Dark Matter Particle Explorer and its First Results

CHANG Jin

(Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008)
(School of Astronomy and Space Science, University of Science and Technology, Hefei 230026)

E-mail: chang@pmo.ac.cn

Abstract

The DArk Matter Particle Explorer (DAMPE) is China's first astronomical satellite dedicated to the indirect detection of dark matter particles and the study of high-energy astrophysics. It can measure high-energy electrons and gamma-rays up to 10 TeV with unprecedentedly high energy resolution and low background. Cosmic ray nuclei up to 100 TeV can also be measured. DAMPE was launched on December 17, 2015, and has been operating smoothly in space for more than two years since then. The first results about the precise measurements of the electron plus positron spectrum between 25 GeV and 4.6 TeV have been reported.

1. Introduction

It has been well established that our Universe is made up of ~4.9% baryonic matter, ~26.8% Dark Matter (DM), and ~68.3% dark energy[1] (see Figure 1). The physical nature of DM is one of the most important fundamental questions of modern physics. One leading candidate of DM particles is a kind of Weakly Interacting Massive Particles (WIMPs) beyond the standard model of particle physics, as motivated by the relic abundance of DM and the bottom-up evolution pattern of the large-scale structures of the Universe[2,3]. Many efforts have been paid to search for the WIMP DM in the laboratory, including the direct detection of the WIMP-nucleus scattering by underground detectors, the indirect detection of the annihilation or decay products in the cosmic radiation, and the collider detection of WIMP pairs produced in particle colliders[4]. After several decades of such searches, no convincing evidence has been found yet.

In recent years some interesting anomalies have been found in Cosmic Ray (CR) and γ-ray observations, such as the positron excess discovered by PAMELA[5], Fermi-LAT[6], and AMS-02[7], and the associated total Cosmic Ray Electron plus positron (CRE) excess by ATIC[8], Fermi-LAT[9], and AMS-02[10]. The excesses of positrons and CREs can be explained by either the astrophysical sources such as pulsars and the DM annihilation or decay[11-16]. There are still debates on the astrophysical or DM origin of the positron and/or CRE excesses, in particular, that the most recent HAWC observations of two nearby pulsars tend to disfavor the pulsar interpretation[17]. Higher precision measurements in a wider energy band are crucial to identifying their physical origin. Other anomalies include the γ-ray excess

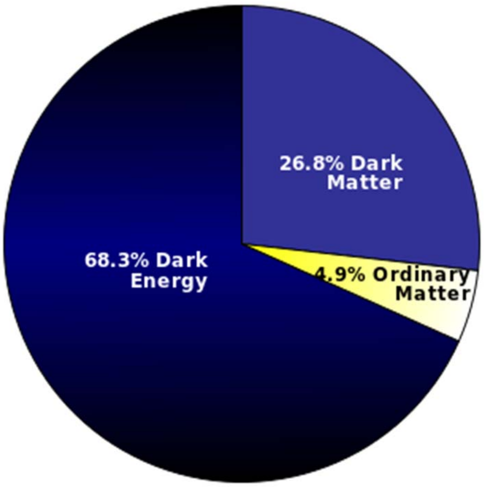

Fig. 1 Composition of the Universe inferred by PLANCK data[1]

in the Galactic center[18], and potential excess of CR antiprotons[19, 20].

The purpose of the DArk Matter Particle Explorer (DAMPE) is to search for possible annihilation/decay relics of DM in CREs, with unprecedentedly high energy resolution and low background[21, 22]. DAMPE is also a general purpose high-energy particle detector for observations of γ-rays and CR nuclei, which can be particularly helpful in the study of high-energy astrophysical phenomena and CR physics[22]. The DAMPE mission was launched into a 500 km sun synchronous orbit on December 17, 2015, with an inclination angle of 97°. It orbits the Earth every 95 minutes. All the detectors perform excellently in space. The daily event rate of DAMPE is about 5 million. It has recorded in total over 4 billion CR events up to now, most of which are CR nuclei. There are about 1% CREs and 3×10^{-5} γ-ray photons in the DAMPE data.

2. DAMPE Detector

DAMPE is made of 4 sub-detectors, which are, from top to bottom, the Plastic Scintillator strip Detector (PSD)[23], the Silicon-Tungsten tracKer-converter (STK)[24], the BGO imaging calorimeter[25], and the NeUtron Detector (NUD)[26]. A schematic plot of the DAMPE detector is shown in Figure 2[22]. The total weight of the payload (satellite) is about 1.5 (1.9) tons, and the power of consummation is 300 (500) W. The size of the satellite is about 1.2 m×1.2 m×1.0 m.

