

Performance of the BGO Detector Element of the DAMPE Calorimeter

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Abstract—A satellite-borne, high energy cosmic ray detector, named the DARK MATTER PARTICLE EXPLORER (DAMPE), was developed in China. The major scientific objectives of the DAMPE mission are observing primary cosmic rays and gamma rays in an energy range from 5 GeV to 10 TeV, to find evidence of the existence of dark matter particle. An electromagnetic calorimeter (ECAL), which contains 308 Bismuth Germanate (BGO) crystal bars, has been built for the DAMPE mission. The performance of 60-cm long BGO crystal bars has been studied with cosmic rays. Electron and ion beam test results of the BGO ECAL are also presented in this paper.

Index Terms—Calorimeter, DAMPE, long BGO crystal.

I. INTRODUCTION

SO FAR, many experiments (AMS [1], Fermi [2], PAMELA [3], CALET [4], etc) are being conducted to find evidence of dark matter particle existence by observing the high-energy electron/positron spectrum in space. DAMPE is a Chinese orbital experiment to measure the spectra of photons, electrons, positrons, and nuclei originating from deep space [5]. It has been launched in the end of 2015. The DAMPE detector is designed to cover a wide energy range, from 5 GeV to 10 TeV, with a good energy resolution of 1.5% at 800 GeV for photons and electrons. It is one of the most precise detectors for energy measurement of these particles in an energy range from sub-TeV to tens-TeV. The basic calorimeter parameters of some space experiments are shown in Table I [6–13]. DAMPE will orbit the earth at an altitude of 500 km. It is designed to withstand a total dose of 20k rad during a three-year mission (20k rad in five years for Fermi satellite [14]).

The BGO ECAL is one of the key sub-detectors of the DAMPE. A full-scale prototype, called the engineering qualified model (EQM), was built with the same technology as

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the flight model (FM) to verify the design and technological choices.

II. DESIGN OF THE DAMPE DETECTOR

The DAMPE detector consists of four sub-detectors (Fig. 1). The plastic scintillator detector (PSD) serves as a charge detector; the silicon-tungsten tracker (STK) provides tracking; the neutron detector (NUD) improves the electron/proton separation for proton background rejection in space; and the BGO ECAL, which is the focus of this paper, provides a high precision measurement of energy.

The BGO calorimeter contains 14 layers of BGO crystals (31.25 radiation lengths, 1.6 nuclear interaction lengths). Each layer is composed of 22 BGO crystal bars, as shown in Fig. 2. The crystal bars are supported by a carbon fiber structure. The layers are alternated in an orthogonal way to measure the deposited energy and profiles of hadron and electromagnetic showers developed in the calorimeter.

Scintillation light is detected at both ends of a BGO crystal bar by two PMTs. The required range of energy response for one BGO detector element (BGO crystal bar + PMTs) varies from 10 MeV to 2 TeV. To obtain a wide dynamic range, a multi-dynode readout structure of the PMT base is used, with dynode 2, 5 and 8 of the PMT corresponding to low, middle and high gain, respectively [15][16].

III. BGO CRYSTAL BAR TEST

The BGO crystal bars of the DAMPE calorimeter, with the dimension of 2.5 cm × 2.5 cm × 60 cm, were produced by the Shanghai Institute of Ceramics (SIC) [17]. Some key parameters of these specific BGO crystals were investigated in the calorimeter R&D period.

A. Light Transmittance

The longitudinal light transmittance of a long BGO crystal is an important parameter for the efficiency of scintillation light collection. A total of 320 BGO crystal bars of this specific kind have been tested. A light source with a different wavelength provided by a spectrophotometer (PerkinElmer Lambda 950) was applied to one end of the crystal bar, and the light transmittance was measured with light intensity at the other end. Fig. 3 gives a typical longitudinal transmittance curve. The transmittance is about 60% at the peak wavelength of BGO scintillation light (480 nm).

TABLE I
BASIC CALORIMETER PARAMETERS OF SOME SPACE EXPERIMENT

Experiment	Acceptance(m ² Sr)	Calorimeter Radiation Length(X_0)	Energy Resolution(for electrons and photons)
DAMPE	0.3	31	<1.5%@100GeV~1TeV
AMS02	0.055	17	2%@100GeV
Fermi	>2	8.4	>8.5%@100GeV
CALET	0.12	28	2%@100GeV(TASC only)
ATIC	0.15	18	2%@100GeV

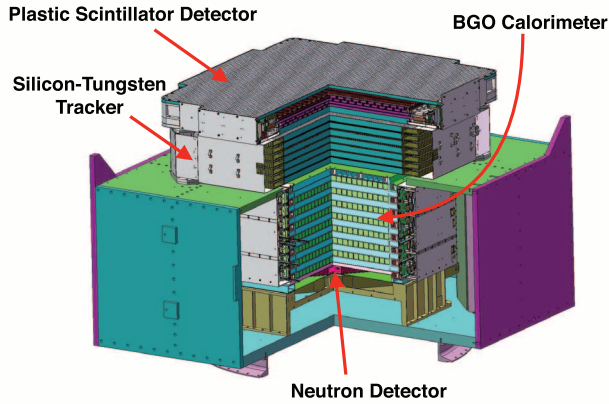


Fig. 1. Sub-detectors of the DAMPE.

