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Precision Measurement of the Helium Flux in Primary Cosmic Rays of 1.9 GV to 3 TV Rigidity with the Alpha Magnetic Spectrometer on the International Space Station

AMS Collaboration*

Sadakazu Haino

Institute of Physics, Academia Sinica, Nankang, Taipei, 11529, Taiwan

Knowledge of the exact rigidity dependence of the helium flux is important in understanding the origin, acceleration, and propagation of cosmic rays. A precise measurement of the helium flux in primary cosmic rays with rigidity (momentum/charge) from 1.9 GV to 3 TV based on 50 million events is presented and compared to the proton flux. The detailed variation with rigidity of the helium flux spectral index is presented for the first time. The spectral index progressively hardens at high rigidities.

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*for the complete list of authors see the AMS Collaboration list in these proceedings.

1. Introduction

Helium nuclei in cosmic rays are believed to be mainly produced by Galactic sources such as supernova remnants. Precise knowledge of the helium (He) spectrum in the GV - TV rigidity region gives important information on the origin, acceleration, and subsequent propagation processes of cosmic rays in the Galaxy [1].

Recent important measurements of the He flux in cosmic rays have reported different variations of the flux with energy [2, 3, 6, 4, 5]. In particular, the ATIC–2, CREAM, and PAMELA experiments showed different deviations of the helium flux from a single power law. Many models were proposed to account for the hardening of the He flux as well as for the proton and He fluxes spectral difference based on different sources, acceleration mechanisms, diffusive propagation effects, and their superposition [7]. In this paper we report the precise measurement of the helium flux in primary cosmic rays in the rigidity range from 1.9 GV to 3 TV based on data collected by the Alpha Magnetic Spectrometer (AMS) during the first 30 months (May 19, 2011 to November 26, 2013) of operation onboard the International Space Station (ISS).

2. Detector

AMS is a general purpose high energy magnetic spectrometer in space. The layout and description of the detector are presented in Ref. [9]. The key elements used in this measurement are the permanent magnet, the silicon tracker, four planes of time of flight (TOF) scintillation counters, and the array of anticoincidence counters (ACC). AMS also contains a transition radiation detector (TRD), a ring imaging Čerenkov detector (RICH), and an electromagnetic calorimeter (ECAL).

The AMS coordinate system is concentric with the magnet and above, below, and downward-going refer to the AMS coordinate system. Timing, location, and orientation are provided by GPS units affixed to AMS and to the ISS. The detector performance has been steady over time.

The tracker [10] has nine layers, the first (L1) at the top of the detector, the second (L2) just above the magnet, six (L3 to L8) within the bore of the magnet, and the last (L9) just above the ECAL. L2 to L8 constitute the inner tracker. The tracker accurately determines the trajectory of cosmic rays by multiple measurements of the coordinates. Together, the tracker and the magnet measure the rigidity $R = p/Z$ of charged cosmic rays. For $|Z| = 2$ particles, the spatial resolution in each tracker layer is 7.5 μm in the bending direction and the maximum detectable rigidity (MDR) is 3.2 TV over the 3 m lever arm from L1 to L9.

Each layer of the tracker also provides an independent measurement of the absolute value of the charge $|Z|$ of the cosmic ray. Together, the charge resolution of the layers of the inner tracker is $\Delta Z \simeq 0.07$ for $|Z| = 2$ particles.

Two planes of TOF counters [11] are located above L2 and two planes are located below the magnet. The overall velocity ($\beta = v/c$) resolution has been measured to be $\Delta\beta/\beta^2 = 0.02$ for $|Z| = 2$ particles. This discriminates between upward- and downward-going particles. The pulse heights of the two upper layers are combined to provide another independent measurement of the absolute charge with an accuracy $\Delta Z \simeq 0.08$. The pulse heights from the two lower planes are combined to provide an independent absolute charge measurement with the same accuracy.

The ACC form a cylindrical shell between the inner tracker and the magnet. They are readout in 8 sectors and have an efficiency of 0.999 99 to reject cosmic rays which enter the inner tracker from the side.

Helium traversing AMS were triggered by any of (i) the 350 ns coincidence of signals from all four TOF planes with amplitudes above $\simeq 0.5$ of a $|Z| = 1$ minimum ionizing particle (MIP) together with an absence of signals from the ACC; (ii) the 350 ns coincidence of signals from all four TOF planes with amplitudes above $\simeq 3.5$ of a $|Z| = 1$ MIP together with signals from no more than 4 out of the 8 ACC sectors; or (iii) the 350 ns coincidence of 3 out of the 4 TOF layers with amplitudes above $\simeq 0.5$ of a $|Z| = 1$ MIP and with no ACC requirement, prescaled by 1%. The scheme ensures high efficiency of detecting cosmic ray ions while effectively rejecting cosmic ray events entering the inner tracker from the side. Trigger (iii), which has an efficiency >99.99% for helium, was used to measure the overall trigger efficiency.

