Decay of a high-energy pion beam in a medium: Formation of a decay channel

G. A. Askar'yan
Institute of General Physics, Academy of Sciences of the USSR

(Submitted 8 May 1985)
Pis'ma Zh. Eksp. Teor. Fiz. **41**, No. 12, 533–535 (25 June 1985)

The nonlinear transport of a pion beam in a medium is analyzed. The energies of the pion beams from the latest generation of accelerators are sufficient to reduce the density of the medium (a gas or liquid) and to form a decay channel which reduces the energy loss and angular divergence of a beam of pions and neutrinos.

The possibility of producing directed beams of high-energy neutrinos by means of proton ring accelerators[1] or pion linear accelerators[2], producing pion beams with energies $\simeq$1 TeV (10^6 MeV), has recently sparked a lively discussion. During the decay of such pions in decay channels, an intense, highly directed beam of neutrinos forms with

 0021-3640/85/120651-04$01.00

an angular divergence[1] of 10^{-5} rad. Such beams could be used, for example, to study the earth[3,1] or for geological exploration. It has been suggested that the neutrino beam could be detected, and the properties of rock formations evaluated, on the basis of the acoustic pulses[1,4–7] or the electromagnetic fields[4,8,9] which arise from the resulting showers and muons and also on the basis of the muons themselves.[1]

Because of the high energies of the pions, however, their decay lengths $L \simeq \tau_0 c/\sqrt{1-\beta^2} \simeq \tau_0 c \mathscr{E}_\pi / \mathscr{E}_{0\pi} \sim$ are several tens of kilometers at the decay half-life $\tau_0 \simeq 3\times 10^{-8}$s of a pion at rest, with $\mathscr{E}_{0\pi} \simeq 150$ MeV and $\mathscr{E}_\pi \simeq 1$ TeV. Even if we restrict the discussion to vacuum decay channels several kilometers long, in practice it would be difficult to develop the facilities which would be required for moving channels of such dimensions in the vertical and horizontal dimensions. This is at present the main difficulty in implementing this idea in neutrino research.

On the other hand, it does not appear possible to do without decay channels, since pions in media lose energy and directionality rapidly in nuclear interactions before they decay.

In this letter we wish to point out that the energies of the proton and pion beams in such accelerators ($N_p \gtrsim 10^{15}$, $\mathscr{E}_p \simeq 30$ TeV, $N_\pi \sim 3\times 10^{15}$, and $\mathscr{E}_\pi \gtrsim 1$ TeV; Ref. 1) are sufficient to give rise to nonlinear processes—decreases in density, energy loss, or beam scattering—in media; i.e., these energies are sufficient to form a decay channel which would provide a high directionality for a neutrino beam during the decay of pions.

At the pion energies $\mathscr{E}_\pi \gtrsim 1$ TeV in which we are interested, the primary mechanism for the loss of energy and directionality of the particles is represented by nuclear interactions which give rise to hadron-electron-photon cascades, ionization losses, and multiple scattering.

The scale length for the nuclear interaction, $L_n \simeq (10^2\ \text{g/cm}^2)\times\rho$, is on the order of a kilometer in air and on the order of a meter in water. At such energies, ~ 10 pions are produced in nuclear interaction events. The lengths of the cascades are several nuclear lengths, $L_c \simeq 3L_n \simeq (3\times 10^3\ \text{g/cm}^2)\times\rho$, and the transverse dimensions are $a \simeq \theta_{\text{eff}} L_c \simeq (1\ \text{g/cm}^2)\times\rho$, where $\theta_{\text{eff}} \sim \mathscr{E}_{0\pi}/2\mathscr{E}_\pi$. The volume of the cascade generated by a beam, $V_c \simeq \pi a^2 L_c \simeq [10^4\ \text{g/cm}^2)^3]/\rho^3$, determines the average energy-evolution density, $\langle q_c \rangle \simeq Q/V_c$, and the energy-evolution density at the axis, $q_c(0) \simeq 3\langle q_c \rangle \simeq 3Q/V_c \simeq [Q\rho^3/(3\times 10^3)]$ (erg/cm^2). Pronounced changes in the properties of the medium should be expected when the energy evolution q becomes comparable to the density of the internal energy of the medium, $q^* \simeq \rho c_s^2$, where ρ is the density, and c_s is the velocity of sound in the medium. We see that the ratio $\alpha = (q_c(0))/q^* \simeq (3\times 10^{-4} Q\rho^2)c_s^2$ is extremely sensitive to the density of the medium and to the beam energy. For a proton beam with $Q \simeq N_0 \mathscr{E} \simeq 5\times 10^{16}$ erg (Ref. 1) and $c_s^2 \simeq 10^9$ cm^2/s^2 (air), we would have $\alpha_c \simeq 10^{-1}$ at normal pressures, while for water we would have $\alpha_c \gtrsim 10^3$. For a pion beam we would have $\alpha_c \simeq 10^{-2}$ and $\alpha_c \simeq 10^2$ for air and water, respectively.

It can be seen from these estimates that a dense medium allows a 1000-fold multistep channel formation, over a distance L_c each time, i.e., over a total distance $L \simeq 10^3 L_c \gtrsim 3$ km. At a transverse expansion velocity $u_\perp \sim \sqrt{p/\rho} \simeq 10^3$ cm/s we find the rate of growth of the channel to be $u \sim L_c/\tau_\perp \simeq L_c u_\perp/a_\perp \simeq 3\times10^5$ cm/s, and we find the time required for the formation of the entire channel to be $T \sim L/u \sim La_0/L_c u_\perp \simeq 1$ s. We note that it is sufficient to evaporate a small fraction of the liquid in the beam volume: The resulting vapor will displace the remainder. During the expansion of the liquid, the gas pressure in the cavity may drop sharply (the inertia of the liquid opposes the external pressure); this circumstance is particularly important for the part of the channel at large depths.

