Detection of an acoustic signal from the muon flux in the U-70 neutrino channel

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An acoustic signal from the muon flux in the muon filter of the U-70 neutrino channel has been studied. Measurements of this signal are reported. Theoretical estimates of this signal based on a thermoacoustic mechanism for the excitation of sound are made. The agreement between the experimental and theoretical results indicates that the thermoacoustic mechanism is predominant. A possible development of this method for remote determination of the global properties of particle beams in accelerators is discussed.

INTRODUCTION

The possibility of detecting charged particles from the acoustic signals which they excite in a medium was first examined by Askar'yan.[1] This possibility has been confirmed in studies carried out by various experimental groups, who have studied this effect in liquid media[2–4] and solids[3] under extremely diverse experimental conditions. At present the thermoacoustic excitation mechanism is the predominant one, at least for such media as water and metals. According to that mechanism, the sound appears as the result of thermal expansion of the region in which energy is evolved on the track of an individual particle or a beam of particles.

According to this mechanism, when energy is evolved in a density ε in a volume V, this volume undergoes thermal expansion $\Delta V/V = \alpha\Delta T$, because of the heating $\Delta T = \varepsilon/\rho C$, where α is the thermal expansion coefficient, ρ is the density, and C is the heat capacity of the medium. The corresponding thermoelastic stress or acoustic pressure pulse is

$$\sigma = K\frac{\Delta V}{V} = \frac{K\alpha}{\rho C}\varepsilon = \Gamma\varepsilon,$$

where K is the bulk modulus, and $\Gamma = \alpha K/\rho C$ is the Grüneisen coefficient of the medium.

The proportionality between the acoustic pulse σ and the energy evolution ε thus makes it possible to estimate both the energy of the individual particles, e.g., neutrinos,[2] which generate the signals, and the intensity and energy of electron beams[3] as they pass through the medium. If the characteristics of the beams are known, one can determine the characteristics of the medium when access is difficult. For example, it has been suggested that intense neutron beams be used to scan the earth's crust.[5]

In this connection there is interest in detecting acoustic signals from the flux of muons produced during the formation of the neutrino beam in the steel muon filter of the neutrino channel of the U-70 accelerator. There are several reasons for this interest. In the first place, this topic is pertinent to the problem of determining the characteristics of a muon beam by a new remote method, involving the results of acoustic measurements. Second, the signals from the U-70 muon beam might simulate the signals from the neutrino beams of multi-TeV accelerators, e.g., the UNK. A study of a method for detecting ultraweak signals characteristic of neutrino beams[5] would naturally begin with the detection of signals with large amplitudes (with a large energy evolution) from muons and would then proceed down the energy-evolution scale to the level of the equilibrium energy evolution from a neutrino beam. This process can be carried out automatically in a muon filter. Third, there is independent interest in directly studying effects of the excitation and propagation of waves induced by a muon beam in various media in various configurations.

1. ESTIMATE OF THE ACOUSTIC SIGNAL

We can find some theoretical estimates of the acoustic signal and evaluate the possibility of detecting it in the muon filter of the U-70 neutrino channel.

The neutrino channel[6] is based on a rapidly dumped proton beam with an energy $E_p = 70$ GeV (the dumping time is $\sim 5\ \mu$s). The basic parts of the channel are the systems for extracting and transporting the proton beam; the target (an aluminum rod 10 mm in diameter and 600 mm long); a device for focusing the secondary particles which are produced in the interaction of the protons with the target; a decay channel, $l_p \approx 150$ m long, in which neutrinos and muons form as a result of the decay of the secondary particles; and, behind this decay channel, a steel absorber which serves as a muon filter. This muon filter is used to absorb the charged component of the secondary beam. It consists of sections made from steel plates with cross-sectional dimensions of 4×4.5 m and a thickness of 0.05 m. These plates are installed vertically and are surrounded with additional shielding of metal and concrete. The individual sections of this filter, ranging in length from 0.5 to 2 m, are separated by gaps in which apparatus is placed to measure the muon fluxes.[6] As a result, the characteristics of the muon flux in the filter are well known.

