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The response linearity of energy measurement up to TeV in the DAMPE experiment

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The DArk Matter Particle Explorer (DAMPE) space mission is designed to measure cosmic rays and gamma rays. The key sub-detector of DAMPE is the Bismuth Germanium Oxide (BGO) Electromagnetic CALorimeter (ECAL), which measures the energies of electrons/gamma-rays ranging from 5 GeV - 10 TeV. A laser test carried out to study the response of the BGO ECAL to up to ~TeV energy deposition revealed that the BGO fluorescence response retains linearity at laser energy deposition densities higher than that induced by a ~10 TeV electromagnetic shower. The energy measurements obtained from on-orbit data were also compared with Monte Carlo simulation results. The present study confirms that there is no fluorescence quenching effect in the DAMPE BGO ECAL.

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Table 1: Deposited energies obtained from different readout dynodes

Side\Dynode	2	5	8
0	3.2 GeV-800 GeV	80 MeV-20 GeV	2 MeV-500 MeV
1	16 GeV-4000 GeV	400 MeV-100 GeV	10 MeV-2.5 GeV

1. Introduction

DArk Matter Particle Explorer (DAMPE) [1] is one of the four space science satellites within the Strategic Priority Science and Technology Projects of China, and was launched into a sun-synchronous orbit at an altitude of 500 km at the end of 2015. One of the main scientific objectives of DAMPE is to search for dark matter particles by measuring high-energy electrons/positrons up to 10 TeV. The satellite carries a Plastic Scintillator Detector (PSD) [2], a Silicon-Tungsten tracKer-converter (STK) [3], a Bismuth Germanium Oxide (BGO) imaging calorimeter [4], and a NeUtron Detector (NUD) [5].

The BGO Electromagnetic Calorimeter (BGO ECAL), a key sub-detector of the DAMPE spectrometer, contains approximately 32 radiation lengths designed to measure the energy range from 5 GeV to 10 TeV of CREs precisely. The sensitive unit of the ECAL is inorganic material BGO, whose fluorescence quenching effect has been observed for low-energy hadrons and relativistic heavy ions with the high Linear Energy Transfer (LET) [6–8]. However, it is still unclear whether there is a quenching effect for ~TeV EM showers with extremely high energy deposition densities.

2. The BGO Caolorimeter

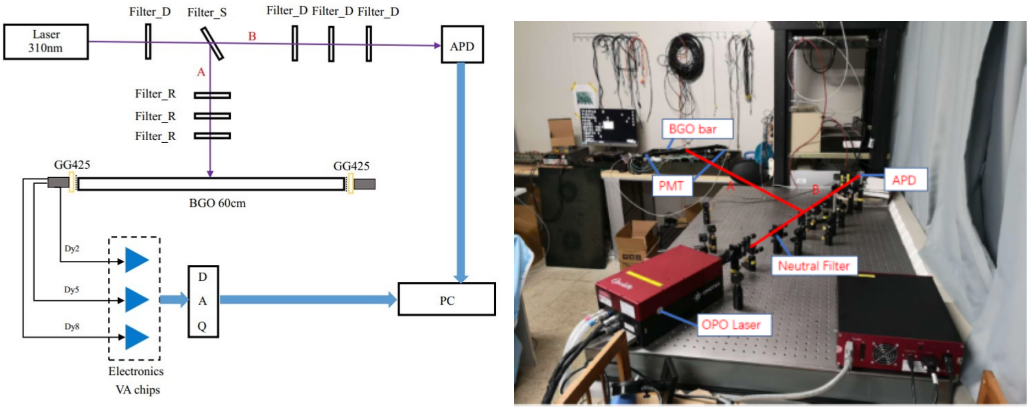
The BGO ECAL is a total absorption-type calorimeter composed of 308 BGO crystals. It contains seven coordinate planes (~32 radiation lengths, ~1.6 nuclear interaction lengths), each of which has two layers arranged orthogonally to provide measurement of shower profiles on the X-Y plane. Each layer consists of 22 BGO crystal bars with dimensions of 25 mm×25 mm×600 mm.

Each end of a BGO crystal is coupled to a PhotoMultiplier Tube (PMT) (Hamamatsu R5610A-01). The signals produced by the PMT are read out by three dynodes (dy2, dy5, and dy8 corresponding to low, medium, and high gain, respectively) to achieve a large dynamic range. To further extend the dynamic range of the BGO crystal, the energy coverages of the two ends of a BGO crystal (named Side0 and Side1) are made to be slightly different to make the amount of energy measurable by Side1 greater than that measurable by Side0 by a factor of five. The energy ranges of different readout dynodes are listed in Table 1.

