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Primary cosmic ray energy spectrum above 1 PeV as measured by the PRISMA-YBJ array

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Primary cosmic ray energy spectrum above 1 PeV has been measured with PRISMA-YBJ being a prototype of PRISMA array at altitude of 4300 m a.s.l. It realized a novel type of EAS recording method measuring hadronic EAS component over the total array area through thermal neutron detection with a specially developed so-called en-detectors sensitive to electron and thermal neutron EAS components. Primary c. r. spectrum was recovered in 2 ways: through usual Ne procedure as well as through measurements of EAS size spectrum in thermal neutrons. Monte-Carlo simulations of the experiments allowed us recover the primary spectrum above 1 PeV. The both obtained spectra follow power law function with index close that measured by direct measurements below 1 PeV.

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1. Introduction

The cosmic ray energy spectrum spans over many decades from about 10^6 eV to beyond 10^{20} eV. It has power law behavior but some index changes are observed. The main feature in region from 1 PeV to 10 PeV is “knee” – well known spectrum steepening at about 3–5 × 10^{15} eV is studied for more than 60 years. Other peculiar features have been observed in this energy interval by the KASCADE-Grande experiment [1] and Tunka-133 [2]. But some contradictions in results of different experiments exist. Tibet ASγ array observed first knee (connected to protons) at about 200 TeV and supposed that hardening at 3 PeV is connected to elements heavier than Helium [3]. On the other hand, KASCADE group claimed the “knee” in primary spectrum is connected with proton acceleration cut-off. The hybrid experiment ARGO/WFCTA has recently established a bending of the light component (protons and Helium nuclei) at about 700 TeV [4]. Earlier we have published a phenomenological explanation of the "knee" origin due to incorrect recalculation of primary spectrum from measured shower size (Ne) spectrum [5]. On our opinion the reason of this indirect method error could be found in the existence of "coreless" showers at low energies (below ~100 TeV/nucleon) and its transformation to normal EAS at higher energies. These showers have no high energy cascading hadrons on the observational level and have another structure and lower attenuation length in comparison with the normal cascades. Appearance of hadrons at observation level transforms the EAS structure and exactly at this energy (depending on atomic number A) the “knee” is observed in electromagnetic component (in EAS size spectrum). The only way to solve this problem is measurement of the main EAS component - hadrons. Only one array has been able to do this, KASCADE, but they also have obtained contradictory result: measured spectrum on hadron multiplicity did not confirm the "knee" existence [6].

More than 10 years ago we developed a novel method to record EAS hadronic component over whole array area by measuring secondary thermal neutrons produced by high energy hadrons of EAS [7]. PRISMA-YBJ was a high altitude prototype of such array, operated for 3.5 years in Tibet (4300 m). The results are presented for discussion.

2. Array

The PRISMA-YBJ array was situated at YangBaJing in Tibet mountains (China). It was deployed in ARGO-YBJ experimental hall upon RPC detectors [8]. It consists of 4 electron-neutron detectors based on ^{6}LiF+ZnS(Ag) scintillator and capable to measure both main components of EAS: electromagnetic and hadronic ones. Detailed description of the detector and the array can be found elsewhere [9].

3. Simulations

Detailed Monte-Carlo simulations were performed using GEANT4.10 and CORSIKA7.5 software. Detailed information on GEANT4 array simulations can be found elsewhere [10]. To simulate extensive air showers the package CORSIKA75600 with models QGSJET-II.04 and

FLUKA-2006 was used. Simulations were performed for 4 different primary particles: protons, N, Fe and gamma. Energy ranges were chosen dependent on particle type: 10 TeV- 300 PeV for protons and gamma, 30 TeV – 300 PeV for N, 100 TeV – 1 EeV for Fe. Differential primary spectrum slope was set as -2.7 without any changes in full energy range.

