Precision measurements of nuclear CR energy spectra and composition with the AMS-02 experiment

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Abstract. The Alpha Magnetic Spectrometer 02 (AMS-02) is a large acceptance high-energy physics experiment operating since May 2011 on board the International Space Station. More than 60 billion events have been collected by the instrument in the first four years of operation. AMS-02 offers a unique opportunity to study the Cosmic Rays (CRs) since it measures the spectra of all the species simultaneously. We report on the precision measurements of primary and secondary nuclear spectra, in the GeV-TeV energy interval. These measurements allow for the first time a detailed study of the spectral index variation with rigidity providing a new insight on the origin and propagation of CR.

1. Introduction
The origin of the charged cosmic rays (CRs) is one of the major issues of modern astrophysics. The Nature gives us a very energetic beam, but does not provide the beam parameters, which are needed for a proper understanding of their origin. The observables are the CR energy spectra, chemical composition and arrival direction at the Earth’s position. From these, the source spectra may be inferred, as well as the features of galactic medium.

This implies that for a proper description of the CRs, the comprehension of the relation between observed data and source properties requires a consistent picture of cosmic ray transport in the galaxy. Propagation models take into account the acceleration at the sources, energy losses, nuclear interactions, diffusion and convective transport of CRs in the galactic environment [1,2,3].

The propagation of CR is modelled using the ratio of secondaries, created by fragmentation of heavier elements during the propagation in the interstellar medium (ISM), to primaries, produced and accelerated in the astrophysical sources.

In particular, the ratios between light nuclei, such as Lithium, Boron, Beryllium, and their main progenitor, as Carbon, Nitrogen, Oxygen are used to constrain parameters such as the average amount of interstellar matter traversed by CRs between creation and observation, or their characteristic escape time from our galaxy in Leaky Box models. In diffusive models, the secondary to primary ratios are sensitive to the energy dependence of the diffusion coefficient D.

An accurate knowledge of CR observables is important also for the search of exotic signals superimposed to the rare components of the cosmic rays. In fact, the flux from astrophysical sources is the background for any potential signal for “new physics” and must be estimated on the basis of the existing models of CR production and propagation.
2. The AMS detector
The AMS is a high energy magnetic spectrometer installed on the International Space Station since May 2011. The detailed description of the detector is presented in Ref. [4]. The relevant elements used in analyses that produced the results presented here are the permanent magnet [5], the silicon tracker, four planes of time of flight (TOF) scintillation counters, and an array of 8 anticoincidence counters (ACC).

The AMS is equipped also with a transition radiation detector (TRD), a ring imaging Čerenkov detector (RICH), and an electromagnetic calorimeter (ECAL). The tracker [6] has nine layers, the first (L1) at the top of the detector, the second (L2) above the magnet, six (L3 to L8) within the bore of the magnet, and the last (L9) 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. The magnetic spectrometer measures the rigidity $R$ of charged cosmic rays. For $Z = 2$ particles, the spatial resolution in the tracker layers is $\sim 7 \, \mu m$ 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 provides an independent measurement of the charge $Z$ of the cosmic ray. The charge resolution of the combined inner tracker is $\Delta Z \approx 0.07$ for $Z=2$ particles.

Two planes of TOF counters [12] 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. The signals from the two upper layers are combined to get an independent measurement of the charge with an accuracy $\Delta Z = 0.08$ for $Z=2$. The signals from the two lower planes provide another independent charge measurement with the same accuracy.

This allows for multiple independent charge measurements along the particle trajectory in the detector, which is crucial for the nuclei species identification. AMS can measure the particle charge up to iron ($Z=26$) and it provides a very good charge separation for light nuclei up to Oxygen, as shown in Fig 1.

![Figure 1. Tracker charge distribution of the light nuclei, as measured by the energy deposits in the tracker planes.](image)

For a given charge, the contamination due to other charges is well below % level up to Oxygen. Actually, the major background for such kind of species is the production of light nuclei inside the detector material from heavier elements crossing it, due to inelastic interactions.

