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High Energy spectra of Electromagnetic Component

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Structured Abstract:

Purpose: To study altitude dependence of high energy spectra of electromagnetic components like gamma rays.

Methods: Using recently measured elemental fluxes at high energies of different experimental researchers, the primary cosmic nucleon spectrum has been estimated. Considering the superposition model, the all-particle nucleon spectrum has been estimated in the energy range 0.1 – 100 TeV. Taking this as the source of parent neutral mesons along with the spectrum weighted moments for neutral pion production after Aguliar Benitez et al., the neutral pion production spectrum in the atmosphere has been calculated. The generated neutral pion decay before reaching in the atmosphere and as a consequence the electromagnetic cascades are generated through $\pi^0 \rightarrow 2\gamma$ decays. The unidirectional intensity of γ rays at atmospheric depths 540 and 735 gm-cm^{-2}air have been calculated by adopting the conventional cascade theory.

Findings: The results are found comparable to the emulsion chamber data obtained at locations Mt. Chacaltaya and Mt. Norikura.

Originality: Our analytical calculation starting from latest primary nucleon spectrum based on direct measurement with the adoption of CERN data for pp collisions and by adopting conventional cascade equation is in fare agreement with the observed results.

Keywords*:* Pion Production, Primary Nucleon Spectrum, Flux of Gamma Rays, Altitude Dependence.

Paper Type: Research Note.

Introduction

Gamma radiation is the most energetic part of electromagnetic spectrum. It provides information about the most energetic process and phenomena in the Universe. Observation of gamma radiation offers one possibility of observational evidence regarding the amount of antimatter in the galaxy. Our motive is to give an analytic estimate of gamma ray background at different atmospheric depths to create an idea about the diffuse photonic background apart from those available from astronomical sources. In gamma ray astronomy, the evolution of primary cosmic rays in the Galaxy is observed and studied. In general, secondary gamma rays are produced by inelastic interactions of primary particles with the gas in the interstellar medium.The search for gamma ray bursts is of astrophysical importance for the study of emission of neutrinos from the sources of gamma rays. Gamma rays and neutrinos are produced in beam dumps during the interaction of high energy protons with stellar targets. In such reactions, gamma rays and neutrinos are generated simultaneously through the decay of neutral and charged pions respectively. The discovery of cosmic microwave background also reveals the fact that Universe would not be transparent to gamma rays above 100 TeV due to photon-photon interactions. Underground muon detectors are designed so that they can measure the direction of arrival of down going muons originating from gamma ray induced electromagnetic showers in the earth's atmosphere. In general, gamma ray showers are muon poor, so long observations of muon events are required in GeV or TeV muon telescopes to determine the direction of incident gamma rays from astronomical sources.

Review of Literature

Investigation of gamma ray bursts also provides the data on dark matter and requires a km-size muon telescopes for the identification of the sources. This helps the search of dark matter in active galactic nuclei. The study of diffuse gamma rays generated by the primary cosmic-ray interactions with the atmosphere is of sufficient importance to estimate the background gamma-ray fluxes and to isolate the radiation reaching the earth from different astronomical objects like Crab Nebula, Cygnus X-3, pulsars and AGN (Bhattacharyya et al. 1998, 1997, 1997, 1998).

Usually the charged pions are produced in the upper atmosphere by primary nucleus-nucleus collisions and they decay into muons and neutrinos, except at very high energies when the time dilation of the relativistic mesons dominates. A portion of low energy muons decay to electrons and neutrinos. On the other hand, the produced neutral pions decay into gamma rays that penetrate the atmosphere producing cascade showers consisting of electrons and photons. Earlier Daniel and Stephens (Daniel et al.1974) have surveyed the spectra of electrons and gamma rays produced by neutral pions in the upper atmosphere at moderate energies of less than 0.1 TeV. Okuda and Yamamoto (Okuda et al.) have studied electron-photon spectra using analytic cascade theory for energies above 1 GeV. Latter Beuermann and Wibberenz (Beuermann et al.1968) have extended such calculations to the energy range 4 MeV to 10 GeV. Daniel and Stephens (Daniel et al. 1973) have also determined similar spectra from near the top of the atmosphere up to the sea level. Jabs and Wibberenz (Jabs et al. 1970) have calculated the energy spectrum of secondary gamma rays at atmospheric depths 0-30 gm-cm-^{2} in the spectral range 1 to 13 GeV.

Lattes et al. (Lattes et al. 1971) investigated the energy spectra of diffuse photons at atmospheric depths 540 and 735 gm. - cm^{-2} in the spectral energy range 0.2-10 TeV. Saito et al.(Saito et al.