The CORSIKA simulations used followingenergy thresholds: 600 keV for gamma quanta, electrons, and positrons; 50 MeV for hadrons; and 0.5 GeV for muons. The mass composition of absorbers close to the installation is very important when performing calculations with thermal neutrons. A program containing a detailed description of the installation and environment was created in the GEANT4 software. The program described (in terms of geometry and approximate mass composition) the buildings in which the array is housed and (in detail) the detectors according to their design and layout. The overall dimensions of the simulation domain are 100 ×100 × 50 m. We used a set of standard models of interaction: QGSP (hadrons with energies in the range of 10 GeV to 100 TeV), BIC (hadrons with energies below 10 GeV), and HP (neutrons with energies below 20 MeV, including thermal neutrons). During a simulation, the particles (hadrons, electrons, muons, and gamma quanta) were scattered directly onto the roof of a building. Simulations with GEANT4 yielded the release of energy in detectors for every type of particle (electrons, gamma quanta, muons, pions, and so on) and their contributions to the neutron production. At the third stage artificial showers were uniformly scattered onto the PRISMA-YBJ array over an area 36 times larger than their own. The energy deposit and the number of recorded neutrons in each detector were determined. When the triggering conditions were satisfied, the detector readings were recorded in the same format as the experimental data. Finally, at the fourth stage, these data were processed by the same program as for the experimental data.

4. Results

Standard Nishimura-Kamata-Greisen function (NKG-function) with Molier-radius equal to 136 m was used to reconstruct shower core position, age and electron shower size (Ne). Only showers passed through some cuts were selected for the analysis. The cuts were following 4-fold coincidence with deposit threshold =10 m.i.p. in each detector, axis inside radius R=6m. First we calculated threshold energy for various primary particles recorded with event selection cuts by the PRISMA-YBJ array as it is shown in fig. 1. One can see that our threshold is close to 1 PeV. Thermal neutrons were recorded inside a delay gate from 0.1 to 20 ms after the EAS passage with recording efficiency of 13%.

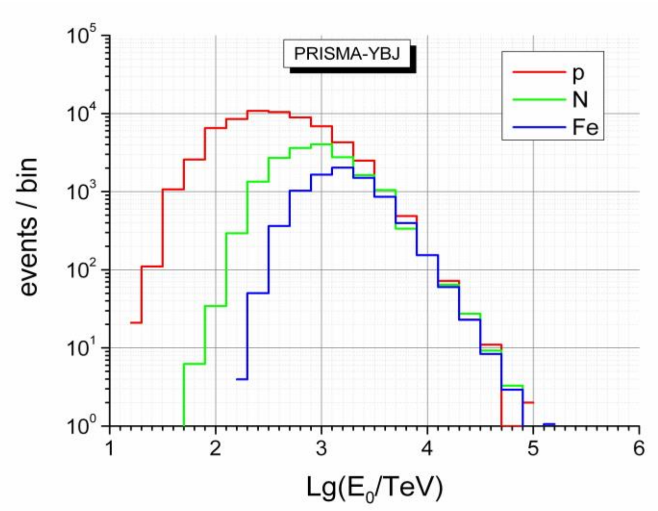

Figure 1: Recorded EAS energy distributions calculated for different primaries.

Correlations between primary particle energy E_0 and EAS size in Ne and in recorded number of neutrons are shown in fig. 2a and 2b. As one can see the first one has the slope changes at energy <~1 PeV while the second one not at least for energy above 3 PeV. It is of great importance to take it into account when recovering the primary energy spectrum. Otherwise, we can obtain a “knee” in the primary spectrum. Maybe this is a reason of the “knee” at ~700 TeV claimed by ARGO-YBJ worked at the same place. This is the energy point where hadrons reach the YBJ level.

