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Cosmic Rays observed by AMS-02: Main results obtained after 5 years of flight

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Summary. — The Alpha Magnetic Spectrometer (AMS-02) is a state-of-the-art particle physics detector which operates onboard the International Space Station since May 2011. The main goals of the AMS-02 project are the indirect search of dark matter, the search of primordial antimatter, and the determination of the cosmic ray energy spectra and composition at the TeV scale. In these proceedings, the main results achieved by AMS-02 in 5 years of operations will be presented and discussed.

1. – Introduction

Cosmic rays (CRs) are charged particles coming from outer space to the Earth's atmosphere with a broad range of energy that extends over several decades. Their origin, their transport in the Galaxy, and their interactions with the matter are not yet well known, so they are subject of extensive research. The experimental investigation of CR composition and energy spectra is focused on seeking answers to fundamental science questions: the origin of CRs in the Galaxy, and the nature of cosmological dark matter (DM) particles.

Proton and nuclei constitute the main component of the observed CR flux. In the $\sim$ GeV–TeV range of kinetic energy, CRs are composed of protons (about $\sim 89\%$), helium ($\sim 9\%$), heavier nuclei, electrons ($\sim 2\%$) and antiparticles ($\ll 1\%$). Part of them such as electrons, protons, ^{4}He, C-N-O, or Fe are believed to be of *primary* origin, *i.e.*, accelerated by supernova remnant (SNR) explosions, although the exact mechanisms are not yet well known [1]. Rarer CR elements such as ^{2}H, ^{3}He, Li-Be-B elements or antiparticles are believed to be of *secondary* origin, *i.e.* produced by collisions of primary nuclei with the interstellar gas. Measuring these components is crucial to understand the fundamental processes of CR acceleration and transport in the Galaxy, especially in the light of the recently observed anomalies in CR hadrons [2, 3] Moreover, the knowledge of the energy spectra of CR nuclei enables us to predict the level of secondary antimatter production in CRs, which constitutes the *astrophysical background* for the search of DM-induced signals. The spectra of CR antiprotons and positrons are indeed recognized to be powerful observables for the search of DM signatures.

In 2008, the PAMELA collaboration reported an unexpected *rise* in the positron fraction $e^+/(e^- + e^+)$ between 1 and 100 GeV of energy, which is in contrast with the standard expectations from secondary production models [4, 5]. This "positron excess" has been recently confirmed by AMS-02 in the extended energy range of 0.5–350 GeV. Unlike hadrons, light CR leptons are subjected to radiative energy losses which limit the range they can travel to distances of $d \lesssim 1\,\mathrm{kpc}$ at $E \gg 1\,\mathrm{GeV}$ [6]. Hence the observed positron excess suggests the existence of an unaccounted source of CR leptons, possibly placed near the solar system [7], which manifest itself as a distinctive excess in the high-energy positron flux. Extra sources may include either DM particles annihilation/decay or nearby astrophysical sources such as pulsars or old SNRs [7-11]. These scenarios can be distinguished by means of precise measurements of CR nuclei and antiprotons in the GeV-TeV energy region, which are currently being performed by the AMS-02 collaboration. With the expected accuracy and dynamic range of AMS-02, these data are of great importance both for the validation of CR propagation models and for indirect searches of DM.

2. – The AMS-02 experiment

AMS-02 is a multi-purpose CR detector operating onboard the International Space Station (ISS) since May 2011. The instrument will be active for the entire ISS lifetime, *i.e.*, until 2024 or beyond. With this long observation time and its large collecting power ($0.5\,\mathrm{m^2 sr}$), AMS-02 is capable to provide high-quality data on CR fluxes at the TeV energy scale with unprecedent precision and sensitivity. Furthermore, the measurements of low energy CR fluxes over an entire 11-year solar cycle will enable us to perform a multichannel investigation of the solar modulation effect of Galactic CRs. The AMS-02 instrument is described in details in ref. [12]. It is composed by several sub-detector systems that permit a redundant determination of the main characteristics of CR particles, *i.e.*, arrival direction, particle identity (signed charge, mass) and its kinetic energy or rigidity ($R = p/Z$). The particle direction and rigidity are obtained by the reconstruction of its trajectory along up to nine Silicon Tracker layers with $\sim 10\,\mu\mathrm{m}$ ($\sim 30\,\mu\mathrm{m}$) of spatial resolution on the Y (X) side. The velocity $\beta = v/c$ can be determined from the transit time between the upper-TOF and lower-TOF scintillator planes along the track (for $Z = 1$, $\Delta\beta/\beta \sim 3\%$), or more precisely using the RICH system (for $Z = 1$, $\Delta\beta/\beta \sim 10^{-3}$). The central part of AMS-02 is surrounded by an anti-coincidence system (ACC). The detector is completed with a Transition Radiation Detector (TRD), which is located at the top of the instrument, and a 18-layer electromagnetic calorimeter (ECAL), which is placed at the bottom. In the measurement of CR leptons, the signals in TRD and ECAL are used to discriminate the leptonic component from the hadronic background. The combination of these information allows for an efficient lepton/hadron separation power.

