Helium in near Earth orbit

AMS Collaboration


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Abstract

The helium spectrum from 0.1 to 100 GeV/nucleon was measured by the Alpha Magnetic Spectrometer (AMS) during space shuttle flight STS-91 at altitudes near 380 km. Above the geomagnetic cutoff the spectrum is parameterized by a power law. Below the geomagnetic cutoff a second helium spectrum was observed. In the second helium spectra over the energy range 0.1 to 1.2 GeV/nucleon the flux was measured to be \((6.3 \pm 0.9) \times 10^{-3} \text{ (m}^2 \text{sec sr)}^{-1}\) and more than ninety percent of the helium was determined to be \(^{3}\text{He}\) (at the 90\% CL). Tracing helium from the second spectrum shows that about half of the \(^{3}\text{He}\) travel for an extended period of time in the geomagnetic field and that they originate from restricted geographic regions similar to protons and positrons.

1. Introduction

Helium nuclei are the second most abundant element in cosmic rays. Helium rigidity spectrum measurements carried out over the past several decades (see [1] and references therein) have yielded insight into the origin of cosmic rays [2]. Since no difference in the rigidity spectra of protons and helium has been detected the same sources and propagation histories were inferred for both species [3]. However, recent and more accurate measurements [4,5] suggest protons and helium may have different spectral indices in the range 10 to 100 GV. The most accurate experiments to date were balloon based [4,6–9], however in balloon experiments the \(\sim 5\) g/cm\(^2\) of residual atmosphere was an important source of systematic errors. Above \(\sim 1000\) GV emulsion experiments [10, 11] have indicated a more pronounced difference. Geomagnetically trapped low energy light isotopes have been studied with satellites [12].

The Alpha Magnetic Spectrometer (AMS) [13] is a high energy physics experiment scheduled for installation on the International Space Station. In preparation for this mission, AMS flew a precursor mission in June 1998 on board the space shuttle Discovery during flight STS-91 at altitudes between 320 and 390 km. In this report the data collected during that flight are used to study the cosmic ray helium spectra in the kinetic energy range 0.1 to 100 GeV/nucleon.

The high statistics \((\sim 10^6)\) available allow measurement of the helium spectrum over a range of geomagnetic latitudes. With the incident particle direction and momentum accurately measured in AMS, the origin of particles below geomagnetic cutoff is studied by tracking them in the Earth’s magnetic field.

2. The AMS experiment

The major elements of AMS as flown on STS-91 were a permanent magnet, a tracker, time of flight hodoscopes, a Čerenkov counter and anti-coincidence counters [14,15]. The permanent magnet had the shape of a cylindrical shell with inner diameter 1.1 m and length 0.8 m. It provided a central dipole field of 0.14 Tesla across the magnet bore and an analyzing power, \(BL^2\), of 0.14 Tm\(^2\) parallel to the magnet, or \(z\)-axis. The six layers of double sided silicon tracker were arrayed transverse to the magnet axis. The outer layers were just outside the magnet bore. The tracker measured the trajectory of relativistic unit charge particles with an accuracy of 10 microns in the bending coordinate and 30 microns in the non-bending coordinate, as well as providing multiple energy loss measurements. The time of flight system had two orthogonal planes at each end of the magnet, covering the outer tracker layers. Together the four planes measured doubly charged particle transit times with an accuracy of 105 psec and they also yielded multiple energy loss measurements. A layer of anti-coincidence scintillation counters lined the inner surface of the magnet. Low energy particles were absorbed by thin carbon fiber shields. In flight the AMS positive \(z\)-axis pointed out of the shuttle payload bay.

Data collection started on 3 June 1998. The orbital inclination was 51.7\(^\circ\) and the geodetic altitude ranged from 320 to 390 km. For this study the data was collected in three periods:

(a) 25 hours before docking with the MIR space station, during which the shuttle attitude was constrained to keep the AMS \(z\)-axis pointing within 45\(^\circ\) of the zenith.
3. Analysis

The incident particle rigidity, \( R = \frac{pC}{|Z|e} \), was fit using two independent algorithms from the deflection of the trajectory measured using hits in at least 4 planes of the tracker. The velocity of the particle, \( \beta = \frac{v}{c} \), was determined using the information of the time of flight hits matching the reconstructed track. The mass of the particle was then determined from the measured velocity and momentum. To obtain \( |Z| \), a reference set of energy loss distributions was obtained from the data samples and the energy measurements of the hits associated to the reconstructed particle were then fit to these reference distributions independently for the tracker layers and for the time of flight planes. For particles with \( |Z| > 1 \) the reconstruction was repeated requiring a higher threshold on the tracker hits. The particle type was then determined by combining the velocity, momentum and \( Z \) measurements.

