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Unique Properties of Primary Cosmic Rays: Results from the Alpha Magnetic Spectrometer

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We present the latest results on primary cosmic rays Proton (p), Helium (He), Carbon(C), Oxygen (O), Neon (Ne), Magnesium (Mg), Silicon (Si), Sulfur (S), Iron (Fe), and Nickel (Ni) with the data collected by the Alpha Magnetic Spectrometer (AMS) during the first 10 years of operation on the International Space Station from May 19, 2011 to May 6, 2021. We found that the primary cosmic rays He-C-O and Ne-Mg-Si belong to the two different classes of cosmic rays. Above 80.5 GV, the rigidity dependence of the cosmic-ray Fe and Ni fluxes is identical to the rigidity dependence of the He, C, and O fluxes, showing that Fe and Ni are in the same class of He-C-O. And our latest result shows that S belongs to the Ne-Mg-Si class. We also found that the lightest and most abundant proton cosmic rays have two components—the first component being the same rigidity dependence as the He, C, and O fluxes and the second component with much softer rigidity dependence.

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1. Introduction

Proton, Helium, Carbon, Oxygen, Neon, Magnesium, Silicon, Sulfur, Iron, and Nickel are thought to be mainly produced and accelerated in astrophysical sources. They are called primary cosmic rays. Precise knowledge of their spectra in the GV-TV rigidity region provides important insights to the origin, acceleration, and subsequent propagation processes of cosmic rays in the Galaxy. We report the latest measurements of these fluxes in the rigidity range from ~2 GV to ~3 TV (from 1 GV to 1.8 TV for proton) based on 10 years of AMS data.

2. AMS Detector and Data Analysis

AMS is a general purpose high energy particle physics detector in space [1]. The key elements used in this measurement are the permanent magnet, the nine layers of silicon tracker [2–4] and the four planes of time of flight TOF scintillation counters [5]. The detailed descriptions of the detector performance and the data analysis can be found in Ref. [6, 9–11]

3. Results

He, C, and O— Helium is next abundant cosmic ray nuclei after the proton. To study the rigidity dependence of He flux at high rigidities, we fit the latest flux above 45 GV with a double power law function in the presence of solar modulation in the force field approximation [12]

$$\Phi = C\frac{R^2}{\hat{R}^2}\left(\frac{\hat{R}}{45\,\mathrm{GV}}\right)^{\gamma}\left[1+\left(\frac{\hat{R}}{R_0}\right)^{\Delta\gamma/s}\right]^{s} \tag{1}$$

where s quantifies the smoothness of the transition of the spectral index from γ for rigidities below the characteristic transition rigidity R_0 to $\gamma + \Delta\gamma$ for rigidities above R_0, $\hat{R} = R + \phi$, and $\phi = 0.50 \pm 0.05$ GV is the solar potential.Fitting over the range 45 GV to 3 TV yields a $\chi^2/d.o.f. = 20/28$ with $C_{\mathrm{He}} = (950 \pm 5(\mathrm{fit}) \pm 10(\mathrm{sys}) \pm 10(\mathrm{sol})) \times 10^{-4}$ $\mathrm{m^{-2}sr^{-1}sec^{-1}GV^{-1}}$, $\gamma_{\mathrm{He}} = -2.750 \pm 0.002(\mathrm{fit}) \pm 0.003(\mathrm{sys}) \pm 0.005(\mathrm{sol})$, $\Delta\gamma_{\mathrm{He}} = 0.164^{+0.016}_{-0.017}(\mathrm{fit}) \pm 0.03(\mathrm{sys}) \pm 0.005(\mathrm{sol})$, $s = 0.04 \pm 0.01(\mathrm{fit}) \pm 0.02(\mathrm{sys}) \pm 0.01(\mathrm{sol})$, and $R_0 = 369^{+44}_{-34}(\mathrm{fit})^{+57}_{-38}(\mathrm{sys}) \pm 1(\mathrm{sol})$ GV. The first error quoted (fit) takes into account the statistical and uncorrelated systematic errors from the He flux. The second (sys) is the error from the remaining correlated systematic errors. The third (sol) is the uncertainty due to the variation of the solar potential ϕ from 0.45 GV to 0.55 GV. Figure 1 (left panel) shows the He flux together with the fit results.

