PROCEEDINGS OF SCIENCE

Study of hadronic cross-sections with cosmic ray Carbon from GeV to TeV by the DAMPE experiment

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The DArk Matter Particle Explorer (DAMPE) is a satellite-borne particle detector launched on December 17th, 2015, with different scientific objectives, looking for signatures of Dark Matter decay or annihilation, performing gamma-ray astronomy and providing precise measurements of galactic Cosmic Ray (CR) energy spectra. Accurate measurements of hadronic interaction cross sections play a key role in the determination of CR fluxes. The survival probabilities have been implemented to study hadronic interaction cross sections with the BGO calorimeter target for Carbon nuclei in a wide kinetic energy range from a few GeV to TeV, by using data collected by the DAMPE experiment. The results have been then compared with Geant4 simulations of the interaction cross-sections performed by adopting the Glauber–Gribov Model. The details of the measured hadronic interaction cross sections are here presented and discussed.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

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1. Introduction

The DArk Matter Particle Explorer (DAMPE)[1] satellite is a Chinese space mission designed to study cosmic rays(CRs), gamma rays, and electrons in space. It was launched into a Sun-synchronous orbit around the Earth at an altitude of 500 km on December 17, 2015, and operated until now. The primary goal of DAMPE is to indirectly search for dark matter by studying the high-energy cosmic rays and gamma rays in space. It focuses on the detection and measurement of electrons and photons[2] with high precision and energy resolution.The DAMPE also measures CRs protons, helium and other nuclei[3-5] to understand the origin, propagation and acceleration mechanisms by studying the properties of these CRs. The hadronic interaction cross sections play a key role in the determination of cosmic ray(CR) fluxes. In this work we present the analysis procedure for cross section on BGO target and specifically the survival probability measured by means of flight data(FD) and simulation models.

2. DAMPE detector

The DAMPE detector [6] consists of a Plastic Scintillator strip Detector (PSD) [7] for charge measurement of incident particles, a Silicon-Tugsten tracKer (STK) [8] to reconstruct the trajectories of the particles, a Bismuth Germanium Oxide(BGO) [9] calorimeter to provides the measurement of energy and a powerful electron-hadron discrimination, and a NeUtron Detector (NUD).

DAMPE's BGO calorimeter is a total absorption calorimeter.It is composed of 308 BGO crystal bars , which enable accurate and detailed three-dimensional imaging of the shape of particle showers. The BGO calorimeter in DAMPE comprise 14 layers, providing 32 radiation lengths and 1.6 nuclear interaction lengths. Each layer consists of 22 BGO crystal bars, with dimensions of 25×25×600 mm^3. These crystal bars are arranged within the calorimeter and serve to measure the energy deposited by particles. The key parameters of the BGO calorimeter are listed in Table I.

The FD used for the analysis described in this work were taken from January 1^{st}, 2016 to December 31^{st}, 2022. The number of collected events per day is about 5 millions, and the FD taking mode of DAMPE is very stable[10]. The Monte Carlo(MC) simulation for carbon and oxygen nuclei is based on Geant4[11] that is the main simulation engine for DAMPE experiment. The model of Geant4 used for this analysis is FTFP_BERT(Hadronic Model) and the energy range is from 10 GeV to 100 TeV. The FLUKA[12] simulation software has been also used to generate MC data from 100 GeV to 100 TeV.

Active area	$60 \times 60 \quad cm^2 (on-axis)$
Radiation lengths	$32X_0$
Nuclear interaction length	$\sim 1.6\lambda_I$
Longitudinal segmentation	14 layers

Table 1: BGO specifications

3. Measurement of survival probability

The BGO calorimeter below the PSD and STK is composed by weight of 56.47% Bismuth, 14.73% Germanium, 16.21% Oxygen, 9.2% Carbon elements and small amount of other elements . When N_{in} incoming nuclei enter the BGO, and N_{out}^{sur} nuclei survive without hadronic interaction, their ratios is the survival probability ε_{sur}, and depends on the amounts of materials and interaction cross sections in exponential form[13]. It can be estimated in the following way:

$$\varepsilon^{sur} = \frac{N_{out}^{sur}}{N_{in}} = exp(-n\sigma_{had}) \tag{1}$$

where n refers to the number of targets per area, which is the weight average of different path lengths of particle through BGO layers on incident direction. σ_{had} is the hadronic interaction cross sections on BGO target.

