

Recent Progresses of the DAMPE Mission*

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Abstract The Dark Matter Particle Explorer (DAMPE) is a space high-energy particle and γ -ray detector whose major scientific goals are the indirect detection of dark matter particles, the origin of cosmic rays and high-energy γ -ray astronomy. Since its successful launch in December, 2015, the DAMPE has been operated smoothly in orbit for more than 10 years. The precise measurement of the secondary boron spectrum reveals a spectral hardening with a very high significance. The spectra of five primary cosmic-ray nuclei, *i.e.* protons, helium, carbon, oxygen, and iron, are measured to unprecedented high energies, revealing the universal charge-dependent spectral softening for the first time. The energy spectrum of nickel is firstly measured to above TeV/n. The Fermi bubbles and GCE are detected in the γ -ray flux map at very high significances. The DAMPE measurements are expected to significantly advance our understanding of the fundamental problems in astroparticle physics.

Key words DAMPE, Dark matter, Cosmic rays, γ -ray

Classified index P35

1 Introduction

It is now well established from precision cosmological observations that the Universe is composed of approximately 4.9% baryonic matter, 26.8% Dark Matter (DM), and 68.3% dark energy^[1]. Uncovering the physical nature of dark matter remains one of the most fundamental questions in modern physics. Since the discovery of the existence of DM, many types of new candidate models have been proposed by the theoretical physicists. Among them, Weakly Interacting Massive Particles (WIMPs) represent one hypothesized class of particles beyond the Standard Model of particle physics, strongly motivated by the relic abundance of dark matter and the bottom-up evolution of the large-scale structures of the Universe^[2,3]. Extensive experimental efforts have been

devoted to searching for WIMPs, including direct detection of WIMP-nucleon scattering with underground detectors, indirect detection of annihilation or decay products in cosmic radiation, and searches for WIMP pair production at high-energy particle colliders^[4]. Despite several decades of dedicated investigation, no conclusive evidence has yet been obtained. Particularly, the direct detection experiments push the WIMP-nucleon scattering strength to a very low level^[5], which has already severely constrained a series of WIMP models.

It is noteworthy that some unexpected anomalies have been revealed in recent Cosmic Ray (CR) and γ -ray observations, such as the cosmic-ray positron flux excess discovered by PAMELA^[6], Fermi-LAT^[7], and AMS-02^[8], and the associated total Cosmic Ray Electron plus positron (CRE) flux excess detected by

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ATIC^[9], Fermi-LAT^[10], AMS-02^[11], DAMPE^[12] and CALET^[13]. Those observed positrons and CRE flux excesses can be explained either by astrophysical sources such as pulsars or by DM annihilation or decay^[14–18]. However, current observational data are limited by detection precision and energy range, making it impossible to identify the physical origin. Higher precision measurements in a wider energy band are thus crucial to draw a definitive conclusion. Other anomalies in high-energy observations, include the γ -ray excess in the Galactic center^[19], and potential excess of CR antiprotons^[20,21], are also related to the indirect detection of DM.

The Dark Matter Particle Explorer (DAMPE) mission is designed to search for potential annihilation or decay signatures of DM in high-energy CREs and γ -rays, benefiting from unprecedentedly high energy resolution and strong background rejection power^[22–24]. Beyond this primary goal, DAMPE serves as a general-purpose high-energy particle detector for observations of CR nuclei and γ -rays, making it particularly valuable for studying high-energy astrophysical phenomena and CR physics^[23]. Since launched into a 500 km Sun synchronous orbit on 17 December 2015, the DAMPE satellite has kept an excellent performance and operated stably in space for more than 10 years. The daily event rate of DAMPE is about 5 million, and it has recorded in total over 18 billion CR events as of May 2026, most of which are CR nuclei.

2 Detector and On-orbit Performance

The DAMPE instrument consists of four sub-detectors^[23], which are, the Plastic Scintillator strip Detector (PSD^[25]), the Silicon-Tungsten tracker-converter (STK^[26]), the $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ (BGO) imaging calorimeter^[27], and the Neutron Detector (NUD^[28]), as shown in Figure 1. The PSD, composed of 82 organic plastic scintillators arranged in double layers, is to measure the electric charge of incident particles from protons ($Z=1$) up to heavy nuclei ($Z>30$) via the ionization effect. It also provides charged-particle background rejection for the γ -ray observation. The STK, composed of 12 silicon strip layers, is to measure the trajectories of incident particles with a very high angular resolution. It can also measure