3. Laser Test

Based on the good linearity of the output of the three dynodes of a PMT and its readout electronics, the fluorescence yield linearity of a BGO crystal was studied using a laser test platform comprising the BGO crystal, the PMT, and readout electronics equivalent to those used for the DAMPE detector. The output linearities of dy8, dy5, and dy2 were studied by using a laser to excite the BGO crystal. The energy deposition of dy2 at Side1 of the BGO crystal reached about 4000 GeV, which is approximately equal to the energy deposited on a crystal located at the shower center produced by a 20 TeV electron. Therefore, our focus was on studying the output linearity of the three dynodes of Side1.

The laser experimental setup is shown in Figure 1. Channel A used to excite the BGO crystal whose coupled PMTs and PMT readout electronics were the same as those used by DAMPE in orbit. Channel B directly injected on to an Avalanche PhotoDiode (APD, Hamamatsu S8664-1010) which is used to monitor the laser intensity during the test. The laser intensity could be tuned easily by the control software. The correlations between the PMT and APD signals are plotted in Figure 2 on which the x-axis represents the output of the APD, and the y-axis represents the signal measured by the dynodes.



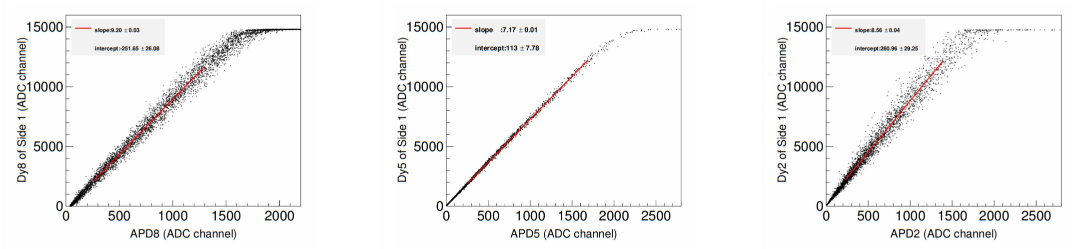
(a) (b)

Figure 1: Experimental setup: (a) schematic diagram, and (b) practicality picture.

Figure 2(a), 3(b), and 3(c) present the outcomes for dy8, dy5, and dy2 of PMT at Side1, respectively. As detailed in Figure 2(c), dy2 provides a linear response of BGO energy deposits from several tens of GeV to ~4 TeV. The response linearities of energy deposition at lower energies are shown in Figure 2(b) and 3(a). These laser test results indicate that there is no fluorescence quenching effect in a BGO crystal located at the shower center of a 10 TeV-order electron.

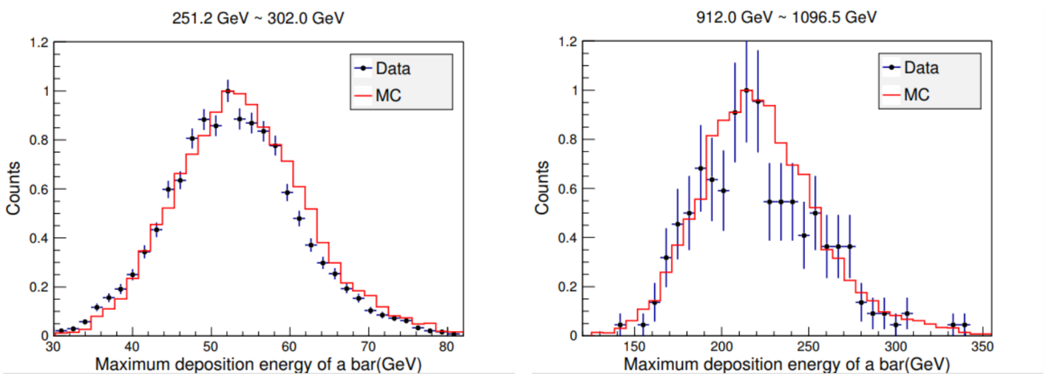
4. Energy response of the BGO crystal to electrons

To further validate the laser test results, energy measurements obtained from CREs using DAMPE in orbit were studied. The energy deposition in the BGO crystal located at the shower center was analyzed and compared with the results of MC simulation without a fluorescence quenching effect using GEANT4.10.02 with the physics list FTFP-BERT [9]. Figure 3 shows the energy deposition distributions of CREs on a BGO bar located at the shower center, with the black dots representing orbital data and the solid line showing simulation results. The simulation and flight data are both fitted by Gaussian functions. Figure 4 shows the correlation between the total deposited energy in DAMPE and the deposited energy in the BGO bar located at the EM shower center. The consistency between the orbital and MC results, further verifies that there is no fluorescence quenching effect in a BGO crystal located at an EM shower center produced by an electron with a total deposited energy up to the TeV range.



