Measurements of the thermal neutrons flux near the EAS core

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Abstract. The characteristics of the thermal neutrons flux have been measured near the EAS core at the “Carpet-2” EAS array. The thermal neutron detectors were placed on the floor of the tunnel of the Muon Detector (MD) and showers with a core near the MD were selected. Thermal neutrons multiplicity spectrum has been obtained for these showers. Measurements of the lateral distribution function of thermal neutrons at distances of 1-16 m from the shower axis have been performed. The mean number of the recorded thermal neutrons as a function of the number of hadrons crossing the MD has been measured.

1. Introduction
A new approach to research the hadronic component of extensive air showers (EAS), the so-called “method of the underground hadronic calorimeter” has been presented in works [1], [2]. Thermal neutrons were recorded, within several milliseconds after EAS, by a thermal neutron detector of 0.375 m$^2$ in the underground tunnel of the muon detector (MD) under a soil absorber of 500 g/cm$^2$. The number of secondary thermal neutrons is expected to correspond to the number of hadrons, crossing the volume of the MD and also to the summarized energy of the hadronic component. In our paper we develop the method of underground hadronic calorimeter and present new results of studying the hadronic component of showers cores crossing the MD. The hadrons with energy of more than 10 GeV are recorded by the detectors of the MD, and the flux of thermal neutrons, accompanying EAS, is measured by four special scintillator thermal neutron detectors (en-detectors) placed in the tunnel of the MD. The spatial characteristics of the thermal neutron flux produced underground near the EAS cores were measured.

2. Experiment
The experiment was performed using the air shower array ”Carpet - 2” of the Baksan Neutrino Observatory INR RAS [3]. It consists of a ground-lever part, ”Carpet”, and of a large underground muon detector. The MD includes 175 plastic scintillation detectors (the thickness of scintillation = 5 cm.) with an area of 1 m$^2$ each. These detectors are placed on the ceiling of the underground tunnel with dimensions of 5×35 m$^2$. Each detector of the MD measures the energy deposit ($\varepsilon$) in an interval of 0.5-100 relativistic particles (1 r. p.), 1 r. p. corresponds to $\varepsilon \approx 10$ MeV. The thickness of the MD absorber is equal to 500 g/sm$^2$ corresponding to the threshold energy for muons of 1 GeV. As the
thickness of the absorber is equal to ~20 radiation lengths, it is enough to absorb the electromagnetic component but not enough to absorb the hadronic cascade (only ~5 hadron interaction lengths). The hadronic cascade developing in the absorber can produce high-energy deposit $\varepsilon$ in the scintillator because it is situated just near the hadronic cascade maximum. This allows one to evaluate the average relation between the hadron’s energy and the energy deposit in the detector. These features of the MD allow us to use it as a single layer hadronic calorimeter, but the abilities of such calorimeters are limited by their narrow dynamic range in terms of the number of detected hadrons, which cannot exceed the number of individual detectors (175 unit). In this work 4 thermal neutron en- detectors [2], [4] were used to study the hadronic component. The neutron detectors with a total area of 2.25 m$^2$ were placed in the center on the floor of the tunnel of the MD in a row (with no space between them). The efficiency of thermal neutron recording is about 20%. The time gate for neutron recording is equal to 5 ms after EAS arrival. Data on thermal neutrons together with data on hadrons obtained using single – layer hadronic calorimeter allow us to study thermal neutrons generated by high energy hadrons in the MD absorber. Nine scintillation detectors (3×3), similar to those in the MD, were placed (E - the detector) on the surface of the absorber in a special room. The anode signals from the nine PMT tubes are summarized and are digitized by linear ADC and stored in DAS of MD. The dynamic range of this measurement corresponds to 1÷ 200 r.p. The E-detector is used to estimate the density of e-$\gamma$ components of EAS.