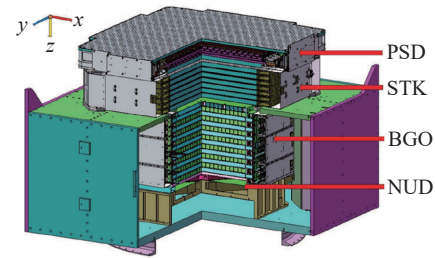


Fig. 1 Schematic plot of the DAMPE detector^[23]

the charge of light nuclei ($Z<8$). The BGO calorimeter, composed of about 32 radiation lengths of BGO scintillation crystals arranged hodoscopically in 14 layers, is to precisely measure the energy deposition and distinguish between electromagnetic and hadronic particles by imaging the 3D profile of the shower development. The NUD at the bottom is to provide additional electron/hadron discrimination by measuring the secondary neutrons mainly produced in hadronic showers rather than in electromagnetic ones.

Dedicated calibration of each unit of the detector has been done using the on-orbit data^[29], which enables precise measurements of the physical quantities of each event. The charge resolution of the PSD is about $0.20e$ (e represents the electron charge) for $Z=8$ (Oxygen) and $0.30e$ for $Z=26$ (Iron)^[30]. Such a good charge resolution is the basis of precise spectral measurements of each species. The angular resolution of the STK is well calibrated using the bright γ -ray sources, which is better than 0.2° for energies higher than 10 GeV^[31].

The considerable thickness of BGO calorimeter, i.e., 32 radiation lengths, ensures that the electromagnetic showers can be well contained without significant energy leakage from the bottom, even at energies up to the TeV scale. The comparisons of beam test data and MC simulations verify that the energy resolution for CREs of DAMPE is better than 1.2% for energies above 100 GeV^[32].

3 Scientific Results

Figure 2 shows the separate CR electron and positron spectra and the positron fraction in the energy range from 10 to 20 GeV measured with the geomagnetic field on DAMPE^[33]. As the DAMPE detector does not carry an onboard magnet, the geomagnetic field is used to dis-