Monte Carlo simulated events were produced using a dedicated program developed by the collaboration based on the GEANT-4.10.1 package [12]. The program simulates electromagnetic and hadronic interactions of particles in the material of AMS and generates detector responses. The INCL++ package [14] was used to model helium-nuclear interactions below 5 GeV/nucleon and the DPMJET-II.5 package [13] was used at higher energies. The digitization of signals is simulated precisely according to the measured characteristics of the electronics. The simulated events then undergo the same reconstruction as used for the data.

3. Selection

In the first 30 months (7.96×10^7 s) AMS collected 4.1×10^{10} cosmic ray events. The collection time used in this analysis includes only those seconds during which the detector was in normal operating conditions and, in addition, AMS was pointing within 40° of the local zenith, the trigger live time exceeded 50%, and the ISS was outside of the South Atlantic Anomaly. Due to the influence of the geomagnetic field, this collection time for primary cosmic rays increases with increasing rigidity becoming constant at 6.29×10^7 s above 30 GV [8].

By selecting events to be downward going and to have a reconstructed track in the inner tracker with charge compatible with $|Z| = 2$, we obtain 1.7×10^9 events. In order to have the best resolution at the highest rigidities, further selections are made by requiring the track to pass through L1 and L9 and to satisfy additional track fitting quality criteria such as a $\chi^2/d.f. < 10$ in the bending coordinate. To remove the events which interacted within the detector, the charge as measured by each of L1, the upper TOF, the inner tracker, the lower TOF, and L9 is required to be compatible with $|Z| = 2$, namely $1.6 < |Z_{\text{L1 and L9}}| < 2.9$, $1.25 < |Z_{\text{upper and lower ToF}}|$ and $1.7 < |Z_{\text{L2 to L8}}| < 2.5$. To select only primary cosmic rays, the measured rigidity is required to be greater than a factor of 1.2 times the maximum geomagnetic cutoff within the AMS field of view. The cutoff was calculated by backtracing [15] particles from the top of AMS out to 50 Earth's radii using the most recent IGRF [16] geomagnetic model. These procedures resulted in a sample of 50×10^6 primary cosmic rays with $Z = 2$.

Due to the multiple independent measurements of the absolute charge, the selected sample contains only a small contamination of particles which had $Z \neq 2$ at the top of AMS. Comparing the protons and helium charge distributions in the inner tracker, the proton contamination was measured to be less than 10^{-4}. The sample also contains helium from other nuclei which interact at the top of AMS (for example, in L1). From the measured flux [17] and Monte Carlo simulation this contribution is below 10^{-3} for the entire rigidity range. The background contributions are accounted for in the systematic errors.

4. Analysis

The isotropic He flux Φ_i for the i^{th} rigidity bin $(R_i, R_i + \Delta R_i)$ is

$$\Phi_i = \frac{N_i}{A_i\, \varepsilon_i\, T_i\, \Delta R_i} \tag{4.1}$$

where N_i is the number of events corrected with the rigidity resolution function (see below), A_i is the effective acceptance, ε_i is the trigger efficiency, and T_i is the collection time. In this paper the helium flux was measured in 68 bins, $i = 1$ to 68, from 1.9 GV to 3 TV with bin widths chosen according to the rigidity resolution. The effective acceptance A_i was calculated using the Monte Carlo simulation and then corrected for the small differences found between the data and the Monte Carlo event selection efficiencies. The trigger efficiency ε_i was measured to range from 95 to 99.5%, where the inefficiency is mostly due to secondary δ-rays produced by He in the tracker materials and entered the ACC. The Monte Carlo simulation agrees with the measured trigger efficiency within 0.5%.

The bin-to-bin migration of events was corrected using the two unfolding procedures described in Ref. [8].

Extensive studies were made of the systematic errors. These errors include the uncertainties in the trigger efficiency, the acceptance, the background contamination, the geomagnetic cutoff factor, the event selection, the unfolding, the rigidity resolution function, and the absolute rigidity scale. The trigger efficiency error is dominated by the statistics available from the 1% prescaled trigger (iii) event sample. It is less than 0.2% below 100 GV and reaches 1% at 3 TV. The geomagnetic cutoff factor was varied from 1.0 to 1.4, resulting in a negligible systematic uncertainty (less than 0.1%) in the whole rigidity range.

The effective acceptance was corrected for small differences between the data and the Monte Carlo samples related to the event reconstruction and selection. Together, the correction on the acceptance was found to be less than 2% above 2 GV. The corresponding systematic error on the flux is less than 1% below 200 GV and reaches 1.4% at 3 TV.

We have developed a method to determine the magnitude and rigidity dependence of the survival probability of He when traversing the detector materials. We used a sample of primary cosmic rays collected with AMS horizontal, that is, when the ISS was oriented such that AMS was pointing within $90^\circ \pm 10^\circ$ of the local zenith, a total of 140,000 s. Particles which passed through from L8 to L2 were identified as $|Z| = 2$ with the dE/dx in the seven inner tracker planes L8 to L2. We then measured the survival probability for helium to traverse the material from L2 to L1 (the upper TOF and TRD) by comparing the charge distributions between L2 and L1.

