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# Electron and thermal neutron lateral distribution functions in EAS at high altitude

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**Abstract.** EAS array of novel type have been constructed on the base of ARGO-YBJ experiment (Tibet, China). It consists of the four specially designed scintillator en-detectors capable to measure two main EAS components: hadrons through thermal neutrons (n) and electrons (e). The results of simulation for these arrays using CORSIKA and GEANT4 codes are presented. Simulated thermal neutron and electron lateral distributions are compared with experimental data. Obtained distributions are compared with those obtained by other arrays.

## 1. Array and detectors.

An idea of a novel type of EAS array proposed for the first time in 2001 [1] was developed later [2, 3] to the PRISMA (PRImary Spectrum Measurement Array) project. The main feature of the array is the ability to measure the main EAS component hadrons, through the measurement of secondary thermal neutrons produced by these hadrons in surrounding matter. Special inorganic scintillator detector (en-detector) has been developed for this purpose. The first prototype of such array consisting of 32 en-detectors (PRISMA-32) has been constructed in Moscow on a base of the NEVOD-DECOR experiment (MEPhI) [4] in 2012 and the second one consisting of 4 en-detectors (PRISMA-YBJ) is located inside the hall of ARGO-YBJ experiment [5] in Tibet at 4300 m a. s. l. Thin layer ($\sim$ 30 mg/cm$^2$) of special inorganic scintillator ZnS(Ag)+$^6$LiF of 0.36 m$^2$ area is placed at the bottom of cylindrical polyethylene (PE) 200-l tank which is used as the detector housing. $\alpha$ and $^3$H resulting in $^6$Li(n,$\alpha$)$^3$H reaction produce scintillation in ZnS(Ag), being the best scintillator to measure heavy particles due to very good $\alpha$/e-ratio and high efficiency. Also ZnS(Ag) is used to measure electron component of EAS if the number of particles passed through the detector exceeds 2. 2-fold coincidence hit of any 2 detectors gives a trigger to the array. FADC (ADLINK 10 bit PCI slot PCI-9812) is used for pulse shape digitizing (20000 samples with a step of 1 $\mu$s, totally 20 ms). Having digital oscillogram of event one can see first big pulse produced by EAS electromagnetic component and then delayed small pulses from thermal neutrons, which need some time ($\sim$ several ms) to be thermalized and collected. The dynamic range of the detector is lasting from $\sim$ 3 to $\sim$ 2560 m. i. p. The detectors absolute calibration was checked using the ARGO-YBJ and PRISMA-YBJ coincident run data [6]. The en-detectors in PRISMA-YBJ are identical to that used in Moscow in PRISMA-32. Details of the en-detector design and PRISMA-32 array can be found elsewhere [7, 8]. To improve the shower core location we use only 4-fold coincidence with a pulse height of >2 FADC channels ($\sim$ 5 m. i. p.) for our analysis.

## 2. Simulation details

Detailed Monte-Carlo simulations were performed in 2 steps: the first one, using GEANT4 to calculate neutron production in surrounding the detector matter by high energy hadrons and second one, using CORSIKA codes to simulate the EAS. The QGSJET-II.03 and GHEISHA (2002) packages were used in CORSIKA with particle energy cuts close to minimal for all particles ( 60 KeV, e-/+ - 60 KeV, mu-/+ - 0.5 GeV, hadrons  50 MeV). We simulated EAS for primary protons and iron both with spectral indices -2.7. For GEANT4 simulation standard QGSP_BIC_HP model package with standard 1 mm cut was used. All geometry and materials (including their chemical composition) were simulated as accurately as possible. As GEANT4 simulation shows in Fig. 1., recorded thermal neutrons are produced mostly locally (local neutrons) from the nearest vicinity of the detector. Fitting function is shown below (1).

$$\rho_n(r) = 1.8(e^{(-r/0.48m)} + 0.0026e^{(-r/6m)}) \tag{1}$$

The first exponent is connected with neutrons produced in the ground right under the detector and second one is connected with neutrons produced in the thin roof of ARGO-YBJ building and in the air upside the array. Keeping this in the mind one can conclude that the lateral

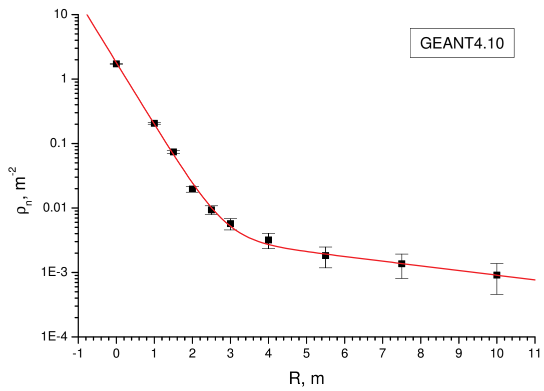


**Figure 1.** Lateral distribution of secondary thermal neutrons produced by 100 GeV hadron (composition of pi-, pi+, p, n) from hadron trajectory (from GEANT4 simulation).