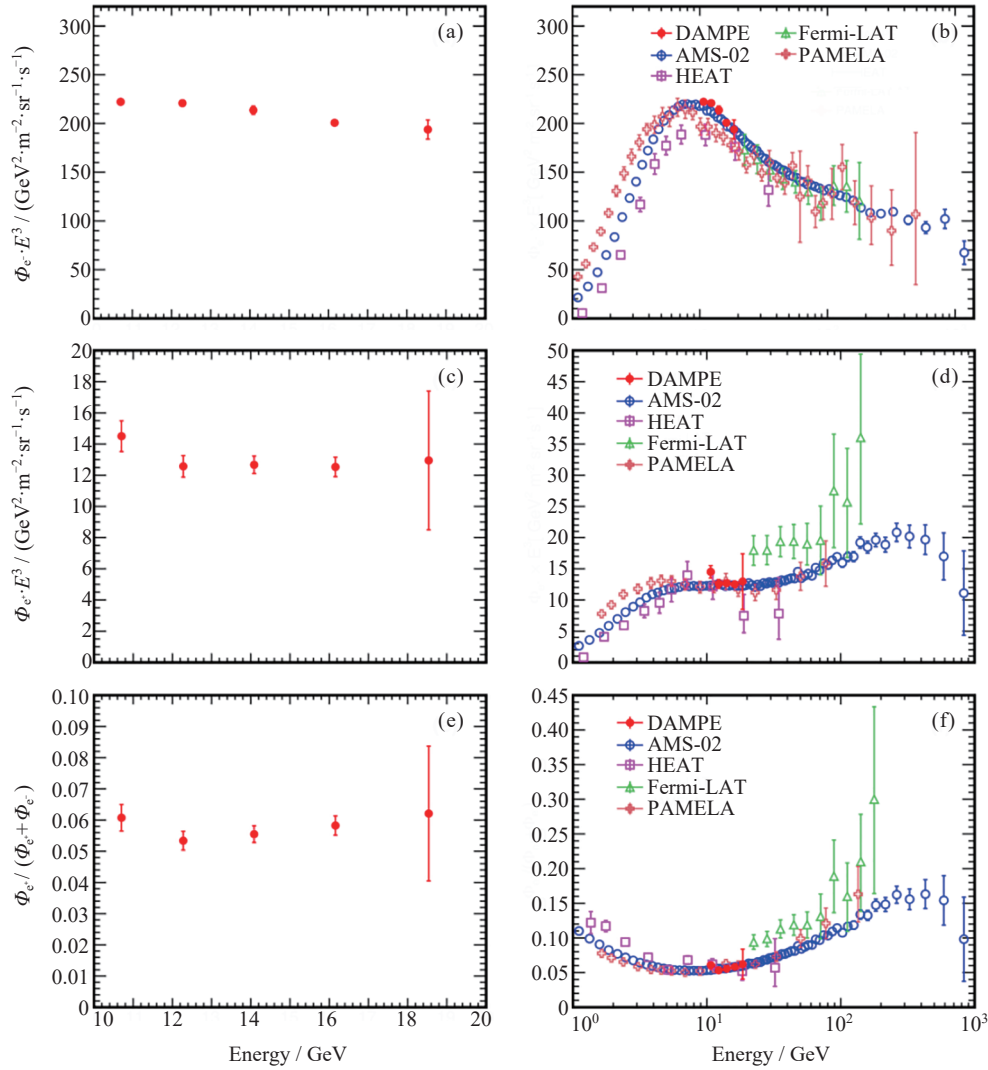


Fig. 2 CR electron spectrum (a), positron spectrum (c) and positron ratios (e) measured by DAMPE. Previous measurements from other experiments are presented for comparisons in (b)(d)(f)

tinguish CR electrons and positrons based on their opposite deflections. The effective energy range of this method is currently limited at high energy by the zenith-pointing orientation of DAMPE. The DAMPE results in the energy range from 10 to 20 GeV are consistent with previous measurements by AMS-02 and PAMELA. In addition, by employing a similar geomagnetic separation technique as that used by the Fermi collaboration, this analysis helps fill the gap in the lower energy region that is not covered by Fermi-LAT.

Figure 3 shows the direct measurement of the secondary CR boron spectrum from 10 GeV/n to 8 TeV/n with 8 years of data collected by DAMPE, with high statistics and well controlled systematic uncertainties^[34].

Boron nuclei in cosmic rays are believed to be mainly produced by the fragmentation of heavier nuclei, such as carbon and oxygen, *via* collisions with the interstellar matter. Therefore, the precise measurement of the boron spectrum is an essential probe to study CR propagation. The measured spectrum shows a hardening at 182 ± 24 GeV/n with a spectral index of -3.02 ± 0.01 before the break and an index change of 0.31 ± 0.05 after the break. A simple power law model is disfavored at a confidence level of 8σ .

For the first time, a spectral hardening is directly observed for the secondary CR nuclei. The spectral index change of 0.31 ± 0.05 suggests that secondary boron hardens about twice as much as primaries such as pro-

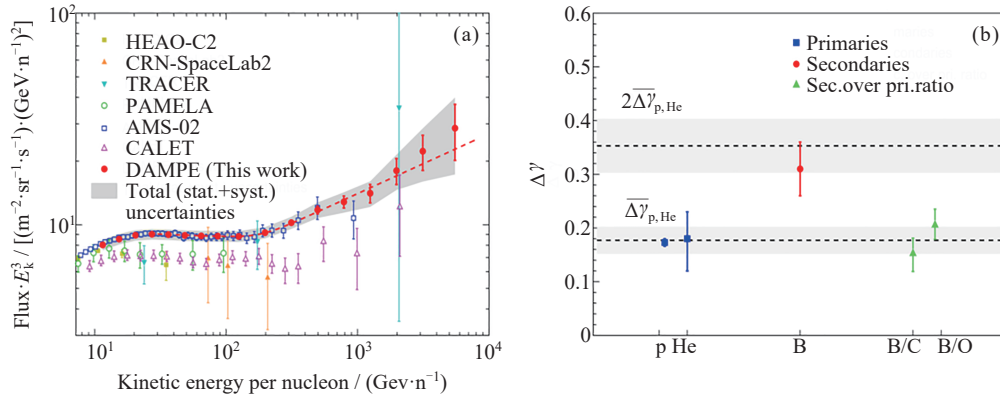


Fig. 3 CR boron spectrum as a function of kinetic energy per nucleon measured by DAMPE^[34] (red filled dots), compared with measurements from other experiments (a), and the spectral index change values of the hardening in the spectra of proton, helium, B/C, B/O, and boron measured with DAMPE^[34] (b)

ton and helium as previously measured by DAMPE^[35,36], as shown in Figure 3(b). The result is also consistent with the hardenings in boron-to-carbon and boron-to-oxygen flux ratios^[37], for case that carbon and oxygen show similar hardenings with protons and helium. Such an observational fact supports a propagation related mechanism to interpret the spectral hardenings of cosmic rays observed at hundreds of GeV/n. With the data accumulation of DAMPE, improved measurement of the boron spectrum with higher statistics and lower systematics is expected to extend to above 10 TeV/n in the future.

