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STUDY OF EXTENSIVE AIR SHOWERS IN THE EARTH'S ATMOSPHERE

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Abstract. Cosmic rays with primary energy greater than 100 TeV have low fluxes. Therefore, the air showers are useful for studying primary cosmic ray particles with high energies. I considered that a primary proton beam with energies in the range 10^5 GeV < E < 10^8 GeV colliding with an atmospheric nucleus target produces an air shower with charged secondary particles detectable at low levels in the terrestrial atmosphere. At ground level (965 m above sea level), for 10^7 shower size, the calculated results for the total number of muons with energies above 1 GeV, ranges between 0.53×10^6 muons to 1.22×10^6 muons, in good agreement with the available experimental data.

Key words: Universe, cosmic radiation, GZK effect, muons, shower size.

1. INTRODUCTION

The Austrian physicist Victor Franz Hess, the father of the cosmic ray physics, best explained the cosmic ray discovery, by the assumption that, cosmic rays enters our atmosphere from above. The original results by Hess were confirmed to be correct and V.F. Hess received in 1936 the Nobel Prize for the discovery of cosmic rays.

Extensive air showers and the main features of the energy spectra of the primary cosmic ray nuclei provide a better understanding of the elemental composition of the cosmic rays at very large energies.

Before discussing the different types of radiation, I first outline some general properties of the primary cosmic ray particles: their internal structure, the mean lifetime and their mass (Table 1). According to [1], by their nature, the radiation is of two types: electromagnetic and corpuscular, the latter being called cosmic rays. The large penetrating power of cosmic rays is the feature that distinguished cosmic rays from other kinds of radiation in the form of electromagnetic waves (the gamma rays or X-rays) or particles with or without electrical charge emitted during the radioactive decay of atoms.

The ejections of magnetized plasma from the Sun, commonly known as coronal mass ejections are one of the most stunning manifestations of solar activity. These ejections play a leading role in the Sun-Earth connection, because of their large-scale, energetics and direct impact on the space environment near the Earth [2]. The penetrating power of an alpha particle trajectory range (cm) in atmosphere is directly proportional to the energy of the alpha particle. For example, an alpha particle with energy E = 10 MeV, traverses in dry air (at 15 degrees Celsius) the range R = 10.1 cm [3]. Typically, the alpha particles are emitted from the nucleus of an unstable atom, such as the radioactive atoms, *e.g.* uranium or radium. Gamma rays are high energy photons. Primary neutrons, over 1000 km altitude in the atmosphere, decays and the decaying results (the protons, electrons and electronic neutrinos) add to the fluxes of the primary cosmic radiation. Beta particles (electrons and positrons), emitted from the nucleus of a radioactive atom, are not able to produce ionization.

The general properties of primary cosmic ray particles are shown in Table 1 [4] that gives the particle properties for the primary cosmic ray nucleons [barions: proton (*u u d* internal structure) and neutron (*u d d* internal structure)]. Included are the primary electrons (leptons, with no internal structure), which are present in the primary cosmic radiation.

Table 1

Some particle properties of the nucleons and electrons in the primary cosmic radiation [4]

Cosmic ray particles	Mean lifetime, τ [time unit]	Mass [MeV/c^2]
proton	10^{32} yr.	938.27
neutron	885.7 ± 0.8 s	939.56
electron	4.6×10^{26} yr.	0.511

The cosmic radiation is composed of all nuclei of atoms of chemical elements of Mendeleev's table. Primary cosmic ray particles are generally stable nuclei of atoms from hydrogen nuclei up to iron nuclei (Z = 26) in quantities whose values decrease with increasing atomic number Z of the atom in question. Along with high-energy protons, electrons, neutrons, and charged mesons (pions, kaons) make up the primary cosmic radiation.

The result of the primary cosmic ray particles interaction with the environmental nuclei is the appearance of extensive air showers with secondary particles. The cosmic ray particles, especially protons, originated in the Universe, are natural sources of high energy relativistic particles. Therefore, the cosmic ray particles are a source of information on the origin and evolution of the Universe and back [5]. Our Universe is an expanding one [6].

