“Direct” component in the neutrino beams from accelerators

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Expressions are derived for the flux of equilibrium muons from neutrinos produced in the production and subsequent decay of charmed particles. At high energies of the primary protons and with short decay baselines, this mechanism is more prolific than the mechanism involving the production and decay of π and K mesons.

Let us consider the mechanism of “direct” production of neutrinos, involving the production and subsequent decay of charmed particles. At present-day accelerator energies this mechanism is responsible for a relatively small fraction of the neutrino beams which are produced, but for accelerators of the next generation, with $E_p \sim 3$–30 TeV, the situation may change. At these energies, the decay lengths of the π and K mesons are very large,[2)] and only a very small fraction of the π and K mesons have time to decay over relatively short decay baselines ($l \lesssim 1$ km). For charmed particles, with lifetimes shorter by five orders of magnitude (and large masses), this hindrance has not yet come into play. For exampler, for Λ_c^+ with $\tau_{\Lambda_c^+} = 1.1\times10^{-13}$ s and $\langle E_{\Lambda_c^+}\rangle = 0.4E_p$ we would have $l_{\rm decay}(\Lambda_c^+) = 5.8$ cm ($E_p = 10$ TeV). The small value of the cross section for production of charmed particles may thus be offset by the absence of the decay hindrance. This circumstance was pointed out by Volkova and Zatsepin.[2]

To calculate the spectrum of direct neutrinos and the flux of equilibrium muons which arise as these neutrinos pass through matter, we take the approach of Refs. 3 and 4, where the decays of π and K mesons were taken into account under the same approximations and with the same notation.

We consider the associative production of Λ_c^+ and $\bar{D}^*$ (followed by the rapid decay $\bar{D}\to\bar{D}^0$), and we parametrize the cross section as

$$E\frac{d\sigma}{d^3p} = \frac{\sigma}{\pi}(n+1)bx(1-x)^n \exp(-bp_T^2), \tag{1}$$

where $\sigma = \sigma(E_p)$ is the total cross section for associative production. From (1) we find $\langle E\rangle \approx E_p/(n+2)$. We choose the decay spectrum of $\Lambda_c^+\to\nu + X$ and $\bar{D}^0\to\bar{\nu}+X$ in the form[5]

$$E_\nu\frac{dN}{d^3p_\nu} = Cg(s),$$

$$g(s) = (m^2 - s)(s - m_X^2)^2(2s^2 + s(m^2 + m_X^2) + 2m^2m_X^2)/s^3, \tag{2}$$

$$s = m^2 - 2E_\nu(E - p\cos\theta_\nu).$$

Here $C = C(m_X/m)$ is a normalization constant, and m and m_X are the masses of the charmed particle and of the X system. From (1) and (2) we find an expression for the muon flux (N_μ) through a detector of radius R at the beam axis at a distance L from the accelerator [see expression (4) in Ref. 3]:

$$N_\mu = A(m_X/m, n)\frac{\sigma'(1+0{,}5\beta)N_A w}{2\alpha m^2}\,\frac{\sigma}{\sigma_{\rm abs}}E_p^4\left(\frac{R}{L}\right)^2 . \tag{3}$$

Here $\sigma'_\nu = 0.63\times10^{-38}$ cm^2/GeV, $\beta_\nu = 0.13$, $\sigma'_\nu = 0.12\times10^{-38}$ cm^2/GeV, $\beta_{\bar{\nu}} = 5.4$, $N_A = 6\times10^{23}\,\Gamma^{-1}$, $(2\alpha)^{-1} = 165\,\Gamma\,\mathrm{cm}^{-2}\cdot\mathrm{GeV}^{-1}$ (for water), $\sigma_{\rm abs} = 32$ mb, and w—the probability for the leptonic decay mode—is 0.045 for Λ_c^+ and 0.06 for $\bar{D}^0$. For numerical calculations we assmed $n = 0.4$ (Ref. 6) for Λ_c^+ and $b = 2.3$ GeV^{-2}, and for $\bar{D}^0$ we assumed $n = 1$ and $b = 1$ GeV^{-2} (Ref. 7). We omit the very lengthy expression for the quantity $A(m_X/m, n)$. For the cases of interest here we have the values (1) $m_X = 1.1$ GeV and $A = 0.023$ for Λ_c^+ and (2) $m_X = 0.5$ GeV and $A = 0.013$ for $\bar{D}^0$. (For obvious reasons, we are assuming that there is no focusing for the charmed particles.) We take the values of the cross section $\sigma(E_p)$ to be 0.1, 0.4, 0.45, 0.47, and 0.5 mb at $E_p = 1$, 3, 10, 20, and 30 TeV, respectively. The spectrum of neutrinos from the decays of Λ_c^+ and $\bar{D}^0$ is

