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Progress of ENDA and Hybrid Detection of Cosmic Ray by Using ENDA and LHAASO

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By accurate measurement of composition and energy spectrum in the knee region, problem of origin of galactic cosmic ray can be solved. Hadrons are the “skeleton” of extensive air shower (EAS) and possess favorable information concerning the cosmic ray composition and energy. The electron-neutron detector (EN-detector) can detect both EAS electrons and thermal neutrons generated by EAS hadrons in surrounding matter. The electron-neutron detector array (ENDA) was proposed to be added into Large High Altitude Air Shower Observatory (LHAASO) to improve its capability of EAS hybrid detection. One cluster (16 detectors) of ENDA, so called "ENDA-16" has been operated at LHAASO (4410 m a.s.l.) for three years. In spring of this year (2023), ENDA was extended to 64 EN-detectors, so called "ENDA-64". In this report, we will describe installation and running status of ENDA-64 and present results of hybrid detection of cosmic ray by using ENDA and LHAASO.

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Contents

1. Introduction

High energy hadrons which constitute extensive air shower (EAS) "skeleton" carry important information for multi-parameter correlation studies of composition and energy of cosmic ray. Thermal neutrons are generated abundantly from EAS hadrons on the ground, up to 2 orders of magnitude more than parent hadrons [?][?][?]. The PRISMA project (Primary Spectrum Measurement Array) led to design of the electron and thermal neutron detector (EN-detector) to measure both thermal neutrons and charged particles [?][?][?]. In order to check the performance of the EN-detector at a high-altitude site, a small array called as PRISMA-YBJ composed of four EN-detectors was installed inside the hall hosting the ARGO-YBJ experiment[?] at the Yangbajing (YBJ, 4300 m a.s.l.) Cosmic Ray Observatory, Tibet, China. The correlation of data between PRISMA-YBJ and ARGO-YBJ confirms the excellent performance of the EN-detector [?]. Besides, it was indicated that the EN-detectors can be used to monitor seismic activity [?][?]. After PRISMA-YBJ, a new type EN-detectors replacing neutron capture isotope ^{6}Li by ^{10}B was developed, and two arrays of 16 new type EN-detectors each were built: PRISMA-YBJ-16 [?][?] at YBJ, and ENDA-16 [?] at Large High Altitude Air Shower Observatory (LHAASO) [?], Haizishan (HZS, 4410 m a.s.l.), Daocheng, Sichuan, China. In this report, we describe the previous results at the different locations, deployment of ENDA-64 and coincident events between LHAASO and ENDA-64.

2. Experimental Set-up

LHAASO [?] is located at Mt. Haizi (4410 m a.s.l., 600 g/cm^2, 29° 21' 27.56" N, 100° 08' 19.66" E) in Daocheng, Sichuan province, P.R. China. LHAASO consists of 1.3 km^2 array (KM2A) of electromagnetic particle detectors (ED) and muon detectors (MD), a water Cherenkov detector array (WCDA) with a total active area of 78,000 m^2, an array of 18 wide field-of-view air Cherenkov telescopes (WFCTA) and ENDA is located in southwest direction inside LHAASO (Fig. ??). The detectors are synchronized with all the other through a clock synchronization network based on the White Rabbit protocol. The observatory includes an IT center which comprises the data acquisition system and trigger system, the data analysis facility, and the high altitude infrastructure.

EN-detector includes a round sheet scintillator of 0.35 m^2 with effective thickness of 50 mg/cm^2, which is made of an alloyed mixture of inorganic scintillator ZnS(Ag) with B_2O_3. The scintillator is mounted inside a black cylindrical polyethylene (PE) 200 litres tank which is used as the detector housing. A 4-inch diameter photomultiplier tube (PMT) (made by Hamamatsu in Beijing, model CR-165) is mounted 31 cm directly above the scintillator. An EVA reflective cone

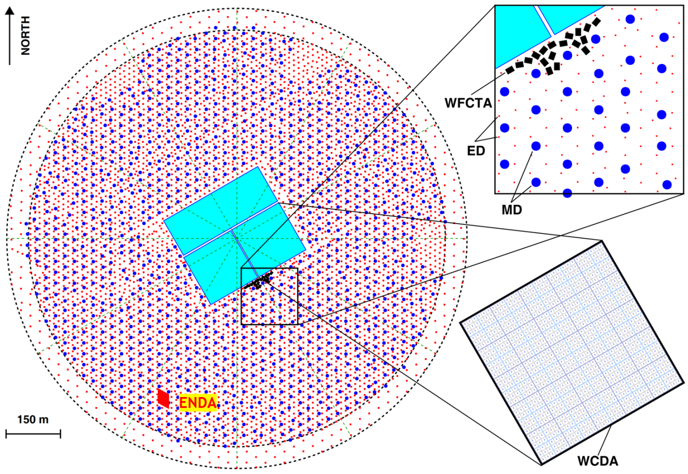

Figure 1: Layout of the LHAASO experiment including ENDA-64.

