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# Investigation on the altitude dependence of the diffuse photon energy spectra initiated by primary nucleon air collisions

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**Abstract** A study has been made on the altitude dependence of the high energy spectra of electromagnetic components like gamma rays initiated by primary cosmic nucleon-air collisions

The primary cosmic nucleon spectrum has been estimated from the directly measured elemental fluxes at high energies obtained from the recent absolute measurements by different groups Considering the superposition model the estimated all particle primary nucleon spectrum follows the form $\simeq 2.56\ E^{-2.73}$ in the energy range 0 1–100 TeV Taking this as source of parent neutral mesons along with the spectrum weighted moments for neutral pion production from the CERN accelerator data on the neutral pion production spectrum in the atmosphere has been calculated.

The generated neutral pions decay before reacting in the atmosphere and as a consequence the electromagnetic cascades are generated through $\pi^0 \rightarrow 2\gamma$ decays. The unidirectional intensity of $\gamma$-rays at different atmospheric depths 540, 650 and 735 $g$-cm$^{-2}$ air have been calculated by adopting the conventional cascade theory discussed earlier by us and the results are found comparable to the emulsion chamber data obtained at locations like Mt Chacaltaya, Mt Norikura and Mt Fuji

**Keywords** : Primary nucleon spectrum, diffuse photon energy spectra, experimental results

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## 1. Introduction

Gamma ray astronomy is strongly connected with the evolution of primary cosmic rays in the Galaxy. In general, secondary gamma rays are originated by the inelastic interactions of primary particles with the gas confined in the Inter Stellar Medium.

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The gamma rays available from different astronomical sources like Cygnus X-3 [1, 2], Vela X-1 [3], LMC X-4 [4], Her X-1 [5] and the latest survey of Thompson *et al.* [6], Halzen *et al.* [7] exhibit that more searches are to be made on the diffuse γ-ray background fluxes to resolve such fluxes from the astronomical sources. Various calculations on the diffuse atmospheric γ-ray induced muon spectra emitted from Cygnus X3, Crab Nebula and Geminga Pulsars have been made by Drees *et al.* [8], Bhattacharyya [9-11], respectively which exhibit the fact that the generation of γ-ray produced atmospheric muons through QED process $\gamma + Z = Z + \mu^+ + \mu^-$ is dominating beyond 2 TeV energy as the muon production through the decay of $\pi^{\pm}$, $K^{\pm}$ in $\gamma N$ interaction which may suffer scaling violation in such interactions and account of nuclear effects. So the search on the background diffuse γ-rays in Earth's atmosphere is necessary for the confirmation of the emission of γ-rays from astronomical objects.

Earlier Lattes *et al* [12], Shibata *et al* [13], and Otwinowski [14] have investigated the energy spectra of diffuse photons at atmospheric depths 540, 650 and 735 g-cm$^{-2}$ in the spectral energy range 0.2–10 TeV.

The availability of balloon and satellite borne passive and active detector experimental data helped us to estimate precise primary nuclei spectra which enabled one to get an accurate information of the nucleon energy spectrum upto energies ≤ 1000 TeV. This may be utilized as a source of parent particles generating electron-photon components in the TeV energy range With the adoption of conventional cascade equation [15-17] the photon spectra at different atmospheric depths like 540, 650 and 735 g-cm$^{-2}$ have been estimated. The derived results have been compared with the available results at mountain altitudes [12-14].

## 2. Nuclear physics

The differential primary cosmic ray elemental spectra for the i-th species in general follow the power law

$$N_i(E)dE = K_i E^{-(\gamma_i+1)}dE, \tag{1}$$

where $K_i$ and $\gamma_i$ are the elemental spectral amplitudes and indices of the i-th species.

