Romanian Reports in Physics, Vol. 68, No. 2, P. 543–553, 2016

SEARCH FOR SPECIFIC SIGNATURES OF THE COSMIC RAY PHYSICS AT THE HIGHEST ENERGIES*

I. BACIOIU

Institute of Space Science, P.O. Box: MG-23, RO-077125 Bucharest-Magurele, Romania,
E-mail: iuliana.bacioiu@spacescience.ro

Received October 19, 2014

Abstract. Our knowledge of the fundamental particles derives from a detailed study of their properties. In this work, attention is directed towards the behavior of the more energetic particles in extensive air showers. Studies of the various components of the air shower particles (the electromagnetic component, the hadronic component, and the muonic component) are of much importance. One of the main tasks of these studies is to determine the energy spectrum of the nucleons in cosmic rays in the Earth's atmosphere. This fact was interpreted as showing that the ultra-high energy cosmic ray particles are believed to be of extragalactic origin. Finally, it is convenient to introduce assumptions about particle interactions because there is a great deal of information about the strong interactions of the nucleons and about the nature of the cosmic rays.

Key words: primary particles, air showers, critical energy, energy spectrum, galactic cosmic rays.

1. INTRODUCTION

The theoretical aspects of the fundamental particles and the properties of the elementary particles have been used in the study of cosmic rays in the Earth's atmosphere and in the human exploration of space. The Physics of cosmic radiation is situated at the border between the Nuclear Relativistic Physics, Elementary Particle Physics, and Astrophysics. Cosmic radiations are a source of information on the origin and evolution of the Universe. The first association of the cosmic rays with their alien origin was made in 1912 by Victor Franz Hess, a fact confirmed in 1926. As a result of the analysis of the electrical conductivity of gases up to 5 km above sea level, Victor Franz Hess discovered, in 1912 that the increase of the ionization up to ten times that at sea level was responsible for the existence of the high penetrating power of radiation of the extraterrestrial origin.

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* Paper presented at the Annual Scientific Session of Faculty of Physics, University of Bucharest, June 20, 2014, Bucharest-Magurele, Romania.

The original results by Hess were confirmed to be correct and the existence of cosmic radiation has been fully accepted since about 1926. The large penetrating power of cosmic rays is the feature which distinguished cosmic rays from other kinds of radiation [1].

The purpose of the present paper is to find out a general background of our knowledge of cosmic radiation in the terrestrial atmosphere and to describe the various aspects of the properties of the elementary cosmic ray particles for elucidating the origin and the nature of the cosmic rays. Cosmic radiation consists by particles with energies up to 100 EeV, much larger than the energies reached in the major terrestrial particle accelerators. The origin of the cosmic radiation with higher energies is considered to be in neutron stars, supernovae, and black holes with the role of accelerators.

Cosmic radiation is treated in: (i) primary cosmic radiation and (ii) secondary cosmic radiation. Primary cosmic radiation consists of charged particles with a positive electrical charge, mostly protons, electrons, neutrons, alpha particles and atomic nuclei. Secondary cosmic radiation, cosmic radiation resulting from neighboring primary radiation with interstellar gas and nuclei of the terrestrial atmosphere, consists of: pions (π^+, π^-, and π^0), charged muons (μ^+ and μ^-), antiprotons, positrons, and light nuclei such as: Lithium (Li), Beryllium (Be), and Boron (B). In this paper, the energy spectra of the atmospheric nucleons have been calculated and compared them with experimental data. Agreement with these data is seen to be good.

Determination of the nucleons energy spectrum in the terrestrial atmosphere was made in the first part of this article. Then the energy spectra of the primary cosmic ray particles are estimated both as a function of the nucleons energy and as a function of the different atmospheric depths in the atmosphere. Because the protons (^{1}H: Z = 1, A = 1, N = 0; 1p) are a source of high-energy particles, their studies have been used to obtain the information in the study of the secondary cosmic radiation. Some considerations led theorists to concentrate on macroscopic (statistical) quantities like collision free path for relating, for example, the nucleon flux to atmospheric depth.

