Calibration and performance of the neutron detector onboard of the DAMPE mission

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Abstract The DArk Matter Particle Explorer (DAMPE), one of the four space-based scientific mission- s within the framework of the Strategic Pioneer Program on Space Science of the Chinese Academy of Sciences, was successfully launched on 2015 Dec. 17 from Jiuquan launch center. One of the most important scientific goals of DAMPE is to search for evidence of dark matter indirectly by measuring the spectrum of high energy cosmic-ray electrons. The neutron detector, one of the four sub-payloads of DAMPE, is designed to distinguish high energy electrons from hadron background by measuring the secondary neutrons produced in the shower. In this paper, a comprehensive introduction of the neutron detector is presented, including the design, calibration and performance. The analysis with simulated data and flight data indicates a powerful proton rejection capability of the neutron detector, which plays an essential role for TeV electron identification of DAMPE.

Key words: neutron detector — particle identification — calibration — simulation

1 INTRODUCTION

Over the past few years, a few balloon-borne and space- borne experiments have published exciting results about indirect dark matter detection by measuring the spectra of cosmic-ray electrons and positrons (Chang et al. 2008; Adriani et al. 2011; Aguilar et al. 2014). The DArk Matter Particle Explorer (DAMPE), a satellite-borne high energ y particle detector supported by the strategic priority science and technology projects in space science of the Chinese Academy of Science (Chang 2014), was successfully launched into a Sun-synchronous orbit at the altitude of 500 km on 2015 Dec. 17 from Jiuquan launch center (Chang et al. 2017). With an unprecedented energy resolution of 1.5% at 800 GeV (Zhang et al. 2016), DAMPE offers an excellent potential for dark matter indirect detection by measuring electrons and gamma-rays in a large energy range from 5 GeV to 10 TeV (DAMPE Collaboration et al. 2017; Yuan & Feng 2018; Pan et al. 2018). Apart from indirect dark matter detection, DAMPE also provides a new opportunity for advancing our knowledge on cosmic ray physics (An et al. 2019; Yue et al. 2019) and gamma-ray astronomy (Xu et al. 2018).

The scientific payload of DAMPE, from top to bottom, consists of four sub-detectors including a Plastic Scintillator strip Detector (PSD) (Yu et al. 2017; Ding et al. 2019), a Silicon-Tungsten tracKer-converter (STK) (Azzarello et al. 2016), a Bismuth-Germanium Oxide (BGO) imaging Energy CALorimeter (ECAL) (Zhang et al. 2012) and a NeUtron Detector (NUD) (He et al. 2016). The layout of DAMPE payload is illustrated in Figure 1. The PSD is utilized to measure particle charge up to Z = 28 (Dong et al. 2019) and identify gamma-rays from charged particles; The STK is utilized to measure the charges and trajectories of incident particles and reconstruct the directions of incident photons converting into e^+ + e^- pairs; The BGO-ECAL is used to measure the energy deposit of incident particles and provide the electron/proton (e/p) separation based on the shower morphology; The NUD is applied to improve the e/p sepa-
ration power by detecting neutrons generated by the shower in BGO-ECAL. The hadronic shower would produce a large number of secondary neutrons through the interaction of hadrons (mainly protons) with the detector material. By detecting secondary neutrons, NUD provides a powerful capability to distinguish electromagnetic showers from hadronic ones, especially in the high energy range above TeV. However, primarily due to the imperfection of NUD simulation at that moment, the signals of NUD were not considered in the electron spectrum analysis published in 2017 (DAMPE Collaboration et al. 2017). In this paper, a comprehensive overview of the NUD is presented, including the design, calibration and performance in orbit.

2 DESIGN OF THE NUD

2.1 Principle

The BGO-ECAL can effectively separate the electromagnetic shower induced by an electron and the hadronic shower induced by a proton by imaging the shower morphology. However, with the increase of energy, the performance of the BGO-ECAL alone is insufficient for satisfying the proton rejection requirement. In this case, an NUD is designed to provide additional e/p separation power in the high energy range. The purpose of NUD is to further distinguish electrons from protons by detecting secondary neutrons from the hadronic shower in the BGO-ECAL. In fact, for a given initial particle of the same energy, the neutron content of a hadronic shower is expected to be one order of magnitude larger than that of an electromagnetic shower. Once the neutrons are created, they are quickly thermalized in the BGO-ECAL, and the total neutron activity over a few microseconds is measured by NUD (Chang et al. 2017).

