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New complex EAS installation of the Tien Shan mountain cosmic ray station

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A B S T R A C T

In this paper we present a description of the new complex installation for the study of extensive air showers which was created at the Tien Shan mountain cosmic ray station, as well as the results of the test measurements made there in 2014–2016. At present, the system for registration of electromagnetic shower component consists of ~100 detector points built on the basis of plastic scintillator plates with the sensitive area of 0.25 m^2 and 1 m^2, spread equidistantly over $\sim 10^4$ m^2 space. The dynamic range of scintillation amplitude measurements is currently about $(3\text{–}7)\cdot 10^4$, and there is a prospect of it being extended up to $\sim 10^6$. The direction of shower arrival is defined by signal delays from a number of the scintillators placed cross-wise at the periphery of the detector system. For the investigation of nuclear active shower components a multi-tier 55 m^2 ionization-neutron calorimeter with a sum absorber thickness of ~1000 g/cm^2, typical spatial resolution of the order of 10 cm, and dynamic range of ionization measurement channel about $\sim 10^5$ was created. Also, the use of saturation-free neutron detectors is anticipated for registration of the high- and low-energy hadron components in the region of shower core. A complex of underground detectors is designed for the study of muonic and penetrative nuclear-active components of the shower.

The full stack of data acquisition, detector calibration, and shower parameters restoration procedures are now completed, and the newly obtained shower size spectrum and lateral distribution of shower particles occur in agreement with conventional data. Future studies in the field of 10^{14}–10^{17} eV cosmic ray physics to be held at the new shower installation are discussed.

1. Introduction

The primary cosmic ray spectrum. For more than five decades, the nature and origin of cosmic rays (CR) remain one of the main open issues in astrophysics, and this uncertainty does steadily increase with the growth of CR primary energy. The measurement of the cosmic rays energy spectrum, estimations of their composition, and the search for anisotropy of arrival directions have been the subject of many experiments.

As it can be seen in Fig. 1, which is taken from the work [1], the intensity of differential energy spectrum of cosmic ray particles varies through 28 orders of magnitude over more than 10 decades of primary energy E_0. The spectrum has a striking power-law behavior, $dN/dE \sim E^{-\gamma}$, with its power index γ having several characteristic irregularities: around the energy $3\cdot 10^{15}$ eV where the well known *knee* resides [2], a less prominent *second knee* approximately at $2\cdot 10^{17}$ eV [3], the *ankle* near $3\cdot 10^{18}$ eV [4], and the strong suppression around $5\cdot 10^{19}$ eV [5,6]. Beyond the energy about 10^{10} eV and until the knee the differential power law index γ is about 2.7, above the first knee γ is ~3.0, with a small increase up to ~3.3 at the second knee. Above the ankle, the spectrum is well described with $\gamma \sim$ 2.7 again up to its cut-off near $5\cdot 10^{19}$ eV, where

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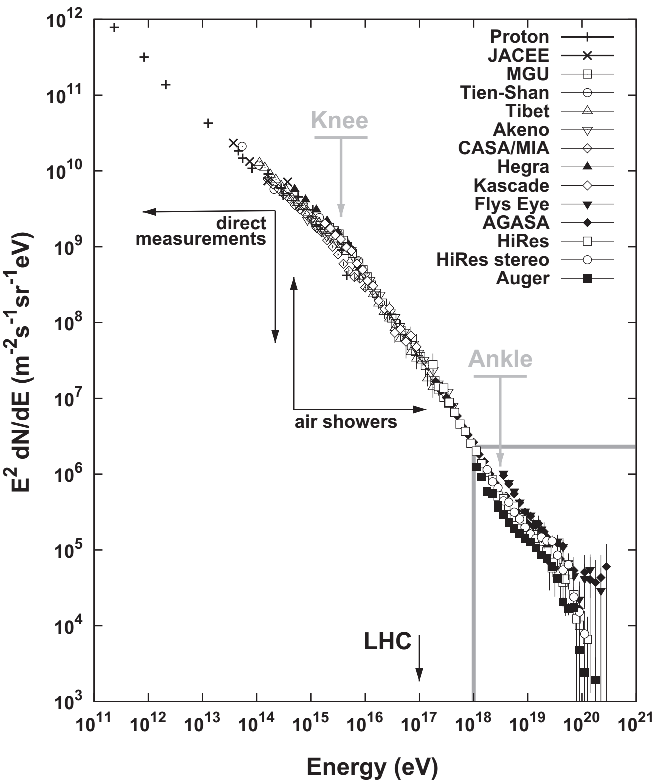

Fig. 1. The differential energy spectrum of the primary cosmic ray particles (the plot taken from publication [1]).

the index roughly changes to $\gamma \sim$ 4.3. Except the well-known Greisen–Zatsepin–Kuzmin (GZK) effect [7,8] which reveals itself as an abrupt spectrum cut-off at extremely high energies, the origin of all these features is still not clear enough, but they might arise from interference among different factors such as the loss of acceleration efficiency in galactic sources, the predominance of extra-galactic CR component at very high energies, and the impact of the CR propagation effects through interstellar medium. Therefore, in order to verify various scenarios for the origin of spectrum features it is necessary to perform accurate high-statistics measurements between 10^{15} and 10^{18} eV.

