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Unique Properties of the 3rd Group of Cosmic Rays: Results from the Alpha Magnetic Spectrometer

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Cosmic Sodium and Aluminum nuclei are a combination of primaries, produced at cosmic-ray sources, and secondaries resulting from collisions of heavier primary cosmic rays with the interstellar medium. We present high statistics measurements of the Na and Al rigidity spectra. We discuss the properties and composition of their spectra and present a novel model-independent determination of their abundance ratios at the source. The systematic comparison with the latest GALPROP cosmic ray model is presented.

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1. Introduction

Sodium and aluminum cosmic rays, like nitrogen, are thought to be produced both in astrophysical sources and by the collisions of heavier nuclei with the interstellar medium [1]. Previously, measurements of the cosmic nitrogen flux with the Alpha Magnetic Spectrometer experiment (AMS) have been reported [2, 3]. Remarkably, the nitrogen flux is well described over the entire rigidity range by the sum of a primary component (proportional to the oxygen flux [3, 4]) and a secondary component (proportional to the boron flux [3, 5]).

We present the precise measurement of the Na and Al fluxes in cosmic rays in the rigidity range from 2.15 GV to 3.0 TV based on 0.46 million sodium and 0.51 million aluminum nuclei collected by AMS during the first 8.5 years (May 19, 2011 to October 30, 2019) of operation aboard the International Space Station.

2. AMS-02 Detector and analysis

The AMS detector is a large-acceptance magnetic spectrometer, the full description of the detector is presented in [3] and references therein.

In it's first 8.5 years of operation, AMS has collected more than 1.50×10^{11} cosmic ray events. Na and Al events are required to be downward going and to have a reconstructed track in the seven tracker layers placed on the top and inside the magnet. The track is also required to pass through tracker L1, and through tracker L9 for the highest rigidity region $R \geq$1.2 TV. Charge measurements on tracker L1, the inner tracker (L2-L8), the upper Time of Flight (TOF), and, for $R \geq$1.2 TV, the lower TOF, and tracker L9 are required to be compatible with charge Z=11 and 13 respectively. Details of the Na and Al flux analysis procedure and particularly the analysis of the systematic errors are discussed in [6].

3. Properties of Sodium and Aluminum Cosmic Ray nuclei

The cosmic ray Na flux $\Phi_{\rm Na}$ and the Al flux $\Phi_{\rm Al}$ in rigidity $\tilde{R}$ with the total errors are shown in Fig. 1 (a) and (b), respectively, in comparison with the AMS N flux [3]. The AMS Na and Al fluxes as functions of kinetic energy per nucleon E_K are shown in Fig. 2, compared with results from previous experiments [7–12]. The latest GALPROP–HELMOD model [14] prediction based on AMS publication on the two primary cosmic ray classes, He-C-O and Ne-Mg-Si and other AMS data (dashed blue lines) is shown in the same figure. Note that above 3 GeV/n, the GALPROP–HELMOD model is in good agreement with the AMS al data.

To examine the rigidity dependence of the Na and Al fluxes, the variation of the flux spectral indices with rigidity was obtained in a model independent way from $\gamma = d[\log(\Phi)]/d[\log(R)]$ over nonoverlapping rigidity intervals with a variable width to have sufficient sensitivity to determine γ. The results are presented in Fig. 1 (c) and (d) in comparison with N [3]. As seen in Fig. 1, below ~100 GV, the Na flux and spectral index follow the N flux and spectral index and, above ~100 GV, the Al flux and spectral index follow the N flux and spectral index.

The Na flux $\Phi_{\rm Na}$ is fitted to the weighted sum of the flux of heavy primary cosmic ray silicon $\Phi_{\rm Si}$ [15], and the flux of heavy secondary cosmic ray flux fluorine $\Phi_{\rm F}$ [16], above 6 GV to estimate

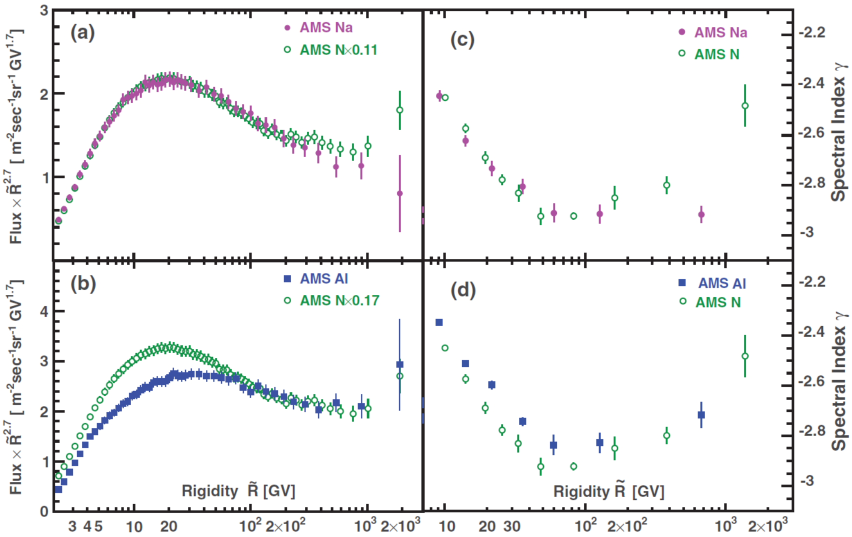

Figure 1: The AMS (a) Na and (b) Al fluxes multiplied by $\tilde{R}^{2.7}$ as function of rigidity with total errors together with the rescaled AMS N flux [3]; (c) Na and (d) Al flux spectral indices together with the N flux spectral index.