The crux of the problem for the experimentalists has been the attenuation of the nucleons through the atmosphere, and for the theorists it has been the role of collision inelasticity and collision mean free path therein [2]. As a result of the analysis of their own results, Auger, Maze, Grivet – Meyer (1938) and many others concluded that the showers might be cascades started by energetic electrons in the atmosphere [1]. In the last century many new results have been obtained and these suggested that primary cosmic rays are positive charged particles, *i.e.*, fast protons with large momenta (p >> 938 MeV/c).

In the process of collision of two particles, the number of collisions suffered by an incident nucleon at its passage through a target nucleus is proportional to the radius of that target nucleus [3].

An energetic fast proton (or a primary cosmic ray) collides the atmosphere and interact strongly with a hydrogen nucleus and two protons plus a neutral pi-meson are generated:

$$p + p = p + p + \pi^0. \quad (1)$$

In the center of the mass system, the energy threshold for this reaction is: $E_{th} = \sqrt{s} = 2m_p + m_\pi = 2.016$ GeV [4]. By interactions, the primary particles loss their energy by ionization and radiation processes. When the primary cosmic ray has the critical energy the energy loss is realized by radiation processes.

A proton with higher energy (>10 GeV) collides with a nucleus in the atmosphere, causing a cascade of particles, which contains the electromagnetic, the hadronic, and the muonic components. The development of a shower in the atmosphere depends on the hadronic and electromagnetic interactions of shower particles with the air nuclei, the interaction cross sections, the secondary particle production, decays of unstable particles, and the transport through the atmosphere including energy loss and deflection [5]. Charged pions decay in pions without electrical charge and charged muons and neutrinos (antineutrinos), and high-energy gamma radiation is capable of forming electron–positron pairs.

The second part of this paper is dedicated to the search for the answers to the questions about the estimate of the cosmic ray contribution to the radiation environment in the Earth's atmosphere. The proportion in which chemical elements occur on the Earth's surface has been analyzed and compared with experimental data. An approximate calculation of radiation doses illustrates the effects of cosmic radiations [6], and contributes to the understanding of the effect of cosmic radiation on living organisms.

Finally, it is convenient to introduce some assumptions about particle interactions, because there is a great deal of information about the strong interactions of the nucleons and about the nature of the cosmic rays.

2. ENERGY SPECTRA OF COSMIC RAY PARTICLES IN THE EARTH'S ATMOSPHERE

Cosmic ray particles with energies less than 1 EeV are usually called the galactic cosmic ray particles and those with ultra-high energies up to 100 EeV are of extragalactic cosmic ray origin. Because the cosmic ray spectrum below 1 EeV is of galactic origin, the interest is focused on the study of the combined influences of the Earth's and the Sun's magnetic fields on the cosmic radiation, on solar contributions to the very low energy radiation and on the so-called anomalous component. It is also this energy regime that is used to explore the time variation of the cosmic radiation and climatological aspects [7].

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.

Conventionally, the spectral index above 100 TeV is obtained by indirect measurements with air shower arrays, in which the cosmic ray particle energy is determined from its shower size. The relation between particle energy and shower size is deduced from air shower simulations assuming hadronic interaction models as a reasonable extrapolation of the accelerator results to the higher energy range [8].

2.1. DIFFERENTIAL ENERGY SPECTRUM OF NUCLEONS AT THE TOP OF THE ATMOSPHERE

Some theories hold that the primary cosmic radiation that consists predominantly of protons, alpha particles, and heavier nuclei is influenced by the galactic and extragalactic fields while approaching the Earth. An air shower is caused by a single cosmic ray with energy high enough for its cascade to detectable at the ground. Shower particles typically reach out to about 100–200 m at energy E = 1 PeV, and to 1–2 km at 10 EeV [9]. Energetic nucleons lose energy mostly by strong interactions, heavy nuclei are fragmented in collisions with nuclei of air molecules, and electrons and photons undergo electromagnetic energy loss processes. We see that the nucleons (protons and neutrons) above 1 GeV/c at ground level are degraded remnants of the primary cosmic radiation.