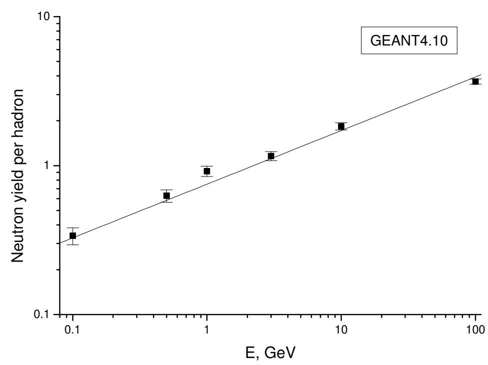


**Figure 2.** Neutron yield as a function of hadron energy for PRISMA-YBJ conditions (from GEANT4 simulation).

distribution of thermal neutrons is mainly connected with the EAS hadron lateral distribution. The yield of secondary neutrons depends on hadron energy and can be fitted well by power law function (2) (line in Fig. 2.):

$$N_n(E_h) = 0.75(E_h/GeV)^{0.36} \tag{2}$$

This and weak dependence of hadron mean energy with EAS size result in thermal neutron number is nearly proportional to the number of parent hadrons passed through the array area

[9]. Experimental and simulated electron lateral distributions for EAS with age 0.8<s<1.7 are shown in Fig. 3. without any normalization. This event selection gives us mostly true EAS

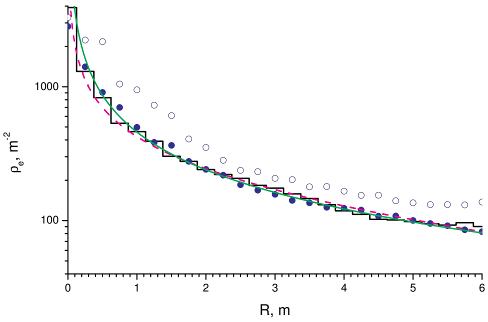


**Figure 3.** Lateral distribution of electromagnetic component of EAS at 4300 m a. s. l. altitude. Histogram - experimental data, ● - simulation for protons, ○ - simulation for iron,——NKG function (4), - - - -ARGO-YBJ experimental fit (3).

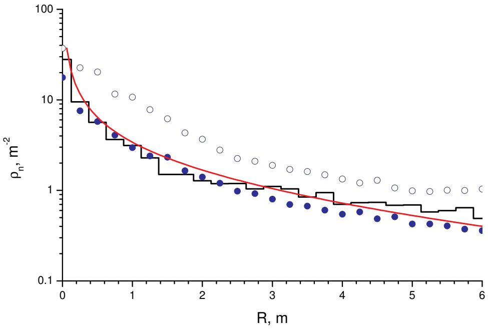


**Figure 4.** Lateral distribution of secondary thermal neutrons in EAS at 4300 m a. s. l. altitude. Histogram experimental data, ● - simulation for protons, ○ - simulation for iron, ——KASCADE function for hadrons with rh raised to 20m (5).

without unaccompanied primary hadrons interacted above the array (young showers with s<0.8). Experimental results are in a good agreement with our CORSIKA + GEANT4 simulation and ARGO-YBJ normalized fit (3) [10] and normal NKG function for this altitude (4).

$$\rho_e{}^1(R) = 470R^{(1.35-2)}(1 + R/30m)^{(1.35-4.5)} \tag{3}$$

$$\rho_e{}^2(R) = 470R^{(1.1-2)}(1 + R/136m)^{(1.1-4.5)} \tag{4}$$

We limited R by 6m level when processing the data due to the array size. Experimental and simulated EAS thermal neutron lateral distributions (again without any normalization) are presented in Fig. 4. along with a fitting function. Here KASCADE NKG-like function for hadrons (5) [11] fits the data rather well if we use hadronic radius rh = 20 m instead of $\simeq$ 10-15 m in KASCADE. It is clear because our array is situated at high altitude where air density is only 60% of that at see level. So mean radius (as well as interaction length) for hadrons is $\sim$ 1.6 times larger.

$$\rho_n{}^2(R) = 4R^{(1.2-2)}(1 + R/20m)^{(1.2-4.5)} \tag{5}$$

## 3. Conclusion.

A novel method of EAS study has been developed and tested. Detector prototype at high altitude (PRISMA-YBJ) has been realized and operates now. The measured parameters of EAS neutrons and electrons lateral distributions are very close to our GEANT4+CORSIKA simulation. As GEANT4 simulation shows neutrons are produced mainly in ground or concrete very close to the parent hadron track. Therefore thermal neutron detection is a unique method to study hadronic EAS component lateral distribution using full array area. Electron lateral distribution measured with our thin scintillator seems to be well fitted by ARGO-YBJ published fit and neutrons LDF is good fitted by KASCADE formula for hadrons with higher $r_h$ in accordance with higher altitude. The agreement is well inside 5 meters due to a small array size and abnormally high errors in core location for far outer showers. Results of this work show that we can adequately simulate the experiment and it will help us to simulate and optimize the future full-scale PRISMA-LHAASO arrays design that we plan to install in the frames of LHAASO project[12].

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