Investigating the Characteristics of Longitudinal Profile of Primary Particles in Extensive Air Showers


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Abstract. One of the characteristics of longitudinal development of extensive air showers is the number of charged particles and depth of shower maximum in extensive air showers as a function of primary energy, which is often used to reconstruct the elemental composition of primary cosmic rays. Studying of extensive air shower characteristics was performed by investigating the longitudinal development parameters depending on Heitler model for different primary particles. The simulation of the number of charged particles and depth of shower maximum ($N$ and $X_{\text{max}}$) in extensive air showers of particle cascades was performed using AIRES code for SIBYLL hadronic model for different primary particles like electron, positron, gamma quanta and iron nuclei at the energy range $10^{14}-10^{19}$ eV. The comparison between the simulated longitudinal development of $N$ and $X_{\text{max}}$ using SIBYLL hadronic model with two hadronic models (QGSJET99 ans SIBYLL16) has shown an opportunity for determination of cosmic ray cascade interactions in extensive air showers.

1. Introduction

Extensive air showers (EAS) are a cascade of particles generated by the interaction of a single high energy primary cosmic ray particle with the atmosphere. As a result of the collision between the incident primary particles with the atmospheric nuclei in EAS, the secondary particles like (pions, muons, kaons etc.) will be produced in each collision [1-3]. In the number of secondary particles likes photons, electrons, muons, and hadrons after reaching their maximum, the shower decays for more and more particles fall below the threshold energy for further particle production. All of these particle multiplications called EAS which are a combination of electromagnetic and hadronic cascades [4]. The basic properties of the development of the cascade in EAS can be extracted from a simplified model due to Heitler model which describes the evolution of a pure electromagnetic cascade [5].

In this article, the total number of charged particles in atmosphere is performed for secondary particles like muons, pions, photons and electrons. The investigation of longitudinal developments in EAS was fulfilled using AIRES code for different hadronic models [6].

2. Longitudinal development in atmospheric cascade

The longitudinal profile of a cosmic ray produced shower can be clarified as a superposition of electromagnetic subshowers. These subshowers are initiated by the decay of neutral pions induced in the hadronic core in extensive air showers. In general, the longitudinal shower profile is defined as the number of charged particles in EAS as a function of atmospheric depth which is related to the type and energy of the primary particle. The atmospheric depth of charged particles ($X_{\text{max}}$) at which...
A shower demonstrates its maximum is quite correlated to the energy of the primary particles [10]. The parameter $X_{\text{max}}$ gives an important information on the composition of the primary cosmic rays. Therefore, the mean $X_{\text{max}}$ distribution holds important proofs about the mass composition of the primary particle in EAS.

3. Results and discussion

3.1 Estimating of longitudinal development in EAS

During the development of an EAS, the secondary particles of each new generation carry less energy per particle than the generation before. The number of particles increases up to the shower maximum, $X_{\text{max}}$, where the energy of the particles becomes too small to produce new particles [2]. EAS is divided into two parts which are called the electromagnetic and hadronic cascades. The primary energy of the two parts is calculated from the following relation [3, 4]:

$$ E_0 = E_{\text{em}} + E_{\text{h}} \quad (1) $$

Where $E_0$ is the primary energy; $E_{\text{em}}$ is the electromagnetic energy part; $E_{\text{h}}$ is the hadronic energy part where ($E_{\text{h}} = N_\mu \xi_c^\pi$): $\xi_c^\pi$ represents the critical energy of secondary pions and $N_\mu$ is the number of muons which is equal to the number of pions ($N_\pi$) that is given through the relation [4, 7]:

$$ N_\mu = (E_0/\xi_c^\pi)^\beta \quad (2) $$

Therefore, Eq. (1) becomes [4]:

$$ E_0 = E_{\text{em}} + N_\mu \xi_c^\pi $$

Thus:

$$ E_{\text{em}} = E_0 - N_\mu \xi_c^\pi \quad (3) $$

By dividing Eq. (3) on the primary energy $E_0$ and by using Eq. (2) one can get:

$$ E_{\text{em}}/E_0 = E_0 - N_\mu \xi_c^\pi / E_0 = 1 - (N_\mu \xi_c^\pi / E_0) $$

