Muons in gamma showers

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ABSTRACT

We study muon production in gamma-induced air showers, accounting for all major processes. For muon energies in the GeV region the photoproduction is by far the most important process, while the contribution of $\mu^+\mu^-$ pair creation is not negligible for TeV muons. The total rate of muons in gamma showers is, however, very low.

1. Introduction

There are two types of processes involved in generation of muons in electromagnetic showers: photoproduction and direct creation of muon pairs. In the photoproduction muons are generated through production and subsequent decay of mesons, thus in addition to the photoproduction cross-section one has to account for the meson interaction cross-section and the interaction-decay competition. At higher energies and in dense atmosphere mesons interact rather than decay and the resulting muon spectrum is steeper than the photoproduction one by one power of the energy. Directly produced muons are not affected by the production depth and their spectrum is a convolution of the photon energy spectrum and the pair creation cross-section.

We shall briefly discuss the cross-sections of both types of processes, introduce the techniques used in the calculations and show the muon production spectra for fixed primary energy. We shall use such spectra to estimate the total muon rates resulting from the observed gamma-ray fluxes of point sources.

2. Photoproduction and muon pair creation cross-sections.

Figure 1[a] shows the energy dependence of the photoproduction cross-section in air used in the calculation. It interpolates gamma-proton data and assumes a $A^{0.91}$ dependence on atomic number. After the resonance region below 1 GeV the cross-section shows a very slow logarithmic rise with the incident photon energy. A constant diffractive cross-section of 194 μb is asumed to result in ρ production. The electron photoproduction cross-section is shown on the same graph with dash line. Although this process has a significant cross-section, it does not contribute much to the muon production because the spectrum of the radiated virtual photons is very soft and the energy loss to photoproduction is small.

The lower part of the figure shows the cross-section for direct production of $\mu^+\mu^-$ pairs by photons in air. This process is analoguous to the creation of electron-positron pairs and in the assymptotic case of full screening of the nucleus field by the atomic electrons $\sigma_{\mu^+\mu^-}/\sigma_{e^+e^-}=(m/\mu)^2$. In addition to that the screening parameter $\xi_\mu=\xi_e(\mu/m)^2$ and the assymptotic cross-section for muon pairs is achieved for $E_\gamma >> 1$ TeV. In the very interesting region between 1 and 10 TeV the cross section increases by a factor of two. The corresponding process of muon pair production by electrons is of higher order and its cross-section is smaller at least by a factor of α.

All cross-sections shown on Fig. 1 are very small. Even at 1000 TeV their values are 2.4 and 2.1 *mb* for photoproduction by photons and electrons and 11.7 *μb* for muon pairs compared to the 502 *mb* cross section for e^+e^- pairs. Only a very small fraction of the shower energy goes into these channels and we can still use the cascade theory to estimate the shower size.

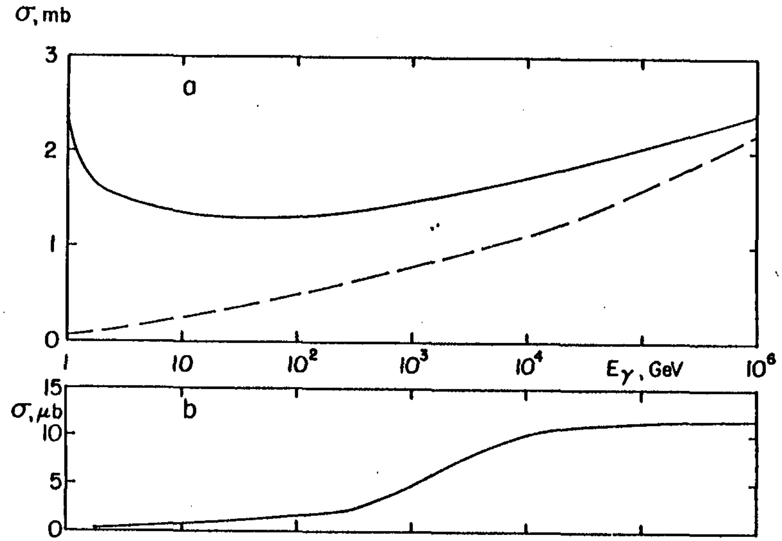

Fig. 1. Cross-sections for photoproduction by photons and electrons (dash line)[a] and for muon pairs creation[b] in air. Note the difference in the units (*mb* for photoproduction and *μb* for pair creation.

3. Calculational technique.

We have used two methods to calculate the muon production in gamma showers due to photoproduction. An electromagnetic Monte Carlo program was used to calculate the photoproduction at fixed primary gamma ray energy and all photoproduction events were recorded. Then the data files were treated with a hadronic Monte Carlo simulation program, which followed the muon production and propagation to the appropriate threshold energies. Results from these runs for GeV muons were discussed in Ref. 1. The same approach was used in Ref. 2 to calculate the number of TeV muons in gamma showers.