Thanks to the multiple charge measurements capability in the upper and lower detectors of the instrument, inelastic interactions in the detector material can be rejected with high efficiency (>96%) and low contamination (<3%).

The AMS nuclear fluxes
The isotropic flux $\Phi$ for the in the rigidity bin $(R, R+\Delta R)$ is:

$$\Phi(R) \propto \frac{1}{R^2}$$
\[ \Phi = \frac{N}{A e T \Delta R} \]

where \( N \) is the number of events corrected with the rigidity resolution function, \( A \) is the effective acceptance, \( e \) is the trigger efficiency, and \( T \) is the exposure time.

Extensive studies of the systematic errors were made. These errors include the uncertainties in the trigger efficiency, the geomagnetic cutoff factor, the acceptance taking into account the event selection and reconstruction and also accounting for particle interactions in the detector, the unfolding, the rigidity resolution function, the absolute rigidity scale, and the background contamination discussed above. Statistical errors are negligible for protons and Helium which are dominated by systematic errors over the whole range of energies studied, while light nuclei such as Li, B, C are dominated by the statistical errors at high energies.

The proton flux is shown in Fig. 2, as a function of the kinetic energy in the range 1-2 TeV/n, together with some data from previous experiments. The details of proton flux analysis can be found in Ref.[7]. Total error (statistical + systematic) is ~6% at 1.8 TeV/n. The flux is well fitted with a double power law, with a continuous change in the protons flux slope observed at ~336 GeV, where the slope changes from \( \gamma = -2.849 \) to -2.716.

**Figure 2.** Proton flux multiplied by \( E^{2.7} \) as a function of kinetic energy.

**Figure 3.** Helium flux multiplied by \( E^{2.7} \) as a function of the kinetic energy per nucleon.
Helium flux is shown in Fig. 3 as a function of kinetic energy up to 2 TeV/n. The details of the analysis can be found in Ref. [8]. Total error (statistical + systematic) is ~8% at 2 TeV/n. As for the protons, the He flux is well fitted by a double power law, with a continuous change in the helium flux slope observed at ~245 GV, where the slope changes from $\gamma = -2.78$ to -2.661.

In Fig.4 the current status of the Boron to Carbon (B/C) flux ratio measurement with AMS is shown up to ~1 TeV/n, together with some previous experimental results [9]. The error is ~10% at 1 TeV/n. The experimental uncertainties at high energy are dominated by the limited statistics, which is $\approx 10\%$ of the expected total data sample that AMS will be able to collect during its long term operation on ISS. It's clear the capability of AMS to provide the first precise measurement of the B/C ratio at very high energy and it will help in solving the model parameters degeneracy. It's clear the capability of AMS to provide the first precise measurement.

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**Figure 4.** Boron over Carbon ratio as a function of kinetic energy per nucleon.

**Figure 5.** Lithium flux as a function of the rigidity R.
Like Boron and Berillium, Lithium is produced by the spallation of heavier nuclei during the propagation in the galaxy with the ISM (C, N, O, …, Fe + ISM --> Li, Be, B) [10] and is sensitive to CR propagation parameters as diffusion, convection, reacceleration.

Fig. 5 shows the current status of the Li flux measurement as a function of rigidity R up to 300 GV[10].

A change of spectral index as a function of rigidity is observed in the Li spectrum as for the lighter primary CR species, however - due to the faintness of the Li flux - further investigation of possible systematics effects and a larger collected statistics are needed to accurately evaluate this effect.

Conclusions
AMS provides the most accurate measurements of H and He in the rigidity range between 1 GV and 2 TV, and 1 GV and 3 TV, respectively. A continuous spectral change is observed for both H and He at about the same energy, a possible indication of a feature at the sources or a propagation effect. The proton to He flux ratio is well described by a single power law above 45 GV [9], which is unexpected if the two species have a common origin. The new precise measurement that AMS will provide on other primary CR nuclear flux ratios, as C/He or C/O, will add valuable information to better understand the origin of this behaviour. At the same time, the simultaneous measurement of secondary components as B/C or Li, whose current status has been reported, will represent a crucial input for any reliable propagation model of CR in the galactic environment.

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