Experimental thermal neutrons multiplicity distribution is shown in fig. 3 in comparison with simulation results. One can a see good agreement between the experiment and simulations made for pure power law primary spectrum with integral index= -1.7.

a) **b)**

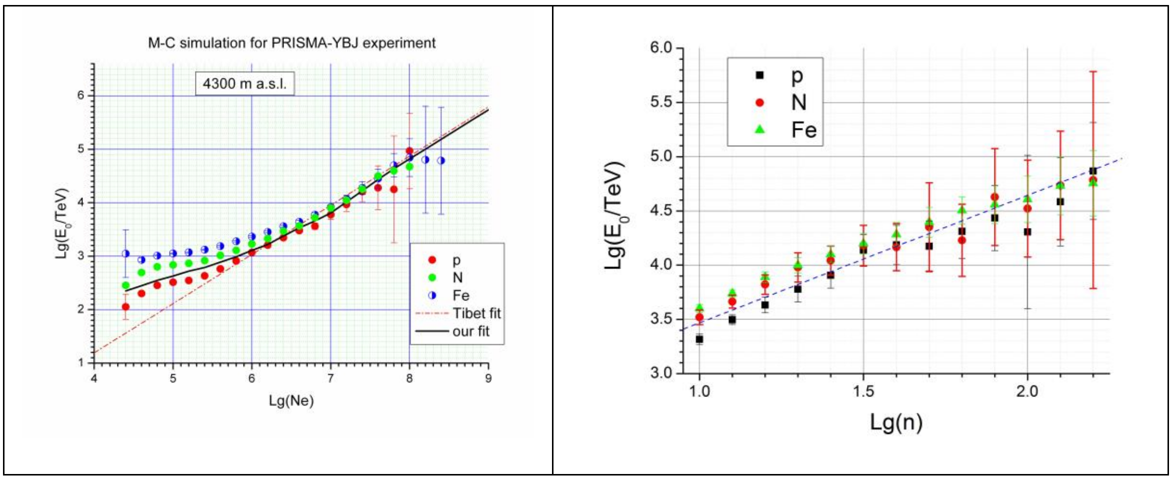

Figure 2: Correlation plots between primary energy E_0 and Ne (a) and E_0 and n (b).

Dashed line on left panel corresponds to the fit used by the Tibet ASγ collaboration [11] while solid black curve (panel a) and dotted line on (panel b) represent our fits used for primary energy recovering.

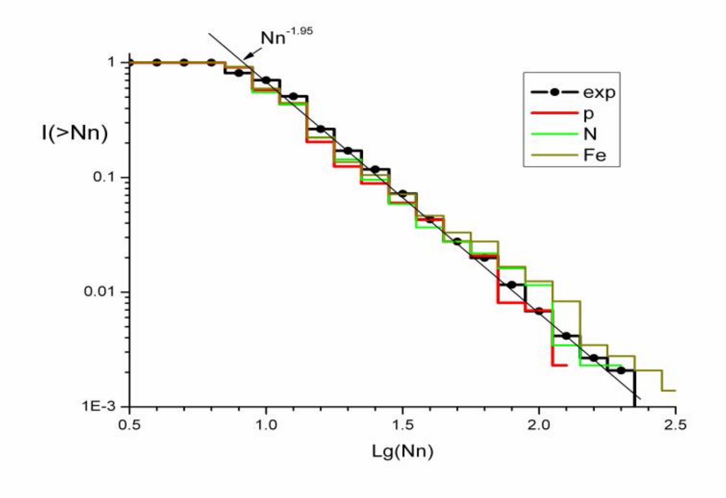

Figure 3: Integral spectrum on neutron density. Experiment and simulations.

Our reconstructed primary energy spectrum is shown in fig. 4. It is close to that measured by direct methods beyond the atmosphere.