Figure 1a shows the total muon flux in a circle 70 cm in radius versus the depth z in the filter in the case in which there is no focusing of the secondary particles. Figure 1b shows the radial profile of the muon flux density $j_\mu(r)$ in the first gap (i.e., the first encountered by the beam). With increasing z, the exponential decay of the muon flux continues. The integral muon flux in the first gap is $N_\mu \approx 10^{11}$ muons/

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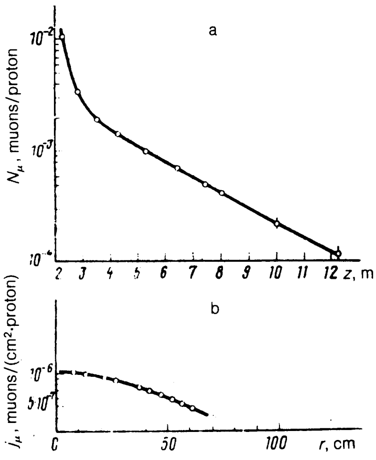

FIG. 1. a—Muon flux in a circle 70 cm in radius versus the depth z in the muon filter; b—the muon flux density j_μ versus the radius in the first gap ($z = 2.3$ m).

pulse under these conditions when 10^{13} protons/pulse are dumped on the target. The radial profile of the beam can be approximated well by

$$j_\mu(r) \sim \frac{1}{1+(r/\sigma_\mu)^2}$$

with $\sigma_\mu = 0.55$ m.

Knowing the characteristics of the beam and its energy evolution per unit length, we can easily estimate the characteristics of the acoustic pulse in a homogeneous solid medium or half-space. The boundary conditions here are not such a trivial matter. The acoustic signal is not a bipolar pulse, and its characteristics require further study.

When a detector is placed on the upper boundary of the stack (Fig. 2), we can use the expression from Ref. 5 to evaluate the bow wave of the acoustic pulse, since symmetry along the beam axis in the half-space is equivalent to the absence of a reflection loss as the sound propagates through the stack.[3] The contribution of the waves reflected from the stack boundaries affects the subsequent temporal structure of the acoustic pulse.

From Ref. 5 we have

$$S(r,t)=4A\frac{dW}{dz}\frac{I(s)}{(r\sigma_\mu^3)^{1/2}},$$

where

$$I(s)=\frac{1-s^2-s(1+s^2)^{1/2}}{8(1+s^2)^{3/4}(s+(1+s^2)^{1/2})^{3/2}},\quad A=\frac{\Gamma}{4\pi},\quad s=\frac{vt-r}{\sigma_\mu},$$

dW/dz is the energy-release density (per unit length), and r is the distance from the beam axis to the detector. For estimates we assumed $A \approx 0.1$, $r = 3.2$ m, $v = 5400$ m/s, and $dW/dz = N_\mu dE/dz \approx 10$ J/m (with $E_\mu \approx 10$ GeV we would have $dE_\mu/dz \approx 1.6$ GeV/m $\approx 2.5 \cdot 10^{-10}$ J/m). The bow wave of the acoustic pulse is shown in Fig. 3a; its frequency spectrum is shown in Fig. 3b.

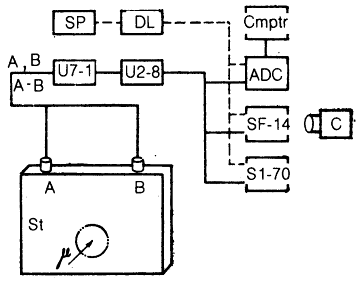

FIG. 2. Block diagram of the experimental apparatus. St—Steel stack of muon filter; μ—muon beam; A, B—acoustic transducers; U7-1, U2-8—amplifiers; SF-14, S1-70—Oscilloscopes; C—camera; ADC—analog-to-digital converter; SP—sync pulse; DL—delay line.

