Investigation of the EAS neutron component with the URAN array: first simulation and experimental results

Z T Izhbulyakova, A G Bogdanov, F A Bogdanov, D M Gromushkin, A D Pochestnev, I A Shulzhenko, K O Yurin

National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 115409 Moscow, Kashirskoe shosse 31

E-mail: izhbulyakovazarina@yandex.ru

Abstract. The URAN array was created in the Scientific and Educational Centre NEVOD (MEPhI). The URAN facility was designed to register neutrons that accompany EAS at the energies of the primary cosmic rays around and above the “knee”. It includes 72 detectors based on a thin inorganic scintillator for registration of the charged and neutron components of the EAS. The total area of the facility is about $10^3$ m$^2$. For the correct interpretation of the experimental data of the URAN, the response of the URAN facility to the passage of EAS was simulated using the CORSIKA7.6900 program and Geant4.10.5 software package. It gave a possibility to study neutron generation in the experimental complex building. Experimental data were processed and analyzed. Results of simulation and experimental data are presented.

1. Introduction
The study of the spectrum and composition of cosmic rays (CR) is an important but non-trivial task. One of the most interesting unresolved questions is the problem of the CR spectrum break (around the "knee"). Registration of primary CR particles outside the atmosphere with the energy in the “knee” range ($10^{15}$-$10^{16}$ eV) is not possible because CR particle flux has very low intensity. Therefore, to solve this problem, an indirect method of registering CR particles, method of extensive air showers (EAS) is used. EAS method is based on the registration of the products of the interaction of CR particles with the atomic nuclei in the atmosphere.

Hadrons are the main component of EAS. Recently a new method for studying the hadron component of EAS was developed [1]. This method is based on registration of thermal neutrons that are generated as a result of interactions of shower hadrons with atomic nuclei in the atmosphere and at the surface of the Earth and then thermalized. An advantage of the thermal neutron component is that the time profile of EAS in thermal neutrons is of the order of 10 ms, which is about $10^6$ times longer than the time profile of charged particles in the near-core region of a shower. This allows to measure the number of neutrons in a wide dynamic range. At the Scientific and Educational Center NEVOD (MEPhI) the URAN array [2] was created to detect the neutron and charged components of EAS at primary particles’ energies around and above the "knee".

2. The URAN array and experimental data
The URAN array consists of 72 electron-neutron detectors (en-detector) [3], which are grouped into a structure of 6 clusters (12 en-detectors in each cluster), which are placed on two roofs of laboratory buildings, a distance between detectors is 5 m, and a total area of array approximately equals $10^3$ m$^2$. The aim of the installation is the study of extensive air showers (EAS) in the energy range $10^{15}$-$10^{17}$

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eV. Figure 1 shows the layout of URAN detectors and a design of the neutron detector. The thermal neutrons registration is realized by capturing with the isotope $^{10}$B (~ 18% in $\text{B}_2\text{O}_3$) contained in the scintillator $\text{ZnS(Ag)} + \text{B}_2\text{O}_3$.

Figure 1. The layout of the URAN array (left) and the design of the neutron detector (right): 1 – light isolation case; 2 – cap with detecting elements; 3 – PMT-200; 4 – scintillator $\text{ZnS(Ag)} + \text{B}_2\text{O}_3$; 5 – reflective cone, 6 – protective case.

Registration of the EAS takes place on the leading edge of the shower and the data are recorded in the time window of 20,000 microseconds, where the neutrons accompanying the shower are detected. Clusters work independently and have the same criteria for triggering and recording of events. During the series of measurements, it was required that the signals from two or more detectors have response of at least 17 charged particles. The signal duration from neutron should be at least 4 μs and have an amplitude more than 10 mV. A more detailed description about registering the neutron and charged components of EAS can be found in paper [4].

In the present analysis the data on air showers accumulated over the period from January 2019 to December 2019 were used. The trigger conditions of the analysis were the coincidence of 6 clusters with the response at least 2 detectors (2948 events). The EAS axis was identified by applying the NKG function to the charged component of the detector data and finding the best axis position by the maximum likelihood method. To determine the angles of direction of arriving showers, we use the data of the NEVOD-EAS array [5].