The PSD is to measure the (absolute) charge of incident particles up to Z=30 via the ionization effect (dE/dx). It also serves as an anticoincidence detector for γ-rays. The PSD consists of two layers of orthogonally placed plastic scintillator bars. For each layer, 41 plastic scintillator bars are further placed in two sub-layers with a shift of 0.8 cm between them to reduce the gaps. The effective area of the PSD is 82.5 cm×82.5 cm[22]. The weight of the PSD is about 103 kg, and the power is 8.5 W.

The main function of STK is to measures the trajectory of a particle. The charge of light nuclei ($z<8$) can also be measured by the STK. The STK consists of 12 layers (6 for x-direction and 6 for y-direction) of silicon trackers, each with two sub-layers arranged orthogonally to measure the x and y positions of a track. The STK is also a gamma-ray converter by means of three 1mm thick tungsten plates inserted in the second, third, and fourth planes. Each silicon layer is made of 16 ladders, each formed by 4 Silicon micro-Strip Detectors (SSD). Every ladder is segmented into 768 strips, half of which are readout strips and the other half are floating strips. In total there are 384×16×12=73728 readout channels of the STK. The effective detection area of STK is 76 cm×76 cm. The STK has a weight of 154 kg and a power consumption of 82 W.

The BGO calorimeter is the major instrument of DAMPE. It has three functions: 1) measuring the energy deposition of incident particles, 2) imaging the 3D profile of the shower development, and providing electron/hadron discrimination, and 3) providing the level 0 trigger

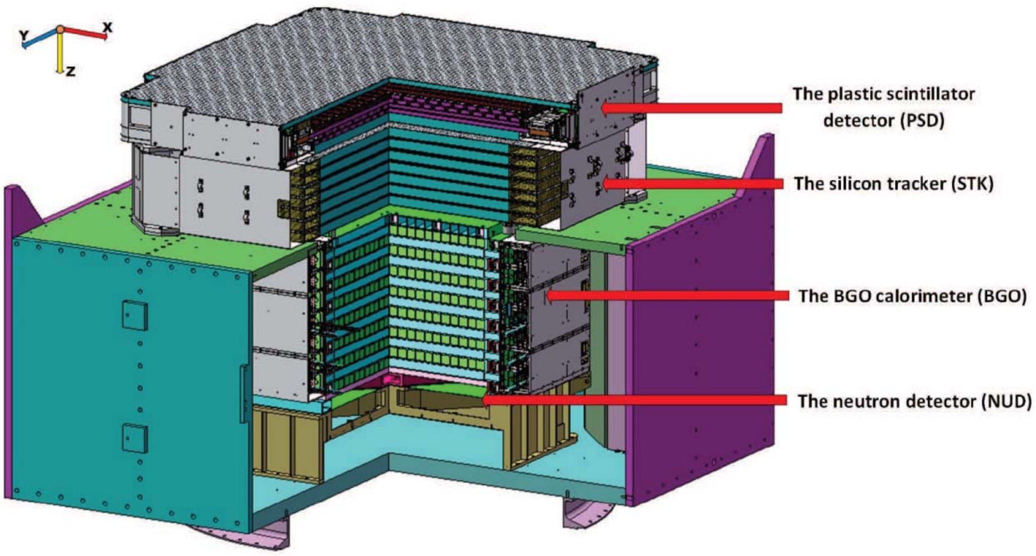

Fig. 2 Schematic plot of the DAMPE detectors[22]

for the DAMPE data acquisition system. The BGO calorimeter is made of 308 BGO bars, each is read out at two ends by PhotoMultiplier Tubes (PMTs). The BGO crystals are placed orthogonally in 14 layers, with a total depth of about 32 radiation lengths and about 1.6 nuclear interaction lengths. The length of the BGO crystal is 60 cm, which is the longest in the world. The calorimeter has an effective area of 60 cm×60 cm, a total weight of 1052 kg, and a power consumption of 42 W.

The NUD is at the bottom of the detector. The main purpose of the NUD is to perform electron/hadron discrimination by means of the fact that neutrons are much more abundant in hadronic showers than in electromagnetic ones. Once the neutrons are created, they are quickly thermalized in the BGO calorimeter and then get captured by Boron-doped plastic scintillators. The NUD is made of four 30 cm×30 cm×1 cm plastic scintillators with 5% (weight) Boron element. The NUD has an effective area of 61 cm×61 cm, a mass of 12 kg, and a power of 0.5 W.

