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Performances of ENDA-INR prototype array

O Shchegolev, V Alekseenko, D Kuleshov, K Levochkin, Yu Stenkin and V Stepanov

Institute for Nuclear Research of Russian Academy of Sciences

E-mail: shchegolev@inr.ac.ru

Abstract. Electron Neutron Detector Array (ENDA) is an ambitious project inside the Large High Altitude Air Shower Observatory (LHAASO) in China, Tibet. ENDA is intended to measure simultaneously electronic and hadronic components of the extensive air showers (EAS) over large area of 10^4 m². The array will consist of 400 specially developed electron-neutron detectors based on inorganic $ZnS(Ag) + B_2O_3$ scintillator compound. The prototype ENDA cluster of 16 electron-neutron detectors has been build in Moscow in the Institute for Nuclear Research of Russian Academy of Sciences and named ENDA-INR. The main goal of the array is to test techniques of simultaneous measurement of extensive air showers and background variations using pulse shape selection. Details of the array and its techniques are presented.

1. Introduction

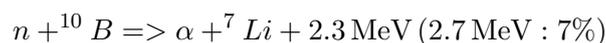
Cosmic rays are important messengers in the Universe giving us information about their acceleration and diffusion processes. The primary energies of cosmic rays go up to extremely high values of more than 10^{20} eV, far exceeding the values achievable with human made accelerators. The main goals of cosmic ray study are primary energy spectrum, mass composition and anisotropy. Unfortunately flux of cosmic rays with energies above 1 PeV is so small that we cannot measure it directly using satellite or balloon experiments. To record high energy cosmic rays the indirect method of extensive air showers (EAS) is used. Extensive air showers are studied for more than 70 years and many installations were build for that. But the main problems as mass composition and primary energy spectrum reconstruction are still unsolved and novel approaches are needed. Mostly EAS arrays record the electronic component of showers and primary energy reconstruction is based on EAS size N_e . But any single shower component is not sensitive to mass of primary particle [1, 2]. To do this some arrays record also muons and N_μ/N_e ratio is used for analysis. Another approach is to use Cherenkov light in atmosphere for both energy and mass reconstruction [3]. Our approach is to use hadronic and electronic components to estimate primary particle energy and atomic number [4]. Hadronic component is a “skeleton” of shower and provides information on it’s development. Using simulations, it was shown that some showers have no high energy hadronic core at observational level, we call them “coreless” [5]. After hadrons disappear from cascade process, electronic component attenuates as pure electromagnetic cascade differently to the case when hadronic and electromagnetic cascades are in equilibrium. Information about number of hadrons in observational level can improve energy reconstruction. Ratio of number of hadrons to number of electrons N_h/N_e (similarly to N_μ/N_e) is sensitive to primary mass. But it is difficult and expensive to measure hadron number using hadronic calorimeter of large area, this is why a novel method has been developed. High



energy hadrons of the shower hit the ground at observational level and produce evaporational neutrons. After thermalization some neutrons escape from soil and could be recorded by special detectors. Number of thermal neutrons is proportional to number of EAS hadrons and could be used to estimate it. Fine and not expensive solution was found to measure both electrons and thermal neutrons simultaneously by the same detectors using inorganic scintillator $ZnS(Ag) + B_2O_3$ compound. Electrons passing through it produce light and give coincidental pulses from several detectors inside $1 \mu s$. Neutrons live about 1 ms in soil and tens of ms in air and they need time after production for thermalization, this is why we record them in time window from $100 \mu s$ up to 20 ms after EAS passage.

2. Electron-neutron detector and front-end electronics

The detector consists of scintillator layer, reflecting cone, photomultiplier (PMT) and plastic tank as a housing. Detector effective area is 0.35 m^2 . Scintillator is based on natural boron that includes $\approx 19\%$ of ^{10}B . Average thickness of the compound layer is 50 mg/cm^2 and thermal neutron capture efficiency is about 20%. $ZnS(Ag)$ is a well known scintillator very good for heavy particles detecting due to high α/e ratio and linearity. Neutrons are recorded through the (n, α) reaction on ^{10}B :



Nuclei produced in the reaction are heavy and slow that's why they excite slow time components of $ZnS(Ag)$ while light relativistic charged particles excite mainly fast components. It gives long pulse rising front for neutron pulses against short one for relativistic charged particles. Due to small thickness signal from a single relativistic charged particle is below the threshold, so only at least three particles simultaneously passing scintillator could be recorded by the detector. Details on the detector design could be found elsewhere [6, 7]. PMT is 4" CR-165 produced by Beijing Hamamatsu. Signals are taken from last and intermediate dynodes to expand the dynamic range. Pulses come to preamplifier and integrated with time constant of $1 \mu s$.