Next, the study on the cosmic ray particle delivers radiation sources about the origin of the Universe. The particles of galactic cosmic rays are studied by direct experimental measurements using small detectors, which are placed in atmospheric balloons in flight and satellites. It is important to recall that, the nuclear photographic emulsions (Ilford emulsions) used both as particle detectors as well as target particles in relativistic nuclear physics experiments are preferred for our simplified study of cosmic radiation particles with energies smaller than 10 GeV. The probability that a particle does not disintegrate in the time interval (0, t) such as its range in the nuclear emulsion is measurable is given by $P = e^{-t/\tau}$, where t and τ are expressed in the laboratory system [7]. Nuclear emulsions are used to determine the very short lifetimes of some cosmic ray particles [8].

For extragalactic cosmic ray particles the studies are necessary indirect, by using information about the properties of particle cascades generated by primary particles with high energy radiation, detectable from Earth's surface.

The primary cosmic rays with energies above 100 TeV by taking into account the main features of the energy spectrum of primary cosmic radiation particles (specific to knee-type and ankle-type regions and of the GZK energy region providing information about the nature of cosmic ray astrophysics sources) are studied in the present paper. I also calculated the total number of muons in the vertical atmospheric cascade detectable on the terrestrial areas and I found that it is an order of magnitude lower than the atmospheric cascade size.

2. ENERGY SPECTRA OF ATMOSPHERIC PROTONS IN THE TERRESTRIAL ATMOSPHERE

The energy spectrum of primary protons is currently of great interest because the majority of the primary particles in cosmic rays are protons, and the cosmic ray spectra of primary protons can be used as input data for simulation of interactions, decay and search of the extensive air showers [9].

Primary cosmic ray particles, while entering the Earth's atmosphere, interact with the atmospheric nuclei and produce secondary cosmic ray particles. Some of the secondary particles decays and interacts as a function of their energy compared with the corresponding critical energy of the particles. As an example, for charged pions the critical energy value is ~ 115 GeV and for charged kaons it is ~ 850 GeV [10, 5].

As indicated by Eq. (1), the number of protons $N(E)$ [protons/($m^2 \cdot s \cdot sr$)], with kinetic energy greater than E [GeV], is giving by [11, 12]:

$$N(E) = k(1+E)^{-b}, \tag{1}$$

where: k = 3800 [11], k = 5000 [12], and b = 1.6 [12].

Because protons are the main component of primary cosmic rays [13], I made the first derivative of Eq. (1) with respect to energy and I got the following approximate expression for calculating the particle flux as a function of energy:

$$\frac{\mathrm{d}N}{\mathrm{d}E} = \frac{a}{(1+E)^{2.6}}, \tag{2}$$

where: a = 0.80 [12], a = 0.608 [11], and b = 1.6 [12].

Then in the calculation of the differential flux of protons as a function of energy, the effects of the decreasing fluxes as a function of the increasing energy particle have been taken into account. The calculated proton fluxes cover the energy range from 100 GeV to 100 EeV. The three energy regions of the cosmic ray particles energy spectrum are called *knee-type region* (around 3×10^{6} GeV, [14]), *ankle-type region* (around 3×10^{9} GeV, [14]), and the energy value 5×10^{19} eV is considered the Greisen-Zatsepin-Kuzmin (GZK) energy region of the cosmological particles. It is important to recall that the Greisen-Zatsepin-Kuzmin limit is an upper limit for the energy of the cosmic rays from "distant" sources. However, the detected energy spectrum may extend beyond 10^{20} eV [15].

The nucleon spectrum can be represented by a power law, with a spectral differential index that increases with increasing the nucleon energy [10, 16, 9]. Next, we consider that the law of absorption of the protons in the atmosphere is of an exponential form [5].

