Nuclear Instruments and Methods in Physics Research A 836 (2016) 98–104

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

The calibration and electron energy reconstruction of the BGO ECAL of the DAMPE detector

Zhiyong Zhang [a], Chi Wang [a], Jianing Dong [a], Yifeng Wei [a], Sicheng Wen [b], Yunlong Zhang [a,*], Zhiying Li [a], Changqing Feng [a], Shanshan Gao [a], ZhongTao Shen [a], Deliang Zhang [a], Junbin Zhang [a], Qi Wang [a], SiYuan Ma [a], Di Yang [a], Di Jiang [a], Dengyi Chen [b], Yiming Hu [b], Guangshun Huang [a], Xiaolian Wang [a], Zizong Xu [a], Shubin Liu [a], Qi An [a], Yizhong Gong [b]

[a] State Key Laboratory of Particle Detection and Electronics (IHEP-USTC), University of Science and Technology of China, Hefei 230026, China
[b] Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210000, China

A R T I C L E I N F O

Article history:
Received 24 September 2015
Received in revised form
25 July 2016
Accepted 5 August 2016
Available online 24 August 2016

Keywords:
Electromagnetic calorimeter
Dark matter
Calibration
Cosmic rays
Beam test

A B S T R A C T

The DArk Matter Particle Explorer (DAMPE) is a space experiment designed to search for dark matter indirectly by measuring the spectra of photons, electrons, and positrons up to 10 TeV. The BGO electromagnetic calorimeter (ECAL) is its main sub-detector for energy measurement. In this paper, the instrumentation and development of the BGO ECAL is briefly described. The calibration on the ground, including the pedestal, minimum ionizing particle (MIP) peak, dynode ratio, and attenuation length with the cosmic rays and beam particles is discussed in detail. Also, the energy reconstruction results of the electrons from the beam test are presented.

1. Introduction

Weakly interacting massive particles (WIMPs) are historically the most popular dark matter candidates [1]. So far, there are many direct and indirect detection experiments [2–5] currently running or planned, aiming to search for evidence of them. The indirect detection experiments search for the products of WIMP annihilation or decay [6,7]. The DAMPE detector is designed to search for dark matter indirectly by measuring the spectra of photons, electrons, and positrons with a wide energy range from 5 GeV to 10 TeV and a good energy resolution of 1.5% at 800 GeV in space [8,9]. The DAMPE detector was launched in December of 2015 and is operated at an altitude of approximate 500-kilometer, on a solar synchronized satellite orbit around the earth, stably oriented to the zenith.

The DAMPE detector is composed of four sub-detectors (Fig. 1). First, the Plastic Scintillator Detector array (PSD), which consists of two layers (*X–Y*) of scintillator strips, is used to discriminate among heavy ion species. It is also used to identify electrons and gamma rays. Second, the Silicon-Tungsten tracker (STK) has six planes (each plane has two orthogonal layers) of Silicon micro-strip trackers and three layers of Tungsten plates of 1.0 mm thickness (full black lines in Fig. 1 STK) inserted in front of tracking layers 2, 3, and 4 for photon conversion. It is designed to provide tracking and $e^{\pm}/\gamma$ identification. Third, there is the BGO electromagnetic calorimeter (BGO ECAL), which is the focus of this paper, and most of the details regarding it will be presented in the following section. Fourth, the Neutron Detector (NUD) at the bottom of the DAMPE aims to improve e/p identification capacity by detecting the thermal neutrons produced in the BGO ECAL by high-energy protons [10].

As a satellite-based experiment, the DAMPE detector required much consideration with regard to design and testing in order to be operated in space. Some important points, such as its weight, power, temperature control, mechanical structure, etc., were taken into account throughout the design process. Many studies on these elements have already been carried out. For instance, the temperature effect, light yield, uniformity of the light yield, and the attenuation coefficient were studied for the crystals and aging effects, operation in a vacuum, charge ratios between dynodes, etc., were studied for the PMTs. After the construction of the sub-detectors, many experiments simulating the rigorous environment in orbit were employed for each sub-detector individually to make sure that they could be operated well in space. The tests included

* Corresponding author.
E-mail address: ylzhang@ustc.edu.cn (Y. Zhang).

http://dx.doi.org/10.1016/j.nima.2016.08.015
0168-9002/

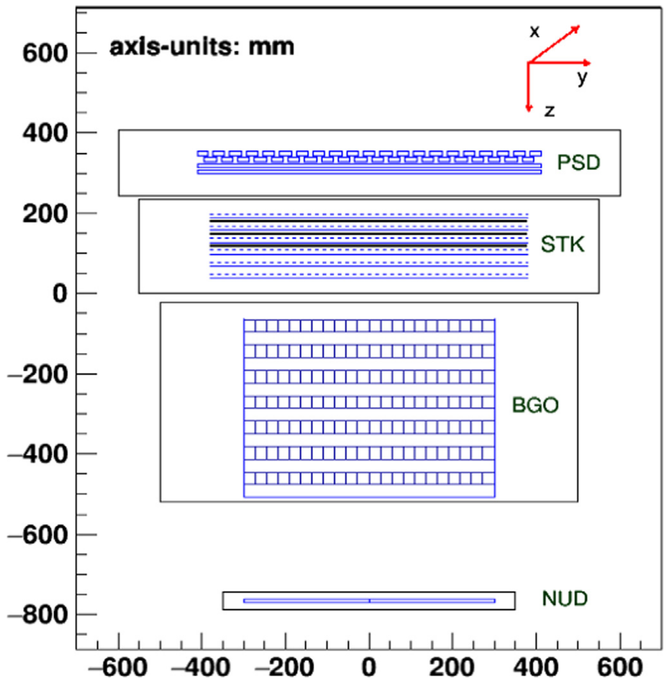

Fig. 1. The structure diagram of the DAMPE detector. The blue box and lines show the sensitive detectors. There the *y*-axis points to the sun, and $-z$ is oriented to the zenith in the red coordinates. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