3.1 Measurement of carbon survival probability

The CRs pass through DAMPE from PSD to BGO. The following selection criteria are applied in order to select the samples. The first is a fiducial cut, which decides the effective geometric volume of the DAMPE detector from the top PSD Layer to the bottom BGO Layer. The track-finding algorithm reconstructs the precise track in the STK to calculate the path length in the BGO. The charge measurement is mainly provided by the PSD as shown in Fig.1. To further reduce the contamnation of other nuclei, like boron, the STK and BGO first layer are uesd to supply the charge measurement too. Fig.2 shows the charge distributions due to BGO measurement for FD and MC. The N_{in} was given by:

$$N_{in}^{Z=6} = N_{Z=6}^{PSD} \cap N_{Z=6}^{STK} \cap N_{Z=6}^{BGO\_1^{st} layer} \tag{2}$$

The contamination of carbon $N_{in}^{Z=6}$ from other nuclei was estimated to be ~2% for deposited energies around 100 GeV and ~10% around 50 TeV. The N_{out}^{sur} is further selected by BGO second and third layers to measure the survival probability that means no hadronic interaction if charge doesn't change. Fig.3 a) shows the measured carbon survival probabilities between second and third of BGO as functions of kinetic energy for FD and different simulation models, as well as their ratio. There are a significant discrepancies between MC and FD, but the discrepancies between FLUKA and FD is smaller than that between Geant4 and FD. Due to the insufficient absolute resolution of the BGO charge, we cannot fully distinguish events without hadronic from events where the CR interacts in BGO.

3.2 Measurement of oxygen survival probability

The survival probabilities of oxygen (Z=8) was analyzed in the same way. Fig.3 b) shows the measured survival probabilities of oxygen for FD and MC, as well as their ratio of MC to FD.

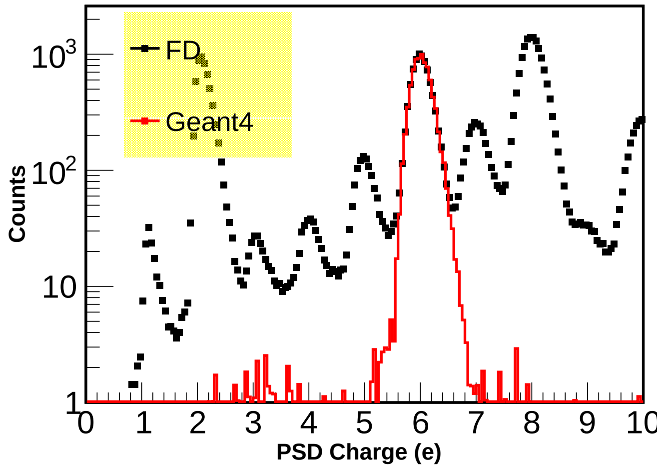


Figure 1: Spectrum of the charge from 0 e to 10 e. A significant suppression of the proton is due to selection of STK.

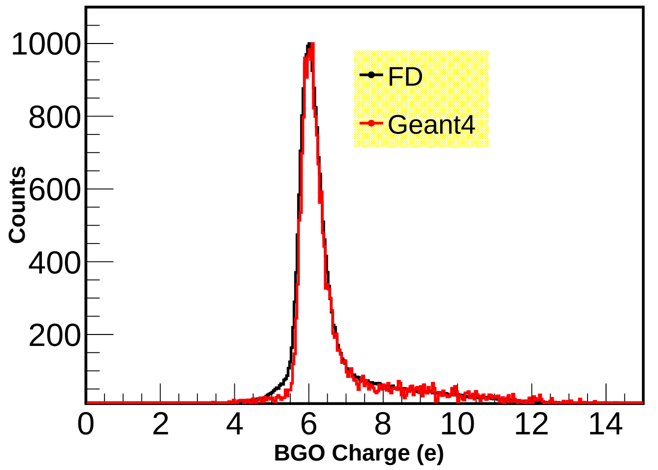
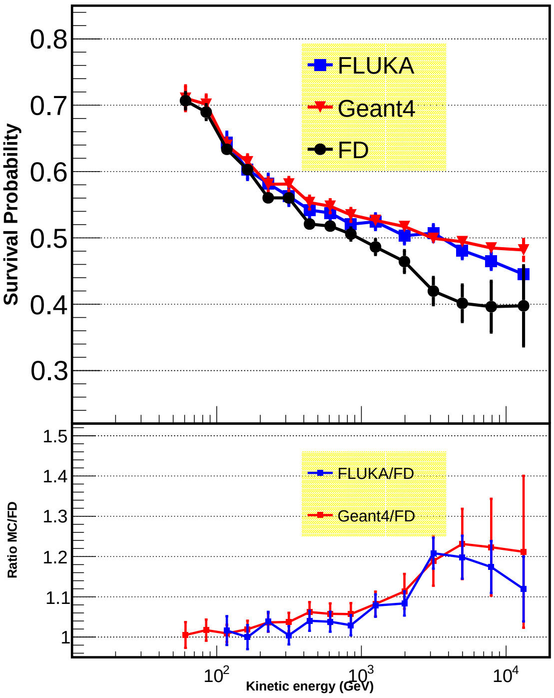
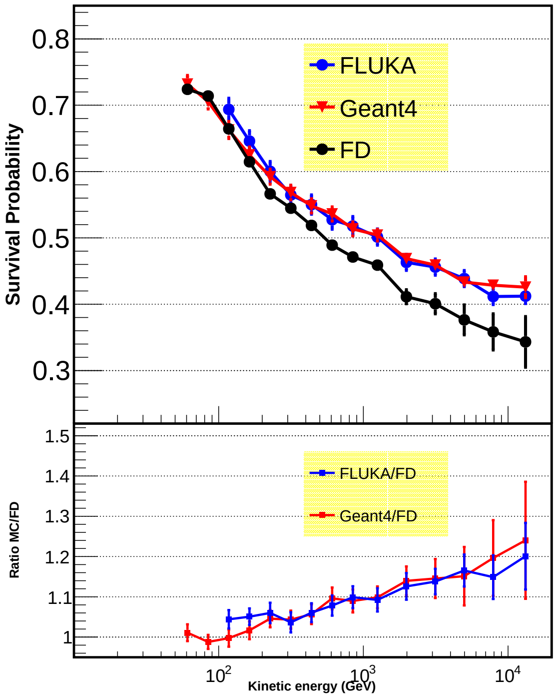