A particle was selected as a helium candidate if the determination of the charge magnitude from the measurements of energy losses in the tracker planes was \( |Z| = 2 \) and the particle type was compatible with a \( |Z| > 1 \) particle.

The main potential source of background to the helium sample were protons wrongly reconstructed as \( |Z| = 2 \) particles. Using the independent measurement of the charge magnitude obtained from the time of flight counters, as detailed in our earlier publication [15], this background was estimated to be less than \( 10^{-4} \) over all energies.

4. Differential helium flux

The differential helium flux was determined by correcting the measured rates for the detector acceptance as a function of the particle momentum and direction. The acceptance was determined via the Monte Carlo method using simulated helium samples which were required to pass through a trigger simulation and the same reconstruction and selection chain as for data. The average acceptance was determined to be \( 0.10 \text{ m}^2 \text{ sr} \) for rigidities above 20 GV, increasing at lower rigidities to \( 0.16 \text{ m}^2 \text{ sr} \).

 Corrections to the acceptance were studied with a sample of events collected with an unbiased trigger and by comparing data and Monte Carlo samples. The average contributions to the uncertainty in these corrections were 4% from the trigger, 3% from the track reconstruction, and 2% each from the modeling of particle interactions and from the selection; leading to an overall systematic error of 6% in the acceptance. The incident differential helium flux was obtained from an unfolding of the measured spectrum based on Bayes’ theorem [18].

For the differential flux analysis, only the data sample from period (c) was considered. The differential spectra for three ranges of the corrected geomagnetic latitude [19], \( |\theta_M| \), are presented in Fig. 1 for the 0° attitude subsample.

The figure shows the effect of the geomagnetic cutoff which decreases with increasing \( |\theta_M| \). In addition to the above cutoff, or primary, spectrum, Fig. 1 also shows the presence of a second spectrum below cutoff for \( |\theta_M| < 0.8 \), which is discussed in detail below.

This cutoff effect varies weakly for the different attitudes (0°, 20°, 45°) due to the anisotropy of the flux at these rigidity ranges. Above cutoff the flux
The spectrum has been fit over the rigidity range 20−<R<200 GV. To avoid cutoff effects, data collected in regions where the expected cutoff in the direction of the AMS z-axis was larger than 12 GV were excluded from the fit. The results obtained on the three different attitude samples were the same within the errors. The combined fit yields:

$\gamma = 2.740 \pm 0.010(\text{stat}) \pm 0.016(\text{sys})$,  
$\Phi_0 = 2.52 \pm 0.09(\text{stat})$  
$\pm 0.13(\text{sys}) \pm 0.14(\gamma) \frac{\text{GV}^{-0.74}}{\text{m}^2 \text{sec sr MV}}$.  

5. Analysis of the primary spectrum

The primary cosmic ray spectrum may be parametrized by a power law in rigidity as $\Phi_0 \times R^{-\gamma}$. The spectrum has been fit over the rigidity range 20−<R<200 GV. To avoid cutoff effects, data collected in regions where the expected cutoff in the direction of the AMS z-axis was larger than 12 GV were excluded from the fit. The results obtained on the three different attitude samples were the same within the errors. The combined fit yields:

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Table 1  
Differential primary helium flux in units of (m$^2$ sec sr GV)$^{-1}$ versus rigidity, $R$, in GV. The errors quoted are the combination in quadrature of the statistical and systematic errors.