Table 1 summarizes the expected detector performance of DAMPE, for observations of electrons, gamma-rays, and protons[22]. With good measurements of the charge, direction, energy of various types of particles, DAMPE is expected to play a significant role in exploring the high-energy Universe.

Table 1 Expected performance of DAMPE

Parameter	Value
Energy range (e/γ)	5 GeV to 10 TeV
Energy resolution (e/γ)	1.5% @ 800 GeV
Energy range (p)	50 GeV to 500 TeV
Energy resolution (p)	40% @ 800 GeV
Effective area (vertical γ)	1100 cm^2 @ 100 GeV
Geometry factor (e)	0.3 m^2 sr above 30 GeV
Angular resolution (γ)	0.1 ° @ 100 GeV
Field of view	1.0 sr

3. Analysis of CREs

Particle identification is one of the most challenging things for the observations of CREs. The background of CREs is CR protons (heavier nuclei can be effectively rejected via the charge measurement in PSD). The fluxes of CREs are about three orders of magnitude lower than that of protons. Therefore a high rejection power of protons is essential for reliable measurements of the CRE fluxes. DAMPE uses the morphology difference between CREs and protons in the calorimeter to distinguish them[27, 28]. This is basically due to different developments of hadronic and electromagnetic showers in the calorimeter. A simple two-parameter method was adopted to describe the longitude and latitude developments of the showers. They are: (1) an energy-weighted Root-Mean-Square (RMS) value of hit positions in the calorimeter (shower spread), and (2) the deposit energy fraction of the last BGO layer (F_{last}). The left panel of Figure 3 shows the distributions of these two parameters for the flight data with BGO energies between 500 GeV and 1 TeV[29]. We can see clearly two populations of events in this plot, with the upper population being proton candidates and the lower one being CRE candidates. To better quantify the separation between these two populations, we further define a shape parameter, $\zeta=F_{\mathrm{last}}\times(\text{shower spread/mm})^4/(8\times10^6)$, which projects these two parameters into one dimension. The distributions of the ζ parameter for the flight data and Monte Carlo (MC) simulations for CREs and protons are shown in the right panel of Figure 3. We select CREs with $\zeta\leqslant8.5$, which gives only about 2% proton background in this energy range[29]. For energies below TeV, the proton background is lower than 3%. The highest background in the energy range from 25 GeV to 4.6 TeV is estimated to be about 18%[29].

The other very important thing for precise CRE observations is the energy measurement. The very thick BGO calorimeter enables that there is no significant leakage of electromagnetic showers from the bottom. There is, however, a few percents of energy loss due to the dead materials of the calorimeter. An event level energy correction method was developed and verified by MC simulations and also the beam test data[30]. The beam test data and the MC simulations show that the energy resolution for CREs is better than 1.2% for energies above 100 GeV. DAMPE also has P- and N-side readouts for each BGO crystal, which have different gains. These two-side readouts give a consistency check of the energy measurement. We find that the energies measured by both sides agree with each other very well. Figure 4 presents the ratios of energies measured by the two sides, together with a Gaussian fit that gives a mean of 1.005±0.005 and a width of 0.016±0.001[29]. Such a result further supports the quoted energy resolution of about 1%.

