Recording of thermal neutron flux underground as a method to study EAS properties

Yu.V. Stenkin*, **V.V. Alekseenko**†, **A.B. Chernyaev***, **D.D. Dzhappuev**†, **D.M. Gromushkin**‡, **A.U.Kudhzaev**†, **O.I. Mikhailova**†, **V.I.Stepanov***, **A.L. Tsyabuk***, **G.V. Volchenko**† **and V.I. Volchenko**†

* *Institute for Nuclear Research of RAS, Moscow 117312, RUSSIA*

† *Baksan Neutrino Observatory, Institute for Nuclear Research of RAS, KBR 361609, RUSSIA*

‡*Moscow Engineering Physics Institute, Moscow 115409, RUSSIA*

***Abstract*. We proposed and first realized a novel method to study Extensive Air Shower (EAS) properties by recording the "thermal neutron vapor" locally produced by high energy hadrons below a soil absorber of 500 g/cm^2. It is shown that special scintillator detectors for thermal neutrons situated underground could be very useful in the study of such EAS properties as the full number of the core hadrons at observational level, primaries mass composition, core location, gamma-shower selection etc.**

***Keywords*: EAS, thermal neutrons, hadrons**

I. INTRODUCTION

In our previous works [1] – [5] we proposed and partially realized a novel method to study EAS properties by recording a "thermal neutron vapor" accompanying its passage. It has been shown that recording of the main EAS component could give us a key to solve the "knee problem" in cosmic ray spectrum. In this paper we propose a developing of the method. Location of the developed by us large area thermal neutron detectors at shallow depths underground (inside the muon detector tunnel in our case) is also a promising method to study EAS properties and thus to study primary cosmic ray spectrum and primaries mass composition.

II. EN-DETECTOR

The thermal neutron detector (en-detector) with an inorganic scintillator in the form of a granular alloy based on ZnS(Ag)+LiF, enriched by an isotope of lithium-6 up to 90%, is used in the measurements. Such counters have advantages over the generally used gas counters: fairly high efficiency and much higher operating speed. In addition, they have 20% efficiency for thermal neutron detection and low sensitivity to a single relativistic charged particle due to a very low thickness of the scintillator ($\sim$ 30 mg/cm^2), This is their undoubted advantage over lithium glass or plastic scintillators with boron (lithium) additives and this allows one to use them in counting regime to study variations of low intensity neutron background [6], [7]. In EAS study the detector can be used as the main EAS array detector capable to record two shower components: hadronic one, through thermal neutron captures by ^{6}Li and electronic one starting from a threshold of $\sim$5 particles per the detector when summarized signal becomes high enough to be measured (that is why we called it *en-detector*). Note that the fastest scintillator component time is of $\approx$40 nsec. It means that signals coinciding in this time (just the EAS case) are summarized and pulse height is proportional to the number of particles passing through the detector. This also means that such detectors equipped with constant fraction discriminators can even be used for timing.

III. MEASUREMENTS AND SIMULATIONS

The en-detector was installed in the center of the Muon Detector (MD) tunnel under the soil absorber of 500 g/cm^2 at Baksan Neutrino Observatory of INR RAS at altitude of 1700 m a. s. l. The tunnel has the following size: 45$\times$5$\times$2.5 m^3. 175 plastic scintillator muon detectors are situated on the tunnel ceiling covering a continuous area of 175 m^2 and can measure energy deposit in a range of $\approx$0.5$\div$200 relativistic particles. In addition to this standard information acquired by the MD, we triggered the en-detector by the EAS trigger produced by Carpet-2 array. The trigger opens 5-ms time gate when delayed pulses from thermalized neutrons are counted and stored, thus giving us the number of neutrons captured in the detector. An example of the MD event with high neutron multiplicity (n=37) recorded in the neutron counter is shown in Fig. 1 (upper panel). The picture represents a particle density map as measured by the MD muon detectors in ADC logarithmic units (d=0.5$\times$1.1^m, where m is readings). Note that the readings more than 62 mean the ADC saturation. The MD detectors form 5 modules with 35 detectors each. One can see from Fig. 1 that EAS axis lies undoubtedly inside the central module where our en-detector is situated. Charged particles density in the module is as high as $>$200 m^{-2}. Remember that the detectors are situated under the absorber of 500 g/cm^2 or $\sim$ 20 radiation lengths. It is enough to absorb electromagnetic component but not enough for hadronic one. That means that power EAS hadronic core penetrated the tunnel and produced the event. Therefore, it is not surprising that so much neutrons were produced and recorded. We estimated the energy of this EAS as $E_0 \sim$ 10 PeV and the number of evaporation neutrons