In the following section, the $e^{\pm}$, p and He measurements published by AMS-02 and based on the first 30 months of observation will be presented and discussed. Preliminary results for light nuclei fluxes (Li, B, C), B/C ratio and $\bar{p}/p$ will be also discussed.

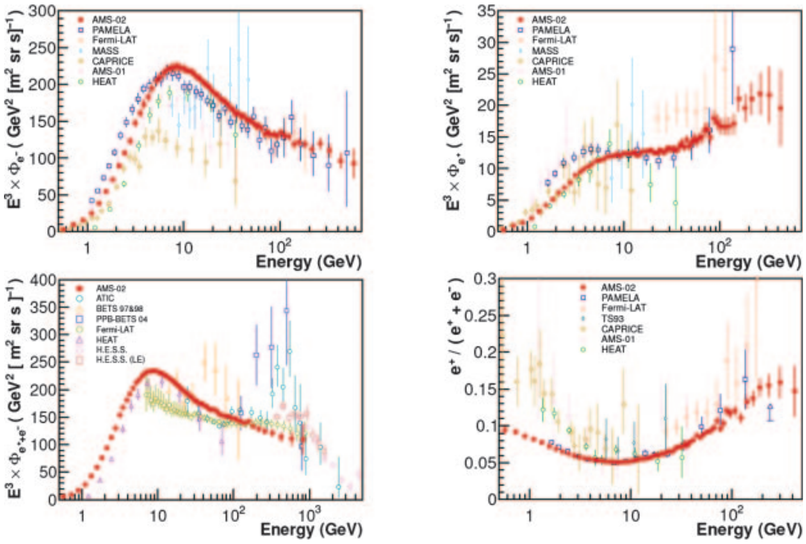

Fig. 1. – AMS-02 measurements of CR leptons compared with the previous experiment results: e$^-$ flux (top left) and e$^+$ flux (top right), all-lepton ($e^+ + e^-$) flux (bottom left), and positron fraction e$^+$/(e$^-$ + e$^+$) (bottom right). All fluxes are multiplied by E^3.

3. – Results and discussion

3·1. *Results on CR leptons.* – Figure 1 shows the AMS-02 results on electron and positron fluxes, arranged in various combinations, in the energy range 0.5–500 GeV. The AMS-02 data are compared with the data reported by previous experiments [4,5,13-15]. It can be seen that, in the low energy range (∼0.5–10 GeV), the positron fraction decreases with energy as naively expected from standard models of secondary production (bottom-right panel). However, at energy above ∼10 GeV, the AMS-02 data show an increase of the fraction up to 200 GeV, which is also followed by an intriguing flattening at $E \sim$ 200–400 GeV. This remarkable trend is in clear contrast with the conventional models of secondary e^+ production, because they predict a persistent decrease of the positron fraction in the whole 0.5–500 GeV energy range. The individual fluxes of e^+ and e^- are shown in the top panels of fig. 1. The data show that above $\sim$ 20 GeV and up to $\sim$ 200 GeV the e^- flux decreases more rapidly with energy than the e^+ flux. This demonstrates that the high-energy rise of the positron fraction is due to a hardening of e^+ spectrum and not to a softening of the e^- spectrum. More detailed studies on the $e^\pm$ spectral shapes are provided in ref. [16]. In the bottom-left panel of fig. 1, we report the $(e^+ + e^-)$ flux measurement, up to 1 TeV of energy, which has been obtained by an independent ECAL-based analysis. The $(e^+ + e^-)$ flux is remarkably smooth and structureless.

The origin of the observed features in the leptonic spectra is currently subjected to extensive phenomenological research. The proposed explanations involve DM annihilation or decay [8], production of $e^\pm$ pairs inside nearby pulsars [7,9], or production of $e^\pm$ from proton-proton collisions inside old SNRs [10,11]. The underlying mechanism can be ascertained by continuing to collect data up to the TeV energy region and by measuring the $\bar{p}/p$ ratio to high energies.

