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Measurement of Heavy Nuclei beyond Iron in Cosmic Rays with the DAMPE experiment

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Dark Matter Particle Explorer (DAMPE) is a calorimetric-type, satellite-borne detector. One important scientific object of DAMPE is to measure the flux of cosmic ray nuclei, which is fundamental for understanding the cosmic ray origin and propagation mechanism. Heavy nuclei beyond Iron in Cosmic Rays play an important role for studying the outstanding issues in the grand cycle of matter in the Galaxy. Thanks to the good charge resolution of the DAMPE PSD detector (~0.06e for protons, ~0.3e for iron), the primary charges in a wide range from proton (Z=1) to Zirconium (Z=40) can be identified. In seven years of data-taking from 2016 to 2022, DAMPE has collected data with more than 3×10^6 nuclei with Z≥26. In order to reduce the contamination of Iron in the flux of heavier nuclei in cosmic rays, new charge identification methods have been studied, and the relativistic rise effect has been corrected. Here, such tools and the methods of charge identification aiming to the spectrum measurement will be introduced.

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1. Introduction

The measurement of heavy nuclei beyond iron in the cosmic ray flux could provide hints to sources of cosmic rays. Fig.1 [1]shows the relative abundances of elements ($1 \leq Z \leq 93$). We see that the abundance of Fe_{26} is at least 10^3 times less than H1. The heavier elements($30 \leq Z \leq 40$) are at most 10^5 times less abundant than Fe_{26}. Because of the rare abundance of those elements($30 \leq Z \leq 40$), the detection needs excellent charge resolution. So far, there are several single-element resolution measurements of heavy nuclei beyond iron in cosmic ray experiments, such as the SuperTIGER [2] balloon-borne instruments at GeV/n and the ACE-CRIS [3] space based detector at hundreds of MeV/n.

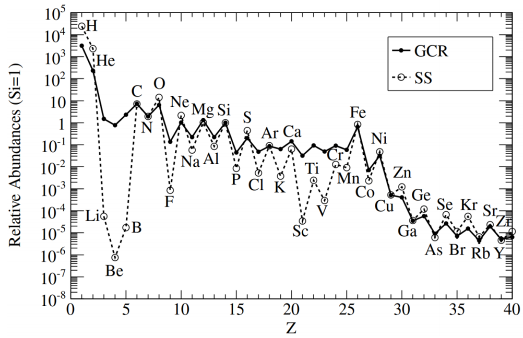


Figure 1: Solar System (SS) [4] and Galactic cosmic-ray (GCR) relative elemental abundances at 2 GeV/n. GCR data are taken for $1 \leq Z \leq 2$ from [5], Z = 3 from [6], $4 \leq Z \leq 28$ from [7], Z = 29 from [8], and $28 \leq Z \leq 40$ from [9] and normalized to Si_{14} .

DAMPE, which has a large acceptance and better charge resolution, has collected over 7 years of data since launched on Dec.17, 2015. To analyze data for selecting heavy nuclei beyond iron, the charge reconstruction algorithms are improved and several corrections are implemented. In this report, we will describe the new algorithms and will show the results after improvement.

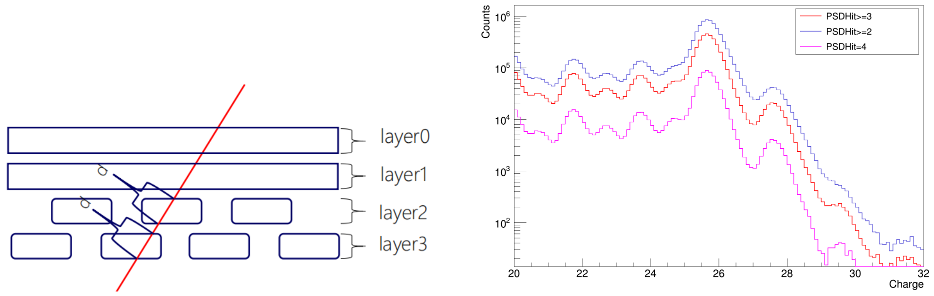
2. DAMPE instrument

DAMPE is composed of four separate sub-detectors. The Plastic Scintillator Detector (PSD) , consisting of two layers of 41 plastic scintillating bars, is used to measure the particle charge. The PSD can also be used as an anti-coincidence detector for gamma-ray selection. The Silicon Tungsten tracKer-converter (STK) is used to reconstruct the particle trajectory. The $Bi_3Ge_4O_{12}$(BGO) calorimeter is used for energy measurement and electron-hadron discrimination. NeUtron Detector (NUD) is used for further electron-hadron discrimination [10].

3. Data analysis

3.1 Charge reconstruction

The PSD, which is the most important detector for charge measurement, is composed of two planes for the two orthogonal views. Actually, each layer includes two superimposed sub-layers, the



(a) The PSD structure and the pathlength inside the bar when the particle crosses it. The pathlength of the particle through a PSD bar is taken into account for the charge measurement.