electromagnetic compatibility (EMC), which is used to check the interference rejection capability and estimate the interferences to the satellite. In the EMC test, a radiation interference with an amplitude of 5 V/m, a frequency up to 10 GHz and a conduction interference injected in the power cord with an amplitude of 50 mV and a frequency up to 50 kHz are applied to the detector, the performance of the detector satisfy the requirements well. The vibration test studies the mechanical properties that should withstand the G-forces for launching. The thermal cycle test checks stability and reliability with in a large temperature range from $-20°$ to $40°$ centigrade. And the thermal vacuum test simulates the environment of space and temperature variations. Following assembly of the entire DAMPE detector, the same environmental tests were required again before launch.

2. The BGO calorimeter

2.1. Detector

The BGO ECAL is the main sub-detector for energy measurement, so it is designed to cover a large energy range from 5 GeV to 10 TeV with a good energy resolution of 1.5% at 800 GeV. The primary purposes of the BGO ECAL are to measure the energy deposition due to the particle shower that is produced by the $e^{\pm}$, γ and image their shower development profile, thereby providing an important hadron discriminator. Therefore, it comprises fourteen layers of BGO crystals, about 31 radiation lengths. Each layer comprises 22 BGO bars in dimensions of $25 \times 25 \times 600$ mm^3, with a PMT coupled on each end of the BGO crystal to collect scintillation light from the bar. Each single crystal and its 2 PMTs constitute a minimum detection unit (MDU, Fig. 2) of the BGO ECAL. The layers of BGO bars are alternated in an orthogonal way to measure the deposited energy and shape of the nuclear and electromagnetic showers developed in the BGO ECAL.

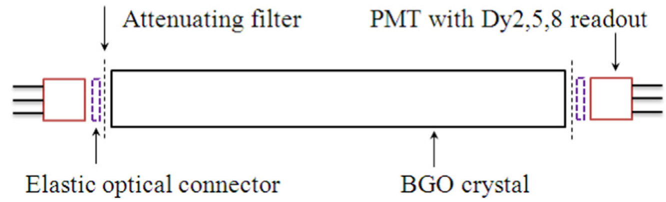

Fig. 2. The minimum detection unit of the BGO ECAL, an attenuation filter, an elastic optical connector, and a PMT with three dynodes readouts are coupled on each end of the BGO.

2.2. Minimum detection unit

The energy deposit from a MIP passing through a 25 mm-thick BGO bar is about 23 MeV by ionization. For the $e^{\pm}$ or γ, they will create electromagnetic showers in the BGO ECAL, a Geant4-based simulation indicates that the energy deposit in one BGO bar at the shower max is about 2 TeV for a 10 TeV electron, which is corresponding to about 10^5 MIPs. On the other hand, a minimum measurable energy deposit of 0.5 MIPs is required for shower shape reconstruction with reasonable precision demanded by particle identification. Thus, each MDU should cover energy measurements in a range from 0.5 MIPs to 10^5 MIPs, corresponding to a high dynamic range of 2×10^5. In order to cover such a large dynamic range of energy measurements, a multi-dynode readout PMT base board was conceived and designed, by which the signals are readouts from the different sensitive dynodes 2, 5, and 8 (Dy2, Dy5, and Dy8) [11].

Fig. 2 shows an MDU in the BGO ECAL. The 600 mm long BGO crystal used is produced by Shanghai Institute of Ceramics, Chinese Academy of Sciences, which is the longest BGO single crystal produced so far [12]. An elastic optical connector and an attenuation filter are inserted between the PMT and the crystal. The elastic optical connector, with a good transparency of ~90% for 480 nm wavelength photons, is used to cushion against mechanical stress to protect the fragile and brittle PMT and crystal. The attenuation filter, an exposure film, is designed to tune the amplitudes of signals by attenuating the flux of scintillation light injected into the PMT with optional factors. In order to further extend the dynamic range, the light generated in the crystals are read out unequally from the two ends by applying the attenuation filters with different factors in each MDU. Where, the less attenuated end is designated as 0 end and the more attenuated end is designated as 1 end. By testing with cosmic rays, the MIP peaks measured from the two ends of the crystals are tuned to about 500 fC for 0 end and 100 fC for 1 end.

To construct the BGO ECAL detector, the MDUs were assembled into a honeycomb carbon fiber frame, in which there are 14×22 rectangular holes of 26 mm $\times$ 26 mm alternated in an orthogonal way. The distance between the centers of the adjacent layers is 29 mm, and the pitch of the bars within each layer is 27.5 mm. The gaps between the BGO crystals and the carbon fiber were filled with black silicone rubber for light blocking and mechanical steadiness [13]. Since the arrangement of the BGO bars and PMTs was very compact, the high voltage supports are provided together for 44 PMTs in every two layers of the four sides of the BGO ECAL.

The BGO ECAL provides the trigger signals from layers 1–4 and 11–14 for the DAMPE. Since the trigger threshold is same for bars within a layer, the signals of a layer should be uniform [14]. Thanks to a high light yield of the BGO crystal, we can adjust the light generated by the BGO passing to the PMT by an attenuation filter. This way, we get better uniformity for each layer to satisfy the trigger requirement. At the same time, a ratio of 1:5 for the two ends of a MDU is set to extend the dynamic range. The sensitive volume of the BGO ECAL is composed of 308 MDUs. In the