a) Observed event

day=184 T= 16772402 M= 22 ev. #6705 Run 13 Mn= 37

32 29 31 50 44 40 52	31 64 55 53 67 69 64	64 64 64 64 63 63 63	63 64 64 63 63 64 64	59 63 57 49 35 48 48
0 33 59 42 60 45 63	38 61 64 64 57 64 64	64 64 64 63 63 63 64	64 63 63 61 57 55 54	57 43 52 44 47 45 33
25 37 45 45 34 53 41	41 64 65 64 69 64 33	64 64 48 64 63 63 63	63 64 64 56 63 64 61	63 49 55 63 59 64 31
20 36 39 40 90 52 58	46 41 68 53 48 65 64	64 64 64 64 63 63 63	63 64 64 63 63 64 60	64 60 57 54 50 59 39
32 34 24 40 46 39 43	52 37 58 47 75 47 60	46 64 64 64 63 63 63	62 64 64 63 55 62 54	57 24 60 54 55 47 48

b) Simulated event

/data/CORSIKA/p1516_1k7

1 N_EAS= 1 Ne= 22737335 Nd=395 LG=12 Nmu= 30 E0/1TeV= 7501.6528

MDg= 19217 Ak= 39 x0= 0.947517m y0= 0.4728842m Nhsoft= 60 Nhcore= 637 83

M= 15 TETA= 8.8212070 FI= -116.80841 Z= 2517574.5cm Part_type= 14 NhMD= 142

0 35 0 36 31 23 49	38 31 51 43 39 51 41	47 67 81 89 94108 97	85 74 76 58 55 51 63	62 37 41 24 29 36 28
0 45 29 31 29 43 30	38 31 48 58 48 47 72	65 73 78 85104141107	92 83 73 72 64 47 52	69 55 63 47 38 36 13
21 13 48 31 7 28 47	44 44 59 48 50 56 65	62 78 79 85 98110102	90 77 69 65 72 22 38	46 72 65 39 43 19 42
0 18 4 33 35 32 34	16 50 38 56 58 44 71	57 74 76 78 86 89 81	79 77 57 63 62 52 47	46 34 38 44 25 33 23
20 12 15 27 41 27 54	36 42 51 51 44 62 56	55 65 70 78 79 76 70	70 72 60 56 64 67 30	29 32 45 33 37 40 43

Fig. 1. An example of the event observed in MD with high neutron multiplicity recorded by the neutron counter and a 7.5-PeV proton event simulated with CORSIKA.

produced inside the MD tunnel as $N \sim 2\times10^5$. The latter agrees with the results of the CORSIKA (ver. 6.501) based Monte-Carlo simulations made taking the experimental details into account. In Fig. 1 (bottom panel) one can see the map of the simulated event along with input and output parameters shown above the map. Primary energy of the proton originated event was equal to 7.5 PeV. The EAS core position was close to the MD center and it is also shown by distances $x0$, $y0$ from the MD center. It is easy to see the similarity of the events with only one difference: ADCs in calculated event have no saturation and therefore, the shower axis is seen more clearly. It is known for simulated event that there were 637 high energy hadrons in the core (inside 1 m radius). Sure, the total number of hadrons in the tunnel exceeds significantly this number. We could estimate the total number of produced evaporation neutrons as follows. Let the number of hadrons reached the MD tunnel be equal to N_h =1000 and their mean energy is equal to $< E_h >\approx$100 GeV. Taking into account an empirical relation [2] between the number of evaporation neutrons produced in 100 g/cm^2 of soil and the hadron energy we obtain:

$n \sim N_h\times35< E_h/1\text{GeV}>^{0.56}= 4.6\times10^5$.