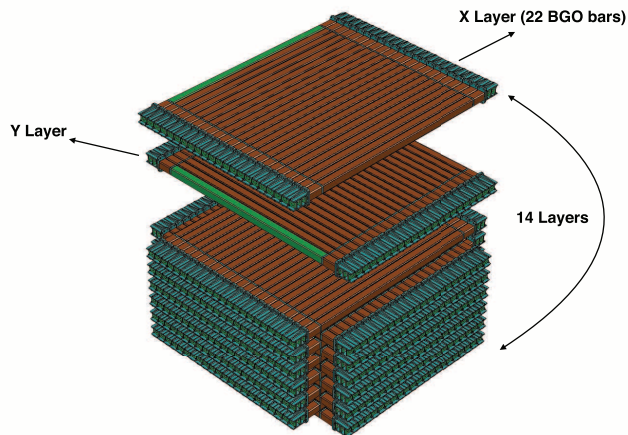


Fig. 2. Structure of the DAMPE BGO calorimeter.

B. Attenuation Length

A study on the light response uniformity (LRU) of a 20 cm long BGO crystal was reported in [18], which indicated that the internal absorption of crystal could be ignored in this case. However, for the specific 60-cm long BGO crystals, it should be taken into account that the scintillation light is attenuated exponentially when it transmits along the axis of the BGO crystal bar.

The attenuation length was calibrated with cosmic rays. Thanks to the orthogonal arrangement of BGO crystal bars, the

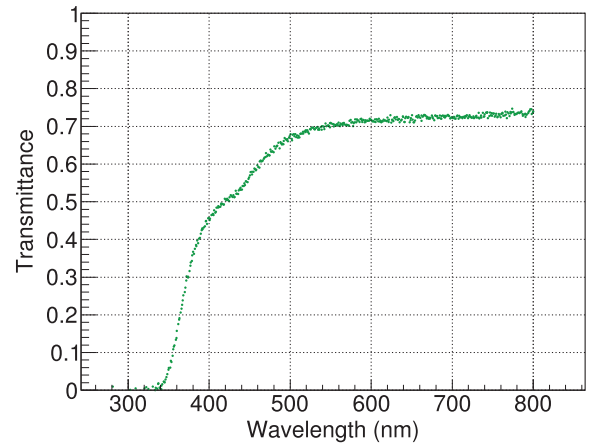


Fig. 3. The typical longitudinal light transmittance curve of a 60-cm long BGO crystal bar.

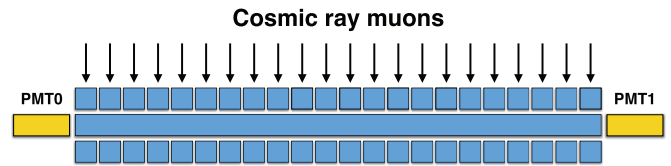


Fig. 4. One BGO crystal bar can be divided into 22 parts by its neighbor layers.

hit position of an incident cosmic ray particle can be located in one bar. Assuming that a bar was divided into 22 parts by its neighboring layers (Fig. 4), we can obtain the cosmic ray spectra of each given hit part. The spectra were fitted with the convolution of a Landau with a Gaussian, where the Landau MPV value corresponded to the light output in the read-out side. The MPV values at different part were fitted with a function:

$$A_i = k_i A_p \exp(-x/\lambda_i) \quad (1)$$

where λ_i is the attenuation length, A_p is the original light output at the hit point, A_i is the light output in the readout side (MPV value), and x is the distance the scintillation photon traveled in the crystal.

Fig. 5 gives a curve of the x (hit position) dependence of the MPV value, based on which we extracted the attenuation length parameter. The amplitude of A_i has been normalized, and the fitting parameter $p1$ exactly is the attenuation length. The typical value of the attenuation length is about 155 cm.

Additionally, due to the attenuation, signals collected by two side PMTs are asymmetrical when particles do not hit in the center of the BGO crystal bar. Therefore, the hit position in one BGO bar can also be given by utilizing signal amplitudes in the both sides. The track of the incident particle can be reconstructed with this method, which offers much higher precision than simply using the position granularity of the orthogonal layers.