Figure 2: Spectrum of 1^{st} BGO layer charge of FD was selected Z=6 by PSD and STK.



(a)



(b)

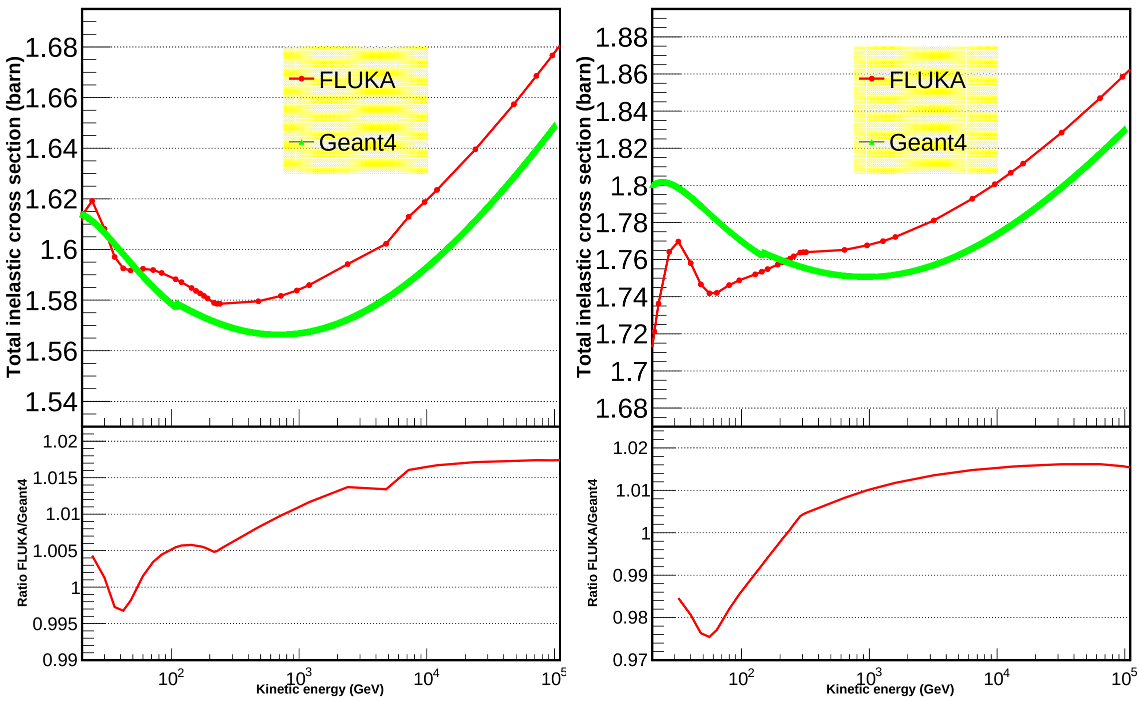
Figure 3: The survival probabilities of a) C and b) O for FD (black circles), Geant4 (green triangles) and FLUKA (blue squares). The difference between simulation models and FD expressed by the ratio as a function of kinetic energy (bottom figures).