This value is more than 2 times higher than our estimation made for the observed event with the highest neutron multiplicity. But, if one takes into account that evaporation neutrons are emitted isotropically to 4π solid angle, that real EAS energy, primary mass and target thickness are unknown, than the agreement is more than reasonable.

IV. RESULTS

Preliminary results of the measurements with only one en-detector were obtain after half a year run of the array. These results are as follows: i) events with very high neutron multiplicity underground do exist; ii) there exists a simple possibility to make an “underground hadronic calorimeter”; iii) there exists a linear dependence between the number of recorded thermal neutrons and the number of high energy hadrons penetrating the underground cave under the shallow absorber. Point i) is illustrated by Fig.1. To confirm the ii) we could argue as follows: even with one en-detector of 0.375 m^2 area and neutron collection factor less than 1/1000, we obtained some results and recorded the event with 37 recorded neutrons in 5-ms time interval. In case of 175 en-detectors with total area of 175 m^2 one would expect the number of recorded neutrons $\sim$400 times higher and the rate of such events at least 5 times higher. Therefore, after 1 year running one would expect about 10 events with up to n=37$\times$400$\approx$15000 recorded neutrons. Note that dynamic range for neutron recording is very wide due to a rather long lifetime in the rock (or concrete) and slow movement of thermal neutrons. This means that usual EAS disc time width is expanded for thermal neutrons by a factor of $\sim$10^6 on the surface and of $\sim$10^5 in underground caves. Clear that in this case it’s not a problem to count all the neutrons without miscounts. To be sure that the number of recorded neutrons is proportional to the number of hadrons we have made the data analysis and plotted the results in Fig. 2. It is seen that the numbers of neutrons

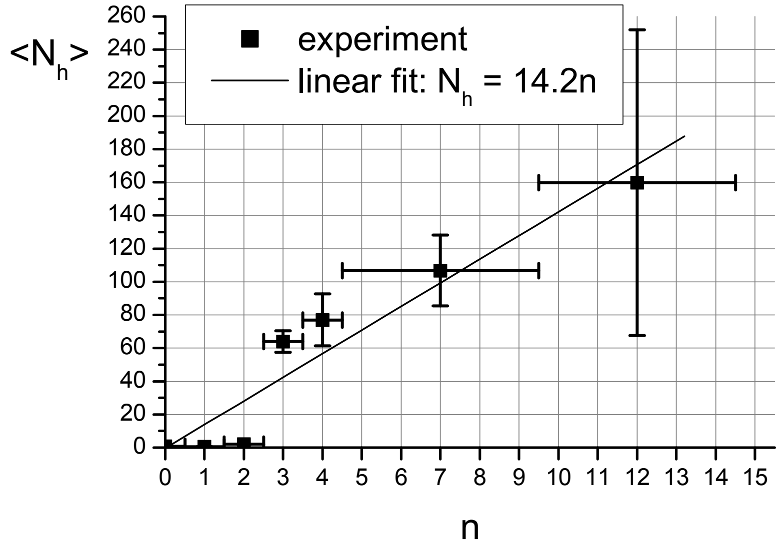

Fig. 2. Correlation between the number of thermal neutrons recorded by one en-detector and the number of hadrons in MD.