By adopting the standard superposition model cited earlier in [18, 19] one can obtain the total primary nucleon spectrum of the form

$$N(E)dE = \sum_{i=H}^{Fe} N_i(E)dE = \sum_{i=H}^{Fe} A_i K_i E^{-(\gamma_i+1)}dE \simeq KE^{-(s+1)}dE, \tag{2}$$

where $K$ and $s$ are the spectral amplitude and integral spectral index of the total primary nucleon energy spectrum incident on the top of the atmosphere.

The CERN accelerator data on $P_T$ integrated Lorentz invariant cross-section for the $p + p \to \pi^0 + X$ inclusive reaction found by Aguliar-Benitez *et al.* [20] follows the relation

$$x\frac{d\sigma}{dx} = A(1-x)^n, \tag{3}$$

where $A$ and $n$ are fitting parameters.

The spectrum weighted moments for $p + p \rightarrow \pi^0 + X$ the inclusive collisions can be estimated from the relation

$$Z_{p\pi^0} = \int_0^1 x^{s-1} f_{p\pi^0}(x)\, dx, \tag{4}$$

where

$$f_{p\pi^0}(x) = \frac{\pi}{\sigma} \int_0^\infty E(d^3\sigma / d^3 p)\, dp_T^2 = A(1-x)^n .$$

The simplified form of the Z-factor follows

$$Z_{p\pi^0} = \frac{A\Gamma(s)\,\Gamma(n+1)}{\sigma_{in}\Gamma(s+n+1)} . \tag{5}$$

The neutral meson production spectrum $g_{\pi^0}(E)dE$ can be estimated from inelastic interactions in primary nucleons with the atmospheric nuclei near the top of the atmosphere using the relation

$$g_{\pi^0}(E)dE = Z_{p\pi^0} \times N(E)dE . \tag{6}$$

Since the life time of neutral pion is short, the spectrum of it decaying to two photons is generated through $\pi^0 \rightarrow 2\gamma$. The energy spectrum of photons $g_\gamma(E)$ may be estimated from the neutral pion production spectrum $g_{\pi^0}(E)$ by the relation

$$g_\gamma(E)dE = \frac{2}{s+1}\, g_{\pi^0}(E)dE . \tag{7}$$

The unidirectional flux of gamma rays at an atmospheric depth $X$ g-cm$^{-2}$, produced by those incident parent gamma rays, can be estimated using the following expression cited earlier in refs. [15-17].

$$g_\gamma(E,X) = g_\gamma(E)\left[\frac{K_1(s)\{exp(\lambda_1(s)X/\lambda_0) - exp(-X/L)\}}{1+\lambda_1(s)L/\lambda_0} + \frac{K_2(s)\{exp(\lambda_2(s)X/\lambda_0) - exp(-X/L)\}}{1+\lambda_2(s)L/\lambda_0}\right], \tag{8}$$

where $s$ = integral primary nucleon spectral index. Here

$$K_1(s) = \frac{a_1 C(s)}{\sigma_0 + \lambda_1(s)}, \quad K_2(s) = \frac{a_2 C(s)}{\sigma_0 + \lambda_2(s)},$$

$\sigma_0$, $\lambda_1(s)$ and $\lambda_2(s)$ are conventional parameters in cascade theory [15] and obey the respective forms

$$A(s) = 1.36\frac{d}{ds}ln(s+1)! - \frac{1}{(s+1)(s+2)} - 0.0750.$$

$$B(s) = 2\left[\frac{1}{(s+1)} - \frac{1.36}{(s+2)(s+3)}\right],$$

$$C(s) = \left(\frac{4}{3}+2b\right)\left(\frac{1}{s} - \frac{1}{s+1} + \frac{1}{s+2}\right),$$

$$\lambda_1(s) = -\frac{[A(s)+\mu_0]}{2} + \frac{1}{2}\left\{[A(s)-\mu_0]^2 + 4B(s)C(s)\right\}^{\frac{1}{2}},$$

