Production of high-energy muons in extensive air showers from primary γ rays

V. A. Kudryavtsev and O. G. Ryazhskaya
Institute of Nuclear Research, Academy of Sciences of the USSR

(Submitted 7 August 1985)
Pis'ma Zh. Eksp. Teor. Fiz. **42**, No. 7, 300–302 (10 October 1985)

The primary mechanism for the production of high-energy muons ($E_\mu > 5$ TeV) in extensive air showers from primary γ rays is the production of muon pairs by shower photons in the field of a nucleus.

Interest in the production of high-energy muons in extensive air showers caused by γ rays arose in connection with the experimental discovery, in the underground NUSEX apparatus, of a significant flux of muons with $E_\mu \geqslant 5$ TeV correlated with the direction to the Cygnus X-3 source of high-energy γ rays.[1–6]

It has previously been believed that the primary mechanism for the production of muons in electromagnetic showers is the photoproduction of π and K mesons, followed by their decay. The direct production of muon pairs in a nuclear field by shower γ rays has not been considered. However, precisely this process should contribute significantly to the production of high-energy muons in extensive air showers caused by primary γ rays, as can be seen from the following considerations. For an air atom we have the cross section $\sigma_{\gamma\to\mu_2} \pm \sim 1.2\times 10^{-29}$ cm^2. The cross section for an inelastic γA interaction is $\sigma_{\gamma A} \sim 10^{-27}$ cm^2/atom. Despite the large multiplicity, the mesons are produced with a rather soft spectrum; i.e., the production of high-energy pions and kaons is suppressed. An additional suppression factor arises from the decrease in the probability for meson decay with increasing energy: $W_p \sim E_0/E_{\pi,K}$. For energies $E_\pi \geqslant 5$ TeV we have $W_p \leqslant 0.024$. Estimates put the flux density of "direct" muons with $E_\mu \geqslant 5$ TeV, produced in a shower with an energy of 5×10^{13} eV, at a level more than twice the flux density of muons from decays.

If the primary γ rays have a power-law spectrum, the spectrum of direct muons will reproduce it, while the spectrum of decay muons will have an exponent one unit

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larger. As a result, the role of the direct process will increase linearly with the energy. High-energy muons ($E_\mu \geqslant 10$ TeV) are produced primarily in the direct production of $\mu^+\mu^-$ pairs.

We have calculated the flux densities of muons for both mechanisms. We take the spectrum of primary γ rays to be $(dN_\gamma/dE_\gamma)dE_\gamma = A(dE_\gamma/E_\gamma^{\gamma_1+1})$, where γ_1 is 1, 1.1, 1.3, 1.5, 1.75, or 1.9. The case $\gamma_1 = 1$ corresponds to the spectrum of the Cygnus X-3 source,[4] which is cut off at $E_\gamma = 10^{16}$ eV. We accordingly introduce a cutoff at the same energy in the calculations. The muon flux density is found by evaluating a triple integral

$$N_{\mu i}(>E_\mu) = \int_{E_\mu}^{E_{\mu max}} dE_\mu P_i \int_{E_i}^{E_{i max}} \frac{d\sigma(E, E_i)}{dE_i} dE \int_{E}^{E_{max}} \frac{dN}{dE}\frac{dN_\gamma}{dE_\gamma} dE_\gamma ,$$

where $i = \pi, K, \mu$; $(dN/dE)dE$ is the equilibrium spectrum of γ rays in the shower[7]; $d\sigma(E, E_i)/dE_i$ with $i = \pi, K$ is the inclusive spectrum of pions (kaons), while with $i = \mu$ it is the cross section for the production of a $\mu^+\mu^-$ pair; and $P_{\pi,K} = C_{\pi,K}/E_{\pi,K}$ for a calculation of the spectrum of decay muons. In the production of direct muons we have $P_\mu = 2$ if both of the muons have energies above E_μ, or we have $P_\mu = 1$ if this is true for only one of the muons. We take $(d\sigma/dE_\mu)dE_\mu$ from Ref. 8 and $(d\sigma/dE_\pi)dE_\pi$ from Refs. 9 and 10, with and without adherence to scaling (models I and II, respectively). Since we do not have inclusive spectra for K mesons in the γA interaction, we can do no more than estimate the flux density of muons from kaons, according to which we would have $N_{\mu K} \approx (0.3 - 0.4)N_{\mu\pi}$.

In the calculation of P_π, it is assumed that the high-energy pions in the shower are produced at the same height in the atmosphere as the pions from primary protons ($x \sim 120$ g/cm^2). We ignore the secondary pion-nucleus interaction, since estimates show that it is inconsequential for the production of high-energy muons.

