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LETTER TO THE EDITOR

MUONS EMITTED FROM SHOWERS PRODUCED BY GEMINGA-PULSAR GAMMA RAYS

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The derivation of integral energy spectrum of muons produced by the interactions in gamma-ray showers induced by energetic photons from the Geminga pulsar has been made. The conventional analytical procedure of Drees et al. has been adopted for muon-number calculations from photoproduced air showers. The FNAL data on $\pi p \to \pi^{\pm} X$ inclusive reactions, and the HERA ep collider results have been used for the evaluation of the hadronic energy moments and the photonuclear cross-sections, respectively. The integral number of muons was derived for $Z_{\pi\pi} = 0.499, \sigma_{\gamma N} = 0.119$ mb and $\sigma_{\pi A} = 198$ mb. It exhibits a drastic decrease with energy.

EGRET instrument flown by the Crompton Gamma Ray Observatory [1] has discovered gamma rays of energies ranging from 20 MeV to 30 GeV emitted from over 100 sources. Among the sources, 16 have been tentatively and 42 well identified with radio counterparts.

The investigation of muon fluxes in photoinduced air showers is of phenomenological importance in astronomy for the exploration of sources of gamma rays and neutrinos. In hadronic showers, most of the moderate-energy muons ($<$ 1 TeV) are generated by the conventional decay of pions, i.e., by the $\pi \to \mu$ mode. The photoinduced electromagnetic showers are also related with the phenomena of muon pair production and bremsstrahlung. Earlier, Drees and Halzen [2] have pointed out that a higher γ-ray threshold can exhibit large photoproduction cross-section and the photon develops a significant gluon structure function.

Stanev et al. [3] have performed Monte Carlo simulation for a photon of a primary energy of 1 PeV, generating muon spectrum through photonuclear interactions. In a recent investigation, we have estimated the muon spectrum from air showers induced by CRAB-emitted photons [4]. It was found that muon fluxes obtained from decay of pions produced in photonuclear γN reactions are adequate for muon energies below 3 TeV. But above that energy, the majority of muons occur from γ–air interactions through $\gamma + Z \rightarrow Z + \mu^+ + \mu^-$ reactions. Halzen et al. [5] have pointed out that the gamma-ray showers produce a number of high-energy muons which allow observation of the sources by the GeV– and TeV–muon telescopes. Gamma-ray showers above the photoproduction threshold contribute to the number of muons N_μ which depends on the primary gamma-ray energy. Energetic gamma rays creating muons in the Earth's atmosphere can be registered by shallow underground neutrino detectors, operating in AMANDA and Lake Baikal, at depths of about 1 km [6]. The moderate-energy gamma-ray showers are detected using a surface detector operating at MILAGRO which detects muons of energies above 1.5 GeV. So, an estimate of photoproduced pions, generating muons in turn, is required for a proper low-energy muon background flux estimation.

In the present work, we have used the maximum cut-off energy of gamma rays $E_{max} =$ 300 GeV, as found from the Geminga-pulsar emitted photon spectrum, cited recently by Halzen et al. [5] from a closer survey of MILAGRO experiments, to estimate the number of muons in a photon-initiated air shower of energy 200 GeV at a zenith angle of 30°. The parametric values of energy moments for photoproduced pions $Z_{\pi\pi}$ in πp $\rightarrow \pi^{\pm} X$ inclusive reactions, and the inelastic interaction cross-section for πA collisions, $\sigma_{\pi A}$, were taken from Refs. 7 and 8, along with the extrapolated ep HERA collider results [9] for γp cross-sections.