AMS found that He, C, and O fluxes have identical rigidity dependence above 60 GV and deviate from single power law at high rigidities. To examine this in detail, we perform simultaneous fit of the latest He, C, and O with Eq. (1) with common parameters s, γ, R_0, $\Delta\gamma$. The fit yields $C_{\mathrm{He}} = (950 \pm 5) \times 10^{-4}$ $\mathrm{m^{-2}sr^{-1}s^{-1}GV^{-1}}$, $C_{\mathrm{C}} = (31 \pm 1) \times 10^{-4}$ $\mathrm{m^{-2}sr^{-1}s^{-1}GV^{-1}}$, $C_{\mathrm{O}} = (33 \pm 1) \times 10^{-4}$ $\mathrm{m^{-2}sr^{-1}s^{-1}GV^{-1}}$, $\gamma_{\mathrm{HeCO}} = -2.760 \pm 0.002$, $\Delta\gamma_{\mathrm{HeCO}} = 0.173 \pm 0.015$, $s = 0.05 \pm 0.015$, and $R_0 = 330^{+40}_{-30}$ GV, where only (fit) errors are shown. The He, C, and O fluxes together with the fit results are shown in Fig. 1, right panel. As seen, at high rigidities, the rigidity dependence of He, C, and O is identical.

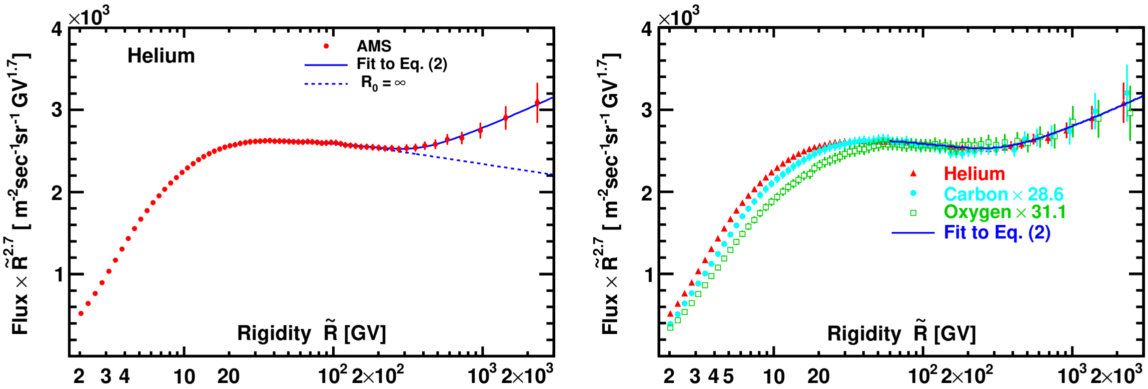

Figure 1: Left panel: The AMS helium flux multiplied by $\tilde{R}^{2.7}$ as a function of rigidity R. The solid curve indicates the fit of Eq. (1) to the data. For illustration, the dashed curve uses the same fit values but with R_0 set to infinity. Right Panel: The AMS He, C, and O fluxes. The solid curve indicates the combined fit of Eq. (1) to the data. As seen, at high rigidities, the rigidity dependence of He, C, and O fluxes is identical.

Ne, Mg, Si, and S— AMS found that Ne, Mg, and Si primary cosmic ray fluxes have identical rigidity dependence above 86.5 GV and deviate from a single power law. Figure 2, left panel, shows the rigidity dependence of the latest AMS Ne, Mg, and Si fluxes compared to the rigidity dependence of the latest He, C, and O fluxes above 86.5 GV together with the fit result of He, C, and O fluxes and Ne, Mg, and Si fluxes with Eq. (1). As seen, the rigidity dependences of Ne-Mg-Si and He-C-O are distinctly different. This shows that the Ne-Mg-Si and He-C-O are two different classes of primary cosmic rays [10]. Using the latest AMS data, we found that, above 86.5 GV, the Ne/O, Mg/O, and Si/O ratios can be described by a simple power law $\propto R^{\delta}$ with $< \delta >= -0.042 \pm 0.007$.