(b) Charge spectrum used for the charge measurement for different cuts on the number of PSD hit bars. When ≥4 bars are requested, the charge resolution is maximized while the efficiency is very low.

Figure 2

top one made by with 20 bars in the top layer and 21 bars in the bottom one. One particle impinging on the PSD surface could hit four layers at most, according to Fig.2(a). More bars are used for charge measurement, a better charge resolution. Finally, the charge measurement is obtained via

$$Z = \frac{\sum_0^3 Q_{\text{hitbar}}}{\text{Number of hit bars}} \tag{1}$$

On the other hand, the number of hit bars required for evaluating the charge will affect the acceptance. According to Fig.2(b), the fraction of surviving events when more than 3 hit bars are required is only 60% compared to the events with a number of hit bars greater than 2. The most stringet request of 4 hit bars reduces that fraction to only 10%. As a reasonable compromise between effective acceptance and charge resolution, a number of hit bars at least equal to 3 is required for charge evaluation. Additionally, a further cut requires the consistency of charge values from the different hit bars.

3.2 Selection

In order to ensure enough statistic, the dataset from 2016 to 2022 was analyzed, using unbiased trigger and high energy trigger. As a first cut, a deposited energy in BGO greater than 10 GeV is required. Besides a geometrical cut is applied to ensure that the particle hits the BGO volume.A further cut is then applied, requiring that the hit bar with maximum energy loss in the layer was intercepetd by the particle track. The last event selection cut imposes that the track should cross the max energy cluster in front two layers of STK. In Fig.3, the effects of the above described cuts on thr charge spectrum is shown.

3.3 Charge correction

3.3.1 Energy correction

As stated by the Bethe-Bloch formula, the energy loss in PSD is related to the primary energy of the particle. In turn, the charge of particle is evaluated from the deposited energy in PSD. So the charge value from the four sub-layers in PSD is related to the deposited energy in BGO, which is

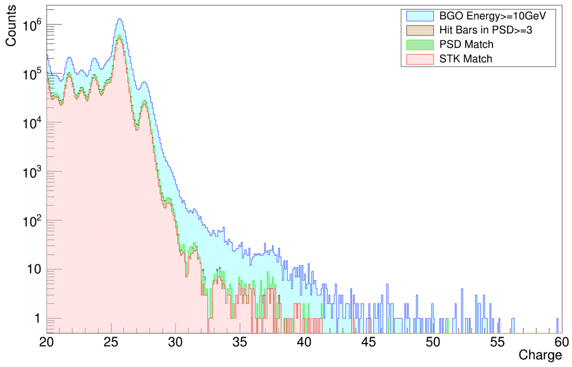
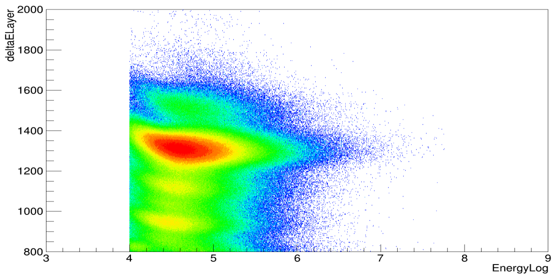
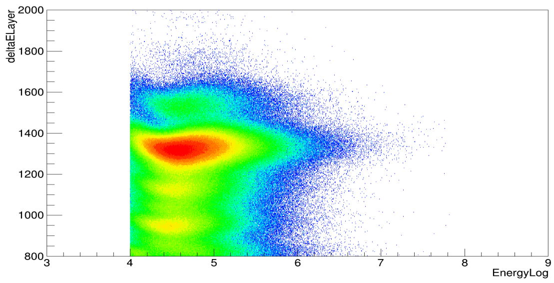


Figure 3: The effect on charge spectrum of the cuts on BGO energy, and in PSD and STK.

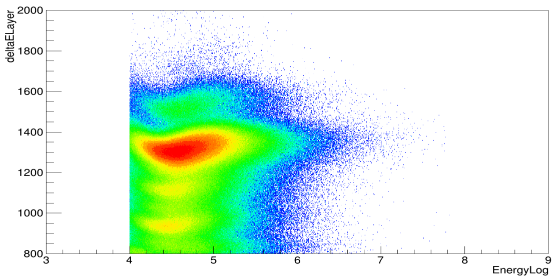
shown in Fig.4. This effect will then affect the measurement of charge. A method which could be used to correct this phenomenon is necessary.



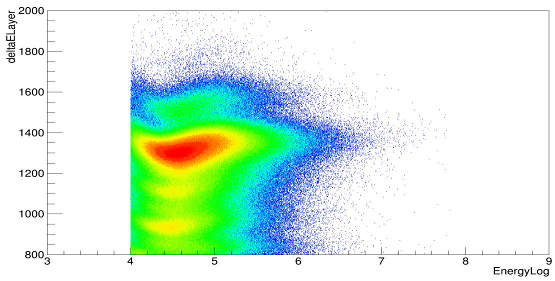
(a) layer 0



(b) layer 1



(c) layer 2



(d) layer 3

Figure 4: Deposited energy (MeV) in different PSD layers by heavy nuclei versus BGO energy (MeV) logarithm.

