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Properties of Cosmic Aluminum Nuclei: Results from the Alpha Magnetic Spectrometer

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We report the properties of aluminum (Al) nuclei in cosmic rays measured in the rigidity range 2.15 GV to 3.0 TV with 0.51 million nuclei collected by the Alpha Magnetic Spectrometer experiment on the International Space Station. We observed that above 6 GV the Al spectrum is well described by the weighted sum of the silicon spectrum (primary cosmic rays) and the fluorine spectrum (secondary cosmic rays). The fraction of the primary component increases with rigidity and becomes dominant at highest rigidities. Al/Si abundance ratio at the source is determined independent of cosmic ray propagation.

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1. Introduction

Aluminum nuclei in 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, the measurement of the cosmic nitrogen flux with the Alpha Magnetic Spectrometer experiment (AMS) has been reported [2]. Remarkably, the nitrogen flux is well described by the sum of a primary component (proportional to the oxygen flux [2]) and a secondary component (proportional to the boron flux [2]). Recently, AMS also reported the properties of primary heavy cosmic-ray Ne, Mg, and Si fluxes [2, 3] and of heavy secondary cosmic-ray F flux [4]. The AMS results revealed that there are two classes of primary cosmic rays: that of the light He-C-O nuclei and that of the heavy Ne-Mg-Si nuclei. They also revealed that there are two classes of secondary cosmic rays: that of the light Li–Be–B nuclei and that of the heavy F nuclei.

We present the precise measurement of the Al flux in the rigidity range from 2.15 GV to 3.0 TV based on 0.51 million aluminum nuclei collected by AMS during its first 8.5 years (from May 19, 2011 to October 30, 2019) of operation on the International Space Station (ISS).

2. AMS-02 detector and analysis

AMS is a long duration, large acceptance precision magnetic spectrometer on space which is able to measure the sign and value of the charge, the momentum, and the rigidity of charged particles. The layout and description of the AMS detector are presented in Refs. [2]. The key elements of AMS detector used in the aluminum flux measurement are the permanent magnet, nine layers of the silicon tracker, and four planes of time of flight (TOF) scintillation counters.

Further information on the performance of the rigidity and charge measurements, and the Monte-Carlo (MC) simulations, the flux analysis procedure including the event selection, background subtraction, bin-to-bin migration correction, and study of the systematic uncertainties are detailed in Refs. [13].

Several independent analyses were performed on the same data sample by different study groups. As shown in Fig. 1, the results of those analyses are consistent.

3. Properties of aluminum cosmic ray nuclei

Fig. 2 shows the AMS aluminum flux as a function of rigidity $\tilde{R}$ with the total errors, together with the AMS nitrogen flux [2]. As seen, at rigidities above ~ 100 GV the Al flux and the N flux have similar rigidity dependence.

Fig. 3 shows the AMS aluminum flux as a function of kinetic energy per nucleon E_K together with earlier measurements [5–10]. Data from other experiments have been extracted using Ref. [11]. Also shown in the figure are the predictions of the latest GALPROP-HELMOD cosmic ray propagation model [12] based on published AMS data. The GALPROP-HELMOD model agrees well with the AMS aluminum data above 3 GeV/n.

To obtain the primary $\Phi^{\mathrm{P}}_{\mathrm{Al}}$ and secondary $\Phi^{\mathrm{S}}_{\mathrm{Al}}$ components in the Al spectrum $\Phi_{\mathrm{Al}} = \Phi^{\mathrm{P}}_{\mathrm{Al}} + \Phi^{\mathrm{S}}_{\mathrm{Al}}$, a fit of Φ_{Al} to the weighted sum of a heavy primary cosmic ray spectrum, namely silicon Φ_{Si} [3], and of a heavy secondary cosmic ray spectrum, namely fluorine Φ_{F} [4], was performed above 6 GV.