Another calibration method for attenuation length has been presented in reference [18].

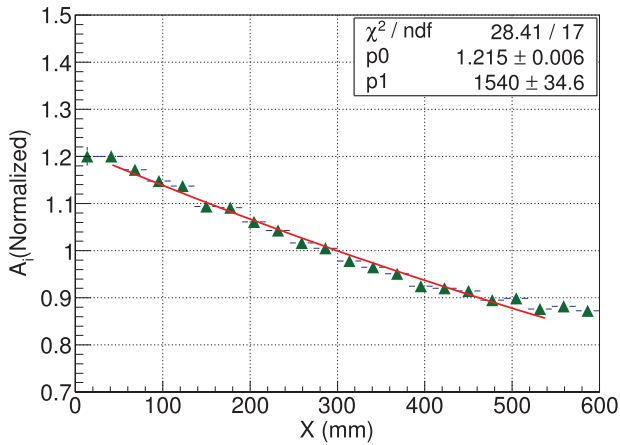


Fig. 5. Normalized MPV value of the cosmic muon spectrum of 22 parts in one BGO bar, with exponential fit.

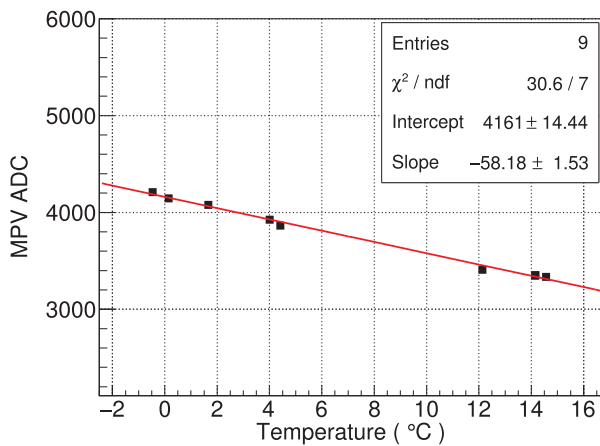


Fig. 6. Temperature dependence of one BGO crystal bar.

C. Temperature Effect

The light yield of BGO crystal depends not only on energy deposition but also on the temperature. Since the temperature of the DAMPE in orbit varies from -15°C to $+20^{\circ}\text{C}$, measurement of temperature dependence is necessary.

We have investigated the temperature dependence of the light yield for a single BGO crystal bar in reference [19]. In order to study the temperature performance of the full calorimeter, a thermal vacuum test with the engineering qualified model was conducted in June 2014.

We chose the data with stable high voltage, and temperature ranged from -1°C to $+15^{\circ}\text{C}$. The MPV value of the muon spectrum decreases with an increase in temperature. For each BGO crystal bar, a linear function was fitted to the MPV value versus the temperature (Fig. 6). As an illustration of the variation from crystal to crystal, Fig. 7 shows the slopes of the BGO crystal bars normalized to 0°C . The mean value is about -1.2% per degree Celsius. In comparison, the PDG reference value of temperature dependence of the BGO crystal is $-0.9\%/^{\circ}\text{C}$ [20], while the value measured by the ATIC experiment is $-1.86\%/^{\circ}\text{C}$ (including the contribution of electronics) [21].

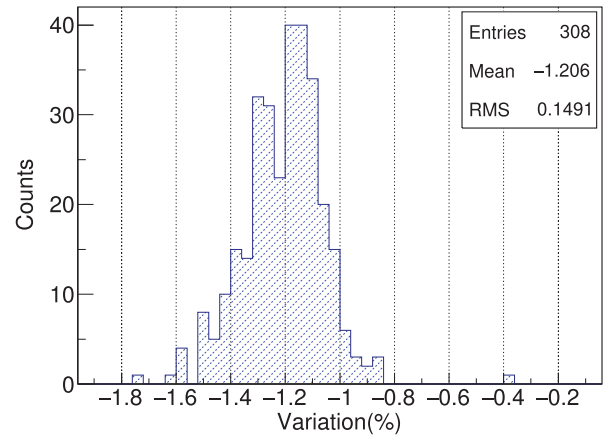


Fig. 7. Distribution of temperature dependence of individual crystals.

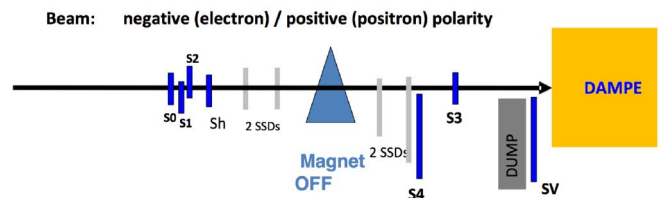


Fig. 8. The typical configuration of a charged particle beam test.

