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Primary cosmic ray mass composition above 1 PeV as measured by the PRISMA-YBJ array

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Primary cosmic ray mass composition 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. mass composition was recovered through measurements of two EAS components with the en-detectors: electromagnetic (energy deposit) and the number of secondary thermal neutrons produced locally by high energy hadrons. Monte-Carlo simulations of the experiments allowed us to find a parameter highly sensitive to the primary particle mass (atomic number) A above 1 PeV. The preliminary obtained mass composition is consistent with light composition and does not show any significant change at higher energies.

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1. Introduction

Cosmic rays mass composition is generally studied by different means, depending on the range of energy. At energies below 1 PeV, studies are performed by direct measurements with spectrometers and calorimeters on satellites or balloons above the Earth's atmosphere; the mass composition is measured quite well at these energies. At higher energies (above 1 PeV), however, measurements are performed by indirect means using ground units, due to the very low intensity of cosmic rays at such energies. This results in a very wide (and obviously non-statistical) variation of data in this field. This problem has yet to be solved despite the large number of experimental installations and studies lasting many years. The mass composition is generally estimated in terms of μ/e (i.e., the ratio of the number of recorded muons to the number of electrons) or $X_{\max}$ (the height of an extensive air shower (EAS) maximum, measured in g/cm^2 according to the depth of the atmosphere). Both parameters are sensitive to a certain average or effective atomic number A of the primary particle, obtained by solving the inverse problem via complex model-dependent recalculation. This, along with a priori assumptions and the inevitable systematic errors, result in the non-statistical variation of data. To confirm this, one could only read any of the reviewing works on this topic. This fundamental cosmic ray problem has thus yet to be solved and requires the development of new methods. Solving this problem will lead to considerable progress in solving such related problems as cosmic-ray sources, the knee observed in the EAS size spectrum, and so on.

2. Experimental set-up

In order to check the performance of this detector and the method at a high altitude site, a small prototype array composed of four en-detectors (PRISMA-YBJ [3]) of 0.36 m^2 each, has been installed inside the hall hosting the ARGO- YBJ [4] experiment at the Yangbajing Cosmic Ray Observatory (Tibet, China, 4300 m a.s.l., 606 g/cm^2). The four en-detectors of the PRISMA-YBJ were composed as follows: three of them are located according to a triangular arrangement, each side of the triangle being about 5 m. The fourth en-detector was installed at the center of the triangle at a distance of 5 m from the other detectors. The signal from the 12th dynode of each PMT is sent to a charge sensitive preamplifier-discriminator where it is split into two pulses: one of them is shaped to a NIM pulse used to build-up the trigger, the other one is integrated with a 1 μs time constant, then amplified and sent to the input of a FADC (ADLINK PCI-9812). The first pulse produced mostly by EAS electrons is used for trigger and energy deposit measurements, and delayed neutron capture pulses are counted within a time gate of 20 ms to give the number of neutrons. The first level trigger which is a coincidence of any 2 out of 4 detectors in a time gate of 1 μs, starts all FADC's working with 1μs step. The on-line program analyzes the input data and stores event if at least 2 detectors generate a signal corresponding to 3 m.i.p.'s or more. In addition, every 5 min the on-line program generates a software trigger which starts the data acquisition by the FADCs. This 'random' trigger, not related to showers, allows the measurement of chance signals which could mimic neutron signals in the 20 ms recording window. The en-detectors were routinely monitored recording the daily charge spectra accumulated by each detector. During off-line data processing additional cuts were applied: 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.

3. Experiment simulation

We used the CORSIKA 6.9 and GEANT4.10 software packages to simulate the experiment. The simulations were performed in four stages. Artificial showers at altitude of and 4300 m above sea level were first calculated using the CORSIKA program and a standard model of the atmosphere (the atmosphere at Karlsruhe). The showers were calculated over zenith angles of 0–45 degrees and energies of 3×10^{13}– 10^{18} eV with a differential spectrum index of –2.7 over the entire range. Simulations were performed for protons, gamma quanta, and iron nuclei using the QGSJET-II (for energies above 80 GeV/nucleon) and GHEISHA-2002 (for energies below 80 GeV/nucleon) models. The CORSIKA simulations used minimum or near-minimum particle energy thresholds: 60 keV for gamma quanta, electrons, and positrons; 50 MeV for hadrons; and 0.5 GeV for muons. The threshold energies of primary particles depended on their masses and the height of the level of observation: from 30 TeV for protons at a level of 4300 m to 1 PeV for iron nuclei at sea level. The mass composition of absorbers close to the installation is very important when performing calculations with thermal neutrons. A program containing a fairly detailed description of the installation and environment was created in the GEANT4 medium. 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 generation of the neutron component. 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. The details of the calculations can be found in [5].