4. Measurement of cross sections

The inelastic hadronic cross sections σ_{had} of carbon and oxygen for Geant4 (FTFP_BERT) and FLUKA are shown Fig.4. The inelastic cross sections of FLUKA is larger than Geant4 of ~ 1 % and for oxygen around 100GeV is the opposite.The measured MC survival probabilities reflect the fact that the survival probabilities is inversely correlated with the cross sections. Particularly for oxygen, both models exhibit a tendencies consistent with the measured survival probabilities, with the cross sections showing opposite performance at low and high energy. So, the DAMPE measured survival probabilities measured can describe the physical variable of hadronic cross sections according to the formula.

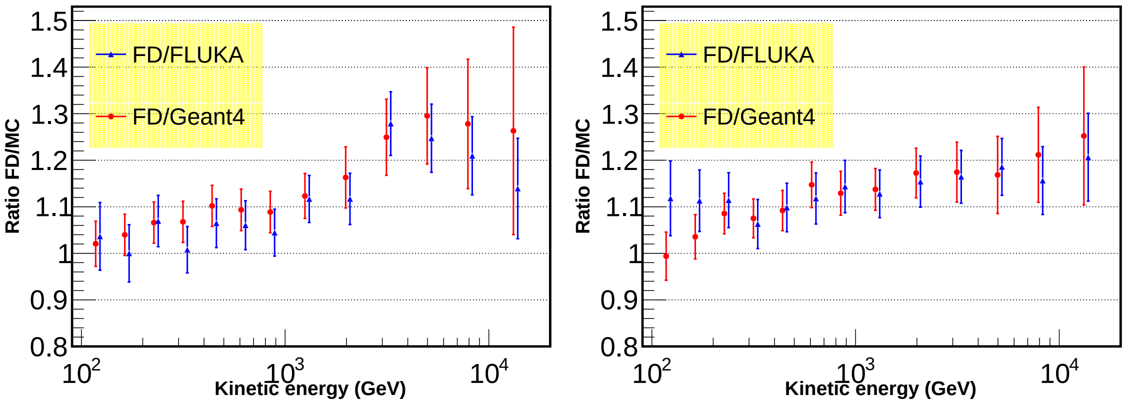
$$\zeta_{ratio} = \frac{\sigma^{FD}_{BGO}}{\sigma^{MC}_{BGO}} = \frac{ln(\varepsilon^{FD}_{BGO})}{ln(\varepsilon^{MC}_{BGO})} \tag{3}$$

Fig.5 shows the FD/MC ratios of hadronic cross sections of carbon and oxygen with systematic uncertainties. The cross sections of FD are even higher than the difference between the simulation models. The main systematic uncertainty is from method of this study and evaluated using MC. The inelastic hadronic cross sections of proton and helium presented in Ref. [14].



(a) (b)

Figure 4: The inelastic hadronic cross sections on BGO target for a) C, b) O as functions of kinetic energy for simulation models, as well as their ratios.



(a) (b)

Figure 5: The ratio of inelastic hadronic cross sections on BGO target between FD and simulation models for a) C, b) O as functions of kinetic energy for simulation models (I shift X-axis of FLUKA to make it easier to distinguish).

5. Summary

In this work, we measured the survival probabilities of carbon and oxygen in BGO calorimeter and they results to be greatly consistent with the hadronic cross sections. The cross sections of FD is larger than simulation models with significant systematic uncertainties.

6. Acknowledgement

The DAMPE mission is funded by the Strategic Priority Science and Technology Projects of CAS. In China the data analysis is supported by the National Key Research and Development Program of China (No. 2022YFF0503303), the National Natural Science Foundation of China (No. 12275266, No. 11673021, No. U1738205, No. U1738208, No. U1738139, No. U1738135, No. 11705197, No. 11851302), the strategic priority science and technology projects of Chinese Academy of Sciences (No. XDA15051100), the Youth Innovation Promotion Association CAS (Grant No. 2021450), the Outstanding Youth Science Foundation of NSFC (No. 12022503), the CAS Project for Young Scientists in Basic Research (No. YSBR-061). In Europe the activities and data analysis are supported by the Swiss National Science Foundation (SNSF), Switzerland, the National Institute for Nuclear Physics (INFN), Italy, and the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (No.851103).

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