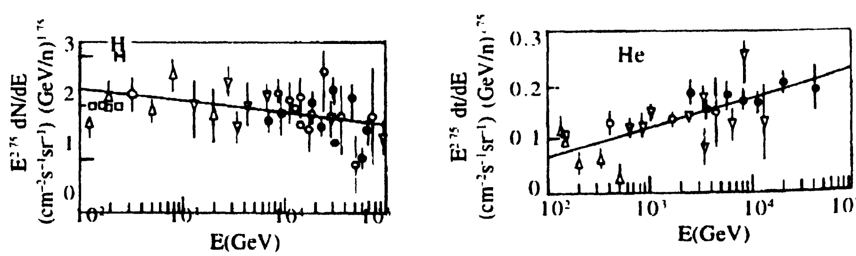
$$\lambda_2(s) = -\frac{[A(s)+\mu_0]}{2} - \frac{1}{2}\left\{[A(s)-\mu_0]^2 + 4B(s)C(s)\right\}^{\frac{1}{2}}.$$

## 3. Results and discussion

The elemental fluxes data of primary cosmic rays of H, He, CNO, Ne-Si and Fe nuclei obtained from active and passive detector experiments obtained by Ryan *et al.* [21], Webber *et al.* [22], Kawamura *et al.* [23], JACEE (Asakimori *et al.* [24]), CRN (Muller *et al.* [25]), SOKOL (Ivanenko *et al.* [26]), Dwyer *et al.* [27], Buckley *et al.* [28], IMAX (Menn *et al.* [29]) displayed in Figures 1 and 2 have been fitted by the power law as found from relation (1) whose spectral amplitudes $K_i$ and indices $\gamma_i$ are displayed in the Table 1.

**Table 1.** The calculated values of the spectral amplitudes $K_i$ $[cm^2\ s\ sec\ sr\ GeV]^{-1}$ and indices $\gamma_i$ obtained from the power law fit (1) to the elemental fluxes measured by different groups [21-29]

| Element | $A_i$ | $K_i$ | $\gamma_i$ |
|---|---|---|---|
| *H* | 1 | $2.979 \times 10^{-0}$ | 1.80 |
| *He* | 4 | $3.765 \times 10^{-2}$ | 1.59 |
| *CNO* | 14 | $2.530 \times 10^{-3}$ | 1.57 |
| *Ne – Si* | 28 | $8.023 \times 10^{-4}$ | 1.57 |
| *Fe* | 56 | $1.431 \times 10^{-4}$ | 1.54 |




(a). (b).

**Figure 1.** Energy spectra of H and He nuclei obtained from the direct measurements using balloons and satellites. (a) H : Δ Ryan *et al* [21], o Kawamura *et al* [23], • JACEE [24], ∇ SOKOL [26], □ IMAX [29], (b) He : Δ Ryan *et al.* [21], o Kawamura *et al* [23], • JACEE [24], ∇ SOKOL [26], □ Dwyer *et al* [27]. Full curve is the power law fit to the *p* and *He* fluxes whose spectral amplitudes and indices are shown in the Table 1.

Using the relation (2) the total primary nucleon spectrum at the top of the atmosphere has been estimated and found to follow the form

$$N(E)\,dE = 2.56E^{-2.73}dE\,[cm^2.sec.sr.GeV]^{-1}. \tag{9}$$

where $E$ is the nucleon energy expressed in GeV units and the relations holds good for energy range $10^2 - 10^5\,GeV$.