Figure 2: Photo of ENDA-64 in a bird view.

layer with thickness of 5 mm connects the scintillator and the PMT. Released photons from the scintillator are collected by the reflecting layer and arrive at the photocathode of PMT. Thermal neutron collection efficiency for the whole detection process is 20%. The EN-detector signals can be divided into two types: weak and fast signals from charged particles mainly including electrons and positrons, and high, slow and delayed signals from thermal neutron capture. Large number of charged particles in thin EAS front plane first pass through the detector, generating a large pulse to trigger the array, and then signals are successively generated by thermal neutrons within about 20 ms. In consequence, EN-detector can record pulses of both thermal neutrons from hadrons and charged particles (electromagnetic content) of EAS.

16 EN-detectors are arranged as a cluster in form of a 4×4 equilateral triangle grid, and the distance between adjacent detectors is 4.5 m[**?**]. Data acquisition system (DAQ) of each cluster consists of 32-channel flash analog-to-digital converter (FADC) connected to a PC via the White Rabbit clock system of LHAASO. The first 16 channels of FADC are used for the 8th dynodes and other 16 for the 5th dynodes. The first pulse produced mostly by EAS charged particles is used for trigger and energy deposit measurements, and delayed neutron capture pulses are counted within a time gate of 20 ms to give the number of thermal neutrons. One cluster works in two modes: the trigger mode [**?**] and the single particle mode which monitors single thermal neutron counting

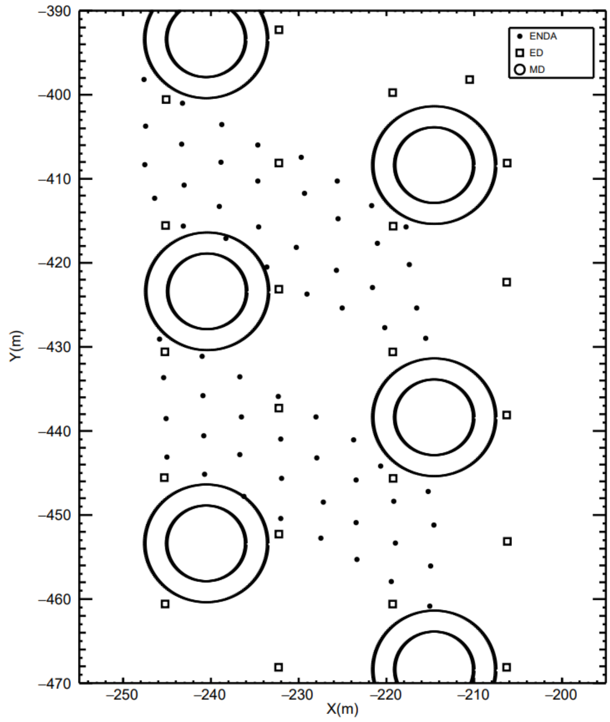

Figure 3: Schema of ENDA-64. The solid circles are EN-detectors. The open squares are EDs. The open circles are MDs. X and Y are the coordinates in the LHAASO coordination system.

rate (/min). In March 2023, PRISMA-YBj-16 and another two clusters were moved to LHAASO to extend ENDA-16 to ENDA-64. ENDA-64 consists of 4 clusters installed among EDs and MDs so that they can detect one same EAS simultaneously (Fig. **??** and **??**).

3. Results

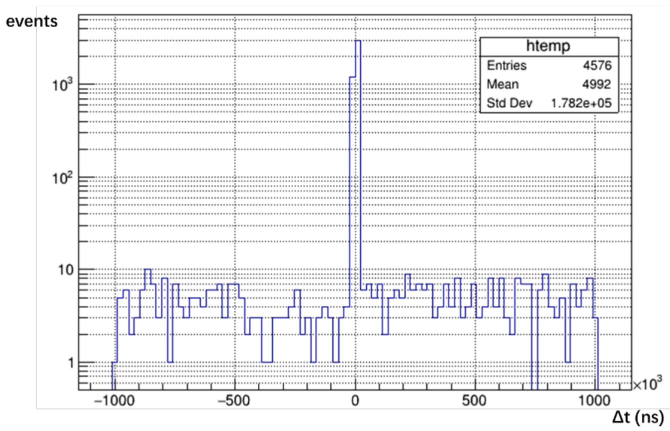

Figure 4: Time difference distribution between ENDA and KM2A.

