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Searching for fractionally charged particles with DAMPE

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The existence of fractionally charged particles (FCP) is foreseen in some extensions to the Standard Model of particle physics, and their detection would be a significant breakthrough. Most of the previous cosmic-rays (CRs) studies are mainly focused on the secondary CRs from the extensive air shower, but there is rarely on-orbit study to search FCP from primary CRs. The DArk Matter Particle Explorer (DAMPE) was launched into space on the 17th December 2015, and it has been working well in space for more than five years with the purpose of measuring CRs and gamma-rays, and as today a large amount of scientific data has been acquired. The FCP is assumed to be a heavy lepton, as a result, the Minimum Ionized Particles (MIPs) are selected. The Geant4 simulations toolkit is used to investigate the signal region and to evaluate selection efficiency of 2/3 FCP in DAMPE. The detailed selection methods are presented and discussed in this work.

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1. Introduction

In early 19th century, the Millikan Oil's drop experiment showed that all charged particles have multiples charge of electron charge [1]. Then the Quark Model by Gell-Mann [2] and Zweig [3] proposed in 1964 that quarks have fractional charge of one third and two third. With the help of accelerators, many searches for free quarks have been studied. But due to the color confinement of QCD theory, the FCP will not exist freely. The current research in this field looks for any free fractional charge particles.

The FCP is generally assumed as heavy lepton which will interact with materials through ionization and without hadronic or electromagnetic process. As a result, the minimum ionized particles (MIPs) is a possible feature of FCP. There are three possible sources of FCP in cosmic rays as Figure 3 shows [4]:

- **First**, it may be produced at the early Universe after the Big Bang and remains in some bulk matter.
- **Second**, it may be produced through high-energy astrophysical processes.
- **Third**, it may be produced in the extensive air shower of cosmic-rays.

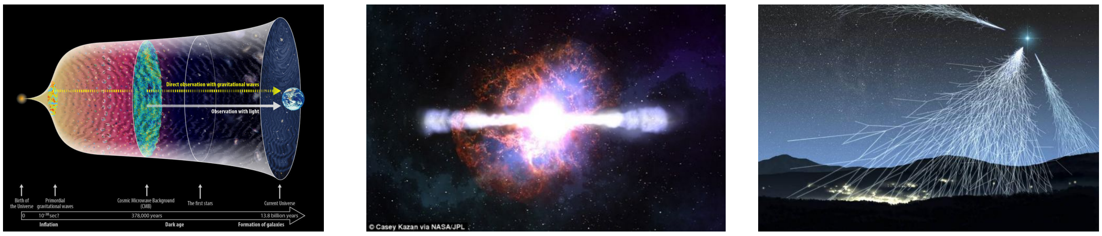

Figure 1: The possible sources of FCP in cosmic rays. From left to right, the figures illustrate the soures of early universe, celestial activities, and extensive air shower.

Table 1: The results from some typical experiments

	Experiments	Upper limit $(cm^{-2}sr^{-1}s^{-1})$
Underground	LSD	2.7×10^{-13}
	Kamiokande II	2.1×10^{-15}
	MACRO	6.0×10^{-16}
In-space	AMS01	3.0×10^{-10}
	BESS	4.5×10^{-10}

Table 1 shows the results of some typical experiments for searching FCP from CRs [4]. Relying on the large acceptance and long duration time, the apparatus underground obtained relatively strict upper limit than the experiments in space while the acceptance and time are shortages. The DArk Matter Particle Explorer (DAMPE) has relatively larger acceptance and has been working well in space for more than five years with the purpose of measuring CRs and gamma-rays and as today a large amount of scientific data has been acquired. It can help to find FCP from CRs as an on-orbit experiment.

2. DAMPE instrument

DAMPE is a satellite-borne experiment funded by the Chinese Academy of Sciences, was launched into a sun- synchronous orbit at an altitude of 500 km in December 2015 from the Jiuquan Satellite Launch Center. The scientific objectives of DAMPE include searching for the signature of dark matter particles, understanding the mechanisms of particle acceleration operating in astrophysical sources, and studying gamma-ray emission from Galactic and extra-galactic sources [5].