The NUD is composed of four identical 30 cm × 30 cm × 1.0 cm blocks of boron-loaded plastic scintillators (Eljen Technologies EJ-254). EJ-254 is a blue-emitting plastic scintillator that contains natural boron at concentrations up to 5% by weight. Its principal applications are fast neutron spectrometry and thermal neutron detection, and the primary function of the boron is to provide a unique scintillation signal for low energy neutrons. The secondary neutrons produced in the BGO-ECAL will be moderated through elastic collision with hydrogen atoms in the detector material. With a rapid energy decay through the moderation process, some neutrons are moderated into the thermal energy range, then the thermal neutrons can be captured by $^{10}$B atoms with the nuclear reaction: $n + ^{10}$B $\rightarrow ^{7}$Li $+ \alpha + \gamma$. The $\alpha$ particles produced by the nuclear reaction will deposit energy through ionization, and generate fluorescent photons in the plastic scintillator. These fluorescent photons are then collected by the photomultiplier (PMT) and converted into electronic signals. To eliminate the ionization signals from the secondary charged particles within $\sim 2 \mu s$ after the shower development, we set a time-delay gate of 2.5 $\mu s$ after the event trigger in orbit (Ambrosi et al. 2019). We thus record only the signals mainly coming from secondary neutrons.

2.2 Requirements

To achieve good performance for detection, the NUD requires a high dynamic range of 2 MeV to 60 MeV, an energy resolution better than 25%@30 MeV and a uniformity of each detection unit less than 25%. As a space device, there are some other constraints on the design of NUD: the effective area of the NUD should cover 600 × 600 mm$^2$, which is the active area of the BGO-ECAL; the envelope size of the NUD should be less than 700 × 700 mm$^2$; the total weight should be less than 12.5 kg. The whole system of the NUD must maintain a high level of performance and stability in the harsh space environment throughout its lifecycle. The mechanical design and thermal design ensure the NUD can survive the vibrations, shocks, accelerations and impact tests during launch.

2.3 Electronic Design

The readout electronics of the NUD consist of four signal channels provided in one data processing board. Each channel contains a fast pre-amplifier, a gating circuit (GC), a shaping circuit (SC) and a main amplifier with peak hold-
ing chip (PHC). Figure 2 depicts the overall circuit diagram. The GC and PHC are controlled by the data control unit of the DAMPE satellite. The GC is designed to prevent any early signal entering the SC, and is switched-on 1.6 $\mu$s after the triggering signal produced by BGO. Then the delayed neutron signal could be shaped and amplified by the PHC. After the analog-to-digital converter (ADC) finishes acquisition of all four signals, a release signal will be sent to the PHC and GC to shut off the signal channel and wait for the next trigger (Chang et al. 2017).

A delay time of 2.5 $\mu$s after the trigger could basically prevent the ionization signals from secondary charged particles, as the shower development would typically finish within 1 $\mu$s. Afterward, the analog switch will turn on and the signals from PMT will be sent to the shaping circuit and the amplifier. At the same time, the peak detection circuit will start working and catch the maximum signal voltage from the amplifier. After 10 $\mu$s, the peak detection circuit will close the gate and hold signals, waiting for the acquisition unit of the NUD in the data processing module to sample and digitalize. The results will be packaged and stored in the satellite to finish the whole acquisition procedure. Then the analog switch will be closed and the peak detection circuit will be discharged to wait for a new trigger for the next acquisition.

2.4 Structural Design

![Fig. 3 The structure composition of NUD.](image)

Four EJ-254 scintillators with size of 300 mm $\times$ 300 mm $\times$ 10 mm are selected for the NUD. The upper and lower sides of the EJ-254 are embedded with wavelength shift fibers for optical transmission in order to reduce the fluorescence attenuation and increase photon collection efficiency. Each EJ-254 is wrapped with a lay-
er of aluminum film for photon reflection and a layer of black tape on the outside, anchored in an aluminum alloy framework by silicone rubber, and readout by a PMT (Hamamatsu R5610A-01). The PMT is a 0.75 inch diameter head-on 10-dynode PMT with a maximum gain of $2 \times 10^6$, and a spectral response ranging from 300 nm to 650 nm, which is a good match to EJ-254’s 425 nm maximum emission wavelength. The space between each EJ-254 and aluminum alloy framework is 1 mm on each side, and is filled with silicone rubber to dampen vibration during launch (Chang et al. 2017). The supporting structure is an aluminum alloy shell. The envelope size of the NUD is $699 \text{ mm} \times 699 \text{ mm} \times 44 \text{ mm}^3$ and the weight is 12 kg. Figure 3 illustrates the overall structure of NUD, which is fixed to the satellite with 41 M4 screws.

