MUON SPECTRUM IN AIR SHOWERS INITIATED BY GAMMA RAYS

S.A. Stephens
Tata Institute of Fundamental Research
Homi Bhabha Road, Bombay 400005, India

R.E. Streitmatter
NASA/GSFC, Maryland 20771, U.S.A.

ABSTRACT

We have derived an analytic representation for the invariant cross-section for the production of charged pions in γP interactions by making use of the available cross-sections. Using this the abundance of muons in a gamma ray initiated air shower is calculated.

1. Introduction. Total hachonic cross-section of γ-rays at energies greater than a few GeV is about two hundred times smaller than hadron inelastic cross-section. Therefore, hadron production by γ-ray showers in the atmosphere is neglected for the study of muons. However, the discovery of pure γ-ray air showers from Cygnus X-3 [1] has renewed interest in this study, because of the observed muon content in these air showers is not very small compared to those from hadron showers. We have attempted in this paper to derive an analytic representation for the invariant cross-section for the production of charged pions in γ-P interaction, using the available data. Making use of this, the pion production spectrum in the atmosphere is calculated for an air shower initiated by γ-rays and muon spectrum at different depths is determined.

2. γ-P Inclusive Cross-section. The frame in which particle production is symmetric in γ-P interaction is found to be the one in which the ratio, Q, of the target momentum to the beam momentum is larger than 1. Experiments performed at energies >a few GeV show that the value of Q lies between 2 and 3 [2-5]. However, at low energies, where P_{33} and D_{13} resonances dominate, the threshold is consistent with that of centre of mass system (CMS) with Q = 1. Therefore, we assume in our investigation that Q is energy dependent of the form

$$Q = 1. + 2.\ \exp(-m_p/E_\gamma) \qquad (1)$$

From a study of the observed invariant cross-section for the production of charged pions, we obtained a representation of the type

$$E\frac{d^3\sigma}{dp^3} = f(E_\gamma)\ \exp(-C_1\mu).\ \exp(-C_2\tilde{x}^{1.5})/\{1.+C_3/(1-p^*/p^*_{max})\}... \qquad (2)$$

Here $\tilde{x} = \sqrt{\{x'^2_{11} + Q(p^2_\perp+m^2_\pi)/S\}}$ and $\mu = \sqrt{(p^2_\perp + 9m^2_\pi)}$, where $x'_{11} = p'_{11}/p^*_{max}$, C_1, C_2 and C_3 have values 6.93, 3.4 and 0.03 respectively. The longitudinal momentum in the Q-system is given by

$$p'_{11} = \{p(S'+m_p^2)-E(S'-m_p^2)\} /2m_p \sqrt{S'} \quad \ldots \quad (3)$$

In the above expressions $S = m_p(m_p+2E_\gamma)$, the square of the invariant mass and $S' = m_p(m_p+2QE_\gamma)$. The last term in Eqn. (2) makes sure that the momentum of pions p^* in CMS does not exceed the maximum allowed momentum p^*_{max}. It is clear that Eqn. (2) is symmetric in Q system except at large values of $\tilde{x}$ due to this restriction.

We have shown in Figure 1, the invariant cross-section for the production of $(\pi^+ + \pi^-)$ as a function of $x^*_{11} = p^*_{11}/p^*_{max}$ for various values of $p_\perp$ at E_γ values 18 and 6 GeV [3,6]. The general fit to this data using Eqn. 2 is very good. Notice that the invariant cross-section does not peak at $x^*_{11} = 0$. The measured $2\int E(d^3\sigma/dp^3)p_\perp\, dp_\perp$ is shown in Fig. 2, for various $p_\perp$ intervals. The filled circles, triangles and squares correspond to respectively data from 9.3, 4.7 and 2.8 GeV. The data plotted in this figure relate to π^- production only. Here again one finds that the overall fit to the data is remarkably good.

