Precision Measurement of the Proton and Nuclei Fluxes
With AMS Experiment

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Cosmic Rays Nuclei Measurements

One of the fundamental measurements in cosmic rays is the determination of the rigidity dependence of spectra of cosmic ray primary nuclei H, He, C, O, Ne, Mg, Si and Fe. These are thought to be produced and accelerated in the supernova remnants in our Galaxy. Their spectra carry the information about their acceleration and propagation.

Another class of nuclei ($^3$He, Li, Be, B, F … ) is produced by nuclear interactions of the primary nuclei during their propagation in the Galaxy. The spectra and relative abundances of these nuclei reveal the propagation parameters, like amount of matter traversed by cosmic rays and the time it took.
Proton Flux

Protons are the most abundant charged particles in cosmic rays. Knowledge of the precise behavior of the proton spectrum is important in understanding the origin, acceleration, and propagation of cosmic rays.

AMS made the precise measurement of the proton flux in primary cosmic rays in the rigidity range from 1 GV to 1.8 TV based on 300 million events.
Measurements of the proton flux before AMS

Previous measurements of the proton flux in cosmic rays have reported different variations of the flux with energy. In particular, experiments showed different deviations of the proton flux from a single power law.
AMS Cosmic Ray Proton Flux Measurement

Tracker (9 Layers) + Magnet
Rigidity and Charge Magnitude
Bending Coordinate Resolution $\approx 10 \, \mu m$
MDR $\approx 2 \, TV$

ToF (4 Layers)
Velocity and Direction
$\Delta \beta / \beta^2 \approx 4\%$

TRD, Tracker, RICH, TOF, ECAL
Charge Along Particle Trajectory $\Delta Z \approx 0.05-0.2$

Residual Background (He, e$^+$) 0.5% @ 1GV and <0.1% above 10 GV
Assuming flux above geomagnetic cutoff is isotropic the differential rigidity flux can be defined as

$$\Phi_i(R) = \frac{N_i}{T_i A_i \varepsilon_i \Delta R_i}$$

where:
- $N_i$: Events Corrected for Bin to Bin Migration due to Tracker
- $T_i$: Rigidity Resolution
- $A_i$: Bin width
- $\varepsilon_i$: Trigger Efficiency from Data
- $\Delta R_i$: Effective Acceptance from MC, Verified with Data

Flux statistical errors are very small (0.1-0.7%), so the final accuracy is defined by systematic errors on trigger efficiency, acceptance, migration and rigidity scale.
(i) Systematic errors on trigger efficiency

Trigger efficiency [4/4 TOF + VETO, 90-95%] was measured using 1% prescaled event sample obtained with unbiased 3 out of 4 ToF coincidence trigger. The error is dominated by the statistics available from the unbiased trigger.

This systematic error is negligible below 100GV and reaches 1.5% at 1.8TV.
(ii) Systematic errors on acceptance due to interactions

The detector components traversed by the particles (TRD, TOF, Tracker, RICH) are mostly made of C and Al. The inelastic cross sections of $p + C$ and $p + Al$ are measured to few percent between 1 and 300 GV.

Using MC samples with cross sections varied by ±10%, we found that the errors on the flux due to uncertainty in inelastic cross sections are

- 1% [1 GV]
- 0.6% [10-300 GV]
- 0.8% [1.8 TV]
(iii) Systematic errors on the rigidity resolution function

The rigidity resolution function was measured with 400 GeV proton beam and verified with the ISS data. The unfolding errors were obtained by varying the width of the Gaussian core of the resolution function by 5% [due to uncertainty of 1μm of L1,9 alignment] and amplitudes of the non-Gaussian tails by 20% [due to uncertainty in large angle p-Nuclei scattering] and found: 1% below 200GV and 3% at 1.8TV.