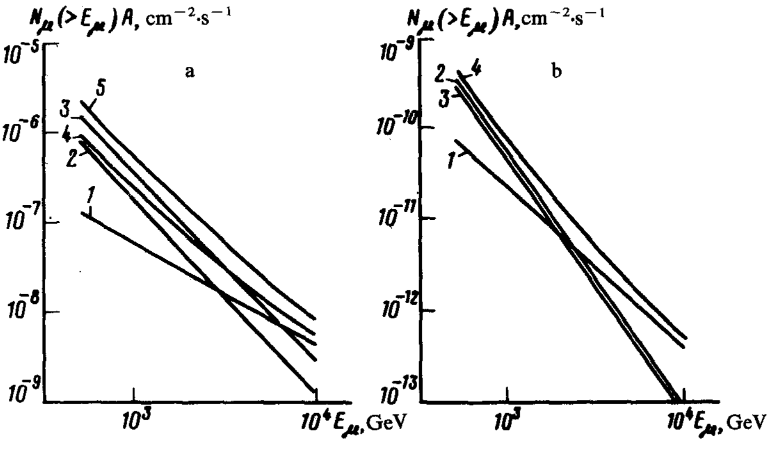

FIG. 1. Integral spectra of muons from primary γ rays. a: $\gamma_1 = 1.0$. b: $\gamma_1 = 1.75$. 1—$\gamma \to \mu^+\mu^-$; 2—$\gamma A \to \pi^\pm \to \mu^\pm$, model I: 3—$\gamma A \to \pi^\pm \to \mu^\pm$, model II; 4—sum of 1 and 2; 5—sum of 1 and 3 with a 40% contribution from K mesons.

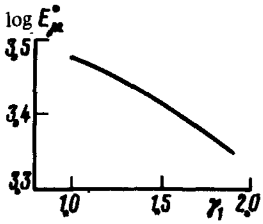

FIG. 2. E_μ^0 as a function of γ_1.

Figure 1 shows integral muon spectra for two exponents of the primary spectrum: $\gamma_1 = 1.0$ and 1.75. All the spectra have been multiplied by the normalization factor A of the primary spectrum. The muon intensity found in model II is twice that found in model I with $\gamma_1 = 1.0$ or 1.22 times smaller with $\gamma_1 = 1.75$. The explanation is that in model II (with a violation of scaling) there are increases in the multiplicity and cross section for meson production, and the inclusive spectra are far softer than in model I. For this reason, with a gently sloping primary spectrum, small values of x_F (x_F is the Feynman variable) contribute substantially to the π flux density. The integral muon spectra found are described by the power law $N_\mu(>E_\mu) = N_\mu^0 E_\mu^{-\gamma_\mu}$. We see that for the process $\gamma \to \mu^+\mu^-$ the values of γ_μ are approximately equal to γ_1. The small difference is due to the cutoff of the primary spectrum at an energy of 10^{16} eV. The difference $\gamma_\mu - \gamma_1$ falls off with increasing γ_1. The same effect is observed for the flux densities of muons from the reactions $\gamma A \to \pi^\pm \to \mu^\pm$, but in this case we have $\gamma_\mu - \gamma_1 \sim 1$.

From Fig. 1 we can find the energy E_μ^0 above which more than 50% of the total muon flux density comes from the production of muon pairs by a γ ray in the field of a nucleus. Figure 2 is a plot of E_μ^0 as a function of γ_1. The flux density of muons from the inelastic scattering of γ rays is taken from model I in this case. With increasing γ_1, the value of E_μ^0 decreases. At $E_\mu > 3$ TeV, however, the direct-production mechanism is predominant for all values of γ_1. Models I and II appear to represent two extreme cases. The actual value of the muon flux density from the inelastic scattering of γ rays should lie between these extreme values.

The overall muon spectrum $N_{\mu\gamma}(E_\mu)$, in showers produced by the spectrum of primary γ rays has a varying exponent, which varies from $\gamma_1 + 1$ at energies $E_\mu < 0.5$ TeV to γ_1 at energies above 10 TeV. This circumstance sharply distinguishes $N_{\mu\gamma}(E_\mu)$ from the spectrum of muons produced by primary nucleons, $N_{\mu p}(E_\mu)$, for which we have $\gamma_\mu = \gamma_1 + 1$. It should be noted that at 10 TeV the flux density of direct muons is more than 70% of the total flux density.

The maximum muon flux density, found in our calculations with model II, with a 40% contribution from kaons, and with the value $A = 10^{-6}$ cm^{-2}·s^{-1}·GeV^{-1} from Ref. 11, is smaller by a factor of 30 than the flux density measured at the NUSEX apparatus if we set the threshold energy E_n at 3 TeV. The difference increases to a factor of 80 if we set $E_n = 5$ TeV.

We wish to thank G. T. Zatsepin and V. S. Berezinskiĭ for useful discussions of this study.

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Translated by Dave Parsons