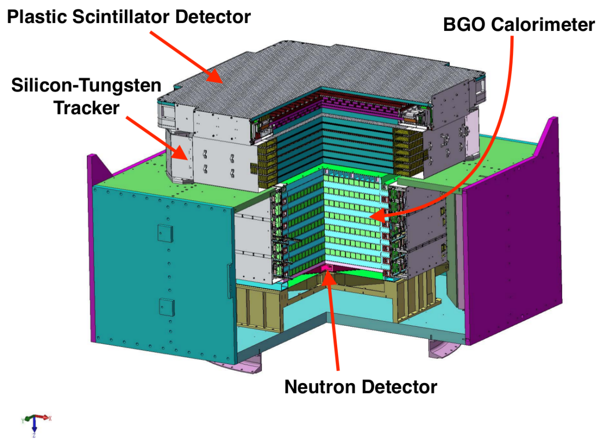

Figure 2: Side view of DAMPE instrument

DAMPE, as shown in Figure 2, consists of four sub-detectors. From top to bottom, they are the Plastic Scintillator Detector (PSD), Silicon-Tungsten tracKer (STK) Bismuth Germanium Oxide (BGO) calorimeter, and NeUtron Detector (NUD). Charge reconstruction is based on Bethe-Bloch Formula. The energy deposited in the PSD and STK is related to the square of particle charge. The PSD and STK achieve good charge resolutions. Figure 3 shows the capability of charge discrimination of PSD in Z from 1 to 28. Figure 4 shows the charge resolution of STK with the charge correction for proton and helium nuclei [6].

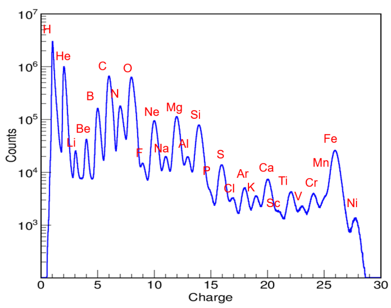

Figure 3: The charge discrimination of PSD in Z from 1 to 28

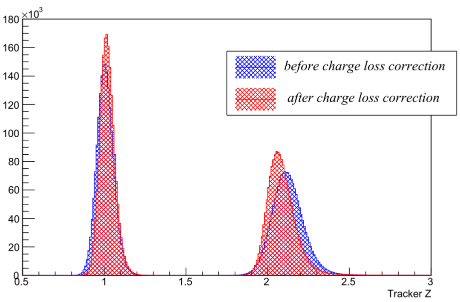

Figure 4: The charge resolution of STK with correction

3. Method of searching FCP with DAMPE

Since the designed trigger threshold of MIPs is 0.2 MIPs [7] which is larger than the $\frac{1}{3}$ charged particles($\frac{1}{9}$ MIPs), this work looks for the $\frac{2}{3}$ charged particles with the following criteria:

- **Fiducial cut**: Geometry angle, latitude restrictions, good track, energy deposition.
- **Angle difference**:Remove the scattered events
- **MIPs selections**:
  - Constrain the fired detector cells in PSD and BGO
  - Require the track going through the PSD strips
  - Require the event penetrate the whole BGO calorimeter
- **PSD end charge ratio**: Maintain the reliability of PSD charge reconstruction
- **STK charge**: Select the good cluster to reconstruct the charge

An MIP event is reconstructed under DAMPE framework and displayed in Figure 5.