Thus:

$$ E_{\text{em}}/E_0 = 1 - (E_0/\xi_c^\pi)^\beta \quad (4) $$

When $\beta = \ln[N_{\text{ch}}]/\ln[\xi_c^\pi N_{\text{ch}}] = 0.85$ for $N_{\text{ch}}=10$ where $N_{\text{ch}}$ is the number of charged particles [9]. The magnitude of $E_{\text{em}}/E_0$ depends on the primary energy of cosmic ray particles and the critical energy of pions as shown in Fig. 1. A nucleus with atomic mass number $A$ and energy $E_0$ is taken to be individual single nucleons, each with energy $E_0/A$, and each acting independently, where $[\xi_c^\pi = 20$ and $30$ GeV] [7, 8]. Therefore, Eq. (4) becomes:

$$ E_{\text{em}}/E_0 = 1 - (E_0/A \xi_c^\pi)^\beta \quad (5) $$

Eq. (2) becomes:

$$ N_\mu / A = (E_0/A \xi_c^\pi)^\beta \quad (6) $$

With: $\beta=0.90; \xi_c^\pi=20$ GeV we have [7]:

$$ N_\mu = (E_0/\xi_c^\pi)^\beta A^{1-\beta} \approx 1.69 \times 10^4 A^{0.10} \frac{E_0}{1 \text{PeV}}^{0.90} \quad (7) $$

Eqs. (4) and (5) can be approximated by [9]:

$$ E_{\text{em}}/E_0 = 1 - (E_0/\xi_c^\pi)^\beta $$

$$ N_\mu / A = (E_0/A \xi_c^\pi)^\beta $$

$$ N_\mu = (E_0/\xi_c^\pi)^\beta A^{1-\beta} \approx 1.69 \times 10^4 A^{0.10} \frac{E_0}{1 \text{PeV}}^{0.90} $$
\[ E_{em}/E_0 \approx a_1 (E_0/\xi_C^{\pi})^{b_1} \quad (8) \]
\[ E_{em}/E_0 \approx a_2 (E_0/A_\xi^{\pi})^{b_2} \quad (9) \]

Where:
\[ \omega = 10^5 a_1 = \frac{(1-\omega^{b_1})}{\omega^{b_1}} \approx 0.57, \quad b_1 = \frac{(1-\beta)}{(\omega^{1-\beta}-1)} \approx 0.032 ; \beta = 0.85 \]
\[ a_2 = \frac{(1-\omega^{b_2})}{\omega^{b_2}} \approx 0.4 \quad ; \quad b_2 = \frac{(1-\beta)}{(\omega^{1-\beta}-1)} \approx 0.046 ; \beta = 0.90 \]

Considering a shower initiated by a single photon with primary energy \( E_0 \), then at \( N = N_{\text{max}} \) the cascade reaches its maximum size when all particles have energy equal to the critical energy \( \xi_C^e \) then [3, 4]:
\[ N_{\text{max}} = E_0/\xi_C^e \quad (10) \]

The number of electrons \( N_{e_{\text{max}}} \) at shower maximum can be extracted from Heitler’s total size \( N_{\text{max}} \), when [4]:
\[ N_{e_{\text{max}}} = N_{\text{max}}/g = E_0/g\xi_C^e \quad (11) \]

Where \( g \) is the correction factor. Therefore when \( E_{em}=E_0 \) one can see that [4]:
\[ N_e = E_{em}/g\xi_C^e \quad (12) \]

Where \( N_e \) is the number of electrons. From Eq. (8) gets [6]:
\[ E_{em} \approx a_1 \left( \frac{E_0}{\xi_C^e} \right)^{b_1} E_0 = a_1 \frac{E_0^{g1}}{(\xi_C^{\pi})^{b_1}} \quad (13) \]

From Eqs. (12) and (13) for \( g = 10; \xi_C^e = 85MeV; \xi_C^{\pi} = 20GeV \) we get:
\[ N_e = a_1 \frac{E_0^{g1}}{g\xi_C^e (\xi_C^{\pi})^{b_1}} = 0.57 \frac{850}{10^9 \text{PeV}} \left( \frac{20}{10^6 \text{PeV}} \right)^{b_1} \]