The resolution function for 400 GeV/c protons measured in test beam compared with simulation.
(iv) Systematic errors on the absolute rigidity scale

a) Residual tracker misalignment, i.e. how the measured average inverse rigidity of straight tracks \((1/\Delta)\) differs from zero. This was measured by comparing the 
\[ \text{Energy} [E, \text{Measured by ECAL}] / \text{Rigidity} [R, \text{Measured by Tracker}] \] ratio for electron and positron events and was found to be less than \(1/(26TV)\), limited mostly by the high energy positron statistics. The corresponding flux error is \(5\% \at 1.8 TV\).
Proton Flux Errors Breakdown

![Proton Flux Errors Breakdown Graph](image-url)
Proton Flux

Flux \times R^{2.7} \left[ \text{m}^{-2} \cdot \text{sr}^{-1} \cdot \text{sec}^{-1} \cdot \text{GV}^{1.7}\right] vs. Rigidity [GV]

AMS-02
300 Million Events

Proton Flux
Fitting Proton Flux with the Double Power Law Model

$R^\gamma$ below $R_0$, $R^{\gamma+\Delta\gamma}$ above $R_0$ (transition rigidity) and transition smoothness $s$.

\[ \Phi = C \left( \frac{R}{45 \text{ GV}} \right)^\gamma \left[ 1 + \left( \frac{R}{R_0} \right)^{\Delta\gamma/s} \right]^s \]

$\gamma = -2.849^{+0.002}_{-0.003} \text{(fit)}^{+0.004}_{-0.003} \text{(sys)}$

$\Delta\gamma = 0.133^{+0.032}_{-0.021} \text{(fit)}^{+0.046}_{-0.030} \text{(sys)}$

$R_0 = 336^{+68}_{-44} \text{(fit)}^{+66}_{-28} \text{(sys)} \text{ [GV]}$

$\chi^2 / \text{NDF}=25/26$
The spectral index varies with rigidity. In particular, the spectral index is progressively hardening with rigidity above \(~100\) GV.

\[ \Phi = C \cdot R^\gamma \]

Spectral Index \(\gamma = \frac{d[\log(\Phi)]}{d[\log(R)]}\)
Proton Flux Comparison with Earlier Measurements

- AMS 300 Million Events
Helium Flux

Helium nuclei are the second most abundant charged particles in cosmic rays.

AMS made the precise measurement of the helium flux in primary cosmic rays in the rigidity range from 1.9 GV to 3 TV based on 50 million events.
Measurements of the Helium flux before AMS

Previous measurements of the helium flux in cosmic rays have reported different variations of the flux with energy. These were the best data before AMS.
AMS measured the Survival Probabilities L2 to L1 and L8 to L9 during “Horizontal” runs [~10^5 sec exposure] in which CRs can enter AMS both right to the left and left to the right. L8->L9 can also be measured in ECAL acceptance during usual conditions. Most importantly, by flying horizontally AMS was able to make Interaction cross sections measurements which were not available from accelerators.
(ii) He Survival Probability L8 to L9
MC GEANT 4.1 Glauber-Gribov Scaled Model to Data Comparison

Ratio of the He survival probabilities from L8 to L9 between the best scaled simulation and data when traversing the lower TOF and RICH. The dashed curve indicates the corresponding systematic errors.

GG model rigidity dependence still need to be modified below ~30 GV.
(ii) He Survival Probability
L1 to L9 MC to Data Comparison

Ratio of the He survival probabilities from L1 to L9 between the best scaled simulation and data when traversing the entire detector. The dashed curve indicates the corresponding systematic errors. GG model rigidity dependence still need to be modified below ~30 GV.
(ii) AMS measured He+C cross section
AMS Materials C(73%) Al(20%)

The AMS measured He+C inelastic cross section in comparison with experimental results. The dashed curve indicates the corresponding systematic errors.
(ii) AMS Tuned He+C cross section Energy Dependence

GG model rigidity dependence still need to be modified below ~30 GV.
(iii) Helium Tracker Resolution

\[ \Delta y [\mu m] \]

ISS He Data 55-65 GV

He Simulation

\[ \pm 7.5 \mu m \]
Helium Flux 2.5 Years

50 Million Events

Flux $\times \tilde{R}^{2.7}$ [m$^{-2}$sr$^{-1}$sec$^{-1}$ GV$^{-1.7}$]

Rigidity ($\tilde{R}$) [GV]