Since the height and width of the rectangular plates of the filter are comparable, while the thickness of these plates is much smaller than either the height or the width and also much smaller than the length of the wave which is excited, it is by no means a simple matter to analytically determine the radiation field in a system with a geometry of this type. To find some estimates, we used a simplified method involving a finite number of imaginary sources, formed as a result of repeated reflections of the acoustic wave from the stack boundaries.[7] This simplification is not completely legitimate here, since it eliminates the interaction of the longitudinal and shear waves at the free surfaces which occurs in solids. Nevertheless, this approach seems justifiable in a study of the leading edge of the signal and the initial stages in the development of the oscillations.

Figure 4 shows the results of the numerical calculations. We clearly see the appearance of oscillations with characteristic frequencies determined by the geometric dimensions of a plate. Since the reflection coefficient of the steel-air interface is very close to unity, and since the quality

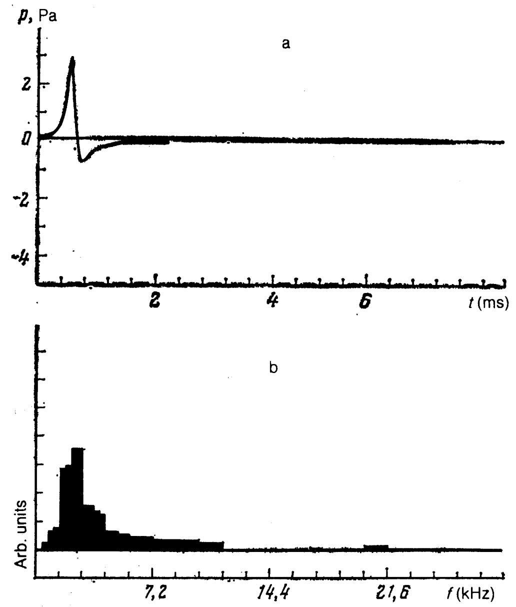

FIG. 3. (a) Temporal structure and (b) frequency spectrum of an acoustic signal without reflections.

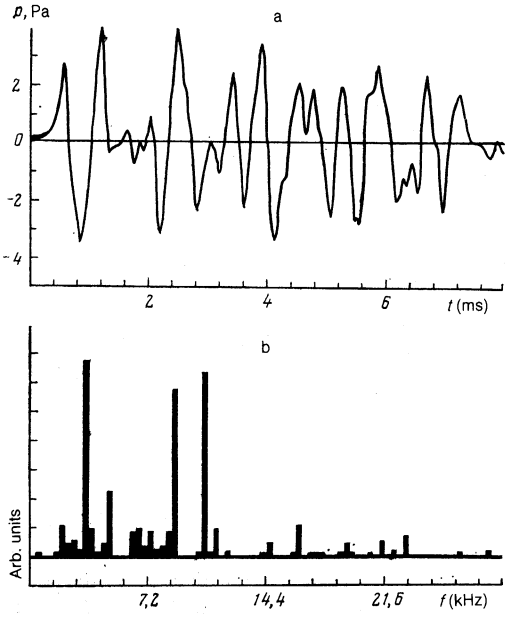

FIG. 4. (a) Temporal structure and (b) frequency spectrum of an acoustic signal in transducer A.

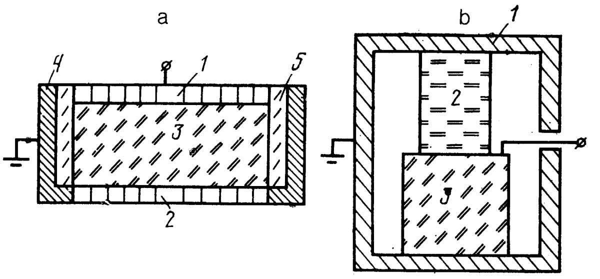

FIG. 5. Acoustic pulse detector. A: 1—Upper electrode; 2—lower electrode; 3—ceramic piezoelectric plate; 4—metal ring; 5—epoxy cement. B: 1—Metal cup; 2—cork cylinder; 3—ceramic piezoelectric plate.

factor of a plate as an oscillator system is extremely high, the damping of the oscillations was ignored in this case.