Therefore:
\[ N_e \approx 10^6 \left( \frac{E_0}{1\text{PeV}} \right)^{a_1} \quad (14) \]

Where: \( a_1 = 1 + b_1 = 1.032 \)

Equation (9) becomes:
\[ E_{em} \approx a_2 \left( \frac{E_0}{A_\xi^{\pi}} \right)^{b_2} E_0 = a_2 \frac{E_0^{g2}}{(A_\xi^{\pi})^{b_2}} \quad (15) \]
From Eqs. (12) and (15) for \( g = 13; \xi_e = 85\, MeV; \xi_c = 20\, GeV \) can get:

\[
N_e = a_2 \frac{E_0^{a_2}}{g \xi_e (A \xi_c^a)^{b_2}} = 0.4 \frac{A^{1-a_2} E_0^{a_2}}{1105 \, \text{PeV} \left( \frac{20}{10^6 \, \text{PeV}} \right)^{b_2}}
\]

Thus:

\[
N_e \approx 5.95 \times 10^5 A^{1-a_2} (E_0/1\,\text{PeV})^{a_2}
\]

(16)

Where: \( a_2 = 1 + b_2 = 1.046. \) Equation (16) is very important for determination the number of electrons in atmosphere as a function of \( E_0. \) The number of particles in atmosphere as a function of the primary energy at the energy range \( 10^{14}-10^{19} \, eV \) is demonstrated in Fig. 2 for different primaries initiated secondary particles like: photons at maximum; primary proton initiated electrons and muons; iron nuclei initiated electrons and muons.

**Fig. 2** The number of particles in atmosphere as a function of the primary energy at the energy range \( 10^{14}-10^{19} \, eV \): (a) represents the number of photons at maximum; (b) the number of electrons for primary protons; (c) the number of electrons for iron nuclei; (d) the number of muons for iron nuclei and primary proton; (e) the number of muons for primary proton.

### 3.2 Simulation of longitudinal developments

Study of particle cascades in EAS was performed using AIRES code for simulating the longitudinal developments (\( N_{\text{mean}} \) and \( X_{\text{max}} \)) of produced particles in EAS like (\( \gamma \) and Fe) at the energy range \( 10^{14} \) to \( 10^{19} \, eV \) for two zenith angles (see Fig. 3). In Fig. 3 demonstrated the simulation of longitudinal development presented by \( N_{\text{mean}} \) and \( X_{\text{max}} \) relation using AIRES code for SIBYLL hadronic model in comparison with two hadronic models (QGSJET version 99 and SIBYLL version 16) for two different particles \( \gamma \) and Fe. In this figure was shown the behavior of hadronic models for different particles, different energies and different zenith angles of longitudinal profile.
Fig. 3 Simulation of longitudinal development ($N_{\text{mean}}$ and $X_{\text{max}}$) using AIRES code for different hadronic models for: (a) primary electron for vertical showers at $10^{14}$ eV; (b) primary $\gamma$ particle at the energy $10^{19}$ eV for $\theta = 10^\circ$; (c) primary positron at the energy $10^{17}$ eV for $\theta = 30^\circ$; (d) primary iron for vertical showers at energy $10^{15}$ eV.

4. Conclusion

In present work the mean number of secondary particles is obtained for different particles like muons, electrons and photons in extensive air showers at the energy range $10^{14}$-10$^{19}$ eV. The fraction into electromagnetic component [$E_{\text{em}}/E_0$] was estimated for two different critical energies (20 and 30) GeV and different primary particles. The dependence of the number of the primary particles on the primary energy was observed within the energy range $10^{14}$-10$^{19}$ eV. Furthermore, the simulation of longitudinal profile ($N_{\text{mean}}$ and $X_{\text{max}}$) in extensive air showers was performed for SIBYLL hadronic models for different primary particles, different energies and different zenith angles. The comparison of the simulated results of SIBYLL hadronic model with other hadronic models like QGSJET99 and SIBYLL16 has shown an opportunity in identification of the primary particle. The main feature of the present approach gives the possibility of longitudinal profile analyzing of real events which detected with extensive air shower arrays and reconstruction of energy spectrum and mass composition of primary cosmic ray particles.
References