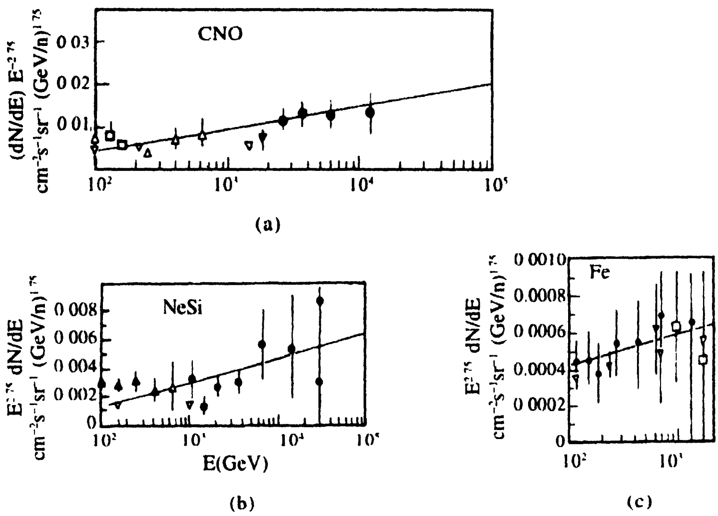



**Figure 2.** Energy spectra of primary cosmic ray CNO, Ne-Si and Fe nuclei fluxes directly measured using balloon and satellites, (a) CNO fluxes . Δ Ryan *et al* [21], ● JACEE [24], ∇ SOKOL [26], □ Buckley *et al* [28] ; (b) Ne-Si fluxes . Δ Ryan *et al* [21], ● JACEE [24], ∇ SOKOL [26]. (c) Fe fluxes ● Kawamura [23], □ JACEE [24], ∇ SOKOL [26]. Full curves are the fits to CNO, Ne-Si and Fe nuclei fluxes data whose parametric values are displayed in Table 1

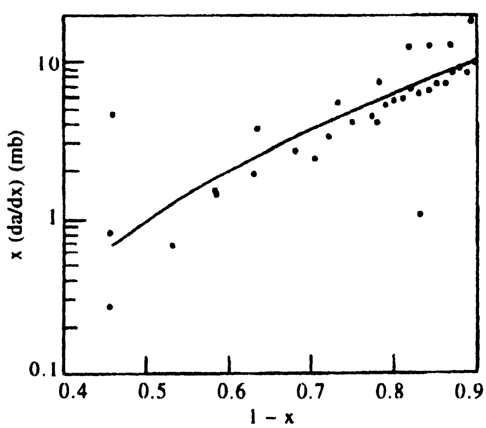



**Figure 3.** Inclusive cross-section $d\sigma/dx_F$ neutral pion production data obtained from the CERN LEBC-EHS experiments of Aguliar Benitez [23] along with NA22 [20] and NA23 [20] results : Experimental $\pi^0$ data, ● Aguliar Benitez *et al* [20], Δ NA22 [20], ∇ NA23[20]. Full line is the numerical fit to data as obtained from the relation (3).

In connection of the derivation of $\pi^0$ production spectrum in the atmosphere the Lorentz invariant cross-section for inclusive reactions $p + p \rightarrow \pi^0 + X$ has been considered from the CERN LEBC-EHS experiments performed by Aguliar-Benitez *et al.* [20]. Figure 3 represents the $\pi^0$ production $d\sigma / dx_F$ data together with the similar results obtained from NA22 [20] and NA23 [20] experiments along with the numerical fit to data available from the fit (3) for $A$ = 15.39 mb and $n$ = 3.97.

Using the relations (1)–(5) spectrum weighted moments for neutral pion production, $Z_{p\pi^0}$ has been calculated for $\sigma_{in}$ = 35 mb, $A$ = 15.39 mb, $n$ = 3.97 and $s$ = 1.73 and found to be 0.022315. The primary nucleon initiated neutral pion production spectrum and the corresponding photon spectrum in the atmosphere have been calculated from the relations (5)–(7) and found to follow the relations :

$$g_{\pi^0}(E)\,dE = 0.057\,E^{-2.73}[cm^2.s.sr.GeV/n]^{-1} \tag{10}$$

and

$$g_{\gamma}(E)\,dE = 0.042E^{-2.73}dE[cm^2.s.sr.GeV/n]^{-1}. \tag{11}$$

By adopting the standard parameters like absorption length of p-air collision, $L$ = 115 g-cm$^{-2}$, $\lambda_0$, radiation length of photons in air = 38g-cm$^{-2}$, and using relations (7) and (8) along with the conventional cascade parameters from the Tables 2 and 3, the integral energy spectra of photons at the large atmospheric depths X=540, 650 and 735 g-cm$^{-2}$ have been estimated and found to follow the power law fits of the forms :