To study the possibility of detecting these signals, we estimate the signal-to-noise ratio, using a method similar to that of Ref. 5. For the parameter values given above for the muon beam in the first gap, the signal-to-noise ratio is 50, so the acoustic signal could be detected. In these estimates we are assuming that the excitation of the acoustic signal occurs during rapid dumping of the proton beam in the U-70, which is used to produce a neutrino beam for physics experiments. It is thus possible to carry out these experiments simultaneously.

The amplitude of the acoustic noise in Ref. 5 corresponds to a "quiet" place on the earth's surface. The amplitude of the acoustic noise and that of the stray pickup in the U-70 muon filter in the course of neutrino experiments are not known. They must be measured directly.

The reduction of the muon flux by four orders of magnitude in the succeeding gaps of the muon filter[6] makes it possible to work with signal-to-noise ratios in the range 10–10^{-2} and to carry out physical modeling of the detection of acoustic signals from the neutrino beam of the UNK.

2. EXPERIMENTAL APPARATUS

Let us discuss the apparatus (Fig. 2) used to detect and analyze the acoustic signals. We will focus on the devices which detect the sound waves.

There are many methods for detecting and measuring weak acoustic signals, among which we might distinguish optical methods[8] and methods based on the piezoelectric effect.[9] Although optical methods are highly sensitive, they are complex and difficult to implement in practice. Although piezoelectric transducers have a slightly lower sensitivity, they are the simplest devices to fabricate, and they are the most reliable in operation. Accordingly, piezoelectric transducers were used in preliminary studies in the muon filter.

Two transducers were fabricated for measurements (Fig. 5, a and b). In the first design, a piezoelectric plate 3, with a thickness of 4 mm and with thick metal electrodes 1 and 2, is placed inside a metal ring 4 in order to reduce electromagnetic stray pickup. A cylindrical weight (50–70 g) on the transducer provides good acoustic contact.

The second transducer (Fig. 5b) is a cylindrical cup 1, which holds a ceramic piezoelectric sample 2, with a thickness of 50 mm. This sample is pressed against the bottom of the cup by a cork cylinder 3, under compression. The transducer is loaded with a 5-kg weight to achieve good acoustic contact. Despite their structural differences, the two transducers exhibit approximately the same sensitivity and approximately the same frequency characteristic. Their sensitivity is $\varkappa \approx 2000$ mV/μm and varies only slightly with frequency over the range 1–10 kHz.

The transducers were placed on the stack of the muon filter in the first gap encountered by the beam, in some specially prepared areas A and B, as shown in Fig. 2. The transducers made acoustic contact with the surface at their lower ends. A thin layer of glycerin was used to improve the contact.

The output signals from the transducer connectors were sent through U7-1 and U2-8 amplifiers in succession to an S8-14 storage oscilloscope and to a digitization unit. The basic advantages of these amplifiers are their high input impedance, their low noise level, the ability to vary the passband, and the ability to use a difference signal.

These signals were detected with an S1-70 oscilloscope, an S8-14 storage oscilloscope (for photography of oscilloscope traces), and a signal digitization system. The data were then fed to a computer. The digitization was carried out in 1000 channels each 10 μs wide. The range of signal amplitudes which could be detected by the system was from 0 to 2 V; it corresponded to 2000 samplings.

The oscilloscopes and the digitization system were synchronized by a special pulse from the neutrino channel of the Institute of High-Energy Physics, which comes 165 μs before the passage of the muon beam and which goes into a delay line.

3. EXPERIMENTAL RESULTS

Oscilloscope traces of the acoustic signal from the muon beam were obtained at a delay of 300 μs. These traces are shown in Fig. 6, for approximately equal intensities of the proton beam but for various time and amplitude sweep rates of the S8-14 oscilloscope. The frequency range of the signal received, 1–10 kHz, corresponds to the main part of the spectrum of the acoustic pulse (Fig. 4b) and lies in a region with a reduced noise amplitude.

The characteristic temporal structure of the signal immediately rules out the white-noise hypothesis, and the arrival time of the bow wave at the detector (at a delay of 600 μs) is evidence that the signal is of an acoustic nature. The arrival time of the acoustic wave at a velocity of 5400 m/s, characteristic of a steel plate,[10] at a detector at a distance of 3.26 m would be 605 μs.

