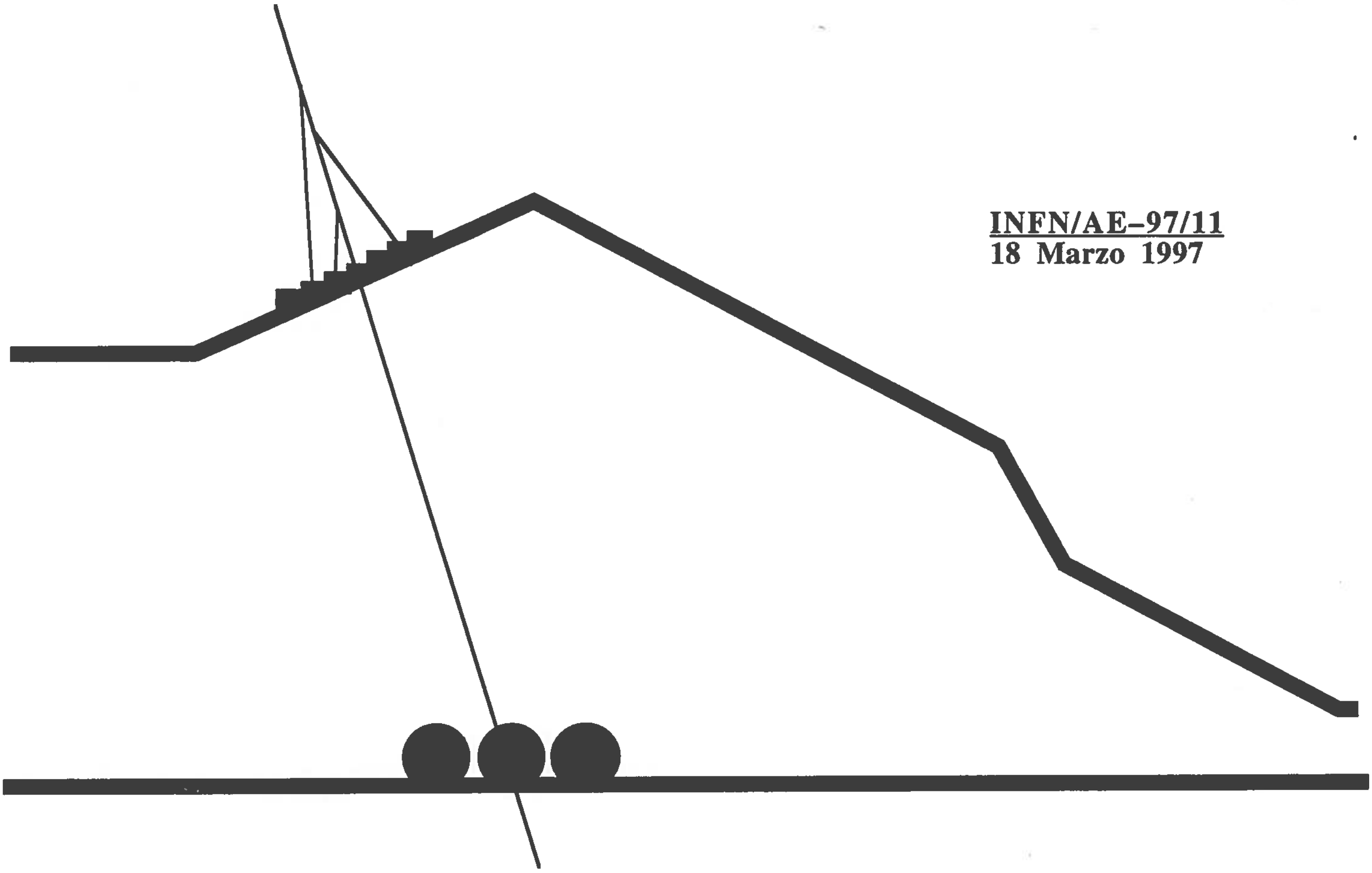

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ROLE OF THE ELECTROMAGNETIC PROCESSES IN THE HIGH-ENERGY MUON PRODUCTION

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Abstract

The muon pair production by gamma's in the atmosphere is discussed as a mechanism of "prompt" muon production at very high energies. It is shown that this process dominates over the conventional muon production through pion and kaon decay at energies greater than several PeV.

It is well known that the main process of muon production in the atmosphere is the decay of pions and kaons which dominates up to at least 50 TeV. The spectrum of cosmic-ray muons at the sea level is steeper than the spectrum of primaries and the spectrum of muon parents (pions and kaons) due to the competition between the interaction and decay of pions and kaons. The power index of muon spectrum at high energies ($E_\mu > 1$ TeV) is greater by about 1 than that of their parents. There is another mechanism of muon production which can dominates at very high energies. This is so called prompt muon production through the prompt (instantaneous) decay of charmed particles produced in the hadron-nucleus collisions at very high energies together with pions and kaons. The life time of charmed particles is so short that they decay immediately (at energies less than 10000 TeV) into muons and other particles. Due to the absence of the competition between charmed particle decay and interaction, the prompt muon spectrum (from the decay of charmed particles) has the same spectral index as the primary spectrum. The difference of spectral indices of conventional (from pion and kaon decay) and prompt muon spectra should result in a dominance of the prompt muon flux at very high energies.