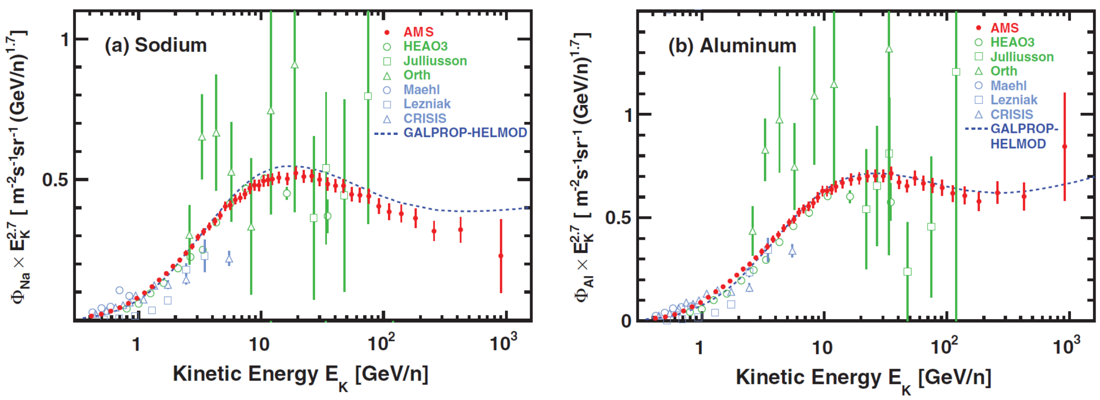

Figure 2: The AMS (a) Na flux $\Phi_{\rm Na}$ and (b) Al flux $\Phi_{\rm Al}$ multiplied by $E_K^{2.7}$ compared with results from earlier experiments [7–12] as functions of kinetic energy per nucleon E_K. For the AMS measurement E_K is calculated as in [6] and results from earlier experiments are taken from [13].

the primary ($\Phi^{\rm P}_{\rm Na}$) and secondary ($\Phi^{\rm S}_{\rm Na}$) components of the Na flux $\Phi_{\rm Na} = \Phi^{\rm P}_{\rm Na} + \Phi^{\rm S}_{\rm Na}$. Similarly, the Al flux $\Phi_{\rm Al}$ is fitted to the weighted sum of the silicon flux and the fluorine flux above 6 GV, as shown in Fig. 3(b), in order to estimate the primary ($\Phi^{\rm P}_{\rm Al}$) and secondary ($\Phi^{\rm S}_{\rm Al}$) components in the Al flux $\Phi_{\rm Al} = \Phi^{\rm P}_{\rm Al} + \Phi^{\rm S}_{\rm Al}$.

Similar to N [2, 3], both the Na and Al fluxes are well fitted as the linear combinations of primary and secondary fluxes over a large rigidity range is an important result. It determines directly the Na/Si and Al/Si ratios at the source, 0.036 ± 0.003 for Na/Si and 0.103 ± 0.004 for Al/Si, without the need of considering the propagation of cosmic rays in the Galaxy.

Figure 4 presents cosmic nuclei fluxes measured by AMS as a function of rigidity from Z=2 to Z=14. It shows that there are two classes of primary cosmic rays, He-C-O and Ne-Mg-Si, and two