In the calculation of Drees et al. [10], which is based on the original formulation of Rossi [11], in the upper atmosphere, a photon of a high energy E_0 produces an electromagnetic shower consisting mainly of photons, electrons and positrons. The atmosphere is considered to consist of layers, each of a thickness $t_0 = \lambda_R \ln 2$, where λ_R is the radiation length over which the average energy of electromagnetic particles is halved. At a depth nt_0, the shower consists of 2^n particles, each of an average energy of about $E_0/2^n$. The process of production of muons of energy larger than a threshold energy E_t continues until the energy of particles in the shower becomes too low to produce muons of energy E_t or higher. The corresponding number of layers which can produce muons of energy $E > E_t$ (minimum energy required to produce a pion of energy E is $E/ < x_{\gamma\pi} >$) can be estimated from the equation:

$$n_{max} = \ln \frac{\eta E_0}{E_t/\langle x_{\gamma\pi}\rangle} \, \frac{1}{\ln 2}, \quad \text{where} \quad \eta = \frac{1-r^3}{5.6(1-r)} \approx 0.34, \tag{1}$$

$r = m_\mu^2/m_\pi^2$ and $< x_{\gamma\pi} >= 0.25$ [10].

Photon shower in the layer n generates $(\lambda_R/\lambda_{\gamma N}) < n_{\gamma\pi} >$ pions of energy $(E_0/2^n) <$ $x_{\gamma\pi} >$, where $< n_{\gamma\pi} >$ is the average number of photo-pions produced in an encounter. The total number of muons produced at the zenith angle θ in the atmosphere, of energy above the threshold muon energy E_t, obtained after summation for $n = 1$ to n_{max}, after Drees et al. [10], is given by

$$N_\mu(E > E_t) = \frac{2}{3} \frac{2^{2n_{max}}}{n_{max} E_t} \frac{\varepsilon_\pi}{\cos\theta} \frac{\lambda_\pi}{\lambda_{\gamma N}} \frac{\langle n_{\gamma\pi}\rangle}{\langle x_{\gamma\pi}\rangle}, \tag{2}$$

where $\varepsilon_\pi = m_\pi h_0/(c\tau_\pi) \approx 115$ GeV is the critical pion energy ($m_\pi = 139.6$ MeV, $h_0 \approx 6400$ m is the effective height of the atmosphere and $\tau_{\pi^\pm}$ is the pion mean life) and λ_π and $\lambda_{\gamma\mathrm{N}}$ are the interaction lengths of pions and photons in air, respectively.

The simplified form of Eq. (2) for the calculation of the number of high energy muons at zenith angle θ, above the threshold energy E_t, is given by [10]

$$N_\mu(E > E_t) = \frac{0.23}{n_{max}} \frac{\varepsilon_\pi E_0}{E_t^2 \cos\theta} \frac{A\sigma_{\gamma\mathrm{N}}}{\sigma_{\pi\mathrm{A}}} \frac{< nx >_{\gamma\to\pi^\pm}}{(1 - Z_{\pi\pi})}, \tag{3}$$

where $Z_{\pi\pi}$ are the hadron moments [10], $A = 14.5$ the average atomic nucleon number in the atmosphere, $\sigma_{\gamma\mathrm{N}}$ the cross-section of the $\gamma\mathrm{N} \to \pi\mathrm{X}$ process, $\sigma_{\pi\mathrm{A}}$ the pion inelastic interaction cross-section and $< nx >_{\gamma\pi^\pm}$ the fraction of energy of photoproduced pions taken by $\pi^\pm$.

In a recent survey, Halzen et al. [4] have shown that the gamma rays emitted from the Geminga pulsar follow the power law fit of the form:

$$\mathrm{d}N_\gamma(E)/\mathrm{d}E = 3.74 \times 10^{-10} E^{-1.55} \mathrm{cm}^{-2}\mathrm{s}^{-1}. \tag{4}$$

Using the FNAL data for meson production cross-section from the measurements of Brenner et al. [7], and by adopting $\gamma = 1.55$ as the spectral index of γ-rays emitted by Geminga pulsar [4], and $\sigma_{\mathrm{in}} = 22$ mb for πp inelastic collisions, the $Z_{\pi\pi}$ factors for π p $\to \pi^\pm X$ reactions have been calculated. They were duly corrected for p–air collisions and EMC effects by using the procedure of Minorikawa and Mitsui [12]. The calculated hadronic energy moment $Z_{\pi^+\pi^+}$ and $Z_{\pi^+\pi^-}$, are found to be 0.573 and 0.455, respectively. The pion attenuation length λ_π has been calculated and found to be 142.3 gcm^{-2}. The DESY ep collider experimental data on the photonuclear cross-sections, for γ-ray energy E_0, are given by