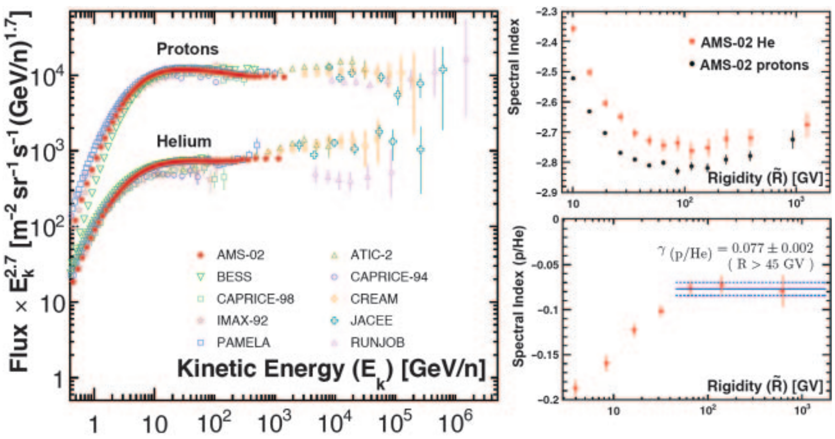

Fig. 2. – Left: AMS-02 measurements of the p and He fluxes as function of kinetic energy per nucleon. Right: rigidity dependence of the proton and He spectral indices (top) and of the p/He index (bottom).

We also emphasize that the low-energy fluxes are significantly affected by CR transport in the solar wind. In order to interpret the $e^{\pm}$ data at $E \sim 0.5$–$20\,\mathrm{GeV}$ in terms of Galactic CR propagation, the solar modulation effect must be taken into account and properly modeled [17]. In this respect, AMS-02 has the capability of providing us with an essentially continuous monitoring of the $e^{\pm}$ flux evolution with time. Time-variation studies of the CR flux are currently being carried on monthly basis and shorter timescales [18]. These data may allow for a substantial progress in the understanding of CR transport in the solar wind [17].

3˙2. *Results on CR hadrons*. – We now turn our attention to the AMS-02 measurements of CR protons and nuclei. The p and He fluxes have been measured by AMS-02 from 1 GV to 1.8 TV of rigidity for CR protons and from 2 GV to 3 TV for helium [19,20]. The results are shown in fig. 2. The AMS-02 data show that both species are described by a broken power-law in rigidity, as the fluxes experience a progressive spectral hardening at about 350 GV of rigidity. Also, the proton-to-helium ratio at $R > 45\,\mathrm{GV}$ if found to falls off steadily as $p/\mathrm{He} \propto R^{-0.077}$. These results confirm the early findings of the ATIC-2, CREAM and PAMELA experiments [21-23]. Interpretations for these phenomena fall into three classes: diffusive shock acceleration mechanisms, propagation effects, or superposition of local and distant sources [3, 11, 24, 25]. The origin of the CR spectral hardening (and its connection with the p/He ratio anomaly [26, 27]) is a open question that may be resolved with high-energy data on light CR nuclei.

With the high statistics collected by AMS-02, the lithium flux is being measured for first time in the GV–TV rigidity range [28]. Preliminary measurements of the carbon flux and the B/C ratio up to 1.8 TV of rigidity have also been presented [29, 30]. Furthermore, the $\bar{p}/p$ ratio is currently being measured by AMS-02 between 1 and 450 GV of rigidity. The preliminary AMS-02 data show that the $\bar{p}/p$ ratio remains essentially flat [31] at rigidity above $\sim 60\,\mathrm{GV}$. This behaviour is at tension with the current astrophysical models of CR propagation, from which the $\bar{p}/p$ ratio is expected to decrease with energy [25,32,33]. Future data on CR nuclei will be extremely useful to pin down the model uncertainties on the $\bar{p}/p$ predictions, and to consequently resolve this tension.

4. – Conclusions

The main scientific results obtained by the AMS-02 experiment during the first 5 years of operations have been presented. The large wealth of CR data collected by AMS-02 and the precise knowledge of the detector performance in space enabled us to determine the basic observational properties of CRs at the level of a few percent. The AMS-02 experiment has the potential to shed light on longstanding physics problems, such as the origin of CRs in the Galaxy or the nature of cosmological DM particles. Accurate multi-channel measurements of the CR energy spectrum are being performed. We whish that the forthcoming AMS-02 data will provide us with a deeper understanding of the Galactic CR physics.

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