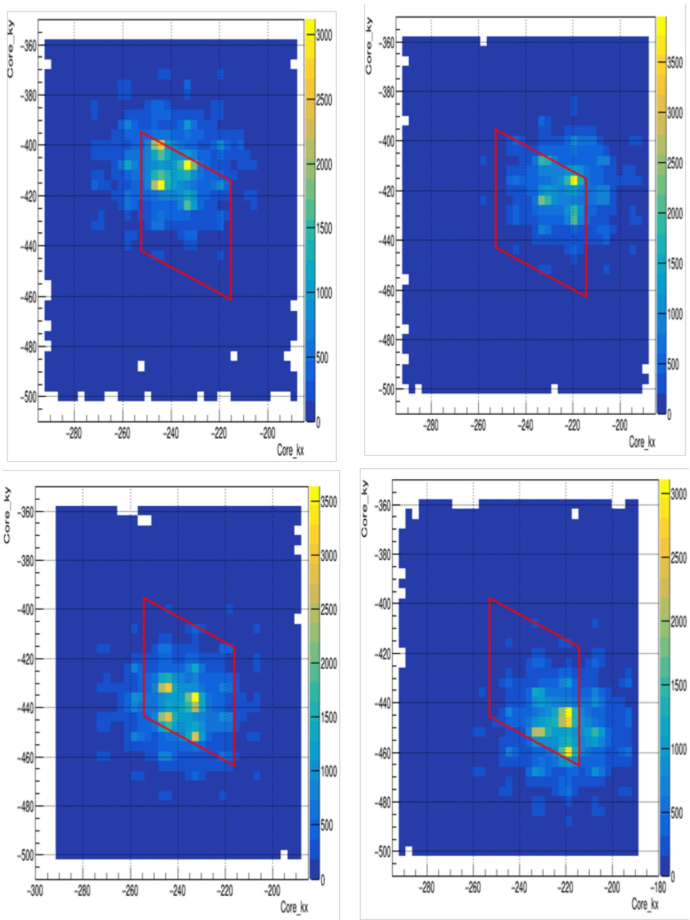

Figure 5: Core position distribution of coincident events between each cluster of ENDA-64 and KM2A. Time selection window is ± 10 μs. The red lozenge is the domain of ENDA-64.

We did several tests to study performance of the array and influence of environment. At PRISMA-YBJ-16, It was found that the yield of thermal neutrons from the soil depends on the water content in the environment. The drier the weather, the higher the efficiency of thermal-neutron detection. The seasonal effect is of about 10%[**?**], so influence of water in soil on thermal neutron detection should be taken into account in systematic uncertainty of spectrum measurement. For quantitative evaluation of influence of soil moisture on thermal neutrons, at the center of ENDA-16, five soil moisture meters were installed at different depth of soil to record soil moisture. Negative correlation between thermal neutron counting rate and soil moisture was obtained. Moreover, it is demonstrated that a soil depth 0.5 m over the soil moisture sensor is enough for monitoring negative correlation between thermal neutron counting rate and soil moisture. Furthermore, It provides us a method to correct the experimental data during the rainy season so as to reduce systematic uncertainty of thermal neutron measurement in the ENDA experiment [**?**].

Meanwhile, so-called "sand cubes" were installed at PRISMA-YBJ-16, to study the influence of the target material, which is a major environmental factor, on the performance of the array . It was indicated that even though the target materials have somewhat different compositions, changing target material by using sand cubes has only a small effect on detection efficiency. Moreover, for the array, due to reduction of target material, the sand cubes cause a reduction in thermal neutrons in EAS events, mostly due to geometrical factor while affect of soil chemical composition is not significant [**?**].

At the first running, ENDA-64 obtained EAS events coincident with LHAASO-KM2A. Event selection is only that the EAS core location of KM2A is inside x ∈ (-290 m, -190 m) y ∈ (-500 m, -360 m). the distribution of time difference (Δt) between one cluster of ENDA-64 and LHAASO-KM2A coincidence events (Fig. **??**) shows that time deviation of ENDA from KM2A is ±6 μs. The location shower core (from KM2A) distribution of the coincident events within Δt < 10 μs between each cluster of ENDA and KM2A are reasonably accumulated around the center of the cluster.

4. Summary

Up to now, ENDA has totally 64 detectors at LHAASO, running stably. Data analysis and simulation are worked on continuously. ENDA-64 has an effective area of 1,000 m^2 so as to in one or two years obtain high statistics of data for studying energy spectrum of light components (H and He) [**?**][**?**]. After it, ENDA will be extended to 400 detectors with array area of 10000 m^2 to study energy spectrum of heavy components such as Fe. During the hybrid EAS detection with all parts of LHAASO, ENDA will provide recording of thermal neutrons from charged hadrons (e.g. π^+ and π^-) and electrons near the EAS core, KM2A and WCDA will detect electrons and muons, WCDA will also detect γ family from neutral hadrons (e.g. π^0), and WFCTA will detect Cherenkov light. Consequently, LHAASO will perform a detection of full secondary particles of EAS. Participation of ENDA-400 will enable estimate of hadron content in EAS thus estimating primary particle mass [**?**], strengthening capability of LHAASO to adequately determine the energy and nature of high energy cosmic rays to solve the knee problem.

5. Acknowledgments

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