The AMS-02 detector on the ISS - Status and highlights, after the first 7 years on orbit

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Abstract. The Alpha Magnetic Spectrometer, AMS-02, detector is operating on the International Space Station (ISS) since May the 19th, 2011. More than 120 billion events have been collected by the instrument in the first 7 years of data taking, providing detailed insight on the features of different species of cosmic rays. This contribution reviews the recent AMS-02 results based on 7 years of operations in space and their contribution to the advances in the understanding of cosmic ray origin, acceleration and propagation physics.

1 The AMS experiment and its scientific objectives

The Alpha Magnetic Spectrometer, AMS-02, is a general purpose high energy particle physics detector. It was launched to space with the Space Shuttle STS-134 mission and installed onboard the ISS in 2011, on May 19th, to conduct a unique long duration mission (up to the lifetime of the ISS) of fundamental physics research in space. More than 120 billion events have been collected by the instrument in the first 7 years of data taking.

The scientific objectives of the AMS collaboration cover a wide range of measurements in the field of the fundamental physics and of the Charged Cosmic Rays (CCR) physics in general:

- direct search of antimatter of primordial origin, through the detection of antinuclei;
- indirect search of “exotic” sources, through the precise measurement of the rare antimatter components (positrons, antiprotons and antideuterons);
- strong constraints on the models of origination and acceleration of the CCR, through the accurate and high statistics measurement of the primary nuclear components (proton, Helium, Carbon, Oxygen, etc... fluxes);
- strong constraints on the models of propagation in the Galaxy and in the Inter-Stellar Medium (ISM), through the accurate and high statistics measurement of the secondary components and of the secondary-to-primary ratios (Boron/Carbon (B/C), and Boron flux, Lithium flux, etc...).

To reach its scientific goals, the AMS-02 instrument, whose schematic layout is reported in Fig.1 (left), has been conceived with a large redundancy in the measurement of particle properties with complementary techniques by different sub-detectors.

The detector core is the magnetic spectrometer, composed of a 0.14 T dipole permanent magnet and

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Figure 1. Left - Schematic view of the AMS-02 spectrometer (bending view). Center - A summary sketch of the measurement redundancy and complementarity of the sub-detectors of the AMS-02 apparatus. Right - Distribution of the events, in the energy range 73-140 GeV, in the $ECAL$ classifier - TRD classifier plane. Negative from positive events are distinguished by means of the sign of the Rigidity in the spectrometer, $sign(R)$. The separation of the various components of e^- , e^+ , p and $\bar{p}$ is clearly visible.

9 layers of double sided Si microstrip tracker detectors. The particle rigidity, R , is measured over a lever arm up to 3 m, the maximum detectable rigidity is 2 TV for $|Z| = 1$ particles and 3.2 TV for $|Z| \geq 2$ particles. The direction of the curvature inside the magnetic field identifies the sign of the charge and consequently separates matter from the rare antimatter CR component. The charge resolution of the inner tracker amounts to $\Delta Z/Z = 3.5\%$ for He and improves up to 1.5% for O nuclei. Four Time-Of-Flight (TOF) planes trigger the readout of the detector and measure the particle flight direction and velocity. The 17 X0 ECAL imaging calorimeter provides the measurement of the $e^\pm$ energy (E), and the topology of the shower is used to separate $e^\pm$ from hadrons. The energy deposit in the 20 layers of the TRD are used to further differentiate between $e^\pm$ and protons. The analysis of the radiation in the Ring Imaging Cherenkov detector (RICH) provides accurate information on nuclei charges and velocity. Details about the performances of the different sub-detectors can be found in the first published result paper [1] and in the references therein.

As sketched in Fig.1 (center) the large number of sub-detectors results, in terms of the measured particle's properties, in a large redundancy (as for example for the measurement of the charge) and, moreover, guarantees a full complementarity that allows for a full Particle Identification (matter from antimatter distinction, electromagnetic from hadronic separation, etc...) at the single event level.

The identification of the various nuclear components is granted by the measurement of the charge of the impinging particles, all along the detector. Essentially all the sub-detectors have some charge measurement capability: the most accurate is the inner tracker, providing a ~ 0.1 c.u. charge resolution, with its 7 layers (each layer, alone, has a resolution of about 0.3 c.u.); the RICH and the TRD have a resolution of ~ 0.3 c.u., while each pair of planes of the TOF has a resolution of ~ 0.16 c.u.. This permits to follow the particle traversing the detector and to search for fragmentation that could spoil the charge reconstruction and constitute a source of background in the less abundant nuclear components (for example the secondaries). The dynamic range of the various detectors permits, with a resolution slightly degrading with Z , the charge measurement up to the higher charges: Iron and above (the Zinc peak is clearly visible) for Tracker, TOF and RICH, and up to $Z \sim 6$ for the TRD.

The discrimination power to the rare electromagnetic components, e^+ and e^- , from the overwhelming background of protons, and from the even rarer antiprotons component is sketched in Fig.1 (right). The two key detectors to distinguish e^+ and e^- from p and $\bar{p}$ are the ECAL (via classifiers exploiting the 3D imaging capability of the detector and built using multi-variate techniques such as BDT [2]

or *log-likelihood* [3]), and the TRD (via a *log-likelihood* to the energy deposit in its straw tubes). The discrimination between matter and anti-matter (i.e. e^+ from e^- or $\bar{p}$ from p) is provided by the spectrometer. The redundancy is also a key capability that permits to build, for example using the TRD classifier and the sign of the rigidity, almost pure control samples of e^- and p , to study the performances of the ECAL.

