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Cosmic ray mass composition analysis method to be used in the LHAASO-ENDA experiment

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The LHAASO-ENDA (Electron Neutron Detector array) array will consist of 400 special electron-neutron detectors (en-detectors) developed at Institute for Nuclear Research of Russian Academy of Science (INR RAS) for the PRISMA project. The main feature of the array is capability to simultaneously measure both number of EAS electrons and number of secondary neutrons produced by high energy hadrons in surrounding matter. Electron/neutron ratio was found to be a good parameter to separate different primary nuclei and also to search for gamma-induced showers. Detailed Monte-Carlo simulations for the first-step array of 64 en-detectors is now performing. Mass composition analysis with machine learning techniques for Monte-Carlo simulated events is presented

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Introduction

An idea of a novel type of EAS array based on special electron-neutron detectors (en-detectors) proposed for the first time in 2001 was developed later to the PRISMA (PRImary Spectrum Measurement Array) project [1-3]. Now this project is transformed to the ENDA (Electron-Neutron Detector Array) and will become a part of the ambiguous LHAASO (Large High Altitude Air Shower Observatory) project [4]. The first step of array construction involves installation of 64 electron-neutron detectors in square grid with 5 m spacing covering area of 1600 m^2. Later we plan to extend it up to 400 detector array with area ~ 10000 m^2.

The main feature of the array is capability to measure simultaneously electromagnetic and hadron components of the shower over whole array area. It is possible due to the novel experimental technique of recording delayed thermal neutrons produced by high energy hadrons. Detailed information on the method and the technique can be found in the section 1 describing detector design and response and also in the related papers [5-8].

The first two prototypes of this array is operating in Moscow, Russia since 2012 up to now (32 en-detectors) and was operated in YangBaJing, China since 2013 up to March 2017 (4 en-detectors). Some related information about obtained results can be found elsewhere [9-12]. Today the first cluster of ENDA (16 en-detectors) [8] is running in test mode together with YBJHA array in Tibet, China [13].

The main scientific goals of the array are:

- mass composition study
- spectra of light, medium and heavy primary particle groups
- high energy diffuse gamma ray search

1. Detector and capabilities

Electron-neutron detector is capable to simultaneously measure electromagnetic and hadronic components of the extensive air shower (EAS). It is based on the special inorganic scintillator compound $ZnS(Ag)+B_2O_3$. High energy hadrons of EAS produce evaporation neutrons in air and mostly in soil under the detector, then these neutrons are thermalized in the soil and some of them escape to air and are captured in scintillator compound. Neutrons are captured by ^{10}B isotope, whose fraction in natural boron is ~20%. The cross section of ^{10}B for thermal neutrons capture is ~3940 barn due to (α, n)-reaction shown below:

$$^{10}B + n \rightarrow {}^{4}He + {}^{7}Li + 0.4\ MeV(\gamma) + Q \qquad (1)$$

Heavy products of the reaction (alpha and ^{7}Li) with total kinetic energy Q (2.3 MeV – 93%, 2.7 MeV – 7%) produce scintillation light in ZnS(Ag).

The capability to measure simultaneously electromagnetic and hadron component is based on the long time delay existing between recording neutrons and the shower front. At the first moment detector records the shower front pulse (a lot of charged relativistic particles penetrating scintillator) and then, after ~ 0.5 ms, delayed thermal neutrons produced by high energy hadrons. Number of recorded neutrons is proportional to the number of EAS high energy hadrons passed through the array area. Details of the detector design, response and features can be found elsewhere [6-8].

2. LHAASO-ENDA array

LHAASO-ENDA array was proposed to add the hadron component detection to the hybrid LHAASO project. LHAASO project is an ambiguous cosmic ray and gamma astronomy research observatory at the high altitude (4400 m above sea level) in Daocheng, Sichuan Province, China. ENDA will consist of 400 electron-neutron detectors in a square grid with 5 m spacing covering area of 10000 m^2. The array is divided to 25 clusters of 16 detectors. Each cluster will work independently with “white rabbit” time synchronization. In the first step we plan to install 64 detectors (4 clusters) at the end of this year. This first part is called ENDA-64. The first cluster of the array is working now in a test mode in YangBaJing.

3. Simulations

Monte-Carlo simulations of ENDA-64 are carried out using CORSIKA7.56 and GEANT4.10 packages. GEANT4.10 is used to simulate detector response to different particles of EAS. We use QGSP_BIC_HP physics list. CORSIKA7.56 is used to simulate EASes produced by primary p, He, N, Si, Fe nuclei. In CORSIKA we use QGSJET-II-04 and FLUKA-2016 models.

Simulated with GEANT4 detector responses are approximated with function fits and used by special program, that reads simulated showers (CORSIKA output), throws core position randomly and writes array response in similar format as real experimental data. Simulation process diagram is shown in fig. 1.