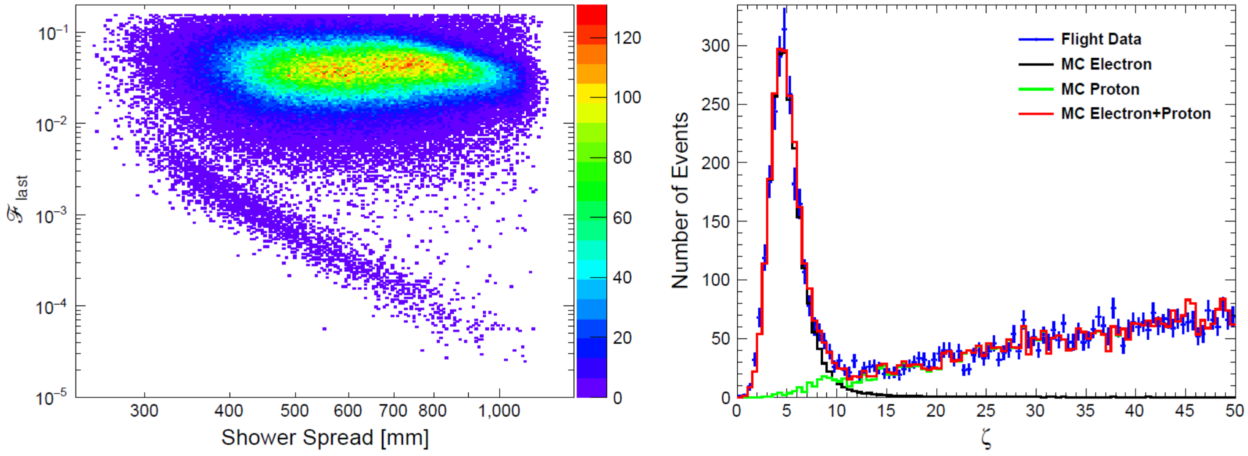

Fig. 3 Left: Shower spread versus the last layer energy fraction for selected events with BGO energies between 500 GeV and 1 TeV. Right: one-dimensional distributions of the shape parameter ζ, compared with MC simulations[29]

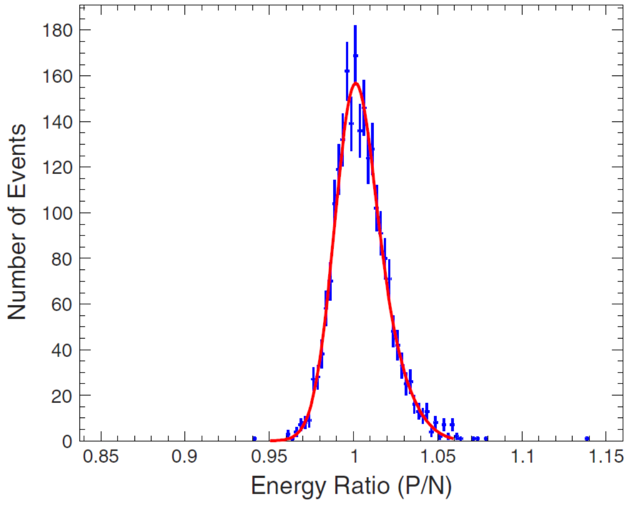

Fig. 4 Ratios of energies reconstructed with P- and N-side data[29]

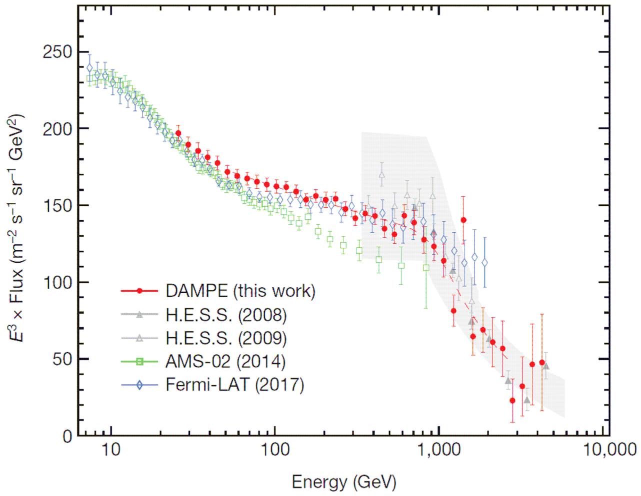

Fig. 5 Cosmic ray electron spectrum measured by DAMPE (red)[29], compared with that by Fermi-LAT (blue)[31], AMS-02 (green)[10], and the indirect measurement by H.E.S.S. (gray)[32,33]

The derived CRE spectrum from 25 GeV to 4.6 TeV, obtained by the first 530 days of DAMPE data is shown in Figure 5[29]. Compared with other measurements[10,31-33], the DAMPE data are more precise with smaller uncertainties and lower background for energies higher than ~500 GeV. For the first time, the CRE spectrum has been directly measured to ~5 TeV. The previous indirect measurements to such high energies by ground-based experiments suffer from quite large systematic uncertainties.

A spectral break at ~0.9 TeV, with the spectral index changing from –3.1 to –3.9 is clearly revealed by the DAMPE data. The significance of this break is estimated to be about 6.6σ. This result confirms the previous weak evidence found by H.E.S.S.[32,33]. The spectral index below the break is consistent with that observed by Fermi-LAT[31], and above the break, it is consistent with the result by H.E.S.S.[32]. The DAMPE spectrum also shows a tentative narrow peak at ~1.4 TeV. This peak structure is not statistically significant enough, and more data are needed for confirmation.