There are a lot of models of prompt muon production (see, for example, [1-5] and references therein). They predict the prompt muon fluxes which differ by 2 orders of magnitude. The predicted ratio of prompt muons to pions varies from about 10^{-4} to about 10^{-2}. However, very large values of prompt muon flux are excluded by experimental data. The experimental data are not in a good agreement, too. The measured ratio of prompt muons to pions varies from 0 to $4 \cdot 10^{-3}$ (see, for example, [6-10]). The uncertainties in the measured and predicted ratios of prompt muon flux to pion flux mean that the crossing point of the spectra of prompt and conventional muons is not known. One of the recent models, so-called dual parton model, which is widely developing now, predicts that the prompt muon flux will dominate over the conventional muon flux at vertical at the energies more than several thousands TeV.

However, in addition to the prompt muon production through the decay of charmed particles, there is another mechanism of muon production which will dominate over the conventional muon production at ultra high energies. This mechanism consists in the muon pair production by photons in electromagnetic showers initiated by gamma's from π^o-decay. As π^o's decay immediately into two photons even at $10^4 - 10^6$ TeV the spectrum of muons produced in this chain has the same index as the spectrum of photons. Hence, the power index of muon spectrum should be close to that of primaries. This spectrum should be quite similar to the spectrum of prompt muons from charmed particle decay at the energies where the decay length of charmed particles is much less than the interaction length. By analogy with the muon production by charmed particles this mechanism can be called also "prompt" muon production. The angular distribution of the muon flux produced by photons is flat that is also similar to the angular distribution of muons from charmed particle decay.

The production of muons in electromagnetic showers initiated by high-energy primary photons in the atmosphere was discussed in [11-13]. It was shown that at the energies more than several TeV the main process is the production of muon pairs by cascade photons.

The spectra of photons in the atmosphere are not known at the energies higher than 100 TeV. This makes difficult an accurate calculation of the muon flux produced by photons. However, an estimation of this flux can be done using the spectrum and depth distribution of photons evaluated analytically for TeV energies and extrapolated to PeV energies.

We have used the depth–energy distribution of photons in the atmosphere evaluated analytically in [14]. The differential cross-section of muon pair production by photons was obtained by analogy with that of electron pair production by photons [15]. It can be obtained also from muon bremsstrahlung cross-section [16] by changing the particles in initial and final states.

The intensity of muons produced by photons in the atmosphere was calculated using the formula:

$$\frac{dI_\mu}{dE_\mu}(E_\mu) = 2\int_0^\infty \int_0^{X_0} \frac{dI_\gamma}{dE_\gamma}(E_\gamma, X)\frac{d\sigma}{dE_\mu}(E_\mu, E_\gamma)dX dE_\gamma \tag{1}$$

where $\frac{dI_\gamma}{dE_\gamma}(E_\gamma, X)$ is the depth – energy distribution of photons in the atmosphere from [14], $\frac{d\sigma}{dE_\mu}(E_\mu, E_\gamma)$ is the cross-section of muon pair production by photons from [15,16], and factor 2 takes into account the production of two muons by one photon.

Since the prompt muon spectra (from either charmed particle decay or electromagnetic showers) are much harder than the conventional muon spectrum, it is interesting to estimate the ratio of prompt muons to pions that is almost independent of energy (in a simple assumption of full scaling). With the assumption that the spectra of photons and pions have the same power index than the primary spectrum (full scaling) the ratio of muons from photons to pions is equal to $4.8 \cdot 10^{-5}$. Comparing the photon-produced muon flux with the conventional muon flux we have estimated the crossing point of these two spectra. It is equal to $3 \cdot 10^3$ TeV. In these calculations we took into account that the primary spectrum at these energies has the power index $\gamma \approx 3.0$.

Unfortunately, the small flux of photon-produced muons cannot be measured by existing underground detectors, but the future large underwater or underice detectors with an area of about 1 km^2 and an ability to measure muon energy using the pair-meter technique would be able to detect several muons per year.

We note again that there is a large discrepancy between the models of prompt muon production by charmed particles. Some models, for example, dual parton model [5] which is extensively developing now, predict the ratio of prompt muon flux to pion flux at a level of 10^{-4} or even less and the crossing point of the prompt and conventional muon spectra at vertical at (1-3) PeV. The photon-produced muon flux is comparable to the charm-produced muon flux predicted by dual parton model. The shape of the photon-produced muon spectrum is similar to that of the prompt muon flux from charmed particles. The ratio of the fluxes remains unchanged with the increase of energy until the energy of muons is much less than the critical energy of charmed particles. At muon energies more than 10^4 TeV the prompt muon spectrum from charmed particles become softer than the photon-produced muon spectrum due to the competition between interaction and decay of charmed particles. Finally, at energies more than 10^6 TeV the power index of prompt muon spectrum will be higher by 1 than that of photon-produced muon spectrum. This means that at some energy the production of muons by photons will dominate over all other processes. This energy depends on the fluxes of prompt and photon-produced muons at the energies of interest where the experimental data are absent.

In the estimations presented here we have used a simple formula from [14] to calculate the photon flux in the atmosphere. This formula was obtained with the assumption of full scaling. However, several experimental data (see, for example, [17,18] and references therein) show that the photon flux decreases with the atmospheric depth faster than expected using this formula, and the power index of photon spectrum is greater than that of primary spectrum. If it is so, we can consider our estimates of the photon-produced muon flux as an upper limit and this flux can be several times less than that predicted by our simple model.

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