4. Results and discussion

The parameters most sensitive to the mass of a primary particle A (atomic number) were sought. Since the electronic and neutron components of an EAS were measured by the same detectors, these components and their combinations were tested for their sensitivity to A. Calculations were performed for level of observation: an altitude of 4300 m (Yangbajing, Tibet), taking the actual geometry and chemical composition of surrounding matter into account. As a result, the integrated and normalized distribution of individual showers over the ratio of total energy deposit *e* to the number of neutrons *n* passed through all detectors (taking recording efficiency into account) in an event (i.e., function F(>*R*, *A*), where *R* = *e*/*n*), proved the most sensitive to *A*. In other words, function F shows a probability to observe an event with a ratio e/n>R. Figure 1 shows the shape of these functions for 4 values of *A*: 0, 1, 14 and 56 (i.e., for primary gamma quanta, protons, hydrogen and iron nuclei) along with our experimental data for events with Lg(Ne) > 6.5, i.e. just above the "knee". These plots represent a probability to find R > e/n for different primaries. As it can be seen from the plots, the difference between the curves is enough to allow us to estimate the effective atomic number of the primary particle and that our experimental data are very close to the proton curve. Sure, now it is only a preliminary estimation of mass composition within existing both statistical and possible systematic errors and later we hope to develop the method and make it useful for further experiments.

Note that the primary energy threshold is in this case determined by the emergence of high-energy hadrons and thus neutrons (in excess over the background flux) at the level of observation. Calculations showed it was slightly less than 1 PeV at the altitude of 4300 m [6]. By introducing additional requirements into the criteria for selecting events, we can move into the range of higher energies. In fig.2 we present plots of the experimental mean ratio R and that calculated for different mass A as a function of shower size Ne. And again one can see that <A> is little bit higher than 1. Within existing errors (including calculation uncertainties shown by green lines) we do not see any significant changes in cosmic ray mass composition at higher energy up to ~100 PeV. We hope that better statistics obtained with the future array PRISMA-LHAASO, the method will give us precise measurements of <A> and also its dependence on Ne and thus on E_0. It is noticeable that this plot in contrast to fig.1 allows one to estimate primary mass A even for individual EAS. The latter is illustrated by 3 the highest energy events for those we can conclude that they are not produced by gammas or protons and most probably by heavy primaries.

An advantage of this method is that the ratio of two equilibrating components (for showers with a sufficient number of handrons) measured by the same detectors is less prone to fluctuations and depends weakly on possible systemic measurement errors and the calculation models that are used.

According to the plots, the method can also be used to search for gamma showers with energies above 1 PeV in ultrahigh-energy gamma-ray astronomy. Investigating the mass composition of cosmic rays would seem to be more promising at altitudes of 4–5 km above sea level (i.e. near the maximum of the cascade curve).

