively, then the value of F evidently depends weakly on the characteristic of the metal of which these plates are made.

Figure 6 shows the dependence of the intensity ($I \propto U^2$) of the acoustic signal on the total number of equivalent γ quanta with E = 620 MeV, which is computed from the data of the measurement of the total energy of the beam of bremsstrahlung by means of a Wilson quantameter.

Existing theoretical predictions of the mechanism of the formation of acoustic vibrations in a metal reduce to the driving of these vibrations by means of a Cerenkov mechanism, produced by supersonic electrons.[1-4] However, a comparison of the experimentally obtained value of the acoustic energy $E_A = FE_0N_e^2$ with that computed, for example, from the data of Lenchenko and Pugacheva[3] shows that $E_A/E_{A\,th} \approx 10^{20}$. This enormous difference indicates that the mechanism of energy transfer to the acoustic vibrations of the lattice of the metal cannot be Cerenkov. A comparison of the data for thin and thick plates shows the important role of ionization losses in the formation of the acoustic waves. Probably, the process of generation of ionization losses is accompanied by acoustic radiation. The principal role is played here by near collisions, which lead to the formation of δ electrons, and the vibrations of recoil nuclei represent the acoustic vibrations of the lattice.

In our experiments, we studied the dependence of the amplitude of the acoustic signals on the order number of the atom of the metallic plate. These experiments were carried out at an energy of the electrons $E_0 = 250$ MeV. Figure 7 shows the dependence of U for these materials, for a plate thickness h = 0.2 cm, on the quantity which is equal to the product of the square of the order number of the atom of the plate material Z^2 and the ratio of the density ρ to the atomic weight A.

The calculated curve in this drawing shows the behavior of the total energy loss (ionization and radiation) of the primary electrons with $E_0 = 250$ MeV in these plates. It is seen that the experimental data for copper and lead are in agreement with the behavior of the curve of total energy loss. Since the copper and lead plates, even for h = 0.2 cm, cannot be regarded as thin in comparison with t_0, and the energy $E_0 \gg E_c$, the role of radiation losses in the total loss is large. Thus the energy of the acoustic losses is proportional to the electromagnetic loss of energy of the untrapped particles. However, all the forms of electromagnetic losses of energy represent only the transfer of energy from one particle to another, and only ionization losses responsible for energy dissipation and therefore these data do not contradict the conclusion made by us earlier on the fundamental role of ionization losses in the formation of the acoustic signal. Detailed investigation of the mechanism of transformation of the ionization losses to the acoustic wave in metals requires theoretical and experimental efforts.

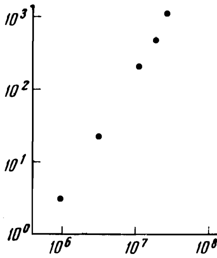

FIG. 6. Dependence of the intensity of the acoustic signal (in relative units) on the total number of equivalent photons for E = 620 MeV for a lead plate of thickness 5.0 cm.

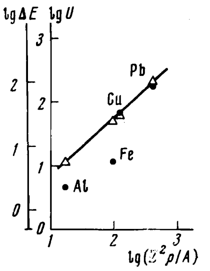

FIG. 7. Dependence of the amplitude of the acoustic signal U on the value of $Z^2\rho/A$. The calculated curve corresponds to total losses of energy of the electrons in plates of the studied metal (h = 0.2 cm, H_0 = 250 MeV). The triangles indicate the calculated values of the total losses of energy of the electrons and the circles, the experimental values of the amplitude of the acoustic signal.

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142