Figure 4 show the spectra of CR proton, helium, carbon, oxygen and iron measured with 9 years of on-orbit data collected by DAMPE^[38]. For the first time, distinct spectral softenings are directly detected in the spectra of carbon, oxygen and iron. The significance of the softening is 3.2σ , 4.1σ and 2.4σ with the break rigidity of (16.1 ± 5.6) TV, (15.4 ± 4.8) TV and (13.8 ± 6.0) TV for carbon, oxygen and iron, respectively. The updated proton and helium spectra yield softening rigidity at (14.6 ± 1.3) TV and (15.3 ± 2.3) TV, respectively. It has been established that the softenings occur at the same rigidity of about 15 TVs for all the five species, and the nuclei-mass-dependent softening is rejected at a confidence level of $>99.999\%$ (4.4σ), as shown in Figure 5. The universal softening feature in the spectra of primary CRs from protons ($Z=1$) to iron nuclei ($Z=26$) and the charge dependence of the softening energy indicate a common origin of the break due to acceleration.

Combined with large-scale anisotropy measure-

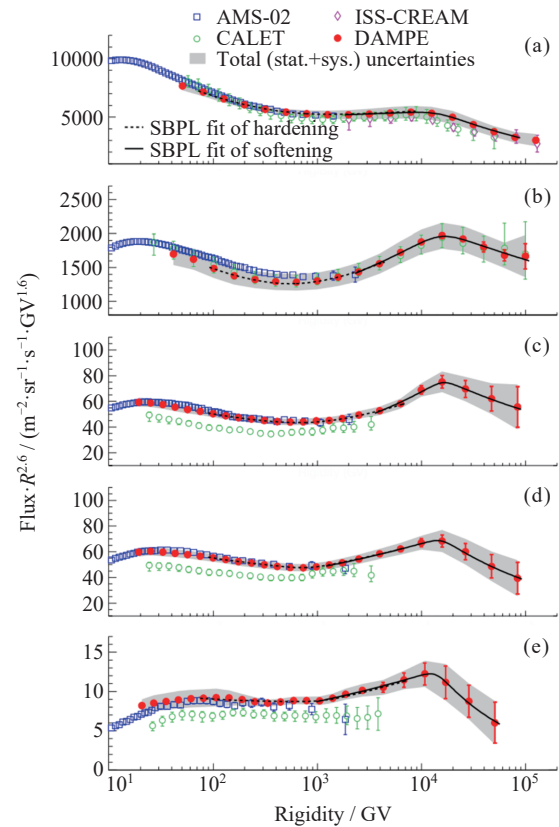


Fig. 4 Spectra of protons (a), helium (b), carbon (c), oxygen (d) and iron (e) measured by DAMPE (red filled dots)^[38], compared with measurements from other experiments

ments, the results indicate a nearby CR accelerator, with the universal spectral softening marking its charge-dependent energy upper limit. The DAMPE observation

provides the first direct experimental verification for the charge-dependent acceleration model first proposed in the 1960s^[39], offering a key clue toward solving the longstanding mystery of CR origin.

Figure 6 shows the CR nickel spectrum from 10 GeV/n to 2 TeV/n measured with 9 years of on-orbit data collected by DAMPE^[40]. Nickel is the most abundant heavy element beyond iron in CRs. With DAMPE's excellent charge resolution and broad energy range, the accurate measurement of CR nickel spectrum is directly extending to TeV/n for the first time. The nickel spectrum is consistent with a single power law with spectral index -2.60 ± 0.03 from 40 GeV/n to 1 TeV/n. In addition, the energy dependence of the nickel to iron flux ratio (Ni/Fe) is well described by a constant fit, which is structurally consistent with previous CALET measurements^[41] in the same energy range. The constant Ni/Fe abundance ratio in CRs further indicates the similar ori-

gin, acceleration and propagation mechanism for both elements. The accumulating experimental data of DAMPE would facilitate more precision measurements of nickel extending to higher energy in the future.