$$\frac{dN}{dE_\nu} = B(\xi, n)\frac{\sigma}{\sigma_{abs}}\,\frac{w}{E_p}\int_{E_\nu/(E_p\eta)}^{1}(1-x)^n\frac{dx}{x}F(\xi, s_x). \tag{4}$$

Here $\xi = m_x^2/m^2$, $\eta = 1-\xi$, $s_x = 1 - E_\nu/(E_px)$

$$F(\xi, s_x) = -\frac{2}{3}s_x^3 + \frac{1}{2}(1+3\xi)s_x^2 + (1-3)s_x + \xi^2(3+\xi)s_x^{-1}$$
$$-\xi^3s_x^{-2} + \xi^2(3-\xi)\ln(s_x/\xi) - \frac{5}{6}\xi^3 + \frac{3}{2}\xi^2 - 3\xi$$

and $B(\xi,n) = 2(n+1)/(1 - 8\xi + 8\xi^3 - \xi^4 - 12\xi\ln\xi)$.

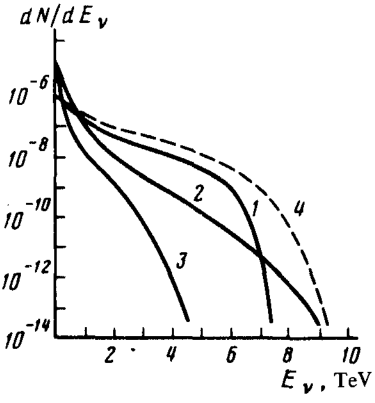

FIG. 1. Components of the neutrino spectrum due to the decay of the following particles: 1—Λ_c^+; 2—K^+ mesons; 3—π^+ mesons; 4—antineutrinos from $\overline{D}^0$, per interacting proton at $E_p = 10$ TeV and $l = 0.1$ km.

The spectrum of neutrinos from π and K mesons could be calculated in a similar way.[3,4]

Figure 1 shows the contributions to the spectrum of neutrinos and antineutrinos calculated for various particles. Figure 2 shows the contributions to the equilibrium muon flux in water from $\Lambda_c^+ + \overline{D}^0$ and $\pi + K$ (from Ref. 4) It can be seen from Fig. 2 that we have $N_\mu(\Lambda_c^+ + \overline{D}^0) \gtrsim N_\mu(\pi + K)$ for $l = 1$ km and $E_p = 30$ TeV, for $l = 0.1$ km and $E = 2.5$ TeV, and for $l = 0.01$ km and $E = 1$ TeV.

The most important practical conclusion to be drawn from these results is that at high energies it is possible to use very short decay channels in the case of direct neutrinos. This possibility dramatically simplifies the use of neutrino beams from multi-TeV accelerators for geology,[1] geodesy, etc.

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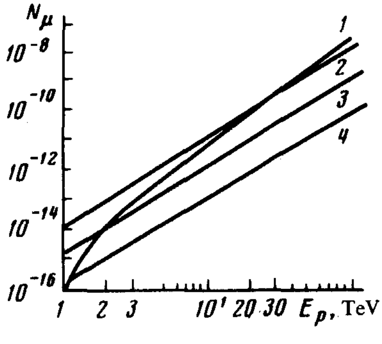

FIG. 2. Components of the equilibrium flux of muons in water per interacting proton for $L = 10^3$ km and $R = 20$ m. 1—$(\Lambda_c^+ + D^0)$; 2—$(\pi + K)$ with $l = 1$ km; 3—$(\pi + K)$ with $l = 0.1$ km; 4—$(\pi + K)$ with $l = 0.01$ km.

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[2] In a study of the use of neutrino beams from multi-TeV accelerators in Ref. 1, for example, decay channels $l = 7.5$ km long for π and K mesons were discussed ($E_p = 10$ TeV).

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