Neutrons and protons exist in separate sets of allowed nucleon states, each characterized by four quantum numbers. The Pauli exclusion principle prohibits any two protons, or neutrons, from having the same quantum numbers but a proton and neutron can have the same numbers, since they are different particles [7].

The low energy cosmic ray particles (below 10 GeV) are affected by the solar activity. The general impression is that at maximum solar intensity the Earth magnetic field is sufficiently distorted to allow low energy particles to reach the Earth’s atmosphere.

A large number of investigations have been performed on the energetic distributions of nucleons in the Earth’s atmosphere as a function of the nucleon energies.

The intensity of primary nucleons in the energy range from several GeV to somewhat beyond 100 TeV is given approximately by the power law spectrum [10]:

$$I_N(E) \approx 1.8\, E^{-\alpha} \frac{\text{nucleons}}{\text{cm}^2 \cdot \text{s} \cdot \text{sr} \cdot \text{GeV}}, \qquad (2)$$

where $I_N\,(E) = \mathrm{d}N/\mathrm{d}E$, E is the energy-per-nucleon, α ($\equiv \gamma + 1$) = 2.7 is the differential spectral index of the cosmic ray flux, and γ is the integral spectral index.

This power law spectrum can be expressed graphically, as in Fig. 1 (a Log – linear graph).

The resultant differential intensity of primary nucleons, in the energy range from the galactic cosmic rays to the extragalactic cosmic rays is shown in Fig. 1.

The differential spectral index changes from 2.7 to 3.1 around the knee at $E \cong$ 4 PeV [8]; $\alpha = 2.7$ if 30 GeV $\leq E < 4 \times 10^6$ GeV, and $\alpha = 3.1$ if 4×10^6 GeV $< E <$ 100 EeV, where E denotes the cosmic-ray nucleon energy at the top of the atmosphere.

The resultant differential intensity of primary nucleons, in the energy range from the galactic cosmic rays to the extragalactic cosmic rays is shown in Fig. 1.

Results of the calculations shown in Fig. 1 seem to indicate that only protons and relativistic particles have the probability of surviving the sea level after traveling from distant sources, while light nuclei and particles with low energies are deflected by the geomagnetic field.

The flux falls steeply with rising energy. At highest energies the existence of the Greisen-Zatsepin-Kuzmin cutoff in the cosmic ray spectrum has been found, an anisotropy in the cosmic ray arrival directions has been detected, hinting at nearby AGN as sources of the cosmic rays [11].

It can be seen from Fig. 1 that the nucleons spectrum can be represented by a power law, (2), with a spectral differential exponent α, that increases with energy.

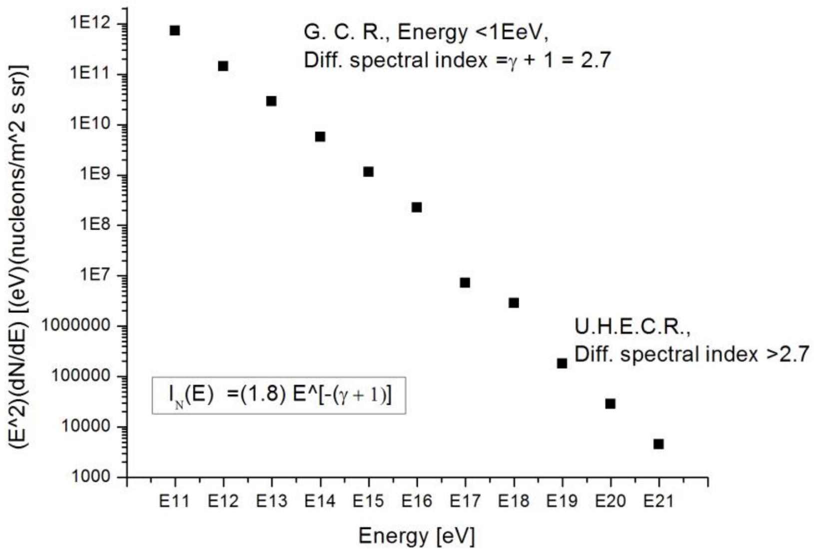

Fig. 1 – Differential energy spectrum of nucleons in the Earth's atmosphere as a function of the nucleon energies.