<table>
<thead>
<tr>
<th>$R$</th>
<th>Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.76–0.91</td>
<td>32 ± 16</td>
</tr>
<tr>
<td>0.91–1.10</td>
<td>48.9 ± 2.9</td>
</tr>
<tr>
<td>1.10–1.32</td>
<td>58.4 ± 3.2</td>
</tr>
<tr>
<td>1.32–1.58</td>
<td>62.8 ± 3.4</td>
</tr>
<tr>
<td>1.58–1.91</td>
<td>63.9 ± 3.5</td>
</tr>
<tr>
<td>1.91–2.29</td>
<td>58.2 ± 3.2</td>
</tr>
<tr>
<td>2.29–2.75</td>
<td>49.4 ± 2.7</td>
</tr>
<tr>
<td>2.75–3.31</td>
<td>39.6 ± 2.1</td>
</tr>
<tr>
<td>3.31–3.98</td>
<td>30.8 ± 1.7</td>
</tr>
<tr>
<td>3.98–4.79</td>
<td>22.6 ± 1.2</td>
</tr>
<tr>
<td>4.79–5.75</td>
<td>(159 ± 8.6) × 10$^{-1}$</td>
</tr>
<tr>
<td>5.75–6.92</td>
<td>(110 ± 5.9) × 10$^{-1}$</td>
</tr>
<tr>
<td>6.92–8.32</td>
<td>(72.8 ± 3.9) × 10$^{-1}$</td>
</tr>
<tr>
<td>8.32–10.00</td>
<td>(47.1 ± 2.5) × 10$^{-1}$</td>
</tr>
<tr>
<td>10.00–12.02</td>
<td>(29.9 ± 1.6) × 10$^{-1}$</td>
</tr>
<tr>
<td>12.02–14.45</td>
<td>(18.9 ± 1.0) × 10$^{-1}$</td>
</tr>
<tr>
<td>14.45–17.38</td>
<td>(119 ± 6.4) × 10$^{-2}$</td>
</tr>
<tr>
<td>17.38–20.89</td>
<td>(73.7 ± 4.0) × 10$^{-2}$</td>
</tr>
<tr>
<td>20.89–25.12</td>
<td>(47.0 ± 2.6) × 10$^{-2}$</td>
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<td>25.12–30.20</td>
<td>(28.9 ± 1.6) × 10$^{-2}$</td>
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<td>30.20–36.31</td>
<td>(172 ± 9.4) × 10$^{-3}$</td>
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<tr>
<td>36.31–43.65</td>
<td>(101 ± 5.6) × 10$^{-3}$</td>
</tr>
<tr>
<td>43.65–52.48</td>
<td>(63.2 ± 3.5) × 10$^{-3}$</td>
</tr>
<tr>
<td>52.48–63.10</td>
<td>(38.0 ± 2.1) × 10$^{-3}$</td>
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<tr>
<td>63.10–75.86</td>
<td>(22.2 ± 1.2) × 10$^{-3}$</td>
</tr>
<tr>
<td>75.86–91.20</td>
<td>(137 ± 8.0) × 10$^{-4}$</td>
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<tr>
<td>91.20–109.65</td>
<td>(82.9 ± 5.0) × 10$^{-4}$</td>
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<td>109.65–131.83</td>
<td>(49.1 ± 3.3) × 10$^{-4}$</td>
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<td>131.83–158.49</td>
<td>(27.8 ± 1.9) × 10$^{-4}$</td>
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<tr>
<td>158.49–190.55</td>
<td>(16.5 ± 1.4) × 10$^{-4}$</td>
</tr>
<tr>
<td>190.55–229.09</td>
<td>(118 ± 8.0) × 10$^{-5}$</td>
</tr>
</tbody>
</table>
Fig. 2. Primary helium flux spectrum multiplied by $R^{2.74}$ in units of $\text{m}^{-2}\text{sec}^{-1}\text{sr}^{-1}\text{GV}^{1.74}$. The band covers the range of the fit including the errors combined in quadrature. The smooth line shows the spectrum used for atmospheric neutrino spectrum calculations [20].

The systematic uncertainty in $\gamma$ was estimated from the uncertainty in the track resolution (0.014) and the variation of the selection criteria (0.009). The third uncertainty quoted for $\Phi_0$ reflects the systematic uncertainty in $\gamma$. This fit is shown with the data in Fig. 2. In Fig. 3 the primary spectrum is compared to the recent balloon measurements [5,7–9].

Fig. 3. Comparison with recent measurements of the primary helium flux spectrum multiplied by $E_K^{2.5}$ in units of $\text{m}^{-2}\text{sec}^{-1}\text{sr}^{-1}(\text{GeV}/\text{A})^{1.5}$.