and hadrons in MD do correlate. Moreover, within the statistical errors this correlation can be expressed by a linear fit: $N_h \approx 14.2n$. Here N_h represents the number of hadrons recorded by the MD detectors using the method developed by us [9], [10]. Note that N_h is the number of hadrons of energy >30 GeV passed through the total MD area equal to 175 m^2, while n is the number of neutrons recorded by only one en-detector placed at its center. Even with such a difference in the detecting area, a probability to record 1 neutron after passage of 1 hadron is high enough and equal to 1/14.2≈7%. Therefore, in case of 14 en-detectors installed uniformly inside the MD tunnel we would record thermal neutrons accompanying hadron passage with 100% probability. In case of 175 en-detectors of 1 m^2 area, we would record >30 neutrons per 1 hadron. Therefore, statistics would be good enough to measure the number of hadrons with accuracy enough to distinguish one-hadron event from two-hadron event. We can add that due to low counting rate of the underground en-detector ($\approx$ 0.4 m^{-2}s^{-1}) a chance probability P to record a neutron by 175×1 m^2 area detectors within the 5-ms time gate is equal to $P \approx$ 0.4×175×0.005=0.35.

We have also to note that the efficiency to detect thermal neutrons in a cave (tunnel) depends on the cave size, surrounding material chemical composition etc. and all the details should be included to the Monte-Carlo simulations.

V. CONCLUSION

We have measured in the cave under 500 g/cm^2 absorber, the thermal neutron flux accompanying EAS core passage through the tunnel of our Muon detector. We thus proposed and first realized a novel method to study EAS properties by recording the "thermal neutron vapor" locally produced by high energy hadrons below a soil absorber. It is shown that the number of produced neutrons is high enough to be recorded even in case of only one passed hadrons with energy E>30 GeV if the total area of en-detectors is equal to or higher than about 100 m^2. It is also shown that the number of recorded neutrons within statistical errors is proportional to the number of passed hadrons. In our opinion, special scintillator detectors for thermal neutrons situated at shallow depth underground could be very useful in the study of such EAS properties as the full number of the core hadrons at observational level, primaries mass composition, core location, gamma-shower selection etc. The method will be used in the PRISMA project along with other innovations proposed there.

This work was supported by the RFBR grants No. 08-02-01208 and No. 07-02-00964 and by the Russian Academy of Sciences Basic Research Program "Neutrino Physics".

REFERENCES

[1] Yu.V. Stenkin, V.I. Volchenko et al. // Izvestia RAN, ser. Fizicheskaya. V. 71. No 4. (2007). P. 558.
[2] Yu.V. Stenkin, D.D. Dhappuev and J.F. Valdes-Galicia. // Phys. Atomic Nucl. (2007). v. 70, No. 6, p. 1088.
[3] Yuri V. Stenkin. /Thermal neutrons in EAS: a new dimension in EAS study. // ArXiv: hep-ex/0702048 (2007)
[4] Yuri V. Stenkin. /On the PRISMA Project. //ArXiv: 0902.0138v1 [astro-ph.IM]
[5] Yu.V. Stenkin, V.V. Alekseenko et al. // Bulletin of the Russian Ac. Sci.: Physics, (2009), Vol. 73, No. 5, p. 609.
[6] V.V. Alekseenko, D.D.Dhappuev et al. // Izvestia RAN, ser. Fizicheskaya, (2007). V. 71. No. 7, p. 1080.
[7] V.V. Alekseenko D.D. Dzhappuev et al.// Proc. 30th ICRC. Merida. (2007). P. 932.
[8] D.M. Gromushkin, V.V.Alekseenko, A.A. Petrukhin et al. //Izvestia RAN, ser. Fizicheskaya, V. 73, No. 3, (2009), p.426.
[9] D.D.Dzhappuev, A.U.Kudzhaev et al. // Proc. of 29th ICRC, Pune, (2005), v.6, p. 233.
[10] D.D. Dzhappuev, V.V. Alekseenko et al.// Proc. of 30th ICRC, Merida (2007), rep. 303.