2 Experimental results

The analysis of the enormous amount of data being collected by the experiment permitted the publication of high statistics and very accurate measurement of the more important CCR components. In particular, in 2018, the Collaboration published four papers:

- Nitrogen flux in the range 2.2-3300 GV [4], based on the first 5 years of the collected data, corresponding to 2.2 million nitrogen nuclei;
- Li, Be and B flux in the range 1.9-3300 GV [5], based on the first 5 years of the collected data, corresponding to 1.9 million lithium, 0.9 million beryllium and 2.6 million boron nuclei;
- p and He fluxes as a function of rigidity (up to 60 GV) and time [6], based on the first 6 years of collected data, corresponding to 79 Bartels [7] rotations;
- e^- and e^+ fluxes as a function of rigidity (up to 50 GV) and time [8], based on the first 6 years of collected data, corresponding to 79 Bartels [7] rotations;

The results about Lithium, Beryllium, Boron and Nitrogen [5] [4] are summarized in Fig.2: as He-C-O were found to have a nearly identical rigidity dependance at high energies, being all primaries [9], also Li-Be-B are found to have a nearly identical dependance, being all secondaries. Their dependance is distinctly different to the one of primaries. The Nitrogen, expected to have both primary and secondary origin, is found to have a distinct rigidity dependance that is well fitted as a weighted sum of the primary and secondary dependences.

Figure 2. He-C-O, N and Li-Be-B fluxes, each one scaled to superimpose the other ones with similar rigidity dependence. The rigidity dependance of primaries (He-C-O), secondaries (Li-B-B) and nuclei with both the origins (N) are distinctly different.

The results about proton and helium [6] are summarized in Fig.3 (left): the proton and the helium

fluxes show nearly identical short-term and long-term structures in both time and relative amplitude. The amplitudes of the flux structures decrease with increasing rigidity and vanish above 40 GV. The electron and positron fluxes [8], as shown in Fig.3 (right), present short-term structures on the timescale of months coincident in both the fluxes. These structures are not visible in the e^+/e^- flux ratio. Differently from p and He, the e^+ and e^- fluxes present also long-term structures that, even if coherent between the two species, have amplitudes markedly different, with the difference that is a smooth function of time.

Figure 3. Left: proton (blue, left axis) and helium (red, right axis) fluxes as function of time for 3 rigidity bins. Detailed structures are clearly present below 40 GV and are nearly identical for the two species. Right: fluxes of positrons (red, left axis) and electrons (blue, right axis) as functions of time, for five energy bins. Prominent and distinct time structures visible in both the positron spectrum and the electron spectrum and at different energies are marked by dashed vertical lines. Long-term trends, instead, are markedly different between the two species.

These new results published in 2018 are part of the systematic campaign of measurement of the AMS-02 physics program:

- $e^+/(e^+ + e^-)$ in the range 0.5-500 GeV [1, 10], based on 30 months and ~ 10.9 million positron and electron events;
- positron flux in the range 0.5-500 GeV and electron flux in the range 0.5-700 GeV [11], based on 30 months and ~ 0.6 million positrons and ~ 9.2 million electrons ;
- *all-electron*, $e^+ + e^-$, flux, in the range 0.5-1000 GeV [12], based on 30 months and ~ 10.6 million positron and electron events;
- p flux in the range 1-1800 GV [13], based on 30 months and ~ 300 million protons;
- He flux in the range 1.9-3000 GV [14], based on 30 months and ~ 50 million helium events;
- antiproton flux and $\bar{p}/p$ ratio in the range 1-450 GV [15], based on the first 4 years of the collected data, corresponding to ~ 350000 antiproton and ~ 2.4 billion proton events;
- B/C, ratio in the range 1.9-2600 GV [16], based on the first 5 years of the collected data, corresponding to 2.3 million boron and 8.3 million carbon nuclei;
- He, C and O fluxes in the range ~ 2 -3000 GV [9], based on the first 5 years of the collected data, corresponding to ~ 90 million helium, 8.4 million carbon and 7.0 million oxygen nuclei.

All these measurements, together, can be seen in Fig.4, where each flux is scaled differently, just for display purpose, to superimpose the other ones with a similar trend as a function of the energy. The resulting ‘scheme’ is populated, so far, by five different ‘families’ of fluxes: electrons, Li-Be-B,

Nitrogen, protons-antiprotons and positrons, He-C-O.

Figure 4. The fluxes measured by the AMS-02 experiment up to 2018. Each flux is scaled differently, just for display purpose, to superimpose the other ones with a similar trend as a function of the energy.

The big amount of collected data is being analyzed for the measurements of the other nuclear components (F, Ne, Na, Mg, Al, Si, etc..) and for the study of the other characteristics of the already published spectra (for example the variability of the C and O fluxes as a function of time). Of particular interest are the extension, in both statistics (factor 3) and energy reach (factor 2) of the $e^\pm$ fluxes and ratios, to be submitted for publication by the end of 2018. In 2019 the measurements of nuclei will be broadened by the first isotopic results (such as $^3\text{He}/^4\text{He}$, $^6\text{Li}/^7\text{Li}$ and deuteron). In the next couple of years also the antimatter search (i.e. anti-deuteron and anti-Helium) analyses should be mature and deep enough for publication.

3 Conclusions

Data recorded in the first ~ 7 years of mission are being analyzed to cover the physics program of the AMS-02 experiment: all the measurements performed so far show interesting features, extending previous observations and adding new findings whose experimental accuracy challenges the actual theoretical predictions. AMS-02 represents the first instrument with the capability to simultaneously study all the different nuclear CR species, including the less abundant ones and up to Iron, electrons and anti-matter with unprecedented accuracy and in an extended energy range. These unique features will allow AMS-02 to shed light on new phenomena and improve the current understanding of CR origin and propagation.

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