IV. BEAM TEST RESULTS

Two beam tests for the DAMPE engineering qualified model (including all sub-detectors) have been implemented at CERN. Electrons and hadrons (e.g., proton, pion etc.) were used in the first test and the second one utilized the ions. Fig. 8 shows the typical experiment configuration of the charged particle beam test, where S (S0, S1...) are plastic scintillator detectors for external trigger and SSD (SSD1, SSD2...) are silicon detectors to obtain the original track of an incident particle.

A. Results of the Electron Beam Test

The electron and hadron beam tests were performed in the T9 line of PS and the H4 hall of SPS, where secondary electrons with momenta from 0.5 to 243 GeV/c are available. It is important to study the DAMPE electron response and evaluate the agreement of real data and the Monte Carlo simulation based on the Geant4 toolkit.

The DAMPE detector was recalibrated in detail during the period of the beam test. The energy scale of each channel was calibrated with the signals produced by 150 GeV/c muons at SPS. To measure the signals in the high-energy range, the exact ratio of PMT dynodes was calibrated with electron/hadron showers in the calorimeter. Other important studies, such as angle scan, trigger efficiency, energy leakage, etc., were also performed.

Fig. 9 shows the distribution of the measured energy deposit in the calorimeter for 243 GeV electrons, without any correction. There is nearly 95% incident energy deposited in the BGO ECAL, and the energy resolution is about 0.9%. Further details regarding electron energy resolution can also be found in reference [18].

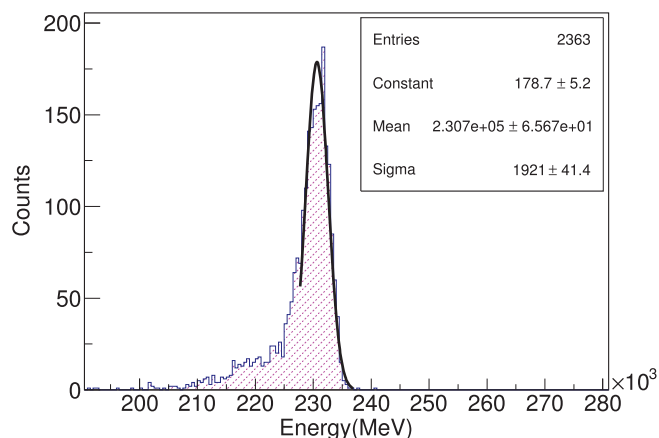


Fig. 9. The energy spectrum of 243 GeV electrons.

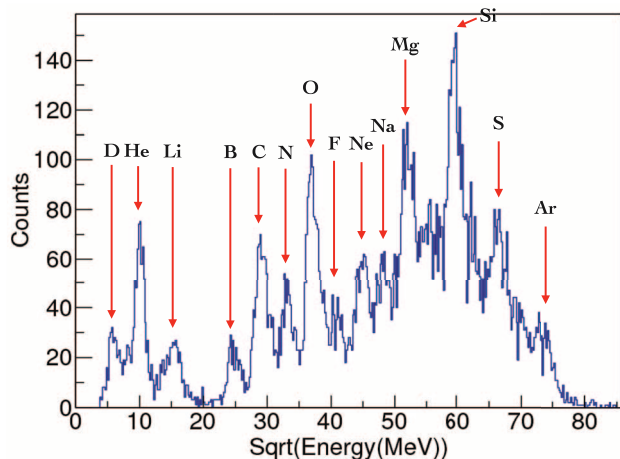


Fig. 10. Ion identification in the first layer of the BGO calorimeter.

B. Results of the Ion Beam Test

The ion response of the DAMPE was studied in the CERN SPS-H8 beam line, where secondary ions with charge number Z of 1~18 and momenta of 40 and 75 GeV/c/nucleon were provided. The secondary ions are generated by a primary ^{40}Ar shooting polyethylene target, which crossed a rigidity $A/Z = 2$ selection collimator.

The ionizing energy loss is well described by the Bethe-Bloch equation, in which the ionization energy loss in material is proportional to the square of the charge of the crossing particle. As shown in Fig. 10, the charge of particles can be identified by the pure ionizing event response of ions in the calorimeter.

V. CONCLUSION

An engineering qualified model of the BGO calorimeter was made for the DAMPE mission. We have tested the 60-cm long BGO crystal element in several respects. The average longitudinal light transmittance of the BGO crystal is about 60% at

480 nm. The typical value of attenuation length is 155 cm. We have also confirmed the temperature dependence of the light yield, and the mean value of the temperature coefficient at 0°C is -1.2% . We performed the beam test twice at CERN in order to confirm the performance of the BGO calorimeter, which is as expected [5] or even better.

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