The differential intensity of nucleons in the energy range from the galactic cosmic rays to the extragalactic cosmic rays is shown in Table 1.

Table 1

Integral intensity of vertical nucleons at various atmospheric depths in the terrestrial atmosphere (calculated results, in the present paper)

Average Atmospheric Depth < *X* > [g/cm^2]	The vertical intensity of nucleons at various depths[1] [nucleons/m^2 s sr GeV]
0.0	3995.857 ± 199.792
5.5	3821.118 ± 191.056
5.8	3811.808 ± 190.590
36	2981.943 ± 149.097
48.4	2695.982 ± 134.799
100	1772.250 ± 88.612
120	1506.288 ± 75.314
150	1180.273 ± 59.013
200	786.031 ± 39.301
400	154.622 ± 7.731
600	30.415 ± 1.520
680	15.872 ± 0.793
800	5.983 ± 0.299
885	2.997 ± 0.149
1000	1.177 ± 0.058
1033	0.899 ± 0.044

[1]Atmospheric depth from 0.1 g/cm^2 (≡ 70 km altitude above sea level) to 1033 g/cm^2 (≡ sea level).

At energies higher than 10^5 GeV cosmic rays are detected by the showers they initiate in the atmosphere. The two main features of the cosmic ray energy spectrum are the knee at about 3×10^6 GeV (where the spectrum steepens from 2.7 to 3.1), and the cosmic ray ankle, at about 3×10^9 GeV, where the energy spectrum becomes again flatter [12].

2.2. THE VERTICAL INTENSITY OF NUCLEONS AT DEPTH *X* IN THE ATMOSPHERE

Cosmic particles with electrical charges arrive into the Earth's magnetic field and interact with it by following the magnetic field lines and reaching the poles. Low energy particles from the cosmic radiation reach the Earth's surface and their energies and intensities depend on latitude (the calculated results are shown in Table 2).

Table 2

The effect of latitude on the proton energy and intensity in the Earth's atmosphere (calculated results)

θ [deg.]	Energy[1] [GeV]	Proton Intensity [protons/(Ge Vs rs cm^2)]
0	19	$(6.63 \pm 3.04) \times 10^{-4}$
10	18.43	$(7.19 \pm 3.31) \times 10^{-4}$
20	16.78	$(9.27 \pm 4.26) \times 10^{-4}$
30	14.25	$(1.44 \pm 0.66) \times 10^{-3}$
40	11.15	$(2.79 \pm 1.29) \times 10^{-3}$
50	7.85	$(7.21 \pm 3.32) \times 10^{-3}$
60	4.75	$(2.80 \pm 1.29) \times 10^{-2}$
70	2.22	$(2.18 \pm 1.00) \times 10^{-1}$
80	0.57	(8.58 ± 3.94)
89	0.06	(3742.40 ± 1721.50)
90	0	Ultra–high energy

[1] Following Ref. [13], Energy ~ constant × $\cos^2(\theta)$.

Particle energy decreases with increasing latitude, and the intensity grows by becoming bigger and smaller at the poles to the equator, a phenomenon called the latitude effect. Cosmic ray particles with energies above 10 GeV are less affected by the effects of solar activity, and the effects of the interstellar and gravitational fields.