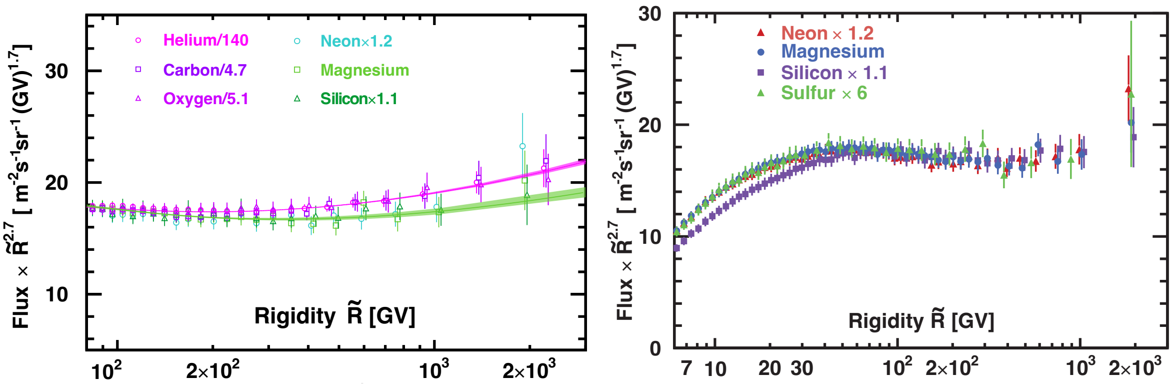

Figure 2: Left panel: The rigidity dependence of the Ne, Mg, and Si fluxes compared to the rigidity dependence of the He, C, and O fluxes above 86.5 GV. The blue solid curve shows the fit result of He, C, and O fluxes with Eq. (1). The magenta shaded area shows the fit result, including errors of Ne, Mg and Si fluxes with Eq. (1) where $\gamma_{\text{NeMgSi}} + \Delta\gamma_{\text{NeMgSi}} = \gamma_{\text{HeCO}} + \Delta\gamma_{\text{HeCO}} + < \delta >$, and $< \delta >= -0.042 \pm 0.007$. Right panel: The rigidity dependence of the Ne, Mg, Si, and S fluxes.

Figure 2, right panel, shows rigidity dependence of the latest AMS Ne, Mg, Si, and S fluxes. As seen, at high rigidities the rigidity dependences of all the fluxes are identical. To examine the

S rigidity dependence in detail, the fits with power law functions of S/Mg and S/O flux ratios have been done and shown in Fig. 3. As seen, the rigidity dependences of S and Mg above 6 GV are identical; in constract, the rigidity dependence of S and O above 86.5 GV are distinctly different.

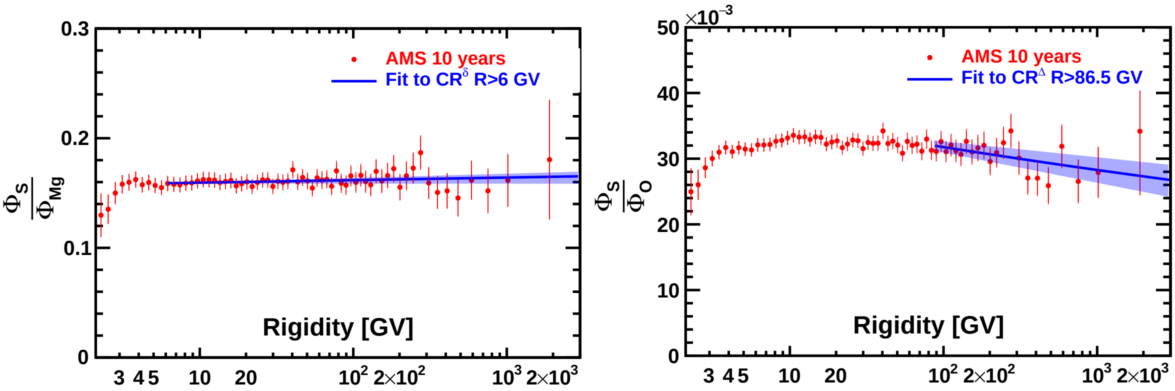

Figure 3: Left panel: The rigidity dependence of the S/Mg flux ratio together with power law fit result CR^δ, $\delta = 0.006 \pm 0.006$. Right panel: The rigidity dependence of the S/O flux ratio together with power law fit result CR^Δ, $\Delta = -0.05 \pm 0.02$. Blue lines and shadows show fit results with uncertainties.