The form of the function $f(E_\gamma)$ is $A[1+g(E_\gamma)]$. In order to evaluate this, we have adopted the following procedure. In the energy region between about 2.5 and 20 GeV, we have made use of the measured cross-sections given in Figures 1 and 2 and the observed π^+/π^- ratio of ≈ 1.1 [2,3,6]. For the rest of the energy region, we have made use of the observed multiplicity in PP collisions with the assumption that multiplicity depends only on the available energy in CMS. It is found that at large E_γ values the observed $< m_\pi >$ agrees well with that calculated using PP data [7,8]. However, in the region, where ρ production dominates, the $< m_\pi >$ in γP interaction is larger. Therefore, at low energies, we have smoothly fitted from the observed data at 2.8 GeV to one pion production region. By setting $<m_{\pi^\pm}> \sigma_T = 2\pi \int\int^{p^*_{max}} (Ed^3\sigma/dp^3)\, p_\perp\, dp_\perp/E^*$ and using the observed σ_T values [9,10], we found that A=4.7 and $g(E_\gamma)$ as

$$\begin{aligned} g(E_\gamma) &= 3350\ (E_\gamma+10)^{-3.5} && E_\gamma \geq .86 \text{ GeV} \\ &= 125 \exp(-5.6\ E_\gamma) && .725 \leq E_\gamma \leq .86 \\ &= 3.5\ E_\gamma^{1.5} && .625 \leq E_\gamma \leq .725 \quad \ldots \quad (4) \\ &= 1.73 && .49 \leq E_\gamma \leq .625 \\ &= 1620 \exp(-14E_\gamma) && .315 \leq E_\gamma \leq .49 \end{aligned}$$

The above expressions approximately characterize $\Delta(1232)$, N(1520) and N(1680) resonances well within a few percent.

From our investigation, we need to know the cross-section for γ-air nuclei interactions. In order to obtain information on this, we have examined the asymptotic total cross-sections for γP, γD, πP, πD, KP, KD, PP, PD, $\bar{P}P$ and $\bar{P}D$ interactions [10]. It is found that photo-hadron cross-section scales exactly as other hadron-hadron cross-sections with atomic number of the target. Therefore, we made use of the scaling for proton interactions and obtained γ-air inclusive cross-section as $\sigma_T < A >_{air}/1.8$.

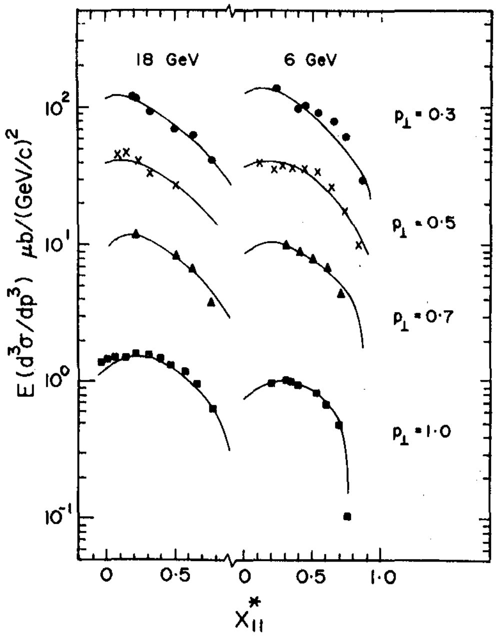

Fig. 1 *Invariant cross-section for ($\pi^+ + \pi^-$) is shown as a function x^*_{11} for E_γ = 18 and 6 GeV*