1993) have studied the high energy air showers using Monte Carlo simulations and have compared their results with the observed data obtained at Mt. Norikura. They have used the primary spectrum in the energy range 10^3 – 10^4 TeV. From a closer survey of JACEE and others (Ryan et al. 1972, Webber et al. 1987, Kawamura et al. 1989, Asakimori et al. 1991, Muller et al.1991, Ivanenko et al. 1985, Dwyer et al. 1993, Buckley et al. 1993, Menn et al. 1997) on primary spectrum and Fuji Kanbala experimental data (Ren et al. 1988), it may be concluded that the proton energy spectrum shows a bending behavior beyond 1000 TeV. Investigation of the proton energy spectrum in the knee region is necessary for the understanding of the acceleration mechanism and propagation of high energy primary cosmic rays in the Galaxy. The large scale emulsion chamber experiment at high mountain altitude performed by Renetal. (Renetal. 1988) has exhibited a peculiar structure of electron-photon air shower sizes.

Objectives of Study

The availability of the balloon and satellite – borne passive and active detector experiments have allowed us to estimate precise primary nuclear spectra up to energies less than equal to 1000 TeV. With the adoption of the conventional cascade equation (Rossi 1952, Hayakawa 1968, Bhattacharyya et al. 1979) the photon spectra at different atmospheric depths of 540 and 735 gm. – cm^{-2}have been estimated. The derived results have been compared with the available results at different mountain altitudes.

Methodology

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

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

Where K_i, γ_i and E are the elemental spectral amplitudes, indices of the i-th species and energy per nucleon respectively.

By adopting the standard superposition model (Yodh et al. 1981, Bhttacharyya 1983) , one can obtain the total primary nucleon spectrum as

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

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

The CERN accelerator data on p_T integrated Lorentz invariant cross-section for the p+p → π^0 + X inclusive reaction found by Aguliar – Benitez et al. (Aguliar-Benitez et al.1991) follows the relation

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

Where A and n are fitting parameters.

The spectrum weighted moments for the p + p → π^0 + X inclusive collisions can be estimated from the relation

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

Where

$$f_{p\pi^0}(x) = \frac{\pi}{\sigma_{in}}\int_0^\infty E\left(\frac{d^3\sigma}{d^3p}\right)dp_T^2 = A\,(1-x)^n \qquad (5)$$

The simplified form of the Z-factor follow

$$Z_{p\pi^0} = \frac{A\,\Gamma(s)\Gamma(n+1)}{\sigma_{in}\,\Gamma(s+n+1)} \qquad (6)$$

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

$$g_{\pi^0}(E)dE = Z_{p\pi^0}\,N\,(E)dE \qquad (7)$$

The lifetime of neutral pion is short and they decay into two photons through the

π^0 → 2γ process. The energy spectrum of photons $g_\gamma\,(E)$ may be estimated from the neutral pion production spectrum $g_{\pi^0}(E)$ using the relation

$$g_\gamma(E)dE = \frac{2}{s+1}\,g_{\pi^0}\,(E)dE \qquad (8)$$

The unidirectional flux of gamma rays at an atmospheric depth X gm.- cm.$^{-2}$, produced by the incident parent gamma rays, can be estimated using the following expression

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

(9)

Where s is the integral primary nucleon spectral index, L is the absorption length of p-air collisions and $\lambda_0$the photon radiation length. Here

$K_1(s) = \frac{a_1C(s)}{\sigma_0+\lambda_1(s)}$ and $K_2(s) = \frac{a_2C(s)}{\sigma_0+\lambda_2(s)}$

σ_0, $\lambda_1(s)$ and $\lambda_2(s)$ are conventional parameters in the cascade theory and they obey the respective forms

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

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

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

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

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

The total primary nucleon spectrum at the top of the atmosphere obtained by Majumdar (Majumdar 2014) which follows the form

$$N(E)dE = 1.38\, E^{-2.7} [\mathrm{cm}^2 \mathrm{sec.sr.GeV}]^{-1} \quad (10)$$

The relation holds for energy range 10^2 - 10^5 GeV.

In connection with the derivation of π^0 production spectrum in the atmosphere, the Lorentz invariant cross-section for inclusive reactions p + p → π^0 +X has been considered from the results of CERN LEBC-EHS experiment performed by Aguilar- Benitez et al.(Aguliar-Benitez et al.1991) for which A=15.39mb and n=3.97.