Fe and Ni— AMS found that above 80.5 GV, the rigidity dependence of the cosmic ray Fe flux is identical to the rigidity dependence of the primary cosmic ray He, C, and O fluxes. In particular, above 80.5 GV the Fe/O ratio is well described by a constant value of 0.155 ± 0.006. Figure 4, left panel, shows the latest AMS fluxes of Fe and He together above 80.5 GV. As seen, their rigidity dependences are identical. Figure 4, right panel, shows the AMS Ni flux together with Fe flux. As seen, the rigidity dependences of Fe and Ni are also very similar.

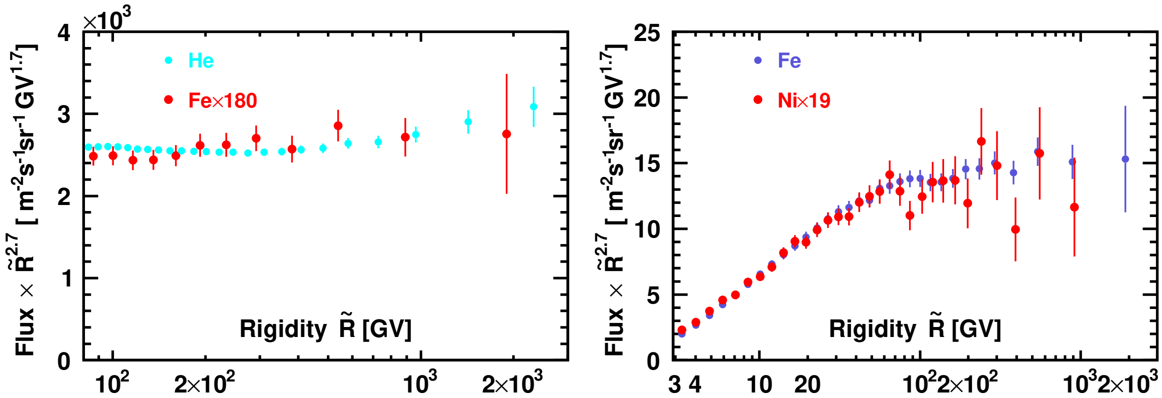

Figure 4: Left panel: The rigidity dependence of the Fe flux compared to rigidity dependence of the He flux above 80.5 GV. Right panel: The rigidity dependence of the Ni flux compared to the rigidity dependence of Fe flux above 3 GV.

To examine the Ni rigidity dependence in detail, a fit of the Ni/Fe fluxes ratio with a power law CR^δ was performed above 3 GV, see Fig. 5. The fit yields $\delta = -0.006 \pm 0.009$ with $\chi^2/d.o.f = 20/29$, confirming that Ni and Fe rigidity dependence is identical.

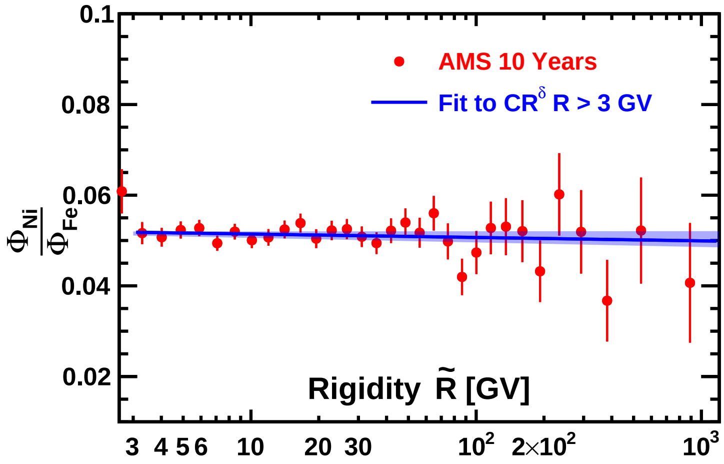

Figure 5: The rigidity dependence of the Ni/Fe flux ratio together with the power law fit result CR^{δ}, $\delta = -0.006 \pm 0.009$. Blue line and shadow show the fit results with uncertainties.