AMS-02
Helium Flux Comparison with Earlier Measurements

![Graph showing helium flux comparison with earlier measurements. The x-axis represents kinetic energy (GeV/n), and the y-axis represents the flux multiplied by E^{2.7} (m^2 sr^{-1} s^{-1} (GeV/n)^{1.7}). The graph includes data from various experiments such as AMS-01, ATIC02, Balloon, BESS00, BESS-TeV, BESS-Polar I, BESS-Polar II, CAPRICE94, CAPRICE98, BESS93, BESS97, BESS98, BESS99, CREAM-I, IMAX92, JACEE, MASS91, PAMELA, RICH-II, RUNJOB, SOKOL, and AMS-02 (2015).]
The spectral index varies with rigidity. In particular, the spectral index is progressively hardening with rigidity above $\sim 100$ GV.

\[ \Phi = C \cdot \mathcal{R}^\gamma \]

Spectral Index $\gamma = d[\log(\Phi)]/d[\log(\mathcal{R})]$
Proton/Helium Flux Ratio

Summary Proton and Helium Flux

• Precision measurement of proton flux from 1 GV to 1.8 TV, and helium flux from 1.9 GV to 3 TV with AMS:
  – The detailed variation with rigidity of the flux spectral index is presented
  – The spectral index is progressively hardening at high rigidities
AMS is capable of measuring the fluxes of all Cosmic Nuclei from Z 3 to 28 and beyond, such as Li, Be, B, C, N, O, Al, Si, Fe, Ni and flux ratios with high precision.
AMS Light (Z up to 8) Nuclei Fluxes Measurement

- Carbon (Z=6) Tracker L1: \( \Delta Z(cu) = 0.3 \)
- Upper TOF: \( 0.16 \)
- Inner Tracker 2-8: \( 0.12 \)
- Lower TOF: \( 0.16 \)
- RICH: \( 0.32 \)

Rigidity (Momentum/Charge):

- Tracker Bending Coordinate Resolution: 5-7\( \mu \)m
- MDR \( \approx 3.2-3.5TV \)

Velocity and Direction:

- TOF (4 Layers): \( \Delta \beta/\beta \approx 0.05\% \)
- Tracker: \( \Delta \beta/\beta \approx 1-2\% \)

AMS Light (Z up to 8) Nuclei Fluxes Measurement

Tracker L9: 0.3
Flux Measurement

Isotropie flux above geomagnetic cutoff in rigidity is defined as

\[ \Phi_i(R) = \frac{N_i}{T_i A_i \varepsilon_i \Delta R_i} \]

- Rigidity 2-3000 GV
- Time \( \sim 123,000,000 \) sec \((R > 30 \text{ GV, 5 Years})\)
- Effective Acceptance from MC, Corrected for Nuclei Interactions Verified with Data
- Trigger Efficiency from Data
- Bin width
- Events Corrected for Background and for Bin to Bin Migration due to Tracker Rigidity Resolution
- Bin width
(i) Trigger efficiency for Nuclei

Trigger efficiency [4/4 TOF + VETO 4/8 ] was measured using 1% prescaled event sample obtained with unbiased 3 out of 4 ToF coincidence trigger. The error is dominated by the statistics available from the unbiased trigger.

This systematic error is small (less than 1%) for Z = 3 to 8, as trigger efficiency exceeds 95% in all measurement range.
The inelastic cross sections of $N + C$, $N + Al$ are only measured below few GV ($C,O$) or not measured ($Li,Be,B,N$).

AMS measured the nuclei Survival Probabilities $L2$ to $L1$ and $L8$ to $L9$ during "Horizontal" runs [$\sim 10^5$ sec exposure] in which nuclei can enter AMS both right to the left and left to the right. $L8\rightarrow L9$ Survival Probabilities can also be measured in ECAL acceptance during normal conditions.
(ii) Carbon Survival Probability L8 to L9 Data to MC Comparison

![Graph showing survival probability ratio and systematic error between L8 and L9 data compared to MC predictions.](image-url)
(ii) Carbon Survival Probability
L1 to L9 Data to MC Comparison
(iii) AMS Nuclei + C Inelastic Cross Section Measurements, 5-100GV Rigidity
(iv) Background to Nuclei Fluxes Measurement