6. Analysis of the second spectrum

As shown in Fig. 1 a second spectrum is observed for $|\Theta_{\eta}| < 0.8$. This spectrum extends from the lowest measured rigidity, 0.8 GV, up to 3 GV with an integrated flux of $\sim 10^{-3}(\text{m}^2\text{sec}\text{sr})^{-1}$.

To ensure these events are not due to resolution effects at low energies or to contamination from single scattering inside the detector, more stringent reconstruction criteria were applied in the examination of the second spectrum. Those $|Z| = 1$ events with a wrongly reconstructed charge magnitude were reduced by an additional factor of 100 by requiring the combined time of flight and tracker charge magnitude determinations to be $|Z| = 2$. Tails in the velocity reconstruction were reduced by requiring at least three matched hits in the four time of flight planes. In this energy range, the accuracy of the velocity measurement is 2.4%. Any large angle scattering in a tracker plane was identified and removed by requiring that the particle was also measured by the tracker in the non-bending projection and by requiring agreement between the rigidity measured with the first three hits along the track, with the last three hits and with all the

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9 A $^3\text{He}$ fraction of 0.15 ± 0.05 was assumed.
Fig. 4. Mass distribution for helium events above geomagnetic cutoff for $|\theta_M| > 0.9$ and $\beta < 0.9$. Filled circles are data for period (c). Histogram is a Monte Carlo simulation with 11.5% $^3$He.

Fig. 5. Correlation between rigidity and velocity for helium events detected at $|\theta_M| < 0.6$. Dots denote events from the primary spectrum, and open circles those from under cutoff. The solid (dashed) line corresponds to $^3$He ($^4$He).

Fig. 6 shows a scatter plot of rigidity versus $\theta_M$ for events with $\beta < 0.9$. The two symmetric clusters at $|\theta_M| > 0.6$ correspond to nuclei from the primary helium spectrum. The same 115 events marked in Fig. 5 form a clear and isolated low energy band ($R < 3$ GV). This second population has the following properties:

- The reconstructed mass distribution given in Fig. 7 shows that most of the events are consistent with $^3$He. At the 90% confidence level, the fraction of $^3$He exceeds ninety percent.
- As shown in Fig. 8, their spectrum extends from the lowest measured kinetic energy, $E_K = 0.1$ GeV/nucleon, to $\sim 1.2$ GeV/nucleon, yielding an average flux of $(6.3 \pm 0.9) \times 10^{-3}\text{(m}^2\text{sec sr)}^{-1}$.
- As shown in Fig. 9, the flux tends to a maximum at the geomagnetic equator.

Within the statistics, there is no preferred direction and the fluxes measured separately with data from the three periods (a), (b) and (c) are equal.

To understand the origin of these events, the trajectories have been traced both backward and forward from their incident angle, location and momentum, through the Earth’s magnetic field, following the same procedure as described in [21,22]. All events were
found to originate in the atmosphere. Analysis of the sum of their forward and backward flight times yields two distinct classes: "short-lived" and "long-lived" for flight times below and above 0.3 sec, respectively.

As shown in Fig. 10 the origins of the "short-lived" helium nuclei are distributed uniformly around the globe whereas the "long-lived" particles originate from two geographically restricted regions. These regions match those from which the second proton flux
and second positron flux originate [21,22]. Within the statistics, $^{3}$He is equally predominate in events from both the “short-lived” and “long-lived” classes.

7. Conclusions

The helium spectrum between 0.1 and 100 GeV/nucleon was measured in near Earth orbit. The primary helium rigidity spectrum has been fit to a power law with a spectral index $\gamma = 2.740 \pm 0.010$ (stat) $\pm 0.016$ (sys). Below the geomagnetic cutoff a second spectrum of helium was observed with a flux of $(6.3 \pm 0.9) \times 10^{-3}$ (m$^{-2}$ sr$^{-1}$). Over ninety percent of this second flux is $^{3}$He (at the 90% CL). This second flux has been traced to originate from the same locations as the corresponding second proton and positron fluxes, with the long lived component originating from two restricted geographic regions.

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[20] Formula 2.1 at solar minimum from M. Honda et al., Phys. Rev. D 52 (1995) 4985, we have recently been informed that their current analysis is in closer agreement with our data. We thank M. Honda for this communication.