(a) (b) (c)

Figure 2: Relation between output of each dynode of PMT at Side1 and APD. Red lines are linear fitted functions. (a) Dy8 of PMT at Side1 versus APD8. (b) Dy5 of PMT at Side1 versus APD5. (c) Dy2 of PMT at Side1 versus APD2.



(a) (b)

Figure 3: Deposited energy distributions in BGO bars located at EM shower centers induced by electrons with energies of (a) 251.2-302 GeV; (b) 1096.5-1318.3 GeV. Black dots with error bars indicate flight data; red lines indicate MC simulation.

5. Conclusion

The response of a BGO crystal located at the EM shower center of a high-energy CRE in orbit was studied using a high-intensity laser system in the laboratory. The experimental results indicate that there is no quenching effect when the energy peak density of the laser exceeds that induced by a 10 TeV EM shower. Further study on the deposited energy distributions of BGO bars located at EM shower centers induced by electron candidates with total deposited energies of up to several TeV revealed that the flight data are consistent with MC simulation results with no fluorescence quenching effect.

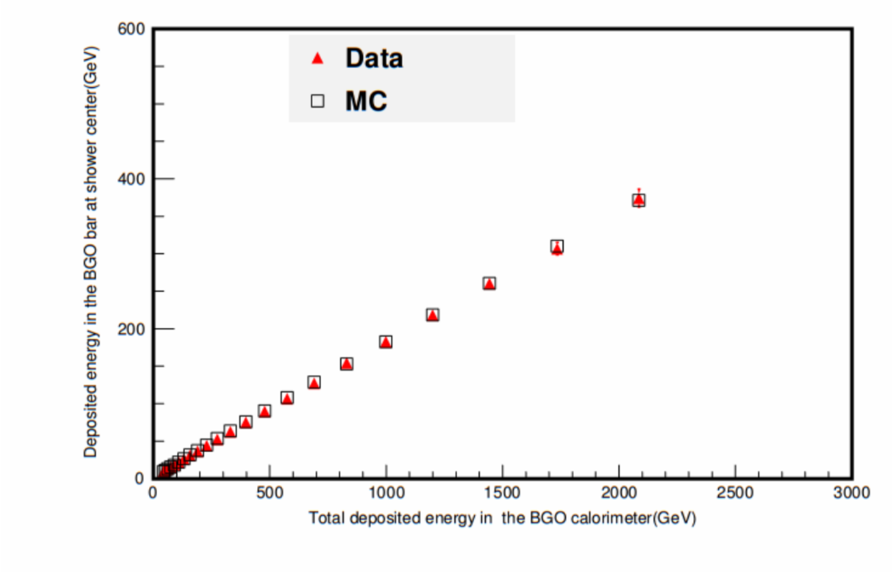


Figure 4: Energy deposited in BGO bar located at EM shower center plotted against total deposited energy. Flight data are indicated by red triangles; MC simulations are indicated by open black squares.

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References

[1] Chang J, Ambrosi G, An Q, et al. The dark matter particle explorer mission[J]. Astroparticle Physics, 2017, 95: 6-24.

[2] Yu Y, Sun Z, Su H, et al. The plastic scintillator detector for DAMPE[J]. Astroparticle physics, 2017, 94: 1-10.

[3] Azzarello P, Ambrosi G, Asfandiyarov R, et al. The DAMPE silicon–tungsten tracker[J]. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2016, 831: 378-384.

[4] Zhang Z, Wang C, Dong J, et al. The calibration and electron energy reconstruction of the BGO ECAL of the DAMPE detector[J]. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2016, 836: 98-104.

[5] Ming H, Tao M, Jin C, et al. GEANT4 simulation of neutron detector for DAMPE[J]. Chinese Astronomy and Astrophysics, 2016, 40(4): 474-482.

[6] Valtonen E, Peltonen J, Torsti J J. Response of BGO and CsI (Tl) scintillators to heavy ions[J]. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 1990, 286(1-2): 169-174.

[7] Bakkum E A, Van Engelen C P M, Kamermans R, et al. The response of BGO scintillation detectors to light charged particles[J]. Nuclear Instruments and Methods in Physics Research, 1984, 225(2): 330-334.

[8] Wei Y, Zhang Y, Zhang Z, et al. The quenching effect of BGO crystals on relativistic heavy ions in the DAMPE experiment[J]. IEEE Transactions on Nuclear Science, 2020, 67(6): 939-945.

[9] Agostinelli S, Allison J, Amako K, et al. GEANT4—a simulation toolkit[J]. Nuclear instruments and methods in physics research section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2003, 506(3): 250-303.