4. Summary

DAMPE has been operating smoothly in orbit for more than two years. Based on its first 530 days of data, the precise measurements of the CRE spectrum between 25 GeV and 4.6 TeV were published[29]. The DAMPE spectrum reveals a break at ~0.9 TeV with a high significance. A tentative narrow spectral feature at ~1.4 TeV needs more data for confirmation. Other analyses about the CR spectra and γ-rays are on-going. DAMPE is designed to operate for 3 years. It is very likely to operate much longer given the very good conditions of all the detector. More data from DAMPE are expected to shed new light on our understandings about dark matter and the high-energy Universe.

Acknowledgments The DAMPE mission was funded by the strategic priority science and technology projects in space science of the Chinese Academy of Sciences. The data analysis was supported in part by the National Key Research and Development Program of China (No. 2016YFA0400200) and the National Natural Science Foundation of China (No. U1738206).

References

[1] P. Ade, *et al.* (PLANCK collaboration), 2016, Astron. Astrophys., 594, A13
[2] G. Jungman, M. Kamionkowski, and K. Griest, 1996, Phys. Rept., 267, 195
[3] G. Bertone, D. Hooper, and J. Silk, 2005, Phys. Rept., 405, 279
[4] X.-J. Bi, P.-F. Yin, and Q. Yuan, 2013, Frontiers of Physics, 8, 794
[5] O. Adriani, *et al*. (PAMELA collaboration), 2009, Nature, 458, 607
[6] M. Ackermann, *et al.* (Fermi-LAT collaboration), 2012, Phys. Rev. Lett., 108, 011103
[7] M. Aguilar, *et al.* (AMS collaboration), 2013, Phys. Rev. Lett., 110, 141102
[8] J. Chang, *et al*. (ATIC collaboration), 2008, Nature, 456, 362
[9] A. A. Abdo, *et al*. (Fermi-LAT collaboration), 2009, Phys. Rev. Lett., 102, 181101
[10] M. Aguilar, *et al.* (AMS collaboration), 2014, Phys. Rev. Lett., 113, 221102
[11] C. S. Shen, 1970, Astrophys. J. Lett., 162, L181
[12] D. Hooper, P. Blasi, and P. Dario Serpico, 2009, J. Cosmol. Astropart. Phys., 1, 25
[13] H. Yuksel, M. D. Kistler, and T. Stanev, 2009, Phys. Rev. Lett., 103, 051101
[14] L. Bergstrom, T. Bringmann, and J. Edsjo, 2008, Phys. Rev. D, 78, 103520
[15] M. Cirelli, M. Kadastik, M. Raidal, and A. Strumia, 2009, Nucl. Phys. B, 813, 1
[16] P. F. Yin, Q. Yuan, J. Liu, J. Zhang, X. J. Bi, S. H. Zhu, and X. M. Zhang, 2009, Phys. Rev. D, 79, 023512
[17] A. U. Abeysekara, *et al.* (HAWC collaboration), 2017, Science, 358, 911
[18] D. Hooper and L. Goodenough, 2009, Phys. Lett. B, 697, 412
[19] M.-Y. Cui, Q. Yuan, Y.-L. Sming Tsai and Y.-Z. Fan, 2017, Phys. Rev. Lett. 118, 191101
[20] A. Cuoco, M. Kramer and M. Korsmeier, 2017, Phys. Rev. Lett. 118, 191102
[21] J. Chang, 2014, Chin. J. Space Sci., 34, 550
[22] J. Chang, *et al.* (DAMPE collaboration), 2017, Astropart. Phys., 95, 6
[23] Y. Yu, *et al*., 2017, Astropart. Phys., 94, 1
[24] P. Azzarello, *et al.*, 2016, Nuclear Instruments and Methods in Physics Research A, 831, 378
[25] Z. Zhang, *et al*., 2015, Nuclear Instruments and Methods in Physics Research A, 780, 21
[26] M. He, *et al*., 2016, Acta Astronomica Sinica, 57, 1
[27] J. Chang, 1999, International Cosmic Ray Conference, 5, 37
[28] J. Chang, *et al*., 2008, Advances in Space Research, 42, 431
[29] G. Ambrosi, *et a*l. (DAMPE collaboration), 2017, Nature, 552, 63
[30] C. Yue, *et al*., 2017, Nuclear Instruments and Methods in Physics Research A, 856, 11
[31] S. Abdollahi, *et al*., 2017, Phys. Rev. D, 95, 082007
[32] F. Aharonian, *et* al., 2008, Phys. Rev. Lett., 101, 261104
[33] F. Aharonian, *et al*., 2009, Astron. Astrophys., 508, 561