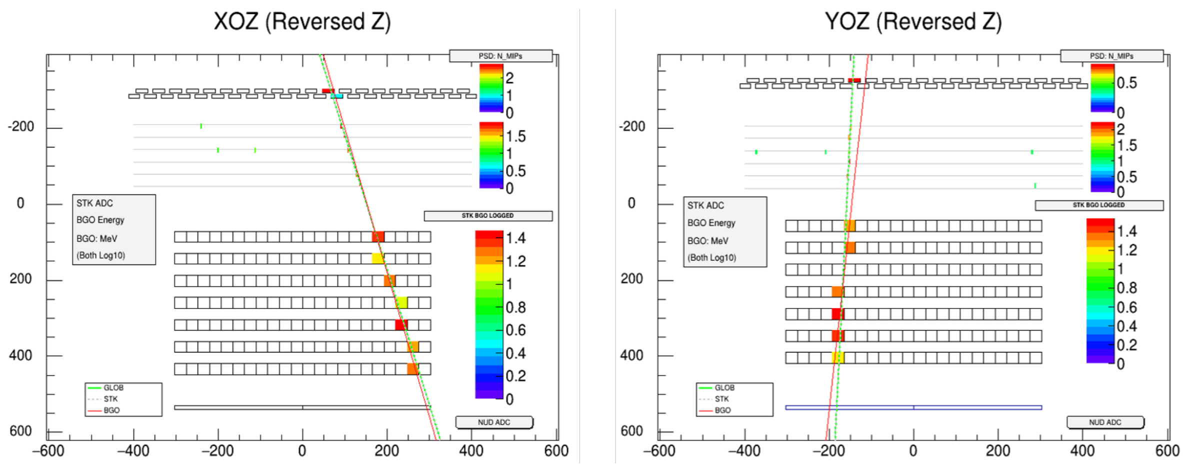

Figure 5: A MIP event reconstructed in DAMPE detector

The background of FCP in space is mainly from the proton MIPs. The DAMPE official proton simulation data is used for analyzing the background. In order to study the response of DAMPE to FCP, a particle with $\frac{2}{3}e$ charge value is simulated within the DAMPE software. After applying these selections, the charges in both the PSD and STK are reconstructed as shown in Figure 6. Thanks to the good charge resolution of DAMPE, a good discrimination between $\frac{2}{3}$ FCPs and singly charged particles is possible.

The signal region can be defined by PSD and STK proton MC as the red lines shows in picture a in Figure 7, the charge of two lines are set to 0.8 e which is about 5 sigma value smaller than the mean value of Gaussian fit to the charge. At the same time, the signal region is also applied to FCP MC and the signal region has a 68% efficiency of covering the FCP.

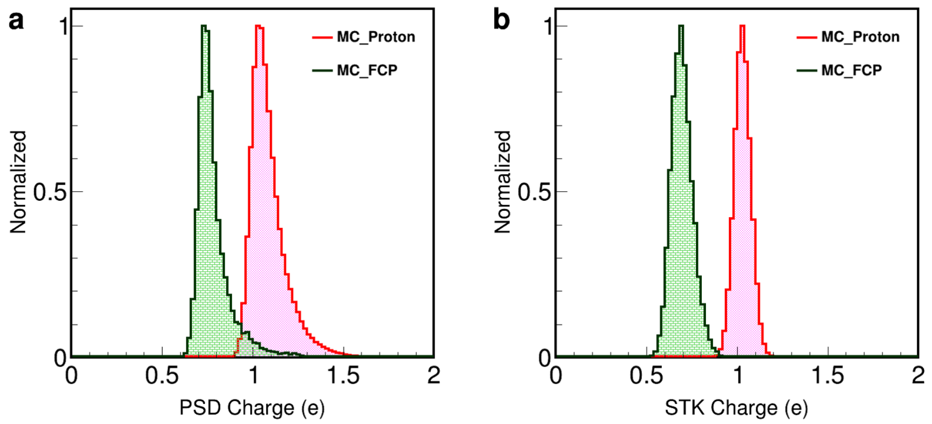

Figure 6: The charge reconstruction of a) PSD and b) STK for proton and FCP MC

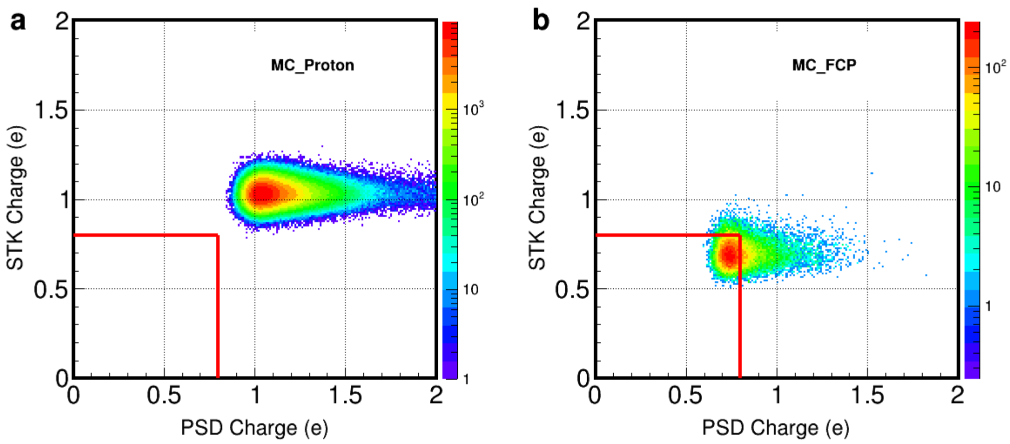

Figure 7: The charge distribution in two dimension of PSD-STK of a) proton MC and b) MC FCP

4. summary

The DAMPE instrument, in orbit since 17 Dec. 2015, has a good charge discrimination thanks to its PSD and STK sub detectors, so it can be used to search for Fractionally Charged Particles. The selection criteria to search FCP with DAMPE have been studied, a MC simulation has been performed and an evaluation of the search efficiency has been carried out.

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