3. Results

Data were obtained during 105 days of the operation of the MD together with the thermal neutron detectors using M3 trigger -, MD’s trigger, produced by the coincidence of 3 from 5 MD modules. A simulation of the experiment with CORSIKA code [5] for primary protons has been performed. The calculations show, that M3 trigger is initialed by showers with $E_0 > 1$ TeV with the axes located in a circle with radius of 30 m from the MD center. The data with the following conditions are analyzed: 1) the axis of the hadronic cascade should be located inside the MD, (excluding the perimeter’s detectors); 2) the number of hit MD detectors with deposit $\varepsilon \geq 1$ GeV should be $\geq 1$; 3) The total number of thermal neutrons in four detectors should be $\geq 1$; 4) the density of the particles for the E-detector on the surface of the MD should be more than100 r.p. According to our calculations [6] we have $E_0/\varepsilon \approx 250$, this means that hadrons with the energy of 250 GeV give a deposit of 1 GeV, i.e. the sum hadronic energy is $\sum E_h \geq 250$ GeV in the selected cascades. The number of the events selected under these conditions is about 5000. These events are the cores of EAS, with the sum of total hadron energies $\geq 250$ GeV, passing through the MD’s absorber and generating hadronic cascades accompanied by the thermal neutron flux inside the MD tunnel.

3.1. Lateral distribution function - LDF

Lateral distribution function (LDF) of thermal neutrons inside the MD tunnel was obtained as the dependence of average density $TN < \rho >$ on average distance $< r >$ in an interval of 1-16 m (Fig.1). The value $< r >$ is the average distance from an axis of the cascades up to the geometrical center $(X_d, Y_d)$ of the four detectors of the thermal neutrons, and it was calculated according to the formula:

$$< r > = \left( \sum R_i \right) / n$$

(1)
where \( n \) is the number of the MD’s detectors with \( \varepsilon > 1 \) GeV, \( R_i \) is the distance from \( i \)-detector’s with \( \varepsilon > 1 \) GeV up to the point \((X_d; Y_d)\). It can be seen from Figure 1, that this dependence can be fitted quite well by an exponential function:

\[
\rho = 5.01 \cdot \exp \left(-r/5.49\right) - 0.09 \tag{2}
\]

3.2. The multiplicity spectrum

In Figure 2 the experimental integrated multiplicity spectrum of the thermal neutrons measured by four thermal neutron detectors in the tunnel of the MD is shown. This spectrum is described well enough by a power law:

\[
N (n_{thd}) = 4467 \cdot <n_{thd}>^{-2.21} \tag{3}
\]

with the spectrum slope of 2.21 for an interval 1-54 of thermal neutrons.
3.3. The correlation dependence between the average number of hadrons and the average number of thermal neutrons

The experimental correlation dependence between the average number of hadrons ($<N_h>$) with $E > 10$ GeV and the average number of thermal neutrons ($<n_{thn}>$) is presented in Fig.3. For cascades with $N_h > 80$, hadron recording efficiency of the MD area is decreased and this is why in this paper we present the dependence only for $N_h < 80$. The dependence of the thermal neutron number on the number of hadrons in cascades with $N_h < 80$ was well approximated by a linear function:

$$<n_{thn}> = -0.47 + 0.05 \times <N_h> \quad (4)$$

The obtained correlation coefficient was equal to 0.97. Using eq. (4) we can estimate the expected number of hadrons for the cascade with the biggest recorded number of neutrons ($n_{thn} = 54$) as $N_h = (54+0.47)/0.05 = 1089$, and then the total energy threshold of hadrons near the core of the cascade is equal to $\sum E_h > 1089*10$ GeV $\approx 10$ TeV.

4. Conclusions

4.1. The precision measurements of the LDF of the thermal neutrons near the EAS core in the underground tunnel of the MD have been performed. It is interesting that the obtained parameter $r_0 = 5.49$ m is rather close to the one obtained on the ground surface level [7] where $r_0 = 6-7$ m.

4.2. The multiplicity spectrum of thermal neutrons in the underground tunnel has been measured. Unfortunately, statistics is poor and it is now difficult to make any conclusion about the spectrum slope.
4.3. The linear dependence of the number of thermal neutrons on the number of hadrons has been obtained. This confirms that the proposed method of the underground hadron calorimeter is correct and it is possible to obtain EAS size spectrum in hadrons using this method.

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