It is important to note that cylindrical discontinuities may form in the liquid even at small values of $q \ll \rho c_s^2$, at which the negative pressure in the rarefaction phase in the thermoacoustic wave is $p_s \simeq \Gamma q \gtrsim p_{\rm disc}$, where Γ is the Grüneisen coefficient of the medium ($\Gamma \sim 1$). Because of dissolved gas and suspensions in the liquid, the conditions $p_{\rm disc} \simeq \Delta p_{\rm ext} < p_{\rm ext} \ll \rho c_s^2$ hold. At a standard external pressure, $p_{\rm disc}$ and q differ from ρc_s^2 by four orders of magnitude.

Let us examine in more detail the formation of a channel in a gaseous medium or in a vapor in a channel in a liquid or a solid.

The change in the gas density for a given energy-evolution density in the case of a subsequent adiabatic or isobaric expansion is described by $(\rho/\rho_0) = \{1 + (\gamma - 1)q/p_0\}^{-k}$, where $k \in 1 \propto 1/\gamma$, and γ is the adiabatic index. We see that the condition $q_c \ll q^*$ holds because of the pronounced expansion of the energy-evolution volume in a gas of normal density.

It can be shown, however, that in a low-density medium, over distances small in comparison with L_c, the ionizational loss of the primary beam may result in a far greater energy-evolution density before energy spreading begins.

Specifying the energy loss per unit path length of a beam on N particles with a cross-sectional area s_0,

$$q_{ion} \simeq \frac{N}{s_0}\frac{dE_1}{dx} \simeq \frac{N}{\pi a_0^2}\frac{dE_1}{dx_m}\rho ,$$

where the specific energy loss of each particle is $dE_1/dx_m \simeq 2$ MeV · cm^2/g, and comparing with $q^* \simeq \rho c_s^2$, we find

$$\frac{q_{ion}}{q^*} = \frac{N}{\pi a_0^2} 3\times10^{-15} \sim 3\times10^{-15} N$$

with $s_0 \simeq 1$ cm^2; i.e., we should expect the nonlinear effects to set in at $N \simeq 3\times10^{14}$ particles. If the total number of particles is $N_\pi \simeq 3\times10^{15}$ (we are using a tenfold meson production multiplicity), we can thus form a channel of length $L \gtrsim 10L_1 \simeq 3$ km in a time $T \simeq 10a/c_s \simeq 0.3$ ms. At higher densities of the gas and the vapor, the energy-evolution density increases; this circumstance is important at large depths.

As meson beams pass through a gaseous medium, a magnetic self-contraction and a gas-induced focusing may occur. The focusing results from the accumulation of excess ions at the axis and the escape of electrons.

The increase in the number of particles in the beam and the contraction of the beam make the processes discussed here even more effective. In particular, it is also possible to discharge a primary proton beam into a medium (the medium serves as a target).

A decrease in the density of the medium over the path of the meson beam sharply reduces the scattering of the beam through nuclear interactions and multiple scattering. The multiple-scattering angle is $\theta_s \simeq [(20\text{ MeV})/\mathscr{E}]\sqrt{L/L_{\text{rad}}} \simeq 2\times 10^{-5}$ rad over a distance $L_1 \sim L_{\text{rad}}$ ($\sim$0.3 km in air under standard conditions or $\sim$30 cm in water).

The net result is to conserve the energy and preserve the directionality of the mesons and neutrinos.

[1]A. De Rújula, S. L. Glashow, R. Wilson, and G. Charpak, Phys. Rep. **99**, 341 (1983).
[2]V. E. Balakin and A. N. Skrinskiĭ, Lineĭnye vstrechnye puchki-perspektivy razvitiya (Collinear Colliding Beams: Outlook for Development), Izd. MIFI, Moscow, 1984.
[3]L. V. Volkova and G. T. Zatsepin, Izv. Akad. Nauk SSSR, Ser. Fiz. **38**, 1060 (1974).
[4]G. A. Askar'yan, Usp. Fiz. Nauk **144**, 523 (1984) [Sov. Phys. Usp. **27**, 896 (1984)].
[5]G. A. Askar'yan, At. Energ. **3**, 152 (1984).
[6]G. A. Askar'yan, and B. A. Dolgoshein, Pis'ma Zh. Eksp. Teor. Fiz. **25**, 232 (1977) [JETP Lett. **25**, 213 (1977)].
[7]G. A. Askar'yan, B. A. Dolgoshein, A. N. Kalinovsky, and A. V. Mokhov, Nucl. Instrum. Meth. **164**, 267 (1979).
[8]G. A. Askar'yan, Zh. Eksp. Teor. Fiz. **41**, 616 (1961) [Sov. Phys. JETP **14**, 441 (1962); **48**, 988 (1965) [Sov. Phys. JETP **21**, 658 (1965)].
[9]G. A. Askar'yan, Pis'ma Zh. Eksp. Teor. Fiz. **39**, 334 (1984) [JETP Lett. **39**, 402 (1984)].

Translated by Dave Parsons