3 GROUND CALIBRATIONS

The dynamic range, energy resolution, difference in sensitivity of each detection unit and light attenuation characteristics of different hit positions of the NUD need to be calibrated on the ground. In the calibration scheme, we rely on muons as a source for performance tests. The deposition energy of muons in the NUD is the minimum ionization energy loss. Figure 4 plots the energy deposition spectrum in the NUD, and its peak position corresponds to 1.83 MeV.

Fig. 4 Simulation of energy deposition of muons in NUD.

In the calibration experiment, we use muons as a source to carry out the calibration and implement two bigger identical plastic scintillator detectors as coincidence detectors. The detection area of plastic scintillator detector covers the area of the NUD. Two plastic scintillator detectors are located above and below the NUD, and Figure 5 features the schematic diagram of our calibration test.

When the two plastic scintillators have hit signals at the same time, they will generate hit signals through logical AND and the NUD starts to measure the energy deposition of the muon in the NUD. By collecting the energy deposition spectrum for a long time, the deposition energy spectrum of muons in the NUD can be obtained. In practice, the output signal of the plastic scintillator is sent to the discriminator, the threshold value is set for the discriminator to filter out the interference of the electronic noise and the trigger signal will be generated by logical operation of the signal from the discriminator. Then the counter records the effective trigger times, while the energy spectrum of muons in NUD will be collected.

The energy resolutions of four detection units are calibrated as 24.95%, 21.24%, 23.71% and 23.61% at 30 MeV, for units I, II, III and IV, respectively, as demonstrated in Figure 6. The energy resolutions of the four detection units can meet the requirement of less than 25% well. Under the 840 V high voltage power supply, the dynamic range of the NUD is measured as shown in Table 1. The dynamic range of the detector can fully meet the detection requirements.

To calibrate the hit output performance of the NUD, we use two smaller coincidence detectors placed in the central area of the NUD. The position relationship between the NUD and the small coincidence detectors 1 and 2 is diagrammed in Figure 8.

The detection efficiency of the central area is the ratio of the acquisition energy spectrum count and the trigger count. The four channels of the NUD follow the above steps to acquire and count for 3600 seconds. The results are listed in Table 3. Table 3 demonstrates that the detection efficiency of the four detection units is higher than 96%. There are differences in energy resolution, dynamic range and muon detection efficiency for the four detection units in the NUD. The differences are mainly caused by
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Fig. 6 Energy resolutions of four detector units.

Table 1 Differences among the Four Channels

| Project   | Detection unit I | Detection unit II | Detection unit III | Detection unit IV | Maximum relative error |
|-----------|------------------|-------------------|--------------------|-------------------|------------------------|
| Energy resolution | 24.95% | 21.24% | 23.71% | 23.61% | 14.87% |
| Dynamic range | 0.31–60.94 MeV | 0.34–67.58 MeV | 0.38–73.92 MeV | 0.31–60.5 MeV | 18.15% |
| Detection efficiency | 97.78% | 99.06% | 100% | 98.8% | 2.22% |

Table 2 Detection Efficiency of Central Area

| Detection unit | Time (s) | Trigger count | Detection count | Trigger frequency (counts min⁻¹) | Detection efficiency |
|----------------|----------|---------------|-----------------|----------------------------------|----------------------|
| Unit I         | 3600     | 90            | 88              | 1.30                             | 97.78%               |
| Unit II        | 3600     | 107           | 106             | 1.78                             | 99.06%               |
| Unit III       | 3600     | 85            | 85              | 1.41                             | 100%                 |
| Unit IV        | 3600     | 83            | 82              | 1.38                             | 98.80%               |

encapsulation, detection materials and other factors. Such differences among the four detection units are inevitable. We compare the energy spectrum of the four detection units, and use the relative error to quantitatively describe their differences through their energy resolution, energy dynamic range and muon detection efficiency, as shown in Table 1. Even though there are small differences among the four channels, it will not affect the normal operation of the NUD.