3. Array layout and back-end electronics

Array is located in Moscow outdoor in INR RAS. Detectors are put in additional metal housing protecting them from rain and snow. Array has a shape of a square of $15 \times 15 \text{ m}^2$ with 5 m step between detectors. In the center of array there is a metal electronic box with warming and cooling containing flash analog-to-digital converter (FADC), high voltage power supply (HV), low voltage power supply (LV) and personal computer (PC). Cables between detectors and electronic box are put in metal hoses. PC is connected to internet for monitoring and data transferring. FADC is 32-channel DT5740D produced by CAEN. Digitization step is 16 ns, pulse timestamp precision is 8 ns, pulse digitization time is $2 \mu s$ (128 steps of 16 ns) and memory buffer is capable to store up to 1024 pulses per channel recording them without dead time. The layout of data acquisition system is shown in figure 1.

4. Pulse processing algorithm

FADC records each pulse above the threshold and sends it to PC. Online software checks if there is a coincidence between 2 or more detectors and if so opens time window of 20 ms for collecting delayed neutrons. If pulse does not coincide with another one and has a timestamp out of last 20 ms window it is judged as background. Each EAS event is written to file with amplitude of first pulse (for two dynodes) and number of delayed neutrons for each detector. Background pulses are collected and written to file every minute. Each non-coincidental signal is checked to be produced by neutron capture or by multiple passage of relativistic charged particles (such pulses we name "charged") using width of rising time front. If it's width is less than $0.2 \mu s$ it is

considered to be “charged” otherwise it is neutron (see figure 3). Flowchart of the algorithm is shown in figure 2. Counting rate of whole array is about 200 Hz.

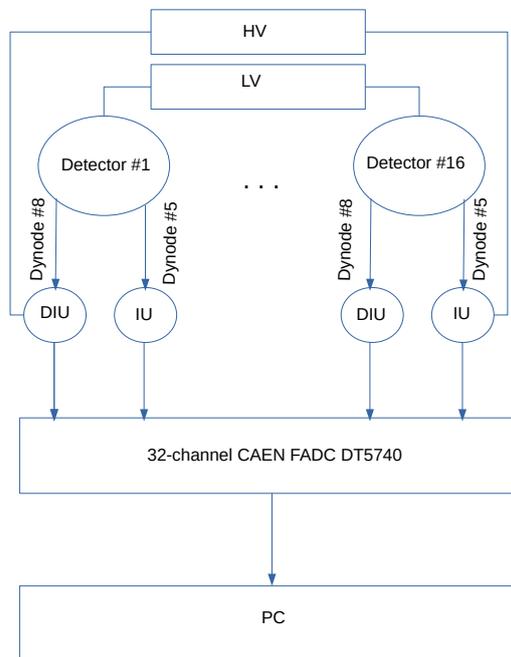


Figure 1. Data acquisition layout.

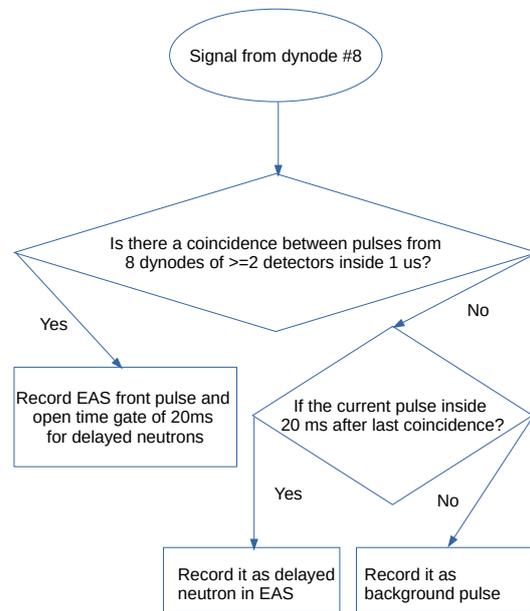


Figure 2. Pulse processing algorithm flowchart.

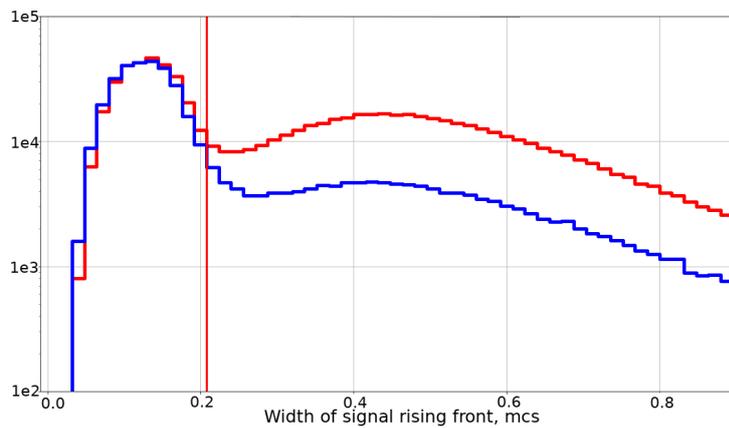


Figure 3. Rising front width distribution of pulses. Pulses to the right from red line are mostly neutrons, while pulses to the left are mostly produced by simultaneous transition of several relativistic light charged particles.