p and p/He— Protons are the most abundant cosmic rays. To study the rigidity dependence of proton flux at high rigidities, we fit the latest proton flux above 45 GV with Eq. (1). The fit yields a $\chi^2/d.o.f. = 22/26$ with $C_\text{p} = (4430 \pm 2(\text{fit}) \pm 30(\text{sys}) \pm 30(\text{sol})) \times 10^{-4}\ \text{m}^{-2}\text{sr}^{-1}\text{sec}^{-1}\text{GV}^{-1}$, $\gamma_\text{p} = -2.848 \pm 0.002(\text{fit}) \pm 0.003(\text{sys}) \pm 0.007(\text{sol})$, $\Delta\gamma_\text{p} = 0.240^{+0.013}_{-0.015}(\text{fit}) \pm 0.03(\text{sys}) \pm 0.007(\text{sol})$, $s = 0.08 \pm 0.02(\text{fit}) \pm 0.02(\text{sys}) \pm 0.01(\text{sol})$, and $R_0 = 330^{+49}_{-36}(\text{fit})^{+58}_{-48}(\text{sys}) \pm 2(\text{sol})$ GV.

Figure 6, left panel, shows the latest AMS proton flux together with the fit results. As seen, the $\gamma_\text{p} \neq \gamma_\text{He}$ while $\gamma_\text{p} + \Delta\gamma_\text{p} = -2.608^{+0.013}_{-0.015}$ is compatible with $\gamma_\text{He} + \Delta\gamma_\text{He} = -2.586^{+0.016}_{-0.017}$ within 1σ.

To examine this observation in detail, we fit the p/He fluxes ratio above 3.5 GV with a function:

$$\frac{\Phi_\text{p}}{\Phi_\text{He}} = A + C \times (R/3.5\ \text{GV})^{\Delta} \tag{2}$$

The fit yields a $\chi^2/d.o.f$ =50/58 with $A = 3.14 \pm 0.06$, $C = 3.28 \pm 0.07$, and $\Delta = -0.30 \pm 0.01$. Figure 6, right panel, shows the p/He flux ratio together with the fit result. As seen the p flux has two components, the first with the same rigidity dependence as He and the second with much softer rigidity dependece than He. We can use AMS data to predict asymptotic p/He ratio at the highest energies: in kinetic energy per nucleon = $A/2^{\gamma+\Delta\gamma+1} = 9.52 \pm 0.38$.

4. Summary

The properties of cosmic rays p, He, C, O, Ne, Mg, Si, S, Fe, and Ni have been presented. We found that primary cosmic rays He-C-O-Fe-Ni and Ne-Mg-Si-S belong to two different classes of cosmic rays. We also found that the lightest and most abundant proton cosmic rays have two components—the first component being the same rigidity dependence as the He, C, and O fluxes and the second component with much softer rigidity dependence.

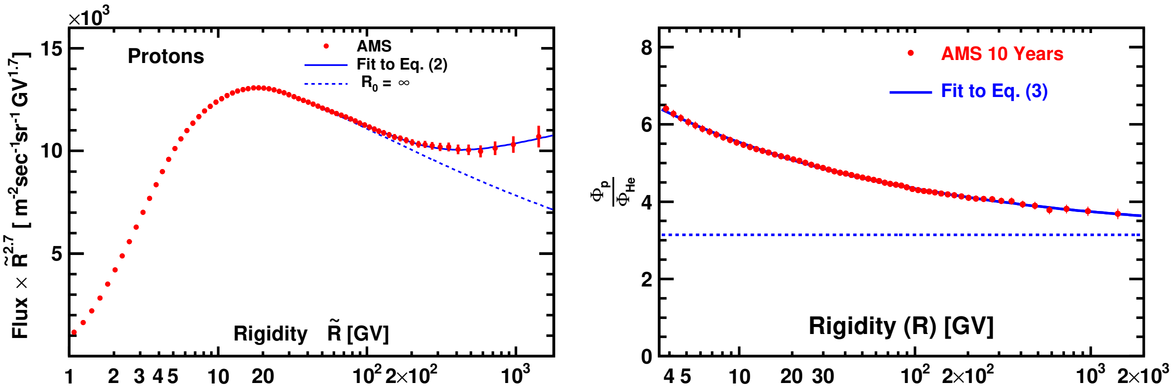

Figure 6: Left panel: The AMS helium flux multiplied by $\tilde{R}^{2.7}$ as a function of rigidity R. The solid curve indicates the fit of Eq. (1) to the data. For illustration, the dashed curve uses the same fit values but with R_0 set to infinity. Right panel: The rigidity dependence of the p/He flux ratio. The sold curve indicates the fit of Eq. (2) to the data. For illustration, the dashed curve shows the value of the constant component A.

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