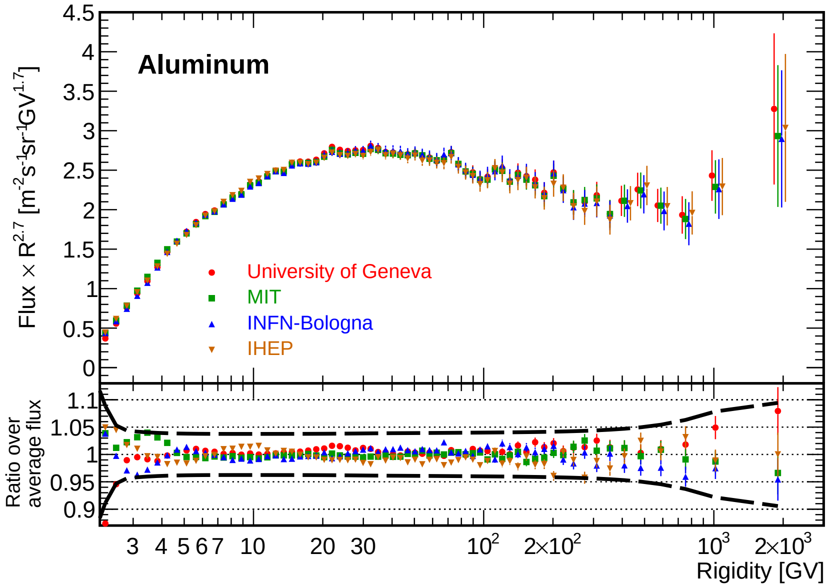

Figure 1: The AMS aluminum (Al) flux multiplied by $\tilde{R}^{2.7}$ as a function of rigidity (upper panel) and the ratio over average flux (lower panel) obtained on the same data sample by four independent study groups from the University of Geneva (red dots), MIT (green squares), INFN-Bologna (blue triangles) and IHEP (brown triangles). The correlation in the flux error from the statistics has been subtracted. The dashed black lines in the lower panel show the average of the systematical error.

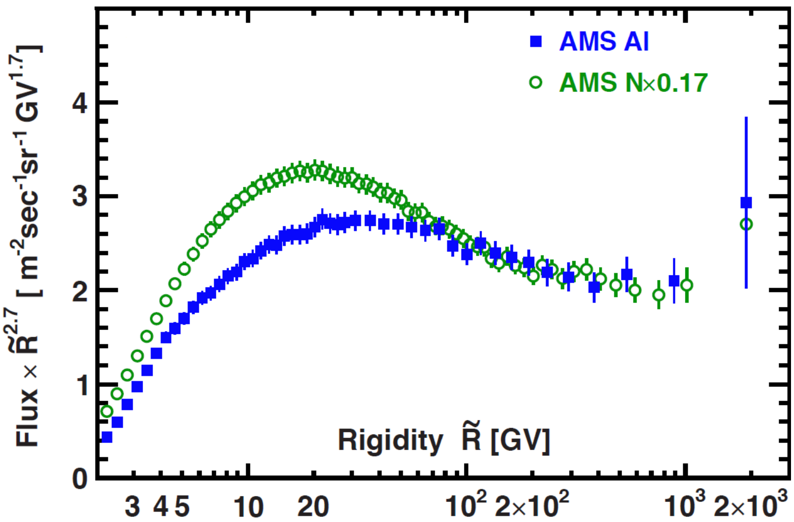

Figure 2: The AMS aluminum (Al) flux together with the rescaled AMS nitrogen (N) flux [2] multiplied by $\tilde{R}^{2.7}$ with total errors as function of rigidity.

The fit yields $\Phi^{P}_{\mathrm{Al}} = (0.103 \pm 0.004) \times \Phi_{\mathrm{Si}}$ and $\Phi^{S}_{\mathrm{Al}} = (1.04 \pm 0.03) \times \Phi_{\mathrm{F}}$ with χ^2/d.o.f=24/36, as shown in Fig. 4.

As seen from Fig. 4, the contributions of the primary component increases with rigidity. The same dependence was also observed for the spectra of nitrogen Φ_{N} [2] and sodium Φ_{Na} [13].

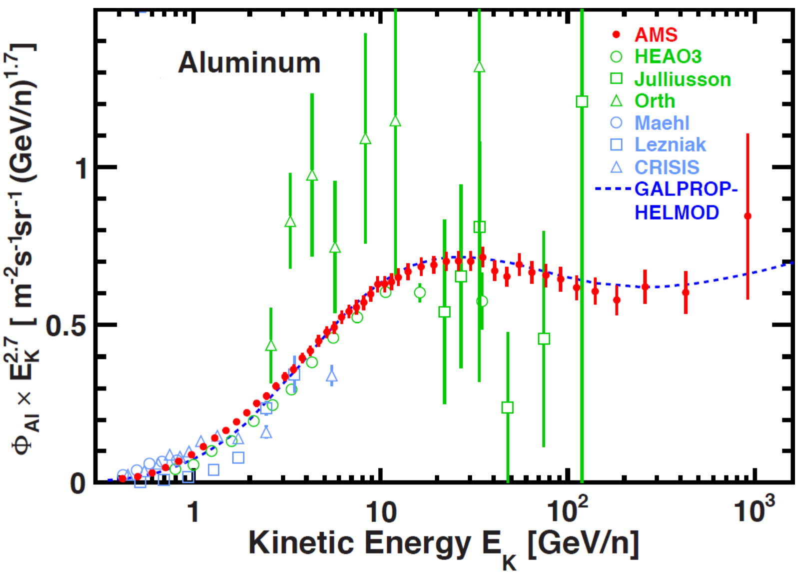

Figure 3: The AMS aluminum (Al) flux as functions of kinetic energy per nucleon E_K multiplied by $E_K^{2.7}$ together with earlier measurements [5–10]. For the AMS measurement the rigidity has been converted to kinetic energy per nucleon as $E_K = \left(\sqrt{Z^2\tilde{R}^2 + M^2} - M\right)/A$ where Z, M and A are the $^{27}_{13}$Al nuclear charge, mass and atomic mass number, respectively. The dashed blue line show the prediction of the latest GALPROP-HELMOD [12] model based on published AMS data on two primary cosmic ray classes, He-C-O and Ne-Mg-Si and other AMS data. Note the latest GALPROP-HELMOD model agrees well with the AMS aluminum data above 3 GeV/n.