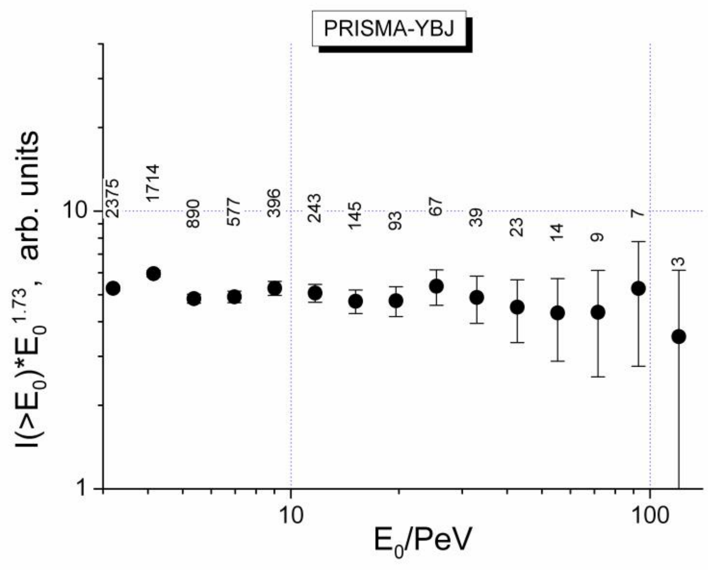

Figure 4: Primary spectrum recovered from EAS size spectrum in thermal neutrons.

Primary particle energy spectrum recovered from the EAS size spectrum (Ne) is shown in fig.5.

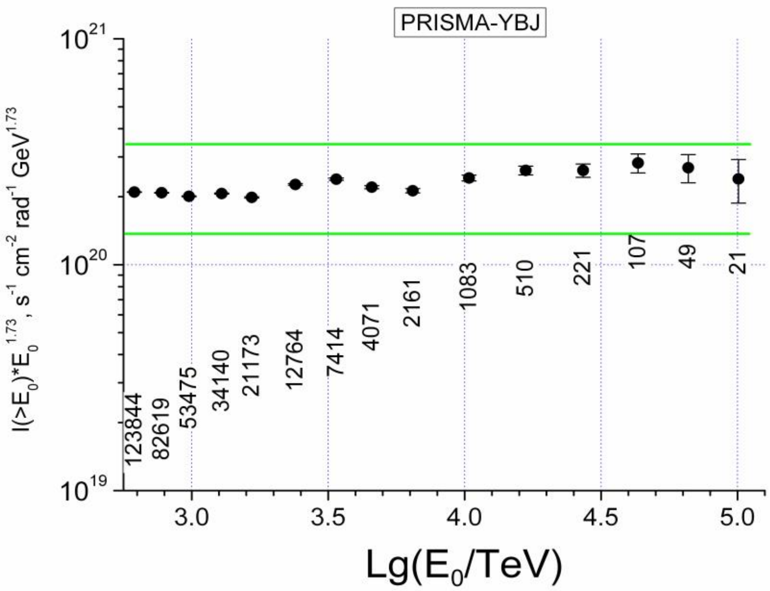

Figure 5: Primary spectrum recovered from EAS size spectrum (Ne) measurement.
Numbers show statistics and green lines indicate recalculation uncertainties while error bars indicate statistical errors.

5. **Discussion**

EAS thermal neutron component being a part of hadronic component is genetically connected with high energy hadron component. Therefore, measured neutron multiplicity spectrum in EAS is strongly connected with high energy hadron multiplicity spectrum also follows a power law behavior: F(Nn) ~ $Nn^{-\gamma/\alpha}$, where γ is primary spectrum index and α is an index of another power law in the dependence of $Nn(E_0)$ ~ E_0^{α}. If γ=1.7 and α=0.9 then the spectrum index can be estimated as 1.7/0.9=1.89. Our measured integral slope is equal to -1.95+/-0.05. This result is in excellent agreement with the hadron multiplicity spectrum published by KASCADE [6]. But, the primary cosmic ray spectrum in a range of 1-100 PeV recalculated from the measured neutron multiplicity spectrum follows pure power law function with a slope of -1.73+/-0.07.

We observed the knee-like behavior in Ne spectrum similar to many other groups. But, by applying the correct recovery procedure, we obtained primary spectrum without "knee" taking into account the carefully calculated dependence of Ne(E0) having a knee at energy ~1-5 PeV. The resulting recovered cosmic ray spectrum follows power law function with the integral index close to -1.73.

Obtained results confirm our previous works on the "knee" origin and allow us to assume that primary spectrum has no steepening up to ~100 PeV and coincides with that measured in direct experiments beyond the atmosphere. Both applied methods also gave very good agreement but, on our opinion, the method based on the neutron multiplicity spectrum measurements is more preferable due to adequate and easy reconstruction to primary energy, very slowly depending on the used model.

Acknowledgments

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