The particle trajectories of cosmic radiation with low energies (less than 10 GeV) and of solar radiation are diverted and the shield of ozone in stratosphere impedes to reach the Earth's atmosphere at low altitudes. Cosmic radiation particles penetrate the Earth's atmosphere in the vertical direction with oblique component less intense. Due to absorption in the field intensity drops as it reaches sea level, the intensity of the oblique component is less intense, because of the length of the road traveled by the particles. The absorption coefficient of the radiation was estimated to be 10^{-5} per cm of air under normal temperature and pressure (at N.T.P.) [1].

An important conclusion was that the vertical intensity of the hard component of the cosmic radiation is 72.8 % by total value (hard + soft) of the vertical intensity [13].

We know that the hard component is poorly absorbed in the atmosphere and is being more penetrating than the soft component. The hard component of the cosmic rays is 2/3 of the total cosmic radiation at low altitudes. The discovery of the East-West asymmetry assumes that the particles that come from the West being more numerous than those from the East, and cosmic radiation contains both kinds of electric charges, the positive particles representing a significant fraction of the total flow [14].

Propagation of cosmic ray particles through cosmic magnetic fields depends on the magnetic rigidity. If all the properties of these reactions were known at all energies, in principle the properties of a shower could be predicted.

The integral vertical intensity of nucleons as a function of different atmospheric depths in the terrestrial atmosphere is given approximately by [10, 13]:

$$I_N(E,X) \approx I_N(E,0)\, e^{-X/\Lambda}, \tag{3}$$

where Λ = 123 g/cm^2 is the attenuation length of nucleons in air, X denote the atmospheric depth [g/cm^2], E is the nucleon energy [GeV], I_N (E, 0) is the vertical intensity of nucleons at upper limit of the atmospheric depth.

The resultant vertical intensity of nucleons, calculated in this paper, as a function of the various atmospheric depths in the terrestrial atmosphere is shown in Fig. 2. Results of the calculations seem to indicate that the absorption of the protons in the atmosphere is exponential.

A calculated set of data on the vertical nucleon intensities as a function of the various atmospheric depths refer to atmospheric depths from the upper limit of the atmosphere (*i.e.*, 0.1 g/cm^2) to the sea level. As an example see the plot below.

At sea level, about 1/3 of the nucleons in the vertical direction are neutrons. About 79% of the primary nucleons are free protons and about 70% of the rest are nucleons bound in helium nuclei [10].

The present conclusion seems to be that the increase in intensity of nucleons with increasing the atmospheric altitude above sea level is clearly visible. At higher energies the flux of single particles is so low that very indirect measurements are necessary.

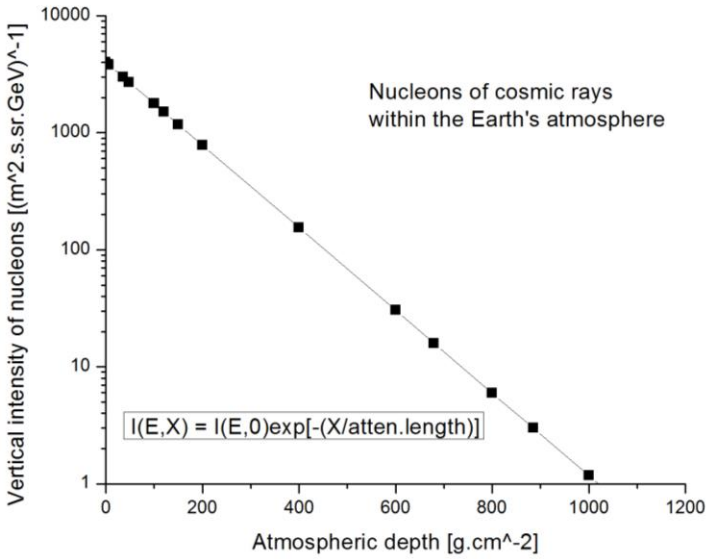

Fig. 2 – Vertical intensity of nucleons at various depth *X* in the Earth's atmosphere.