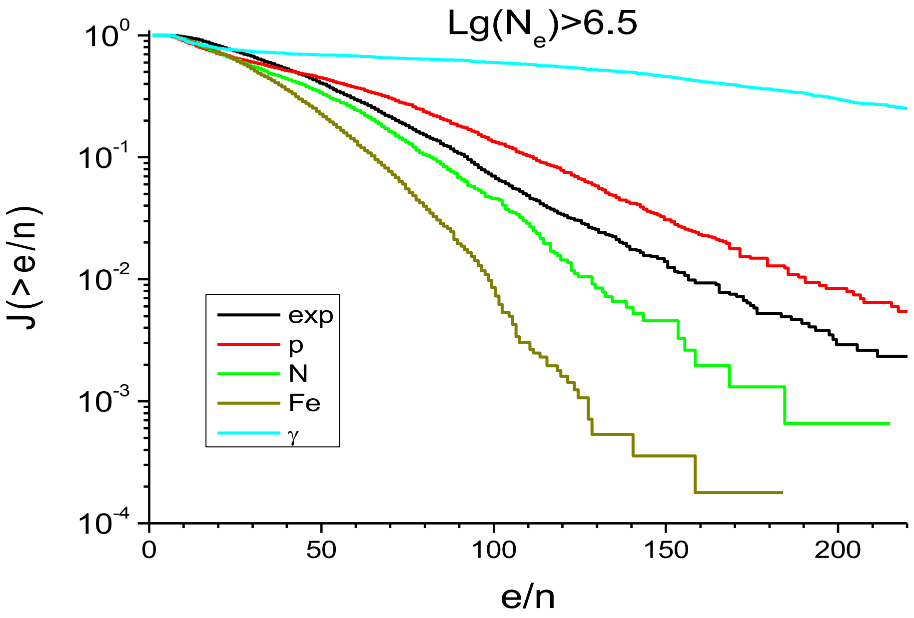

Figure 1: Simulated function *F*(>*R*, *A*) for different primary particles at an altitude of 4300 m in comparison with observation.

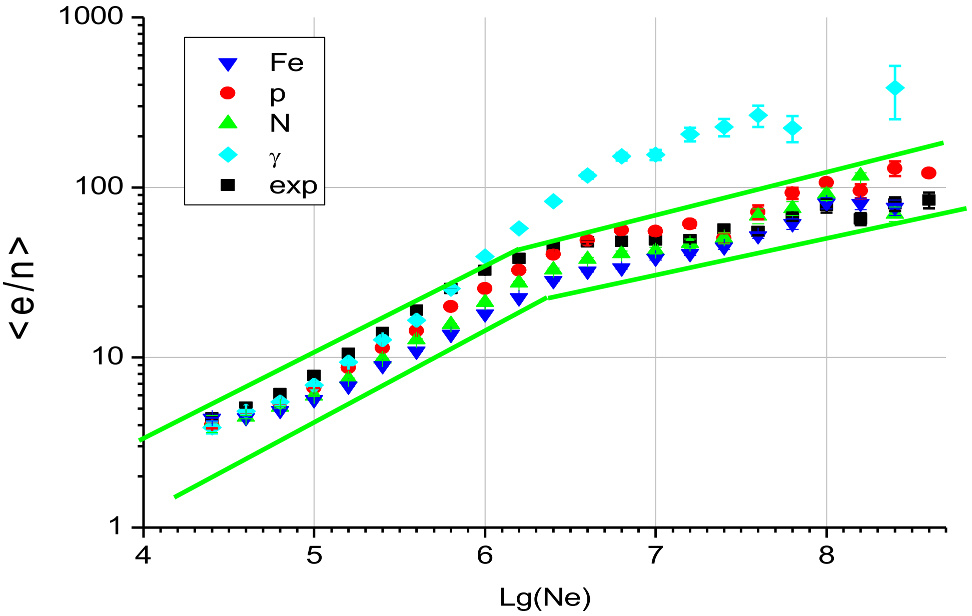

Figure 2: The e/n ratio as a function of Ne: measured and calculated for different A. Green lines indicate a corridor of possible statistical and systematic errors.

5. Conclusions

A new method of determining the effective atomic number of primary cosmic rays, based on simultaneously measuring the electronic and neutron components of an EAS over the whole area of en-detector array, was proposed and realized. Monte Carlo simulations of the experiment showed that a parameter most sensitive to mass composition of cosmic rays is the distribution of the ratio *R* of electronic to neutron components recorded by en-detectors in individual EASes. Our preliminary result is consistent with the light composition above ~1 PeV. This method can also be used to effectively distinguish (search for) showers from gamma quanta in the range of energies above 1 PeV.

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References

[1] Stenkin Yu.. *On the PRISMA project*. Nucl. Phys. B (Proc. Suppl.) **196** (2009) 293

[2] Stenkin Yu. *Large scintillator detector for thermal neutron recording,* in: Nuclear Track Detectors: Design, Methods and Applications, Nova Science Publishers (2010) chapter 10, 253

[3] Bartoli, B. et al., Astropart. Phys. **81** (2016) 49.

[4] D’Ettorre Piazzoli B. on behalf of the ARGO-YBJ collaboration, in proceedings of 32nd International Cosmic Ray Conference, Beijing, **12** (2011) 93.

[5] Shchegolev, O. and Stenkin, Yu., Bull. Lebedev Phys. Inst. **43** (2016) 7, 223.

[6] Stenkin Yu. et. al. *Primary cosmic ray energy spectrum above 1 PeV as measured by the PRISMA-YBJ array.* This conference.