**UNIVERSIDADE DE SÃO PAULO
INSTITUTO DE FÍSICA DE SÃO CARLOS**

Eduardo Ferronato Bueno

**Measurement of the deuterium flux in cosmic rays with
the Alpha Magnetic Spectrometer on the International
Space Station**

São Carlos

2018

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the Alpha Magnetic Spectrometer on the International
Space Station**

Dissertation presented to the Graduate Program in Physics at the Instituto de Física de São Carlos, Universidade de São Paulo, to obtain the degree of Master in Science.

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Advisor: Prof. Dra. Manuela Vecchi

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In memory of my father.

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*“Sometimes I like to brag, sometimes I’m soft spoken
When I’m in Holland, I eat the pannekoeken”
Beastie Boys, *Super Disco Breakin’**

ABSTRACT

BUENO, E.F. **Measurement of the deuterium flux in cosmic rays with the Alpha Magnetic Spectrometer on the International Space Station.** 2018. 84p. Dissertation (Master in Science) - Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, 2018.

This work presents the measurement of the deuterium flux, and the deuterium-to-hydrogen flux ratio from 0.6 to 10 GeV/n, using data collected between May 2011 and May 2015 by the Alpha Magnetic Spectrometer (AMS-02), a cosmic ray detector operating aboard the International Space Station (ISS) since May 2011. The isotope separation is performed by combining the measurements performed by the AMS-02 sub-detectors. In particular, the mass measurement is carried out by taking advantage of the precise momentum measurement provided by the silicon tracker and by the velocity measurement provided by the Cherenkov detector. The event counting method is performed using reference spectra of simulated signal and background events, where the agreement between data and Monte Carlo has been carefully checked and eventual differences have been mitigated by means of corrections based on the comparison between the resolution of the velocity and momentum as obtained from data and simulated events. Production mechanisms, acceleration and propagation of cosmic rays are not completely clear, therefore precise measurements of the flux and composition of these particles may help to understand these phenomena. In the conventional model, supernova remnants are the sources of cosmic rays in the GeV to TeV energy range. The so called *primaries*, such as ^1H , ^4He , e^- and C are believed to be produced and accelerated at the sources, while *secondaries*, such as e^+ , ^2H , ^3He and B originate from the collisions of primary cosmic rays with the interstellar medium. Hence, secondaries carry information about the propagation of cosmic rays in the galaxy, and, the measurement of their flux is used to constrain the parameters of cosmic ray propagation models; in particular, studying secondary-to-primary ratios is useful as it factors out the unknown source spectrum of the progenitor.¹ One of such commonly studied ratios is the B/C ratio, but other ratios, such as $^2\text{H}/^1\text{H}$ and $^3\text{He}/^4\text{He}$, can be used to probe a different A/Z regime and test the universality of the propagation mechanisms.

Keywords: Deuterons. Cosmic ray flux. AMS-02. Astroparticle physics. Cosmic ray isotope separation.

RESUMO

BUENO, E.F. **Medida do fluxo de deutério nos raios cósmicos com o Espectrômetro Magnético Alfa na Estação Espacial Internacional.** 2018. 84p. Dissertação (Mestrado em Ciências) - Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, 2018.

Este trabalho apresenta a medida do fluxo de deutério e da razão deutério sobre hidrogênio nos raios cósmicos, de 0.6 até 10 GeV/n, utilizando dados coletados entre maio de 2011 e maio de 2015 pelo Espectrômetro Magnético Alfa (AMS-02), um detector de raios cósmicos instalado na Estação Espacial Internacional desde maio de 2011. A separação dos isótopos é feita através da combinação de medidas feitas pelos subdetectores do AMS-02. Em particular, a medida da massa é feita utilizando as medidas do momento fornecidas pelo tracker de silício e a velocidade medida pelo detector Cherenkov. A contagem de eventos é feita através da utilização de espectros de referência obtidos a partir de simulações de eventos de sinal e fundo, os quais foram utilizados para checar a concordância entre dados e simulações de Monte Carlo, corrigindo eventuais diferenças através de correções baseadas em comparações das resoluções de velocidade e momento obtidas nos dados e em simulações. Mecanismos de produção, aceleração e propagação dos raios cósmicos partículas não são completamente claros, portanto medidas precisas dos fluxos e composição dessas partículas podem auxiliar na compreensão desses fenômenos. Remanescentes de supernovas são as fontes de raios cósmicos com energias entre GeV e TeV. Acredita-se que os chamados raios cósmicos primários, tais como ^1H , ^4He , e^- e C são produzidos e acelerados nas fontes, enquanto os secundários, tais como e^+ , ^2H , ^3He e B, têm origem na colisão dos raios cósmicos primários com o meio interestelar. Portanto, os secundários carregam informação sobre a propagação dos raios cósmicos na galáxia, sendo as medidas dos seus fluxos utilizada para restringir os parâmetros de modelos de propagação de raios cósmicos; em particular, estudar a razão entre secundários e primários é útil pois remove o desconhecido espectro da fonte da espécie progenitora.¹ Uma das razões comumente utilizadas é B/C, mas outras, tais como $^2\text{H}/^1\text{H}$ e $^3\text{He}/^4\text{He}$ podem ser utilizadas para estudar outro regime de A/Z e testar a universalidade dos mecanismos de propagação.