Using the relation (5), the spectrum –weighted moment for neutral pion production,$Z_{p\pi^0}$, has been calculated for σ_{in} = 35 mb and s=1.7 and found to be .023419. The primary nucleon initiated neutral pion production spectrum and the corresponding photon spectrum in the atmosphere have been calculated from equation (5) to (7) and found to follow the relations

$$g_{\pi^0}(E)dE = 0\,.032318\, E^{-2.7}\, dE \quad [cm^2 sec.sr.GeV]^{-1} \quad (11)$$

$$g_\gamma(E)dE = 0.023939\, E^{-2.7} dE \quad [cm^2\, sec.sr.GeV]^{-1} \quad (12)$$

By adopting the standard parameters, like absorption length of p-air collision, L=115 gm. – cm^{-2}, radiation length of photons in air, λ_0 = 38 g cm^{-2}, and using relation (7) and (8) along with the conventional cascade parameters from Table-1, the integral energy spectra of photons at large atmospheric depths X = 540 and 735gm. cm^{-2} have been estimated and found to follow the power law fits of the forms:

$$g_\gamma(\geq E, 540gm.cm^{-2}) = 2.66 \times 10^{-4} E^{-1.7} (m^2.sec.\mathrm{sr.})^{-1} \quad (13)$$

$$g_\gamma(\geq E, 735gm.cm^{-2}) = 0.607 \times 10^{-4} E^{-1.7} (m^2.sec.\mathrm{sr.})^{-1} \quad (14)$$

The cascade parametric values obtained from relations after Rossi (Rossi 1952) have been displayed in Table-1.

Discussion

The derived integral energy spectra of photons at the atmospheric depths 540 and 735 g cm^{-2}have been displayed in Fig.1. along with the high altitude data of Lattes et al.(Lattes et al. 1971) and Otwinowski (Otwinowski 1968) at locations Mt. Chacaltaya and Mt. Norikura, respectively. An approximate 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 favorable position for the altitude variation of the secondary electromagnetic components of primary cosmic rays. We could not extend our calculations beyond 10 TeV photon energy due to non-availability of data as well as statistical uncertainty of the available results. The scale-breaking phenomena in H-H collisions may interpret the spectral bending phenomena i.e. the knee region of the primary cosmic ray spectrum (Saito et al.1993).Figure shows the comparison of our derived spectrum with the observed results of Lattes et al. and Otinwoski. The curves indicate that our derived result is in well agreement with the observed resultof Otinwoski but flatter than the experimental result of Lattes et al.

Conclusion

Starting from the primary nucleon spectrum based from the latest direct balloon-borne detector measurements, and by adopting conventional cascade formulation, the photon energy spectra at different atmospheric depths have been derived. The results are in fair agreement with the observed results at Mt. Chacaltaya and Mt. Norikura obtained by Lattes et al. and Otwinowski. Our theoretical curve is flatter than the experimental data obtained by Lattes et al. Here we have assumed the spectral index for the secondary spectrum is the same as that of the primary due to scaling and constant cross section. Our investigated spectral index is about 1.7 which is smaller than the fitted value of the experimental results of Shibata et al.

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Table-1: The cascade parametric values

A(s)	B(s)	C(s)	λ_0	K_1	K_2	λ_1	λ_2
1.1870	*0.5804*	*0.5595*	*0.7730*	*0.5783*	*0.2839*	*-0.37*	*-1.58*

						37	***63***

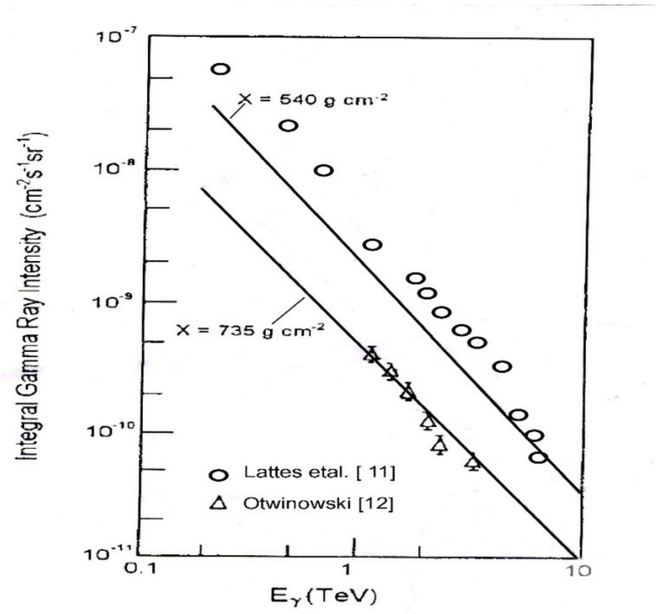

Fig.1; Energy spectra of secondary diffuse photons generated by primary neucleon air inelastic interactions; solid lines are the derived photon energy spectra at two atmospheric depths.