The amplitude of the bow wave of the acoustic signal corresponds to the theoretical estimates of the pressure pulse (Figs. 3a and 4a) found with allowance for the coefficient $\varkappa$ from the expression[3]

$$p = \frac{\Delta U}{\varkappa} \frac{\rho v}{t_{\text{pulse}}},$$

where ΔU is the height of the signal, in microvolts, and $t_{\text{pulse}} \approx 500$ μs is the length of the bow pulse. The observed agreement between the theoretical prediction (Fig. 4) and the measured signal (Fig. 6) in terms of height, temporal structure, and frequency spectrum is evidence that the thermoacoustic mechanism is dominating the excitation of the acoustic signal.

The increase in the signal amplitude $\sim 1000\,\mu$s after the arrival of the bow wave and the period of this signal, ~ 1 ms, characterize a transition of the frequency spectrum of the signal into the natural vibration spectrum of the stack—the stack starts "ringing." This ringing lasts ~ 0.5 s.

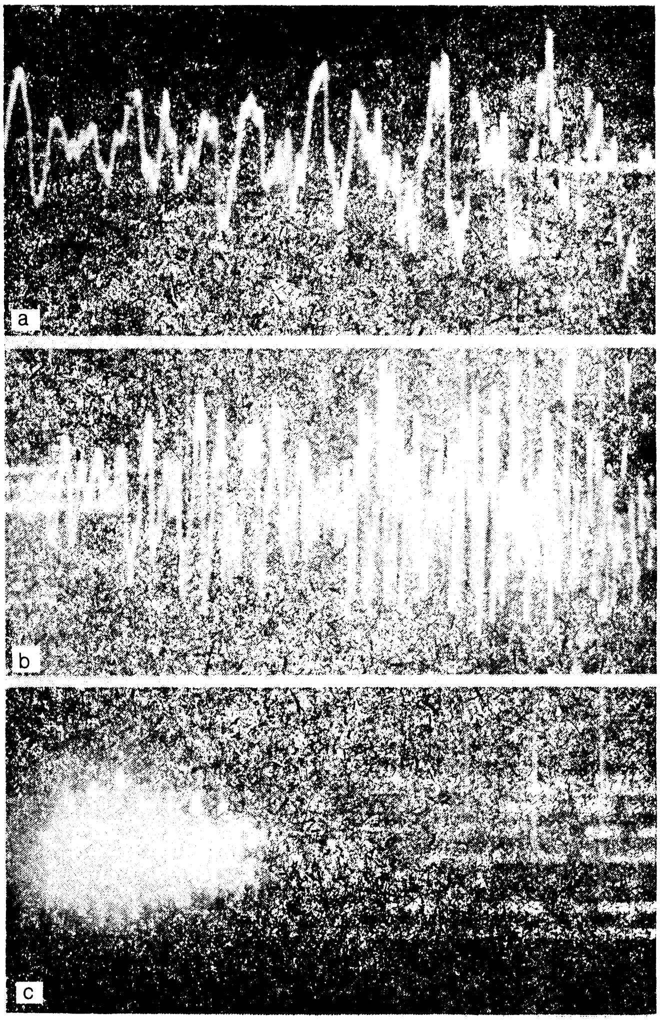

FIG. 6. Oscilloscope traces of the acoustic signals at various sweep rates. A—1 ms/div; B—2 ms/div; C—50 ms/div. The number of protons on the target is $N_p = 1.2 \cdot 10^{13}$ protons/pulse.

CONCLUSION

This study constitutes the first few steps toward the detection of an acoustic signal from a muon beam in the steel shielding of the neutrino channel of the U-70. The results obtained here showed that it is possible in principle to use this signal for diagnostics in experiments with muon and neutrino beams. The characteristics of the signal agree qualitatively with a thermoacoustic mechanism for the excitation of the signal. There is a need for some more-detailed studies aimed at resolving the questions of the dynamic range over which this method is applicable, the suppression of noise effects, and the stability. There is also interest in the physics of the process itself. All these considerations provide motivation for further work in this direction.

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