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Thermal Neutrons In EAS: A New Method In EAS Study

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Abstract: A new method to study Extensive Air Shower (EAS) is proposed. It is shown that recording of thermal neutron flux accompanying the EAS gives absolutely new information which could give a key to the knee problem. Results of CORSIKA based Monte Carlo simulations as well as preliminary experimental results lead authors to a proposal of novel type of EAS array.

Introduction

The study of cosmic ray neutron component started in 30-s of last century. A summary of the early experimental data and their interpretation can be found in [1]. Later, in 40-s, in parallel with understanding of the EAS hadronic structure, measurements of neutron component in EAS have began [2, 3, 4]. All the data obtained in these early works were correctly understood and interpreted. Later, when the neutron monitors [5] were constructed and spread widely, people tried to use them in conjunction with EAS arrays to study hadronic component of secondary cosmic rays (see for example [6, 7, 8, 9]). Many "anomalies" were observed in these experiments: in hadron spectrum [7], in lateral distribution [8], etc. Explanations of these "anomalies" can be found in an *a priori* assumption that they recorded a single hadron. But, with primary energy rising, there will be a moment when the number of hadrons entering the monitor becomes bigger then 1. This is a new class of events, which we called as *hadron group* [10]. Starting from this moment, all secondary processes including evaporation neutron production, depend mostly on the hadrons number reached the detector instead of their energy rising very slowly. This results in sharp changes in many observables: locally produced neutrons number distribution becomes flatter, their lateral distribution becomes difficult for interpretation while it remains constant for each center of generation (for each interacting hadron).

The idea to use neutrons moving with a subluminal velocity at long distances from EAS core for the estimation of hadronic component energy, has been proposed by J. Linsley [11].

The idea to use thermal neutrons as a key to select muon hadronic interactions underground has been proposed and realized by G.T.Zatsepin and O.G.Ryazhskaya [12, 13]

On our opinion only hadrons being the main EAS component could give us a key to solve the "knee" problem.

A prototype of the MultiCom array

A novel type of an array for EAS study (MultiCom) proposed by us in 2001 [14, 15], has been realized in 2005 near the existing Baksan Carpet-2 EAS array as a prototype, consisting of one working module of $5 \times 5m^2$. 4 thick liquid scintillator detectors $(70 \times 70 \times 60cm^3)$ in the corners were used for triggering with a threshold of 106 MeV in each detector (M2 trigger). The trigger counting rate is equal to 3.3 min^{-1}. Additional requirement for event to be stored (software trigger) is energy deposit in the central ZnS detector equivalent to 1/2 of the most probable neutron pulse height (or $\sim$8 relativistic particles). Corresponding energy threshold for such trigger conditions was calculated to be $\sim$ 7 TeV for proton originated EAS, $\sim$ 30 TeV for He EAS and $\sim$300 TeV for Fe EAS. In the center of module there is situated unshielded thermal neutron detector of $0.7 m^2$ at 2.5 m above ground level (fig. 1). We used a thin layer of a mixture of old inorganic scintillator ZnS(Ag) with LiF enriched with ^6Li up to 90%. Thermal neutrons are recording due to $^6Li(n,\alpha)^3H + 4.78$ MeV reaction. ZnS scintillator is the best scintillator for heavy particle detection and produces $\sim$ $160,000$ light photons per one captured neutron. That means one could make a large detector viewed by a single PMT and have enough light. In our case we have $\sim$50 photo-electrons from PMT photo-cathode.

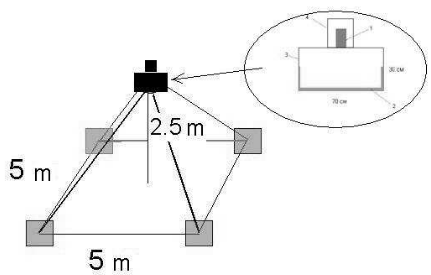

Figure 1: MultiCom prototype set-up.

The efficiency of thermal neutron detection was found to be 20%. Pulse duration (the fastest component) is equal to $\sim$ 40 ns. Taking into account that heavy particles also excite slower component one can use it for pulse shape selection. Due to very thin scintillator layer (30 mg/cm^2), it is almost insensitive to single charged particles and gamma-ray, but it can be successfully used for EAS particle density measurements as it will be shown below.

4-channel digital oscilloscope TDS224 connected to a PC via GPIB interface is used for data acquisition. Integrated analog pulses from the PMT anode are put to the oscilloscope inputs with different gain. Digitizing step is equal to 4 μs while full time scale is equal to 10 ms. Full wave form information is collected in a case of the triggering.

Experimental results and data analysis

The results of this experiment can be found elsewhere [16, 17, 18]. Here only additional information will be shown with the aim to illustrate the method performances. First of all, we have measured the thermal neutron yield per event for 2 different triggers: M1 and M2. M1 is a usual EAS trigger of the Carpet-2 array produced by 5-fold coincidence of 5 detectors (central one of 200 m^2 and 4 outside detectors of 9 m^2 each) with a threshold on primary energy of $\sim$ 100 TeV) while M2 is a local trigger produced by the array shown in fig.1. The time structures of delayed pulse distributions for each trigger are shown in fig.2. The explanation of very flat neutron time distribution for local triggers (M2) can be found elsewhere [18]. Here I'd like to explain "strange" behavior of the rising time distribution of delayed neutron pulses for the EAS trigger M1.