The number of primaries with energy greater than 10^6 GeV falling on one square meter at the top of the atmosphere is about one every month. These very energetic particles produce dense showers of secondaries, which multiply in the atmosphere [15] to form the Extensive Air Showers (E.A.S.).

3. THE PROPORTION OF THE CHEMICAL ELEMENTS IN THE EARTH'S ATMOSPHERE

The cosmic ray particles are exceptionally penetrating and they readily undergo nuclear reactions [7]. The most common elements in nature are the ones with smaller atomic number Z. Chemical elements such as Li, Be, B exist in primary cosmic rays as a result of their training in interactions of the high energy heavy nuclei with interstellar matter [14].

In terms of the distribution of elements in the structure and metabolism of living organisms, the hydrogen, carbon, nitrogen, and oxygen have the greatest abundance. A lower abundance have sodium, potassium, magnesium and calcium, as well as elements with non-metallic character such as phosphorus, sulfur, and chlorine. The proportion in which chemical elements occur on the Earth's surface shows the sparse quantity of hydrogen; Clark theory (1942) shows that the proportion in which chemical elements occur in the Earth's surface are as follows: 49 % Oxygen, 26 % Silicon, 7.5 % Al, 4.7% Fe, 1% Hydrogen, etc. [16].

Below 10 km altitude above sea level, the composition of the atmosphere in the volume element is: 70.09% N_2, 20.95% Oxygen, 0.93% Argon, 5×10^{-5} H_2 and 8% other elements [16]. Chemical elements such as He, Ne, and H_2 are leaving Earth's atmosphere, reaching the upper atmosphere.

Also, exposure from the natural and artificial radiation sources can affect health. Applications of interest include dosimetry and space radiation effects. Dose and dose rates are important parameters to better predict the radiation response. Estimations of radiation dose on human tissue were summarized in [6]. Due to the fact that the primary cosmic radiation is essentially positively charged, the secondary component in the atmosphere has a positive charge excess, too [17, 18].

The tracked results at high altitudes in the terrestrial atmosphere are as follows:

(1) We see that it is extremely difficult to calculate accurately the radiation dose rate of a whole-body monitoring. On the other hand, an approximate calculation of radiation doses is informative since illustrates the effects of cosmic radiations and develop the ability to understand the cosmic-ray physics, in which high energy particles of extraterrestrial origin are studied.

(2) At high altitudes above sea level doses of radiation have high values and can endanger satellites sent to space missions, manned spaceships, and aircraft components. Therefore, studies are required on the interaction of cosmic ray with atomic nuclei.

At values exceeding the limits of radiation dose the normal human organism is affected at the cellular level. The nervous system receives, processes, and transmits information captured from the internal or external environment of the human body. Molecular composition of the cell from the body enters the water, protein, fat, carbohydrates, ADN, RNA, mineral salts and essential chemical elements: oxygen, carbon, hydrogen, and nitrogen. But the 10^{15} cells in the body are affected in different ways [19]. According to [16], the human body contains: 65 % oxygen, 18 % carbon, 10 % hydrogen, and 7 % other elements.

In the future, it is necessary the evaluation and the interpretation of the radiation dose values of the Radon, the terrestrial radiation, the cosmic radiation particles and the radionuclides such as K^{40} (radioactive), U^{238}, and Th^{232}. This activity requires deep knowledge of the methods of analysis of the cosmic radiation and in the ultra–high energy frontier of physics, and skills to use them.

4. CONCLUSIONS

The main conclusion seems to be that for nucleon cosmic rays, the increase in intensity with increasing the altitude above sea level is clearly visible. The general flux of nucleons contains particles with energies extending from below 10 GeV/nucleon to 10^{21} GeV/nucleon.

The cosmological origin of the ultra-high energy cosmic-ray particles, the proportion in which chemical elements occur on the Earth's surface, the propagation of cosmic ray particles through cosmic magnetic fields as a function of the magnetic rigidity are just some of the specific signatures of the cosmic ray physics at the highest energies.

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