ACOUSTIC PEAK OF PROTONS IN A SOLID PLATE

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The low-frequency component of the acoustic pulse excited in a thin solid plate by interaction with a dense proton beam is investigated. Good agreement between experiment and theory is obtained in the vicinity of the peak of the acoustic signal.

It has been shown [1] that the excitation of an acoustic pulse in a solid by a beam of charged particles can be described within the framework of thermoelastic theory [2]. The investigations in [1] pertain to the case of a thin target (plate), in which the energy losses of the beam particles are insignificant. Also of interest is the case in which the range of the beam particles in the target material is of the same order as the thickness. An experimental study of this type has been carried out for an aluminum target and a proton beam [3]. The dependence of the amplitude of the acoustic signal on the mean proton energy in the beam exhibited a maximum (acoustic peak). Inasmuch as the protons in the beam had a considerable energy scatter, the analysis of the data proved ambiguous. The present study is concerned with a more detailed theoretical and experimental investigation of the given dependence.

Let a pulsed cylindrical beam of protons of radius R with a uniform particle distribution in the beam impinge normally on a solid plate of thickness h. The temperature increase due to the transfer of energy from the short pulsed beam of particles to the target material can be written in the form

$$T(r, z)=\begin{cases}0, & r>R,\\ T(z), & r\leqslant R;\end{cases} \tag{1}$$

$$T(z)=\frac{N}{\pi R^2 \rho C}\left(\frac{\partial E}{\partial z}\right)_i,$$

where N is the number of particles in the beam, ρ and C are the density and heat capacity of the plate material, and $(dE/dz)_i$ are the ionization losses of the protons at a depth z in the plate (the z axis coincides with the beam axis, and r is the distance from the z axis).

In general the calculation of the shape of the acoustic pulse presents considerable mathematical difficulties. We confine our analysis to its low-frequency components U_ω for

$$\omega \ll S/X,$$

for the determination of which it is sufficient to know the maximum displacements x_1 (x_2) of the front (back) surface of the plate (S is the speed of sound in the plate material, and X is the characteristic scale of the heating zone).

We consider the case of wide beams:

$$R \gg h,$$

for which the influence of the boundary of the heating zone (r = R) on its expansion is small. In this case

$$x_1+x_2=\alpha\int_0^h T(z')\,dz'=\frac{\alpha E_t}{\pi R^2 \rho C}, \tag{2}$$

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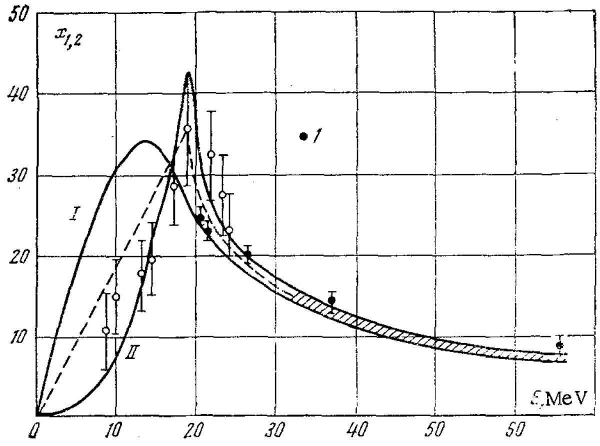

Fig. 1

where α is the coefficient of linear expansion and E_t is the total energy absorbed by the plate material. From the condition of force equilibrium at the boundary of the cylinder we obtain for x_1

$$x_1 = \frac{\alpha}{h} \int_0^h \int_0^h T(z')\, dz'\, dx. \tag{3}$$

Subtracting (3) from (2), we have for x_2

$$x_2 = \alpha \int_0^h dx \left(T(x) - \frac{1}{h} \int_0^x T(z')\, dz' \right). \tag{4}$$

The displacements x_1 and x_2 can be estimated on the basis of the approximate expression for the ionization losses of heavy charged particles in the nonrelativistic energy domain [4]:

$$-(dE/dx)_i = \beta/2E, \tag{5}$$

where β is a factor depending on the physical properties of the plate material and not on the particle energy E. Substituting expression (1) and (5) into (3) and (4) and integrating, we obtain for the displacements x_1 and x_2

$$x_1 = D \frac{\alpha E_t}{\pi R^2 \rho C}; \quad x_2 = (1 - D) \frac{\alpha E_t}{\pi R^2 \rho C}; \tag{6}$$

$$D = \begin{cases} 1 - \frac{2}{3} \frac{l}{R}, & E < E_h, \\ \left\{1 - \frac{2}{3} \frac{l}{h}\left[1 - \left(1 - \frac{h}{l}\right)^{3/2}\right]\right\} \left(1 - \sqrt{1 - \frac{h}{l}}\right)^{-1}, & E > E_h, \end{cases}$$

where $l = E^2/\beta$ is the range of a proton with energy E in the plate material and E_h is the energy for which the proton range is equal to the plate thickness h ($E_h = \sqrt{\beta h}$). Integrating expression (5), we obtain the following relation for the absorbed energy E_t as a function of E:

$$E_t = \begin{cases} NE, & E < E_h, \\ (1 - \sqrt{1 - h/l})NE, & E > E_h. \end{cases} \tag{7}$$

To investigate the low-frequency acoustic signal (detection frequency $\omega \approx 66$ kHz) excited in a thin aluminum plate ($50 \times 10 \times 0.2$ cm^3) we used the procedure described in [3]. A proton beam from the injector of the ITÉF (Institute of Theoretical and Experimental Physics) synchrotron (duration $t \approx 20.0\ \mu$sec) with an initial energy $E \approx 24.6$ MeV was collimated (diameter $d \approx 0.75$ cm) and directed onto the center of the plate. The proton beam energy was varied by passing it through a packet of copper-retarding foils placed in front of the collimator. The beam current was measured by means of an induction pickup mounted on the collimator.

Curves of the displacements x_1 (curve I) and x_2 (curve II) as a function of the proton energy E are given in Fig. 1 for an aluminum plate with a thickness $h = 0.2$ cm. Expressions (6) and (7) were used for the numerical calculation of x_1 and x_2 (solid curves). The observed peak of curve II corresponds to the energy E_h for which the proton range in the plate material is equal to the thickness of the latter (in the given case $E_h \approx 19$ MeV). The dashed curve represents half the sum of the displacements of the front and back surfaces and, according to (2), is proportional to the absorbed energy. The experimental points 1 are taken from [3].

In the interval $E \geq 20$ MeV the experimental results are in good agreement with the theoretical. Curves I and II correspond to the displacements of the plate surface in the zone of interaction with the beam. The measurement of the signal at a large distance from the beam-entry site yields a value different from the calculated value, because the excited symmetric and antisymmetric Lamb modes propagate in the plate with different speeds. It is impossible to state the exact dependence of U_ω on E, but the experimental points must fall in the domain bounded by curves I and II.

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