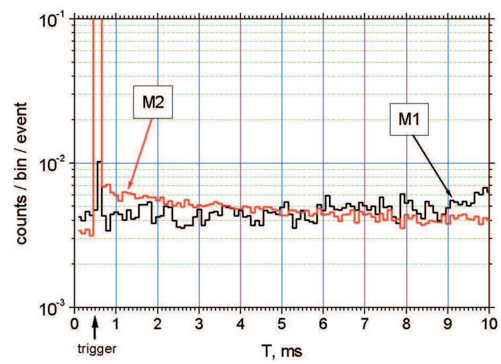

Figure 2: Pulse delay distributions measured by the ZnS detector for different triggers.

As it was mentioned in [16, 18] there are two sources of thermal neutrons producing delayed pulses in neutron detector after EAS passage. 1st one (local) is local one i. e. surrounding the detector solid matter which can moderate evaporation neutrons produced by high energy hadrons nearby, and 2nd one (atmospherical) is the atmosphere where neutrons also can be moderated with rather low efficiency. Time distributions of these sources in the window of 10 ms after EAS front, are different: 1st one gives rather steep distribution depending on the EAS core position, while 2nd one gives increasing time distribution independently on core location. This becomes clear if we take into account that the time (τ) of neutron moderation in air is ≈180 ms. Therefore, expected distribution can be written as F(t)∼ $(1 - exp(-t/\tau))$. If $t << \tau$ then F(t)∼t/τ. Under the M1 trigger which does not need high local particle density, the neutron detector detects mostly atmospherical neutrons as we can see in fig.2. Under the local trigger M2 the detector is sensitive to both sources and a contribution of the first one rises with EAS size [16]. This results in such a different behavior of the time distributions shown in fig.2. Additional interesting feature can be seen in the fig.2: the histogram for M1 shows no excess in the recorded neutrons flux in the first few milliseconds after the trigger. This means that no neutrons are produced locally for a great bulk of these events. The latter confirms our idea [19] that a great bulk of EAS with energy $E_0 \sim 100$ TeV are *coreless*, i. e. these showers have no high energy hadrons at observational level.

A possibility to measure charged particles number passed through the ZnS detector using the same detector has been demonstrated in [18]. The measured particle density spectrum for all evens follows well known power law function with integral index equal to ~ -1.5, while that for events with recorded neutrons changes the slope. It confirms that our ZnS detector works properly not only for neutron detection but for charged particles as well.

The e-n-array proposal

The first obtained experimental results as well as results of Monte Carlo simulations, made on a basis of CORSIKA codes, makes me sure to propose a novel type of EAS array which could consist only of the large area ZnS detectors measuring both the main EAS components: hadronic and electromagnetic. The array could look like a simple grid of say 121 detectors like those shown in the upper right corner of fig.1, with a spacing of $5 \div 10$ m covering an area of 100×100 m^2. It could be very informative in spite of its simplicity and compactness. Detection of thermal neutron flux accompanying the EAS passage through the surrounding matter gives absolutely new information, which was never used before. First of all, the number of detected neutrons is proportional (in the first approximation) to the number of hadrons reached the observational level in a radius of $\sim$ 300÷500 m around the detector location, including an air layer of the same thickness. Such a large distance evaporation neutrons can cover during their movement in air before moderation. Detailed study of the hadronic component with a large area detector (10^4 m^2 in proposed array, which can be extended without any problem) is very interesting problem because hadrons form the EAS skeleton and only they can preserve the adequate information about primary particle. Starting from a low threshold on primary energy of $\sim 10 \div 30$ TeV and covering the "knee" region with a wide enough range, this array could make a significant improvement of experimental situation and probably would solve the "knee" problem. Another interesting advantage of the array is its possibility to locate the EAS axis more precisely due to steep lateral distribution of hadronic and neutron components in comparison with electron one usually used for this purpose. That means primary energy can be recalculated with higher accuracy. A usage of n/e -ratio instead of μ/e-ratio for primary mass composition measurements would give better results because of first, a number of thermal neutrons is much higher than a number of muons and second, electron and hadron components are in equilibrium on an observational level, while muonic component is not, due to its integral properties [16]. And finally, the time structure of the *neutron vapor* is absolutely new dimension in EAS study, which could give us unexpected result.

Summary

The method to study EAS with thermal neutron scintillator detectors is proposed. Promising data obtained with a pioneer experiment let us to conclude that *the neutron vapor* associated with EAS passage does exist and can provide experimenters with an additional very useful information. A scintillator detector for neutron detection developed by us showed very good performance and made it possible to measure thermal neutron flux with very low background. Moreover, it showed rather good performance in charged particle density measurements thus lead me to a conclusion that EAS array could consist only of these detectors measuring both main EAS components hadronic and electronic. Finally, the detector showed an excellent performance in thermal neutron background flux measurements. First very interesting results of this study can be found in [20, 21].

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