Firstly, the range of logarithm of deposited energy is divided into several bins. In each bin, a Gauss function is used to fit the iron peak.Then the peaks of iron in different bins are used to describe the relationship between the deposited energy in PSD and in BGO. Since the primary energy of the particle is not directly expressed by the BGO energy, a smooth piecewise function is used for fit instead of Bethe-Bloch formula. The fit function consists of a fifth order polynomial multiplied by fractions related to BGO energy, a third order Hermit series and a formula approximately following the logarithmic law. The four sub-layers in PSD are fit separately because of the different behavior in each one. As shown in Fig.5, this function fit well these behaviours in the four sub-layers. Finally such phenomenon disappears when the correction is applied, as shown in Fig.6.

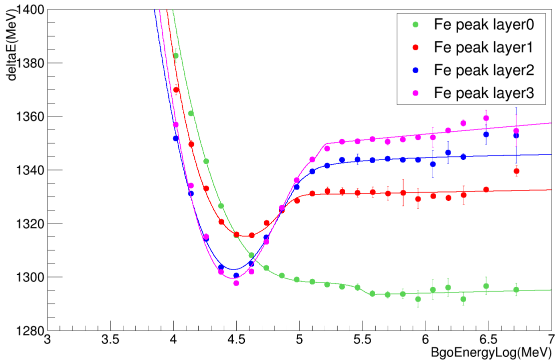
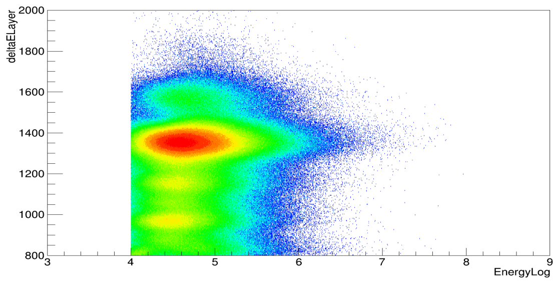
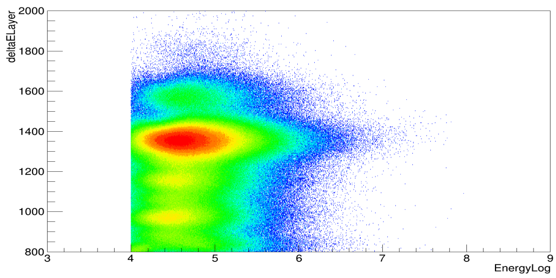


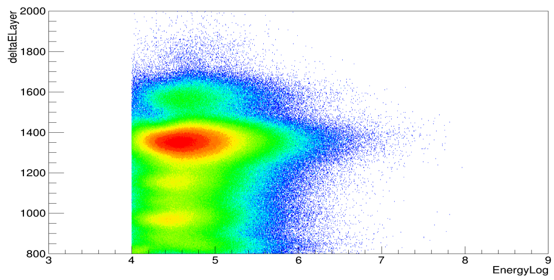
Figure 5: The points of different color mean MPV of deposited energy by iron versus BGO energy logarithmic in different layers of PSD. The line is the fit function in different layers.



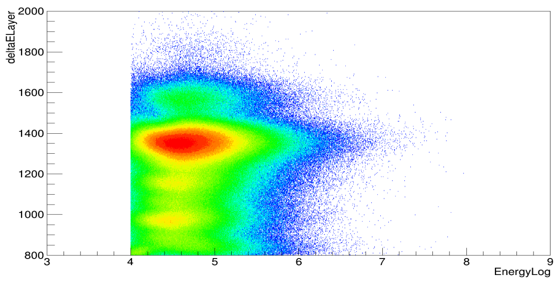
(a) layer 0



(b) layer 1



(c) layer 2



(d) layer 3

Figure 6: The energy deposited (MeV) in different PSD layers by heavy nuclei versus BGO energy (MeV) logarithm after correction.

3.3.2 PSD uniformity

Heavy nuclei show different patterns of PSD signal as a function of hit position along bars. This feature is caused by the light reflecting material (Tyvek) which was not uniformly wrapped on the scintillator bar surface, thus producing tiny wrinkles. This variation could be removed by using an empirical method[11]. Besides, there are some small differences on peak position of iron among different PSD bars. Also this non-uniformity could be removed by applying a proper additional correction.

4. Results and summary

After the above analysis, a preliminary result about the charge spectrum of elements ($20 \leq Z \leq 40$) could be obtained. Thanks to these corrections, the charge resolution is improved to 0.27e for iron. This is a crucial prerequisite for next analysis of relative abundance and flux energy spectrum of heavy nuclei beyond iron in cosmic rays.

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