Figure 7 shows the detection of Fermi bubbles by DAMPE and the measurement of spectral energy distribution (SED)^[42]. With the 102 months of data collected by DAMPE, the Fermi bubbles are detected at a significance of $\sim 26\sigma$ from the observed γ -ray flux map above 2 GeV. The SED values measured by DAMPE are consistent with the results from Fermi-LAT^[43]. By the comparison of the fitting with Power-Law (PL) and Power-Law Cutoff (PLEC) models, a cutoff at ~ 200 GeV is detected with a significance of 3σ . The SED values of the northern and southern lobes are also measured separately and they are in excellent agreement, supporting the identical physical origin of the two lobes.

Figure 8 show the spectral measurement of the

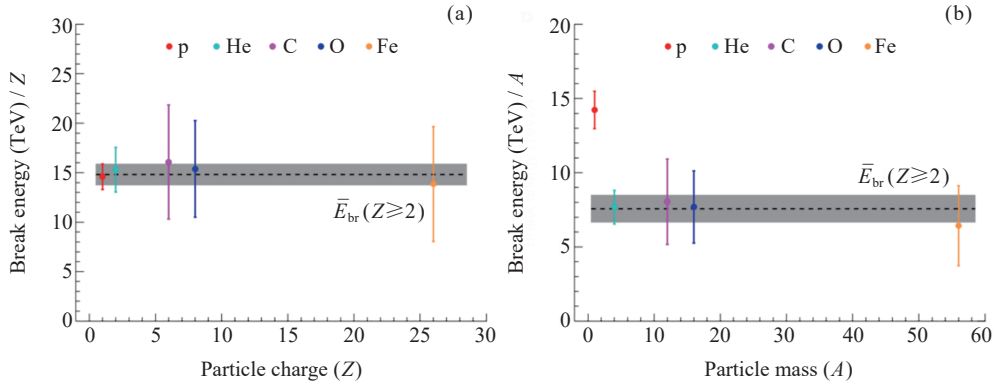


Fig. 5 Break energies for different species divided by particle charge Z (a) and particle mass A (b) ^[38]

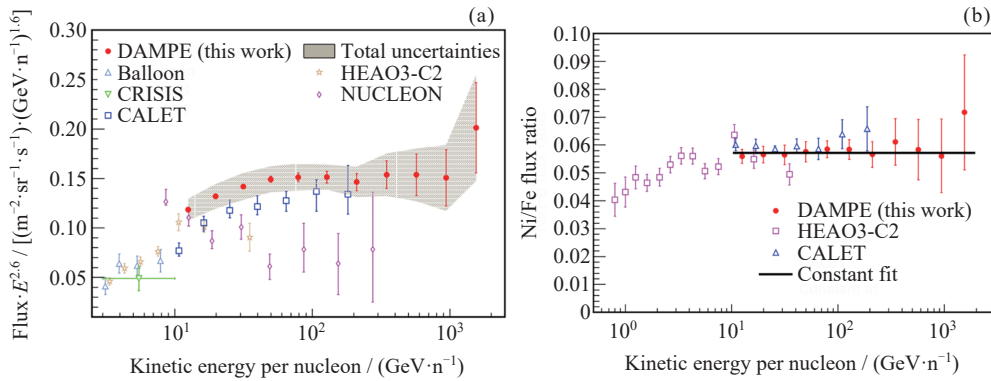


Fig. 6 CR nickel energy spectrum as a function of kinetic energy per nucleon measured by DAMPE^[40] (red filled dots), compared with measurements from other experiments (a), and the nickel to iron flux ratios measured by DAMPE (red filled dots) fit with a constant function (black line)^[40] (b)