A numerical integration including the photoproduction energy spectrum and the three first generations in the hadronic cascades was also performed to check the Monte Carlo calculation and to extend the results for GeV muons to higher primary energies.

To calculate the number of muons with energy greater than E_μ in gamma showers of primary energy E_o due to creation of muon pairs one has to evaluate the integral

$$N(>E_\mu) = \int_{E_\mu}^{E_o} \int_{E_\mu}^{E_\gamma} \frac{dN_\gamma(E_o,E_\gamma)}{dE_\gamma} \sigma_{\mu^+\mu^-}(E_\gamma,E)\,dE\,dE_\gamma$$

where dN/dE_γ is the total number of γ rays in the shower. We evaluated the integral using the tracklength (total number of particles with energy E_γ in the cascade) given by Rossi [3] $g_o^{(\gamma)}(E_o,E_\gamma)=0.572E_o/E_\gamma^2$.

4. Results

The calculation confirmed that the number of GeV muons in gamma showers is at least one order of magnitude smaller than the number of muons in hadronic showers. For muon energy > 2 GeV we obtained a factor of 25 in the muon content of hadronic and electromagnetic showers for shower sizes between 10^5 and 10^6 particles at sea level. We also found that the fluctuations in the muon production are very large and most of the gamma showers will have only half of that amount of muons.

At muon energies below 1 GeV, where the muon decay is extremely important, the number of photoproduced muons grows in the same shower size region faster than linearly with the energy. We agree with the conclusions of McComb et al. [4] that at energies around 10^{18} eV the photoproduction will significantly contribute to the number of low energy muons.

Fig. 2 compares the production spectra of muons by photoproduction and muon pair creation in gamma showers with primary energy of 10^6 GeV. Photoproduced muons have integral energy spectrum of E^{-2} and directly created muons of $E^{-0.80}$. If the same trend continues at higher muon energies the production spectra will cross over at muon energies 10 TeV. At energy 3 TeV directly produced muons contribute about 1/4 of the total muon number.

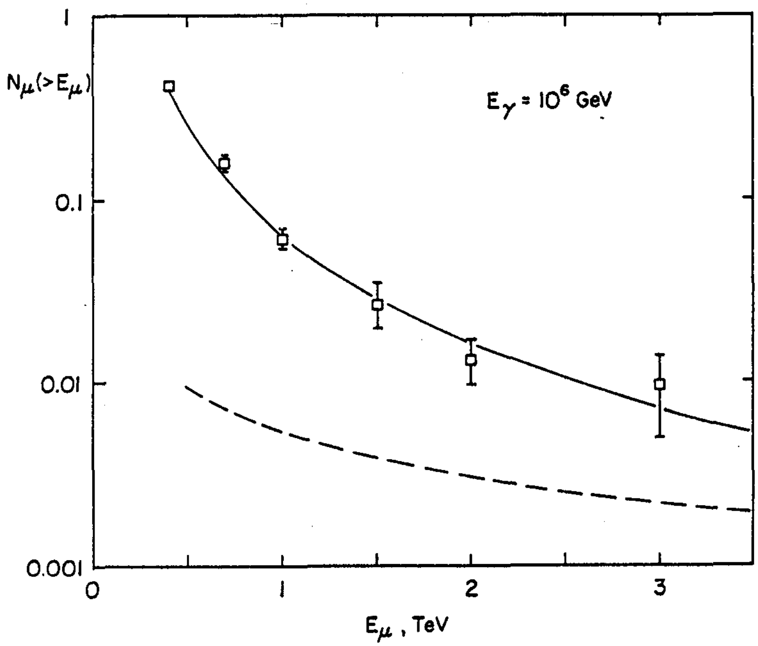

Fig 2. Muon production spectrum in 10^6 GeV showers through photoproduction and muon pairs creation (dash line).

5. Discussion and conclusion.

One can now use the flux of high energy γ rays measured at Kiel [5] $N(>E_\gamma)=6\times10^{-7}E_\gamma(GeV)^{-1.11}photons.cm^{-2}.s^{-1}$ with cut-off at 10^7 GeV as suggested by the measurement at Haverah Park [6] and calculate the flux of muons at different depths underground due to both photoproduction and pair creation. The vertical muon flux resulting from this photon flux at depths 2 and 4 km.w.e. underground are respectively 1.60×10^{-13} and $2.05\times10^{-14}cm^{-2}\times s^{-1}$. These rates are very low and the expected muon rates in a 1000 m^2 detector are respectively 45 and 6 yr^{-1}. For the 0.92 yrs running time of the 9 m^2 Soudan [7] detector the expected number of muons from gamma showers is 0.4.

Gamma showers are inefficient in producing muons in the TeV as well as in the GeV region. The photon induced air showers are "mu-poor" and this feature can be used as identification signature. It is not possible to understand the underground muon signals from point sources[7] as a result of photon showers in the atmosphere.

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