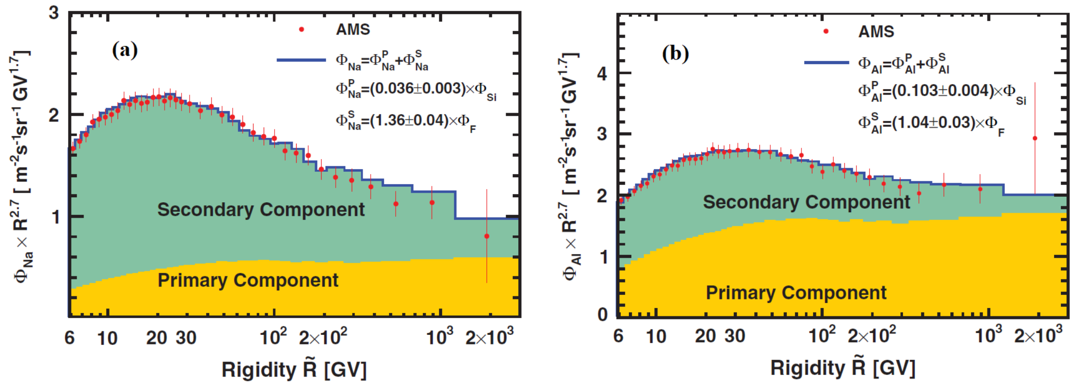

Figure 3: (a) The AMS Na flux $\Phi_{\rm Na} = \Phi^{\rm P}_{\rm Na} + \Phi^{\rm S}_{\rm Na}$ with the fit result to the weighted sum of the Si flux $\Phi_{\rm Si}$ and the F flux $\Phi_{\rm F}$ above 6 GV. The result gives $\Phi^{\rm P}_{\rm Na} = (0.036 \pm 0.003) \times \Phi_{\rm Si}$ and $\Phi^{\rm S}_{\rm Na} = (1.36 \pm 0.04) \times \Phi_{\rm F}$ with a $\chi^2/\text{DOF} = 19/36$. (b) The AMS Al flux $\Phi_{\rm Al} = \Phi^{\rm P}_{\rm Al} + \Phi^{\rm S}_{\rm Al}$ with the fit result to the weighted sum of the Si flux $\Phi_{\rm Si}$ and the F flux $\Phi_{\rm F}$ above 6 GV. The result gives $\Phi^{\rm P}_{\rm Al} = (0.103 \pm 0.004) \times \Phi_{\rm Si}$ and $\Phi^{\rm S}_{\rm Na} = (1.04 \pm 0.03) \times \Phi_{\rm F}$ with a $\chi^2/\text{DOF} = 24/36$. The primary and secondary component contributions are shown by the yellow and green shading respectively in (a) and (b). As seen, the sodium and aluminum fluxes have decreasing secondary component and increasing primary component with increasing rigidity.

classes of secondary cosmic rays, Li-Be-B and F [16]. As seen from Fig. 4, N, Na, and Al belong to a distinct group and are the combinations of primary and secondary cosmic rays.

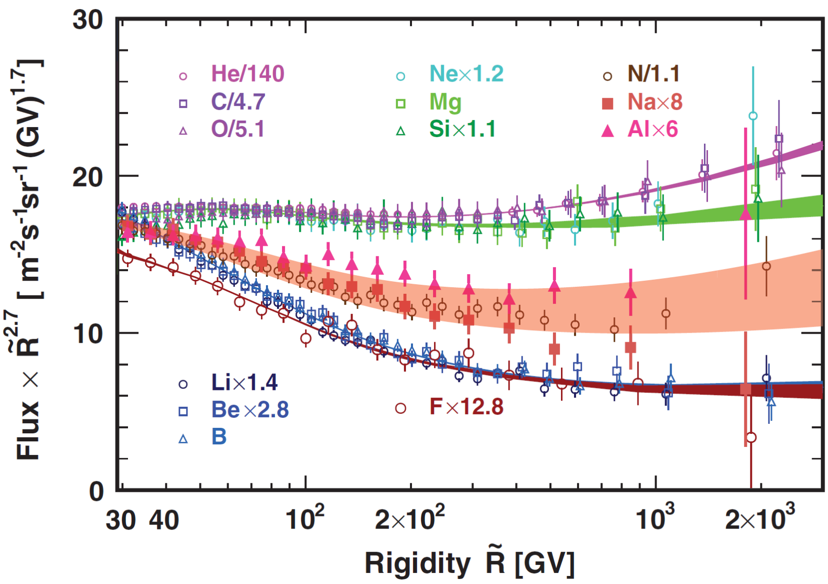

Figure 4: The fluxes of cosmic nuclei measured by AMS as a function of rigidity from Z=2 to Z=14 above 30 GV. As seen, there are two classes of primary cosmic rays, He-C-O and Ne-Mg-Si, and two classes of secondary cosmic rays, Li-Be-B and F [16]. Nitrogen (N), sodium (Na), and aluminum (Al), belong to a distinct group and are the combinations of primary and secondary cosmic rays. For clarity, data points above 400 GV are displaced horizontally. For display purposes only, fluxes were rescaled as indicated. The shaded tan band on N, Na, and Al is to guide the eye.

4. Conclusion

In conclusion, following the study of nitrogen, we have presented the precision measurement of the Na and Al fluxes as functions of rigidity from 2.15 GV to 3.0 TV, with detailed studies of the systematic errors. We found that Na and Al, together with N, belong to a distinct cosmic ray group and are the combinations of primary and secondary cosmic rays. Similar to the N flux, which is well described by the sum of a primary cosmic ray component (proportional to the oxygen flux) and a secondary cosmic ray component (proportional to the boron flux), both the Na and Al fluxes are well described by the sums of a primary cosmic ray component (proportional to the silicon flux) and a secondary cosmic ray component (proportional to the fluorine flux). The fraction of the primary component increases with rigidity for the N, Na, and Al fluxes and becomes dominant at the highest rigidities. The abundance ratios at the source of Na/Si (0.036 ± 0.003) and Al/Si (0.103 ± 0.004) are determined directly without the consideration of cosmic ray propagation in the Galaxy. These are new and unexpected properties of cosmic rays.

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