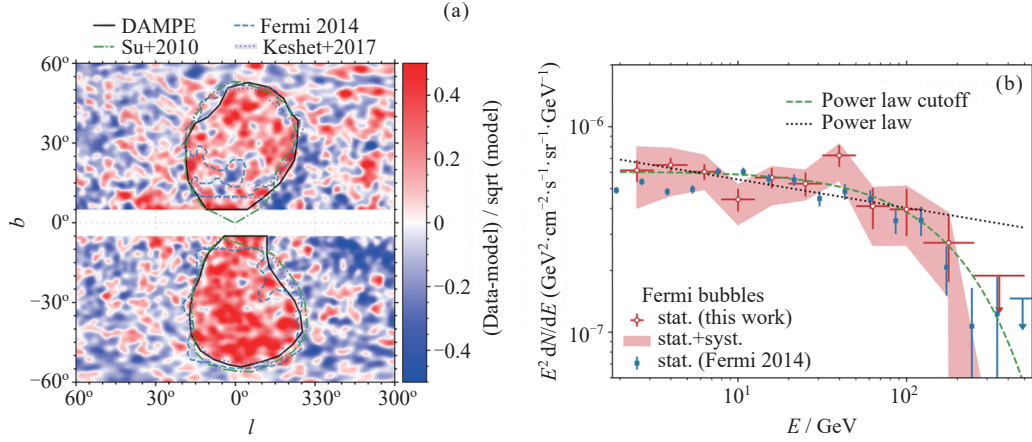


Fig. 7 Significance of the residual maps for the model without Fermi bubbles (a)^[42] and the SED of the Fermi bubbles measured by DAMPE^[42] (red points) compared the results from Fermi-LAT (b)^[43]

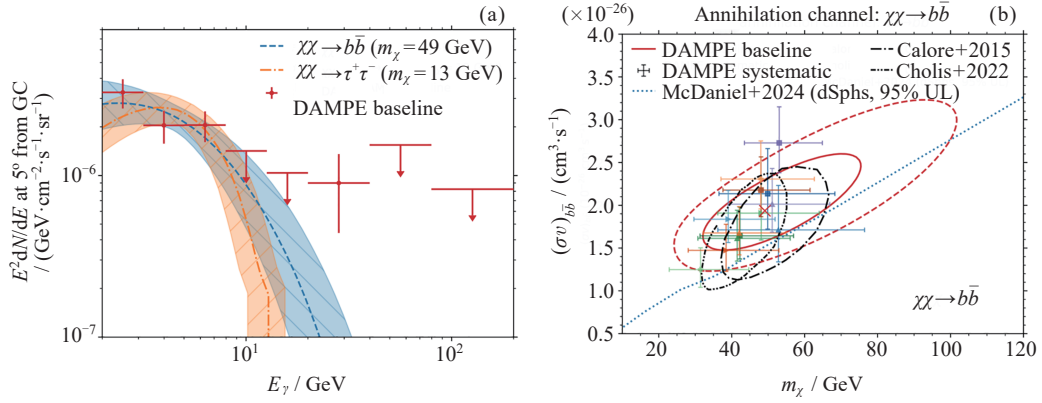


Fig. 8 Spectral measurement of the GCE by DAMPE (a) and the preferred DM parameter space for the annihilation channel $\chi\chi \rightarrow b\bar{b}$ (b)^[42]

Galactic Center Excess (GCE) by DAMPE and the preferred DM parameter space for the annihilation channel $\chi\chi \rightarrow b\bar{b}$ ^[42]. With the 102 months of data collected by DAMPE, the GCE is detected with a TS value of 80.1, which corresponds to a significance of 7.5σ with 8° of freedom. If the excess is explained with the DM annihilation into $b\bar{b}$, DM particles with mass $m_\chi = 49^{+16}_{-12}$ GeV and cross section $\langle \sigma v \rangle = (1.9^{+0.4}_{-0.3}) \times 10^{-26} \text{ cm}^3 \cdot \text{s}^{-1}$ is required. The DM parameter space is consistent with the Fermi-LAT^[44].

4 Summary

DAMPE has been operating smoothly in orbit for more than eight years. Based on the accumulated high-quality data recorded by DAMPE, multiple latest scientific re-

sults have been obtained, regarding CR physics and γ -ray astronomy. The precise measurement of the secondary boron spectrum reveals a spectral hardening with a very high significance, which provides important implications in understanding the CR propagation. The latest measurements of the spectra of five primary cosmic-ray nuclei, *i.e.* protons, helium, carbon, oxygen, and iron, provide the first direct experimental verification for the charge-dependent acceleration model. The energy spectrum of nickel is firstly measured to above TeV/n and a constant Ni/Fe ratio is observed. The Fermi bubbles and GCE are detected at very high significances, providing the first independent detection of these two intriguing diffuse γ -ray sources besides Fermi-LAT. In the near future, more scientific progresses from DAMPE are expected to shed new light on our understandings about

DM, CR origin and the high-energy Universe.

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Conflict of Interests The authors declare that there is no conflict of interests

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Author Biography



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