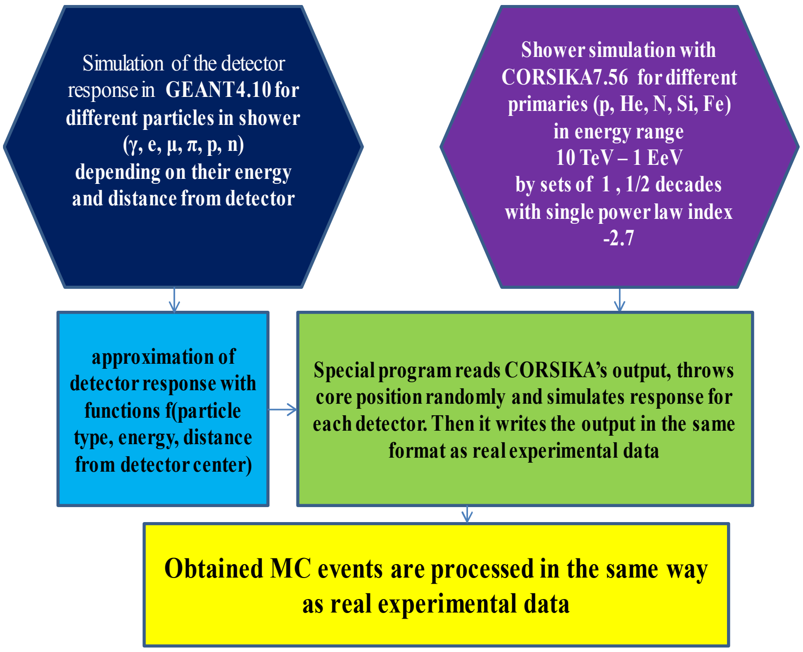

Figure 1: Simulation process diagram.

Showers were simulated in range from 10 TeV to 1 EeV with single power law energy spectrum with index -2.7. The whole range was divided into decades and half decades. The total number of simulated events recorded by ENDA-64 array with energy above 1 PeV is ~ 200000.

Simulated dependences of shower size and neutron number vs primary energy are shown in fig. 2.

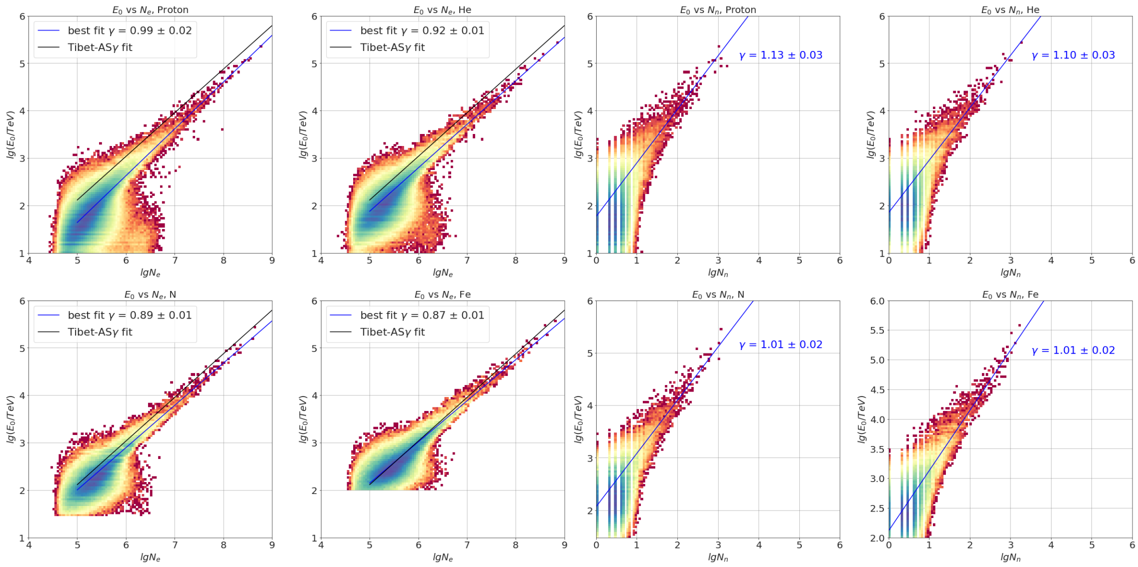

Figure 2: Left: Dependence of Ne from primary energy for p, He, N, Fe. Blue lines – our fits, black lines - Tibet-ASγ fit [9]. Right: Dependence of the number of recorded neutrons on primary energy for p, He, N, Fe. Blue lines – our fits.