$$g_{\gamma}(\geq E, 540g-cm^{-2}) = 4.60\times10^{-4}E^{-1.73}[m^2.s.sr]^{-1}, \tag{12}$$

$$g_{\gamma}(\geq E, 650g-cm^{-2}) = 2.023\times10^{-4}E^{-1.73}[m^2.s.sr]^{-1}, \tag{13}$$

$$g_{\gamma}(\geq E, 735g-cm^{-2}) = 1.063\times10^{-4}E^{-1.73}[m^2.s.sr]^{-1}. \tag{14}$$

The cascade parametric values obtained from relations discussed in the text after Rossi [15] have been displayed in the Table 2.

**Table 2.** The cascade parametric values

| $A(s)$ | $B(s)$ | $C(s)$ | $m_0$ | $K_1$ | $K_2$ | $\lambda_1$ | $\lambda_2$ |
|---|---|---|---|---|---|---|---|
| 1.1870 | 0.5804 | 0.5595 | 0.7730 | 0.5783 | 0.2839 | −0.3737 | −1.5863 |

The derived integral energy spectra of photons at the atmospheric depths 540 g-cm$^{-2}$, 650 g-cm$^{-2}$ and 735 g-cm$^{-2}$ have been displayed in the Figure 4 along with the high altitude Emulsion Chamber data of Lattes *et al.* [12], Shibata *et al.* [13] and Otinowski [14], at locations Mt. Chacaltaya, Mt. Norikura and Mt. Fuji, respectively. An approximate agreement of the derived photon energy spectra below 10 TeV from the primary nucleon spectrum reveals the fact that the conventional cascade formulation and Feynman scaling phenomena are still in favourable position for the altitude variation of the secondary electromagnetic components of primary cosmic rays. We could not extend our calculations byond 10 TeV photon energy due to the non availability of the data as well as statistical uncertainty of the available results. The scale breaking phenomena in h-h collisions may interpret the spectral bending phenomena *viz.* in the knee region of the primary cosmic ray spectrum.

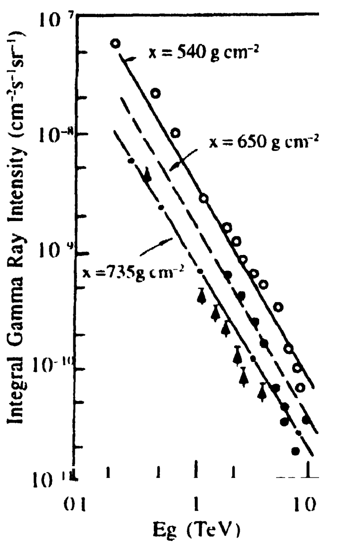



**Figure 4.** Energy spectra of the secondary diffuse photons generated by primary nucleon air inelastic interactions Experimental Emulsion Chamber data, o Lattes *et al* [12] at location Mt Chacaltaya (X = 540 g-cm$^{-2}$), ● Shibata *et al* [13] at location Mt Norikura (X = 650 g-cm$^{-2}$) and ▲ Otinowski [14] at location Mt Fuji (X = 735 g-cm$^{-2}$) Full, broken and chain lines are the derived photon energy spectra at three atmospheric depths X = 540, 650 and 735 g-cm$^{-2}$, respectively

## 4. Conclusion

Starting from the primary nucleon spectrum based on the latest direct measurements, with the adoption of CERN LHS data for pp collisions and also by adopting the conventional cascade equation the photon energy spectra at different atmospheric depths have been derived. The results are in fair agreement with the observed results at Mt. Chacaltaya, Mt. Fuji and Mt. Norikura by Lattes *et al.*, Shibata *et al.* and Otinowski.

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