3. Simulation

For correct interpretation of the experimental data, a detailed mathematical model of the URAN array has been developed. Geant4.10.5 software package [6] was used to simulate the arrays’ geometry and response. The geometry of the facilities and the chemical composition of the materials are close to real conditions. The environmental model includes the concrete walls and floor of the Experimental Complex (EC) NEVOD, roofs of concrete and ceramic coating, Cherenkov water detector (CWD) [7] tank, its steel cover and concrete floor with wooden elements. Under the EC NEVOD building there is the ground whose composition corresponds to the soil in the Moscow region. The included physical processes take into consideration the features of the interaction of thermal neutrons with matter. The physics list used in this simulation is QGSP\_BIC\_HP.

Generation of neutron occurs in heavy and dense materials such as steel, concrete, etc. Therefore, the number of registered neutrons depends on the location of the detector relative to the structure of the building. First of all, it was important to study neutron generation in the EC building. To solve this task, the simulation of interactions of hadrons (10 GeV) with the roof of the EC building was simulated. Figure 2 shows time distribution of neutrons generated in various parts of the EC building.
and registered by the URAN array. As we can see, the largest contribution to the generation of thermal neutrons is given by dense materials such as roof and walls of the building.

![Figure 2](image-url)  
**Figure 2.** Temporal distribution of neutrons generated in various parts of the building registered by URAN array (red - neutrons generated in the roof, black - the roof and floor, blue - the roof and walls, green - the roof, floor and walls, blue - all building elements)

Simulation of EAS is carried out using the CORSIKA7.6900 [8] program. For simulation, the models QGSJET-II-04 (for high-energy interactions) and FLUKA2011 (for lower energies) were chosen. Air showers were simulated for primary protons for level of observation of 170 m. Proton energies were sampled in the range of $10^{15} - 10^{17}$ eV according to the power-law CR spectrum, and the zenith angles $\theta$ varied in the range from $0^\circ$ to $50^\circ$.

4. Results

One of the important characteristics of the detector response is the temporal distribution of thermal neutrons. The temporal distribution of registered thermal neutrons for experimental data and simulation is shown in Figure 3. The obtained time distributions may be approximated by superposition of two exponential functions:

$$f(t) = A_0 + A_1 \cdot e^{t/t_1} + A_2 \cdot e^{t/t_2}, \quad (1)$$

The first parameter ($t_1$) can be associated with the average neutron lifetime in concrete. The second parameter ($t_2$) is associated with neutrons produced in the air. A comparison of the exponents parameters of temporal distributions of thermal neutrons according to the results of simulation and experiment is shown in the Table 1. The time distribution is similar to that obtained on the URAN prototype, PRISMA-32 [9].

|            | $t_1$ (ms)     | $t_2$ (ms)     |
|------------|----------------|----------------|
| **Simulation** | 2.11 $\pm$ 0.71 | 0.58 $\pm$ 0.04 |
| **Experiment** | 2.72 $\pm$ 0.93 | 0.43 $\pm$ 0.03 |

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Lateral distribution function (LDF) of neutron component can be described by an exponential function:

\[ f(r) = A_0 + A_1 \cdot e^{-\frac{r}{r_0}}, \]  

(2)

The parameter \( r_0 \) can be associated with the average neutron path in concrete before the capture. A comparison of the exponents parameters of LDF of thermal neutrons for simulation and experimental data is given in the Table 2.

|                  | Simulation | Experiment |
|------------------|------------|------------|
| \( r_0 \) (m)    | 3.94 ± 0.89| 3.25 ± 0.26|

Figure 3. Temporal distribution of thermal neutrons registered by the URAN array (black line corresponds to experimental data, green line represents the results of simulation)

Figure 4. LDF of EAS neutron component registered by URAN array (blue points are experimental data, black once represent simulation results)
5. Conclusion
The data on the neutron EAS component accumulated in one year of operation of the large area facility URAN were analysed using detailed Monte-Carlo simulation with Geant4 and CORSIKA. The generation of neutrons in various parts of the NEVOD building has been studied. The temporal distribution was described by two exponential functions, LDF can be approximated by one exponential function. The experimental data are consistent with simulation results.

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