Similarly, using particles collected with AMS horizontal which passed from L2 to L8 and were identified as $|Z| = 2$, the He survival probability was also measured between L8 and L9, that is, when traversing the thin inner tracker aluminum and carbon fiber enclosure, the lower TOF, and the

RICH radiator. The accuracy of this method was verified using the data when AMS was pointing within 40° of the local zenith.

The small ($< 3\%$) interaction probability between tracker L2 and L8 was calculated by comparing the charge distributions between the upper and the lower TOF for He events.

Averaged over path lengths within the acceptance, the material traversed by particles between L1 and L9 is composed, by weight, of 73% carbon, 17% aluminum, and small amounts of silicon, oxygen, hydrogen, sodium, gold, and other elements. The corresponding inelastic cross sections of He+C and He+Al have only been measured below 10 GV [18]. The Glauber-Gribov model [12] of inelastic cross sections is used in the Monte Carlo calculation of the acceptance. In this model the corresponding cross sections have small rigidity dependencies of 5% from 8 GV to 3 TV. To obtain the best agreement between the data and the simulation, dedicated event samples were simulated with the inelastic cross sections scaled by ±5%, ±10%, ±15%, and ±20%. Then the survival probabilities for He between L2 and L1 and between L8 and L9 were compared between data and the dedicated simulated event samples and the simulated event sample with the best agreement to data was chosen. Using these scaled interaction probabilities and the rigidity dependence of the cross sections from the model, the systematic error on the flux due to uncertainties of He inelastic cross sections was evaluated to be 1% below 100 GV and 2% at 3 TV.

An additional systematic error on the flux is due to differences in ^{3}He and ^{4}He interactions with the detector materials. This was assigned according to the uncertainty in the He isotopic composition. The error of 0.3% on the flux was obtained by varying the ratio of ^{3}He/^{4}He in the simulation from 0 to 0.2 [19]. The flux was then treated as containing only ^{4}He.

The rigidity resolution function for helium was obtained from the simulations and verified with the data. First, the differences of the coordinates measured in L3 or L5 to those obtained from the track fit using the measurements from L2, L4, L6, L7, and L8 were compared between data and simulation. This procedure directly measures the tracker coordinate accuracy of $\pm 7.5\mu$m. Second, the differences between the coordinates measured in L1 and L9 and those obtained from the track fit using the information from only the inner tracker were compared between data and simulation. Third, the RICH velocity resolution is $\Delta\beta/\beta = 8.0\times10^{-4}$. The rigidity resolution function up to 20 GV, including non-Gaussian tails, was obtained with data using the RICH velocity measurements only and compared with the rigidity resolution function from the simulation. Fourth, in order to validate the alignment of the external layers L1 and L9, the difference between the rigidities measured using the information from L1 to L8 and from L2 to L9 was compared between data and the simulation. These four verifications provided the MDR of 3.2 ± 0.16 TV and an uncertainty on the amplitude of the non-Gaussian tails in the rigidity resolution function of 10%.

The systematic error on the He flux due to uncertainties in the rigidity resolution function was obtained by varying the width of the Gaussian core of the resolution function by 5% and the amplitude of the non-Gaussian tails by 10% over the entire rigidity range in the unfolding procedures and found to be 1% below 200 GV and 4% at 3 TV. The small differences between the two unfolding procedures results ($< 0.5\%$) were also accounted as a systematic error. We have checked the sensitivity of the results to the binning by increasing the bin width by factors of 2 and 4 as well as reducing the bin width by factors of 2 and 4. The resulting uncertainty is well within the assigned systematic errors.

There are two contributions to the systematic uncertainty on the rigidity scale, discussed in detail in Ref. [8]. The first is due to residual tracker misalignment. This error was estimated by comparing the E/p ratio for electrons and positrons, where E is the energy measured with the ECAL and p is the momentum measured with the tracker. It was found to be $1/26\,\mathrm{TV}^{-1}$, limited by the current high energy positron statistics. The second systematic error on the rigidity scale arises from the magnetic field map measurement and its temperature corrections and amounts to less than 0.5% over the entire rigidity range. The error on the He flux due to uncertainty on the rigidity scale is below 0.6% up to 100 GV and reaches 6% at 3 TV.

To ensure that the treatment of systematic errors is correct, several additional, independent verifications were performed.

Most importantly, several independent analyses were performed on the same data sample by different study groups. The results of those analyses are consistent with this paper.

5. Results

The results will be shown in the conference.

6. Conclusion

In conclusion, precise knowledge of the helium flux is important in understanding the origin, acceleration, and propagation of cosmic rays. Previous measurements of the helium flux in cosmic rays have reported different variations of the flux with energy (or rigidity) and this has generated many theoretical models. Our precise measurement of the He flux from 1.9 GV to 3 TV is based on 50 million events with detailed studies of the systematic errors. The flux deviates from a single power law and the spectral index progressively hardens at high rigidities. The magnitude of the helium spectral index is different from that of the proton spectral index, but the rigidity dependence is similar for helium and protons.

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