Cosmic rays with the energy E_0 up to 10^{14} eV can be studied directly through detection of primary particles by means of balloon and satellite based apparatus, but as the energy increases, the CR flux becomes too negligible for direct measurements, since it is impossible to use any detectors large enough for this purpose on the balloons or in space. On the other hand, the interaction cross-section of primary particles with $E_0 \gtrsim 10^{14}$ eV is quite sufficient for initiation of an atmospheric cascade due to succeeding collisions of CR particles with air nuclei, and numerous, wide spread components of the particle shower (called the extensive air shower—EAS) can be detected at the ground [9]. At those energies, the cosmic rays are investigated through observation of EAS with the use of ground based detectors which have the appropriate sum sensitive area, and which are placed on suitable altitude. The necessary aperture of any shower installation depends on the range of primary cosmic ray energies being under investigation. The CR particles whose energy exceeds 10^{15} eV can be effectively detected only with a shower array of the area above 10^4 m^2.

Until now, investigations of the primary CR energy spectrum and composition in the energy range $E_0 \lesssim 10^{17}$ eV have been made with the help of a number of ground-based installations spread throughout the globe. Between them, the distribution of the charged EAS particles was studied with the use of different types of electronic particle detectors both at mountain sites such as Akeno [10], GAMMA [11], Tibet [12], and at the sea level by KASCADE [2] and KASCADE-Grand [13] experiments. The Cherenkov and fluorescent light emitted by EAS particles was registered by the Fly's Eye [14], HEGRA [15], Tunka [16], and Yakutsk [17] arrays. The nuclear-active component of EAS was studied by the Tien Shan ionization calorimeter [18], and the properties of high-energy hadronic interactions in the mountain experiments Pamir [19] and Chacaltaya [20] which were based on the method of X-ray emulsion chambers (XREC). In the complex Hadron experiment at Tien Shan the combination of EAS and XREC methods [21] was applied.

The installations mentioned here have registered a multitude of EAS components at different scales of energy and spatial variation:

- shower electrons and positrons with the energy $E_e \gtrsim 1$ MeV, multiplicity $N_e \sim 10^5$–10^9, and typical lateral distribution within a $R_e \lesssim 1$ km range;
- the Cherenkov radiation of relativistic shower particles at a distance up to 100 m from EAS core;
- low-energy muons with $E_\mu \gtrsim 1$ GeV, $N_\mu \sim 10^2$–10^6, and $R_\mu \lesssim 100$ m;
- high-energy muons with $E_\mu \gtrsim 200$ GeV, $N_\mu \sim 10$–1000, and $R_\mu \lesssim 1$ m;
- the flow of hadronic (nuclear active) particles with $E_h \gtrsim 1$ GeV in a close vicinity of EAS core, $R_h \lesssim 10$ m;
- genetically connected groups (*families*) of high-energy hadrons and “gamma-quanta” (γ, e^-, e^+) with the energy above 2–4 TeV and typical lateral size of the order of 2–10 cm registered within the EAS core region by XREC method;
- evaporation neutrons in a wide energy range, from thermal energies of the order of $E_n \sim 10^{-2}$ eV, and up to some tens and hundreds of GeV, both around the EAS core and at its periphery up to some tens of meters;
- 30–300 MHz radio-emission from EAS particles.

All these characteristics are sensitive both to elementary composition of primary cosmic rays and fundamental properties of strong interaction, though in different proportions; hence, the detection of any of them is complimentary to each other. Ideally, any array intended for EAS study should detect simultaneously all the components but the majority of real experiments have registered only one or few of them. Besides, a large part of existing and past shower installations do reside at the sea level where the EAS observation is less appropriate than at the high mountain altitudes for a number of reasons.

Investigation of the 10^{14}–10^{17} eV EAS with a relatively compact detector system is mostly effective at the mountain height (3000–4000 m above the sea level, and with integral atmosphere thickness around 600–700 g/cm^2), since at these altitudes the showers occur being close to the maximum of their development, reaching the highest value and minimal fluctuation of particle multiplicity. Besides, this observation level is nearer to the point of primary interaction, so the reconstruction of shower parameters becomes more reliable, and their values are more sensitive to predictions given by the particle interaction models to be verified. The *Mollier radius* which defines the lateral scattering of EAS particles is somewhat larger at high altitude, and correspondingly the spatial distribution of shower particles is flatter resulting in a smaller probability to miss the shower than at the sea level. These specific features of mountain installations give a unique possibility to study the properties of primary cosmic ray particles, both from the nuclear physics and astrophysics points of view, and in particular to elucidate the nature of the knee in primary CR spectrum which remains one of the most urgent problems in the cosmic ray physics since its discovery in 1958.