$$\sigma_{\gamma\mathrm{N}} = (0.147 - 0.017 \ln E_0 + 0.0022 (\ln E_0)^2)\ 10^{-28}\ \mathrm{cm}^2, \tag{5}$$

which yields a value of 0.119 mb for the incident photon energy $E = 200$ GeV. Taking the cut-off energy of the Geminga-pulsar emitted gamma-ray spectrum as $E_{max} = 300$ GeV [4], $< x >_{\gamma\to\pi^\pm} = 0.25$, $r = 0.58$ and $\sigma_{\gamma\mathrm{N}} = 0.119$ mb, one can calculate $\lambda_{\gamma N}$ from the relation $\lambda_{\gamma\mathrm{N}} = (\sigma_\mathrm{R}\lambda_\mathrm{R})/(\mathrm{A}\sigma_{\gamma\mathrm{N}})$ which yields a value of 3789 gcm^{-2}, assuming the adopted values $\sigma_\mathrm{R} = 480$ mb, $\lambda_\mathrm{R} = 38$ gcm^{-2} and $A = 14.5$. Using relation (1), and by adopting the interaction parameters $\eta = 0.34, E_0 = 200$ GeV and $< x_{\gamma\pi} > = 0.25$, the effective number of layers in the atmosphere that can produce muons of threshold energy E_t and higher is given by

$$n_{max} = 1.443 \ln[29/E_t(\mathrm{GeV})]. \tag{6}$$

Taking the calculated values of n_{max}, and assuming $< nx >_{\gamma\to\pi^\pm} = 2/3, \theta = 30°$, $\varepsilon_\pi = 115$ GeV, $\sigma_{\pi\mathrm{A}} = 198$ mb [7], $Z_{\pi\pi} = 0.499$ and $E_0 = 200$ GeV, the number of muons produced by γ-ray interactions in air has been estimated using Eq. (3):

$$N_\mu(E > E_t) = 69.51/[n_{max} E_t^2(\mathrm{GeV})]. \tag{7}$$

The estimated number of muons obtained from the photon–induced air showers at threshold energy E_t in the range 1 – 20 GeV is displayed in Table 1. The derived muon flux from $E_0 = 200$ GeV photon interactions in air at zenith angle $\theta = 30°$ exhibits a drastic decrease with the increase of muon energy.

TABLE 1. The calculated values of $n_{\max}$ *for different muon threshold energies* E_{th} (GeV) *and the derived muon fluxes initiated by* $E_0 = 200$ GeV *photon showers in usual interactions in air obtained from the present work.*

E_t (GeV)	n_{max}	N_μ present work
1.5	4.273	7.230
2	3.866	4.495
5	2.544	1,093
10	1.544	0.450
20	0.544	0.320

The Geminga-pulsar gamma-ray induced muon flux has been derived for lower muon threshold energies (1.5 GeV and higher). Since the muon energy is relatively low, the contribution of muons from charmed mesons and directly produced muons have been neglected. The standard analytical formulation of Drees et al. has been adapted for the estimation of the flux of muons produced by decay of photoproduced pions.

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MUONI NASTALI U PLJUSKOVIMA PROIZVEDENIM GAMA ZRAČENJEM GEMINGA PULSARA

Izveden je integralni energijski spektar muona nastalih u pljuskovima izazvanim fotonima visoke energije sa Geminga pulsara. Primijenjena je uobičajena analitička metoda Dreesa i sur. za računanje broja muona. Podaci iz Fermijevog laboratorija za $\pi p \to \pi^{\pm} X$ inkluzivne reakcije i podaci iz HERA za ep reakcije primijenjeni su za računanje hadronskih energijskih momenata odn. fotonuklearnih udarnih presjeka. Izvedeni integralni broj muona pokazuje snažan pad s njihovom energijom.