Background from elements of higher charges, which interact between Tracker L1 and Tracker L2 can be measured from Data by fitting the Charge Distribution in L1. This systematic error is typically <0.5%
(iv) Background to Nuclei Fluxes Measurement

background from elements of higher charges, which interact at very top of AMS, i.e. above Tracker L1 is important for secondary nuclei like Li, Be, B, N where it can reach up to 10% @MDR. MC break-up channels have been verified with data, background systematic error <1 %.
(v) Systematic errors on the rigidity resolution function

The rigidity resolution functions were verified with the ISS data. The unfolding errors were obtained by varying the width of the Gaussian core of the resolution function by 5% [due to uncertainty of 1\(\mu\)m of L1,9 alignment] and amplitudes of the non-Gaussian tails by 20% [due to uncertainty in large angle N-N scattering] and found to be typically 1% below 200GV and 3% to 5% at MDR.

Difference between measured coordinates in L3-L6 and whose interpolated from fitted track
Verification of the Systematic Error of Unfolding, Acceptance and Rigidity Resolution

Carbon Flux obtained using the rigidity measured by only the L1+inner tracker in a larger acceptance is in very good agreement with the flux measured using the full lever arm, specifically at high rigidities (200 to 1000 GV) where the unfolding effects and resolution functions of the L1+inner tracker (1.3 TV MDR) and the full lever arm one (3.5 TV MDR) are very different.

![Graph showing flux ratio vs. rigidity with error bars and a systematic uncertainty band.](image-url)
Carbon Flux Errors Breakdown

- Total 13%
- Statistical 10%
- Rigidity Scale 6%
- Unfolding Acceptance
- Trigger
Carbon Flux

The current precision of the data at highest energies is limited by statistics.

FIG. 3. The AMS carbon flux (a) and oxygen flux (b) as a function of kinetic energy per nucleon multiplied by $E^2$. Compared with measurements since the year 1980 [4–12]. For the AMS measurement kinetic energy per nucleon is derived from the rigidity $\tilde{R}$ using

$$E_C = \frac{1}{12} \left( \sqrt{\left( \frac{6}{\tilde{R}} \right)^2 + M_C^2} - M_C \right)$$

where $M_C$ is the $^{12}$C mass and

$$E_O = \frac{1}{16} \left( \sqrt{\left( \frac{8}{\tilde{R}} \right)^2 + M_O^2} - M_O \right)$$

where $M_O$ is the $^{16}$O mass. Data points from [4–12] are extracted using [29].

The current precision of the data at highest energies is limited by statistics.

8.3 Million Events
The High Rigidity Behavior of Carbon Flux

\[ \Phi = C \left( \frac{R}{45 \text{ GV}} \right)^\gamma \left[ 1 + \left( \frac{R}{R_0} \right)^{\Delta \gamma/s} \right]^s \]

- **AMS Carbon**
- **Fit to Model**
- **Single Power Law**

![Graph showing the relationship between flux and rigidity with data points and fits using a power law model.](image_url)
Oxygen Flux

The current precision of the data at highest energies is limited by statistics.

The graph shows the oxygen flux as a function of kinetic energy per nucleon, multiplied by $E^2.7$. The data points are compared with measurements since the year 1980 [4–12]. For the AMS measurement, kinetic energy per nucleon is derived from the rigidity $\tilde{R}$ using $E_K = \frac{1}{12} \left( \sqrt{\left( \frac{6}{\tilde{R}} \right)^2 + M_C^2} - M_C \right)$, where $M_C$ is the $^{12}$C mass, and $O_K = \frac{1}{16} \left( \sqrt{\left( \frac{8}{\tilde{R}} \right)^2 + M_O^2} - M_O \right)$, where $M_O$ is the $^{16}$O mass. Data points from [4–12] are extracted using [29].

7.4 Million Events
The High Rigidity Behavior of Oxygen Flux

\[ \Phi = C \left( \frac{R}{45 \text{ GV}} \right)^\gamma \left[ 1 + \left( \frac{R}{R_0} \right)^{\Delta \gamma/s} \right]^s \]
Carbon/Oxygen Flux Ratio

![Graph showing the Carbon/Oxygen Flux Ratio against Rigidity (GV)].

- **AMS**
- **Constant Fit R>60 GV**

The graph demonstrates the C/O flux ratio changes with increasing rigidity.
Summary (on nuclei)

The flux ratios of primary cosmic rays are energy independent except p/He.