4 ON-ORBIT PERFORMANCE

To carefully estimate the performance of the DAMPE detector, including NUD, we have developed extensive Monte Carlo (MC) simulation software based upon the lat-
Fig. 7 Dynamic range of four detector units

Fig. 8 Schematic diagram of test scheme.

est GEANT4 toolkit (Allison et al. 2016). The hadronic interaction model FTFP\_BERT\_HP, which includes highly-precise neutron cross-section data, has been chosen for high energy proton and electron simulations. A digitiza-
The rejection power of NUD for energy deposit between 1 TeV and 5 TeV.

The $\text{\(\zeta\)}$ distributions for on-orbit events with energy deposit from 1 TeV to 5 TeV before (left) and after (right) NUD selection. The black points represent the flight data. For MC simulated data, the blue, green and red histograms signify the protons, electrons and their sum, respectively.

To validate the MC simulation, we select high energy protons and electrons from flight data based on the preselection criteria applied in DAMPE proton spectral analysis (An et al. 2019). Figure 9 depicts comparisons of the energy signal in NUD between flight data and MC simulated data, for protons and electrons with energy deposit in the BGO-ECAL between 1 TeV and 5 TeV. The NUD signals of protons display a dramatic difference with the ones of electrons, which suggests that NUD has good capability for e/p discrimination. The good agreement between flight data and simulated data indicates that the MC simulation is reliable for further study.

The e/p discrimination capability of NUD is studied with the simulated protons and electrons. To characterize the e/p discrimination power, we define electron efficiency and proton rejection as follows

$$
\text{Eff}_e = \frac{N_{e_{\text{sel}}}}{N_{e_{\text{acc}}}}; \quad \text{Rej}_p = \frac{N_{p_{\text{acc}}}}{N_{p_{\text{sel}}}}
$$

where $N_{e_{\text{acc}}}$ and $N_{e_{\text{sel}}}$ represent the number of accepted electrons and number of electrons selected by NUD respectively, $N_{p_{\text{acc}}}$ and $N_{p_{\text{sel}}}$ signify the number of accepted protons and the number of protons mistaken as electrons by NUD respectively. Figure 10 plots the relationship between electron efficiency and proton rejection. When the
electron efficiency is 95%, the proton rejection power is \( \sim 25 \), which indicates that the NUD can distinguish electrons and protons effectively under a satisfying electron acceptability.

With the help of shower development information in BGO-ECAL, we can further study e/p discrimination capability of NUD with on-orbit flight data. Applying only the calorimeter-based electron analysis, a dimensionless variable, \( \zeta \), is defined to evaluate the e/p discrimination capability of BGO-ECAL (DAMPE Collaboration et al. 2017). The e/p discrimination capability of NUD is evaluated by comparing the residual proton contamination in electron candidates before and after applying the NUD selection of \( \text{Eff}_{e} = 95\% \). The \( \zeta \) distributions for on-orbit events with energy deposit in the BGO-ECAL from 1 TeV to 5 TeV before (left) and after (right) NUD selection are shown in Figure 11. The MC simulated data and the flight data are in good agreement with each other for both the left and right panels. By comparing the right panel to the left one, we can see that the proton events have been effectively rejected. With a \( \zeta \) selection cut for the electron detection efficiency of 90%, the proton contamination ratio reduces by a factor of \( \sim 50\% \) after applying the NUD selection, which indicates that the NUD provides independent proton rejection power by a factor of \( \sim 2 \) on the basis of BGO-ECAL.

5 CONCLUSIONS

The NUD is an essential sub-payload of the DAMPE satellite. The NUD is designed to detect the signals of secondary neutrons produced by the hadronic shower in the BGO-ECAL, thereby providing an important e/p separation power in the high energy range. Detailed calibrations indicate that the NUD is designed well and assembled to meet the requirements. Based on the MC simulations, we obtained a proton rejection power of \( \sim 25 \) under an electron efficiency of 95% for the NUD in the TeV energy range. The on-orbit performance shows that the NUD achieves significant proton rejection power independently from the BGO-ECAL. Thereby, the NUD plays an essential role for TeV electron/proton discrimination of DAMPE.

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