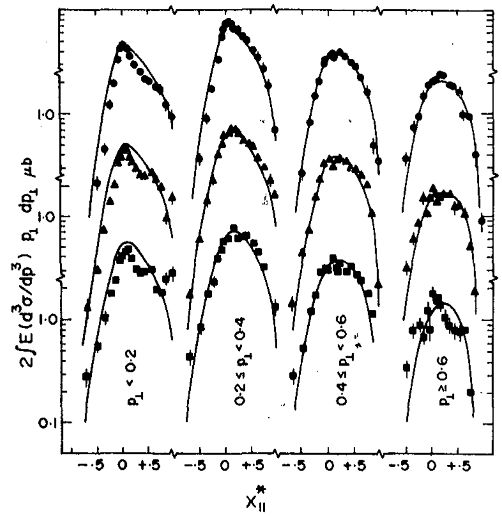

Fig. 2 *π^- invariant cross-section integrated over $p_\perp$ is shown for different $p_\perp$ intervals. The filled circles, triangles and squares correspond to E_γ = 9.3, 4.7 and 2.8 GeV respectively.*

3. <u>Muon Production in γ-ray Showers.</u> Pion production spectrum in the atmosphere is given by

$$P_\pi(E,x) = \iint J_\gamma(E_\gamma,x)dE_\gamma \, . \, \{2\pi \, (E \, d^3\sigma/dp^3) p_\perp \, d\theta \quad \ldots \qquad (5)$$

Here, the photon spectrum J is obtained using one dimensional propagation of cascade initiated γ-rays in the atmosphere without approximations [11]. From this the spectra of pions and muons in the atmosphere are calculated by taking into account the decay, energy loss processes and the 2nd generation of pions as described by Stephens [12].

In Figure 3, we show the preliminary results based on a representation of invariant cross-section, which has the same form as that for π°-inclusive production. The integral flux muons is shown as a function of primary γ-ray energy for different energy thresholds and for a few sample depths. It is seen that the total muon flux is small at all depths and therefore, the observed large flux of muons with γ-ray showers associated with Cygnus X-3 [1] could be due to other reasons.

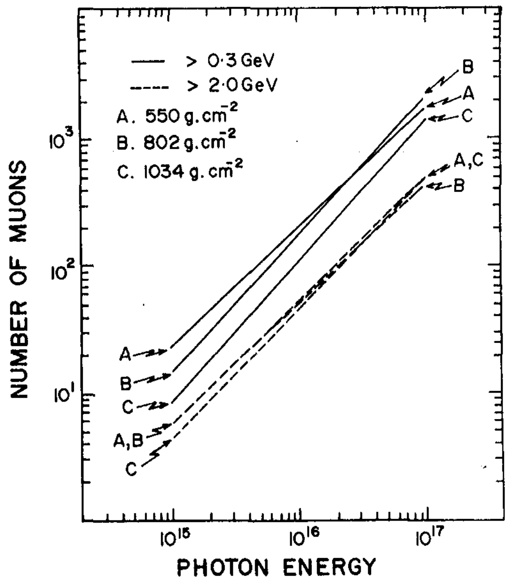

Fig.3 *Total muons above .3 and 2 GeV are shown as a function of primary γ-ray energy at 3 atmospheric depths.*

One of the possible explanation for this anomaly is that some of the air shower electrons and photons, which continue their propagation are registered by the muon detectors.

References

[1] M. Samorski and W. Stamm, Ap.J., 268, L17 (1983)
[2] P. Rankin, Ph.D. Thesis, Imperial College, London (1982)
[3] A.M. Boyarski et al., Phys. Rev., D14, 1733 (1976)
[4] K.C. Moffeit et al., Phys. Rev., D5, 1603 (1972)
[5] G. Alexander et al., Phys. Rev., D8, 712 (1973)
[6] H. Burfeindt et al., Nuclear Phys., B74, 189 (1974)
[7] G.D. Badhwar et al., Phys. Rev. D15, 820 (1977)
[8] S.A. Stephens and G.D. Badhwar, Ap.Sp. Sci., 76, 213 (1981)
[9] T.A. Armstrong et al., Phys. Rev., D5, 1640 (1972)
[10] M.A. Benitez et al., Rev. Mod. Phys., 56, No.2 (1984)
[11] R.E. Streitmatter and S.A. Stephens (This Conference)
[12] S.A. Stephens, Proc. 16th ICRC (Kyoto), 10, 90 (1979)