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<th>Rigidity (GV)</th>
<th>C/He Ratio</th>
<th>AMS (2016)</th>
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</tr>
<tr>
<td>100000000</td>
<td>1.6</td>
<td></td>
</tr>
</tbody>
</table>

AMS, C, O, ..., Fe + ISM → Li, Be, B + X

Carbon-to-helium flux ratio

Carbon-to-oxygen flux ratio
Nitrogen Flux

The current precision of the data at high energies is limited by statistics.

The graph shows the nitrogen flux as a function of kinetic energy. The flux is given by $N \times |E_K|^{2.7}$ [m$^2$ s$^{-1}$ Sr$^{-1}$ (GeV/n)$^{1.7}$]. The data points are compared with the GALPROP prediction and include contributions from CREAM-II, CRN/Spacelab2, HEAO3-C2, and AMS. The graph highlights a total of 2.1 million events.
The spectra of oxygen, carbon and nitrogen do not follow the traditional single power law.
Lithium Flux

Li Flux \times E_{K}^{2.7} \left[ \text{m}^{2} \text{s}^{-1} \text{sr}^{-1} (\text{GeV/n})^{-1} \right]

Kinetic Energy $E_{K}$ [GeV/n]
The spectra of protons, helium, and lithium do not follow the traditional single power law.
Nitrogen-to-Oxygen and Lithium-to-Oxygen Ratio Approaches constant at High rigidities
The flux ratio between primaries (C) and secondaries (B) provides information on propagation and the ISM.

Cosmic ray propagation is commonly modeled as a fast moving gas diffusing through a magnetized plasma.

At high rigidities, models of the magnetized plasma predict different behavior for $B/C = kR^{\delta}$.

With the Kolmogorov turbulence model $\delta = -1/3$ while the Kraichnan theory leads to $\delta = -1/2$. 
Boron-to-Carbon Ratio

$B/C = kR^\delta$, $\delta = -0.333 \pm 0.015$

Boron Flux

The current precision of the data at high energies is limited by statistics.
Be isotopes (\(^{7}\)Be, \(^{9}\)Be, \(^{10}\)Be) are generated by spallation of B, C,N,O ... \(^{10}\)Be is not stable, decays into \(^{10}\)B with half-life of 1.5 M years. Due to relativistic time dilation, the fraction of \(^{10}\)Be increase with energy, so the raising energy dependence of Be/B reveals the characteristic lifetime of cosmic rays in the Galaxy.
Be-to-Boron Ratio
Rigidity Dependence is seen

Be/B Flux Ratio
AMS, 2.5% common scale error not shown

Fit, $R_0$

$= \frac{30}{62}$

$\chi_{GV}^2 = -23 + 44 = 76$

Rigidity Dependence is seen

Rigidity [GV]

Be/B Flux Ratio
Be Flux

Be Flux × $E_K^{2.7}$ [m$^{-2}$s$^{-1}$sr$^{-1}$ (GeV/n)$^{1.7}$]

Kinetic Energy $E_K$ [GeV/n]

0.9 million beryllium nuclei
Primary and Secondary Nuclei Energy Dependence Summary

![Graph showing the dependence of flux on rigidity for different nuclei.
Oxygen, primary
Carbon, primary
Nitrogen, partially secondary
Li, partially secondary?
Boron, secondary
Be, secondary]
Future Examples: Iron

2 million Iron Nuclei
Summary Nuclear Fluxes

• Precise measurements of nuclear fluxes for Li, Be, B, C, N and O as well as the flux ratio measurement based on 5 Years AMS Data were presented:
  – The detailed variations of fluxes dependence with rigidity are being studied.
  – The measurements are still limited by statistics, and are expected to be significantly improved towards 2024.
Summary Nuclear Fluxes

- To Year 2024 AMS will provide precision measurements of nuclear fluxes up to Z=28 ... from GV to few TV:
  - The detailed variations of fluxes dependence with rigidity will be studied.
  - The flux ratios measurements will allow to extract precise information about cosmic ray propagation.
backup
Lithium-to-Boron Ratio
No rigidity dependence 10-100 GV

Li/B Flux Ratio

Rigidity [GV]

AMS
Constant @ R > R₀ Fit, R₀ = 9.5 GV