4. Mass composition analysis

One of the main goals of the ENDA project is study of mass composition of primary cosmic rays above the knee. Using simulated data we tested some machine learning techniques to recover average atomic number on the base of electrons and neutrons measurements. Firstly, we recalculated primary energy using linear regression on several parameters: lgNe (shower size logarithm), s (shower age), ln(Nn+1) (number of recorded neutrons logarithm). Comparison of energy reconstruction by this technique and using only Ne is shown in fig. 3. One can see that such technique is more correct in comparison with using only shower size as energy estimator.

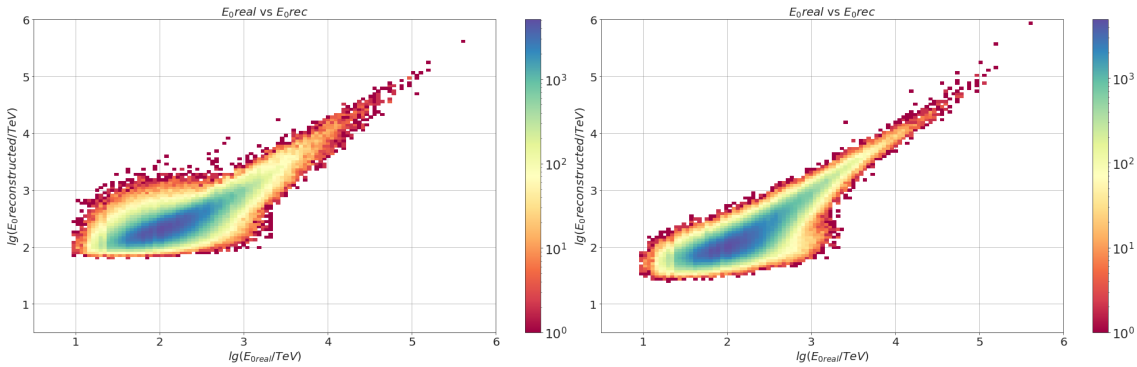

Figure 3: Left: Energy reconstruction using Ne as the only energy estimator. Reconstructed energy vs true (real) energy. Mass composition is the mixture of p, He, N, Si, Fe. Right: The same but energy was reconstructed with linear regression on multiple variables: lgNe, s, ln(Nn+1).

After energy reconstruction we divided all data set to several energy regions by 0.5 of energy logarithm. After that we used k-Nearest Neighbors technique [14] with exponential kernel on multiple variables (lgErec – reconstructed energy logarithm, s – shower age parameter, ln(Nn+1)) to determine the primary particle group (p, He, N, Si, Fe) and then we found the mean atomic number for each energy region. The mean atomic number of the initial data set was chosen randomly by making random fractions of different primary nuclei just to learn the possibility to recalculate the <A>. Results of this analysis are shown in fig. 4.

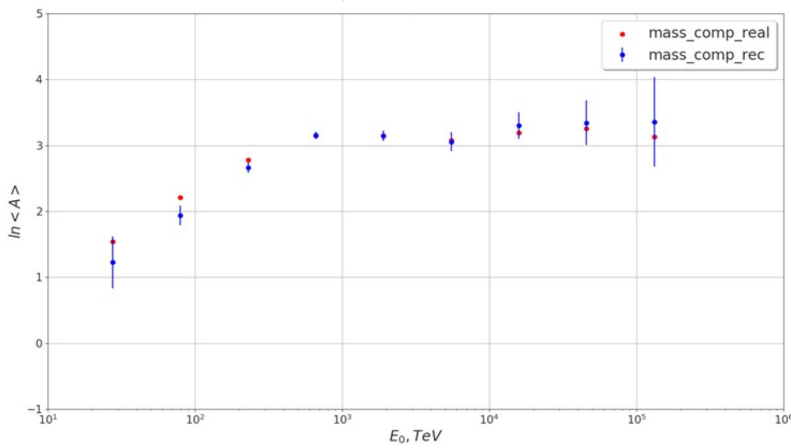

Figure 4: Mean atomic number reconstruction as a function of primary energy made using k-NN technique on multiple variables: lgErec, s, ln(Nn+1). Mass composition is the random mixture of p, He, N, Si, Fe. Red circles – real values of used composition and blue circles – reconstructed values.

5. Conclusions

ENDA (Electron-Neutron Detector Array) is a novel type of EAS arrays capable to simultaneously measure electromagnetic and hadron components of extensive air showers in the energy region of 10^{15} – 10^{17} eV.

MC simulations performed via CORSIKA7.56 and GEANT4.10 show that ENDA-64 will be sensitive to CR mass composition in range of 10^{15} – 10^{17} eV. Further calculations will be performed to show capabilities of our detectors to reconstruct different primary particle groups energy spectra and sensitivity to gamma ray selection in considered energy region.

ENDA-64 is planned to start data collection in the beginning of 2020 inside LHAASO project at the altitude of 4400 m above sea level in Daocheng, Sichuan, China. After that we'll be able to analyze the data and compare our results with the other LHAASO detector arrays results.

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