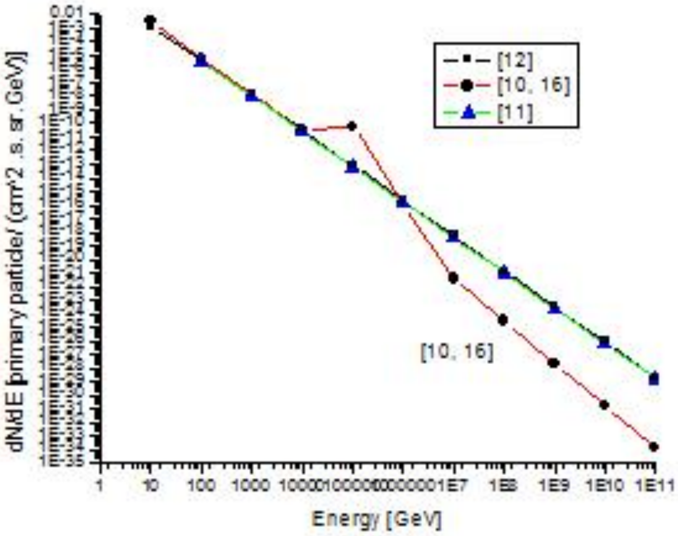

Fig. 1 – Energy spectra of primary cosmic rays as a function of energy. Symbols are the calculated data. The plot shows the calculation of dN/dE, where the lower line represents the results adapted from Refs. [10, 16], and the two upper lines represent the calculation of dN/dE = f (E) adapted from Refs. [12, 11].

It is to be mentioned that the air showers detectable at ground level are composed by electrons, positrons, photons, muons and other secondary particles.

3. INVESTIGATIONS ON THE VERTICAL SHOWERS AT LOW LEVEL IN THE EARTH'S ATMOSPHERE

The relevant energy range, considered in this paper, is ~ 10^5 GeV < E < 10^8 GeV and the atmospheric depth is 920 g/cm^2. At higher energies the flux of primary cosmic ray particles is so low that indirect studies of the air shower features are necessary. Because only muons and neutrinos penetrate to significant depths underground [4], I have calculated the total number of muons, N_μ, with energies above 1 GeV, with the following approximate expression [10]:

$$N_\mu(>1\,\mathrm{GeV}) \approx 0.95\times 10^5 \times \left(\frac{N_e}{10^6}\right)^{3/4}, \qquad (3)$$

where the shower size, N_e, is the total number of the charged particles in the air shower.

In the present investigation I have considered that a primary cosmic ray proton initiated the vertical air showers with $N_e = 10^7$ shower size detectable at ground level. In establishing the value region of primary energy, E_0 [GeV], which generated the muon air shower detectable at ground level, I took into consideration that the primary energy is dependent on the shower size [10].

4. DISCUSSION OF THE RESULTS

The main conclusion seems to be that the investigations of the air showers are useful for studying cosmic rays with primary energy greater than 100 TeV. Muons are one of the most numerous particles present in the low levels of the terrestrial atmosphere. The secondary component of cosmic rays in the atmosphere has a positive charge excess [17].

Table 2 gives the calculated results of the present paper, for primary energy and the total number of muons with energies in the energy range ~ 10^5 GeV < E < < 10^8 GeV for vertical air shower at 965 m above sea level.

Table 2

The calculated results of the total number of muons, N_μ, and the estimated primary energies, E_0, for 920 g/cm^2 atmospheric level and 10^7 shower size

Energy region of air shower at g.l.	N_μ [muons]	E_0 [GeV]
$10^5 < E < 10^8$	$0.53\times10^6 < N_\mu < 1.22\times10^6$	$3.10\times10^7 < E_0 < 8.33\times10^7$

The investigations on the elemental abundances of the cosmic ray nuclei show that the distributions of the nuclei abundances are different in the Universe and in the cosmic ray fluxes:

(1) According to Ref. [11], Hydrogen and Helium are both in the Universe and in the cosmic rays: abundance of the Hydrogen in the cosmic rays is equal with the abundance in the Universe, *i.e.*, ~ 100,000.

(2) Abundances of Li, Be, and B elements are present in the cosmic rays (~ 500) and are not present in the Universe [11].

5. CONCLUSIONS AND PROSPECTS

The number of cosmic ray particles N (E) [particles/($m^2 \cdot s \cdot sr$)], decreases with increasing the particles energy. In high energy region of cosmic rays near 5×10^{19} eV where the decreasing particle flux is maximum, the Greisen–Zatsepin–Kuzmin effect is sometimes referred to as possible assumption of natural source near our Milky Way Galaxy and there is evidence of the cosmological origin for ultrahigh energy cosmic ray particles.

The total number of muons, with energies above 1 GeV, in the vertical air showers detectable at ground level, is an order magnitude lower than that of the shower size at this atmospheric level. It is clearly visible that the primary energy of cosmic ray proton that initiated the vertical air showers detectable at ground level, in the Earth's atmosphere, should be approximately in the following energy region: 3.10×10^7 GeV $< E_0 <$ 8.33×10^7 GeV.

Thus a good knowledge of the possible sources of the cosmic ray particles provides a better understanding of the chemical composition of the cosmic ray fluxes.

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