Pulse shape selection efficiency was tested using radioactive sources: ^{252}Cf , producing neutrons and ^{232}Th , that has products giving multiple gamma. Neutron source was put under the detector center with 6 cm layer of paraffin above. Thorium also was put under detector center. Results of the test are presented in figures 4, 5. On the left side effect of Cf addition is clearly visible in neutron counting rate (97% of additional pulses were judged as neutrons) and on the right side addition of thorium effected only to counting rate of “charged” (about 100%). From that we can conclude that pulse shape selection algorithm based on rising front width is effective. Using that, the background of pulses in the time window after EAS front was decreased by a factor of 3.

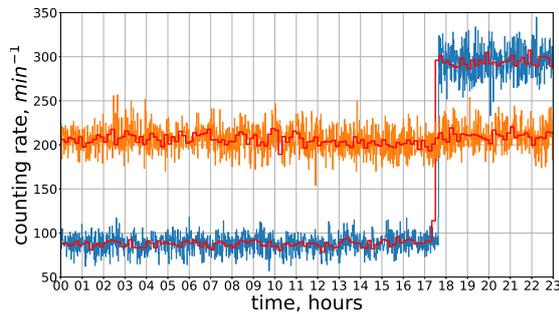


Figure 4. Counting rate of one en-detector. Blue line: neutrons, orange line: “charged”. Rising of neutrons counting rate corresponds to adding ^{252}Cf .

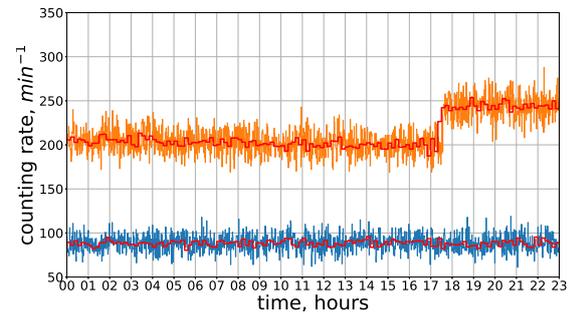


Figure 5. Counting rate of one en-detector. Blue line: neutrons, orange line: “charged”. Rising of “charged” counting rate corresponds to adding ^{232}Th .

5. EAS and background variations recording

Previously in prototypes of electron-neutron detector arrays [6, 7] we used additional electronic circuit for coincidence selection and used its pulse as a trigger for digitizing of 20 ms with a step of 1 μs . That approach had some disadvantages: additional device was needed, pulse shape selection had bad efficiency due to rough step of digitization, variations recording was realized using admixture of each 256 pulse for triggering [7].

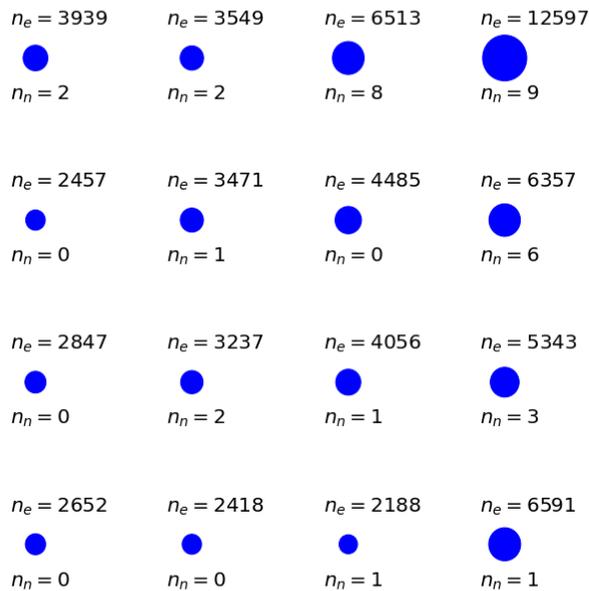


Figure 6. Recorded event with 36 neutrons, 05/07/2020. Number of electrons recorded in each detector is shown above the corresponding circle and number of neutrons below is shown below it.

Now, using the novel technique we can measure EAS and neutron background variations simultaneously. In that case 16 detectors can serve as a big neutron monitor. Moreover it records not only neutron background variations but also variations of some radioactive nuclides concentration in air (^{214}Bi and ^{214}Pb) [8]. These variations are of great interest for us as they are products of ^{222}Rn decays and are sensitive to geophysical processes, for example earthquakes [9]. Construction of a full-scale array of 400 en-detectors in Tibet near the seismic regions is very promising from this point of view. Example of a big event recorded with ENDA-INR is shown in figure 6.

6. Conclusions

The novel type array prototype of 16 en-detectors has been installed in INR RAS in Moscow. Novel approach to pulse processing was developed and simultaneous measurement of extensive air showers and background variations was realized. Pulse shape selection has been checked with neutron and gamma radioactive sources and showed good pulse separation.

Acknowledgments

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