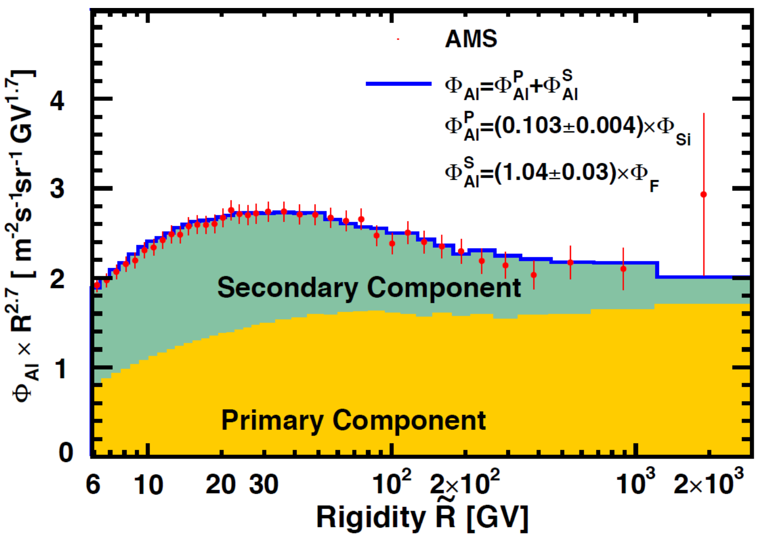

Figure 4: The AMS aluminum flux Φ_{Al} fit to the weighted sum of the silicon flux Φ_{Si} and the fluorine flux Φ_{F} above 6 GV, i.e. $\Phi_{\mathrm{Al}} = \Phi^{\mathrm{P}}_{\mathrm{Al}} + \Phi^{\mathrm{S}}_{\mathrm{Al}}$. The contributions of the primary and secondary components are indicated by the shading (yellow and green, respectively).

The observation that, similar to N and Na, the Al spectrum can be fit over a wide rigidity range as the linear combination of primary and secondary spectrum permits the direct determination of the Al/Si abundance ratio at the source, 0.103 ± 0.004, without the need to consider the Galactic propagation of cosmic rays.

Figure 5 presents cosmic nuclei fluxes measured by AMS as functions of rigidity from He ($Z = 2$) to Si ($Z = 14$). It shows that 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 [4], and that N, Na, and Al belong to a distinct group of cosmic rays which are the combinations of primary and secondary cosmic rays.

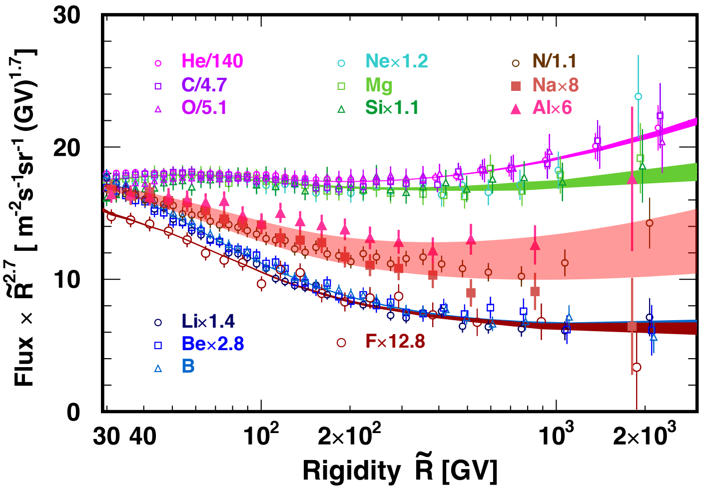

Figure 5: Cosmic nuclei spectra measured by AMS as functions of rigidity from $Z = 2$ to $Z = 14$ above 30 GV. For clarity, data points above 400 GV are displaced horizontally. For display purposes only, fluxes were rescaled as indicated. The shaded tan band on N, Na, and Al is to guide the eye.

4. Conclusion

We have presented the precision measurement of the Al flux as a function of rigidity from 2.15 GV to 3.0 TV based on the data collected by AMS during its first 8.5 years operation.

We found that Al nuclei, together with N and Na, belong to a distinct group of cosmic rays which are combinations of primary and secondary cosmic rays. Similar to N and Na spectra, the Al spectrum is well described by the sum of a primary cosmic ray component and a secondary cosmic ray component. The fraction of the primary component increases with rigidity and becomes dominant at the highest rigidities. The Al/Si abundance ratio at the source (0.103 ± 0.004) is directly determined independent of cosmic ray propagation. These are new and unexpected properties of cosmic rays.

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