Palavras-chave: Deuterons. Fluxo de raios cósmicos. AMS-02. Astrofísica de partículas. Separação isotópica nos raios cósmicos.

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LIST OF ABBREVIATIONS AND ACRONYMS

AMS-02	Alpha Magnetic Spectrometer
ISS	International Space Station
SNR	Supernova Remnant
CR	Cosmic Rays
GCR	Galactic Cosmic Rays
ISM	Interstellar Medium
TRD	Transition Radiation Detector
TOF	Time of Flight
ACC	Anti Coincidence Counter
RICH	Ring Imaging Cherenkov Detector
ECAL	Electromagnetic Calorimeter
MC	Monte Carlo
PMT	Photo-multiplier Tube

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1 INTRODUCTION

The term cosmic rays (CRs), coined by Robert Millikan in 1925,² refers to charged particles produced outside the Solar System which striking the Earth's atmosphere from all directions.³ In this chapter, the physics of these cosmic particles will be discussed: first, their sources as well as their composition will be presented, followed by a description of all the physical processes that CR undergo in their journey from the sources to Earth. Finally, the presence and origin of deuterium in CRs will be discussed, showing the importance of the measurement of its flux, that constitutes the main results of this work.

1.1 Spectrum and composition

The *all particle* flux of CRs ($\Phi_{CR}(E)$), namely the number of particles per surface, time, solid angle and energy unit that reach the top of Earth's atmosphere is shown in figure 1 as a function of the energy. The CR flux spans over more than 10 decades in energy, from 10^8 to 10^{20} eV. At first glance, the spectrum shows a simple power law dependence on energy, where $\Phi_{CR}(E) \propto E^{-\gamma}$, being γ the spectral index and E the energy. The spectral index ranges from 2.7 to 3.0, depending on the energy. A better view of the spectral index transitions can be obtained if one multiplies the flux by a power of E , as shown in figure 2, where the flux was multiplied by $E^{2.6}$. Three features are very pronounced: the first spectral index transition, known as *knee*, occurring around 10^{15} eV; the *second knee*, around 10^{17} eV; and the *ankle* around 10^{18} eV. These features are related to the origin and propagation processes of CRs, which will be discussed in the following section.

In the current models, CRs from 10^8 to 10^{15} eV are thought to be produced and accelerated inside our own galaxy by astrophysical sources such as supernova remnants (SNRs),⁴ and therefore they are called *galactic cosmic rays* (GCRs). In terms of relative abundance, direct measurements performed by balloons and satellites outside Earth's atmosphere show that CRs in this energy range are mostly made of protons ($\approx 86\%$), helium nuclei ($\approx 11\%$), electrons ($\approx 2\%$) and heavier nuclei ($\approx 1\%$). Small traces ($< 1\%$) of anti-matter (anti-protons and positrons) are also present.⁴

It is an interesting exercise to compare the relative abundances of CRs elements with the abundances of these elements in the Solar System, as done in figure 3. From this figure it is possible to note certain similarities between CRs and the Solar System's composition: carbon, nitrogen, oxygen and iron have roughly the same relative abundance in both measurements. However, there is a clear discrepancy between species such as lithium, beryllium boron and other elements with atomic numbers between calcium and iron, which are more abundant in CRs. Lithium, beryllium and boron, unlike carbon and oxygen, are almost absent in the end-products of stellar nucleosynthesis. For this reason

Figure 1 – The “all particle” flux of CRs as a function of energy, as measured by several experiments. The arrows indicate the flux value at the corresponding energy. The center of mass energies of human-made colliders are also indicated for comparison.

Source: LONGAIR⁴

they are rare in the Solar System; however, they are easily produced in the spallation of CR carbon and oxygen during their propagation in the interstellar medium (ISM).

The GCR spectrum observed at the top of the atmosphere comprises *primary* and *secondary* CRs. The primaries are the species produced and accelerated at the sources, while secondaries are by the interaction of primaries with the ISM. Electrons, protons, helium, carbon, iron and other nuclei synthesized in stars are primaries, while nuclei such as lithium, beryllium and boron are secondaries, produced by the spallation of carbon and oxygen in the ISM, made of hydrogen. These differences in their origin explain the discrepancies seen in figure 3.

1.2 Sources and propagation

1.2.1 Sources

The exact sources, propagation and acceleration mechanisms of CRs are still unanswered questions. It is known that the Sun is a source of CRs with energy between 10^7 and 10^{10} eV,⁴ however, all Sun-like stars in the Milky Way do not produce enough CRs

Figure 2 – The CR spectrum scaled by $E^{2.6}$ as a function of energy.

Source: PATRIGNANI⁵

to account for the cosmic radiation intensity observed at Earth, where $\rho_E \sim 0.5 \text{ eV/cm}^3$.³ It is possible to assume the same CR energy density across the whole Galaxy and try to estimate the power required from the source to supply the measured CR intensity. Since the Milky Way is a spiral galaxy, a simple estimation of its volume (within the galactic disk) is given by:

$$V_D = \pi R^2 d \approx (15 \text{ kpc})^2 (200 \text{ pc}) \approx 4 \times 10^{66} \text{ cm}^3, \quad (1.1)$$

where R is the galactic radius and d the height of the galactic disk. The confinement time, τ_R , of a CR in the galaxy can be estimated by the abundance of radioactive isotopes (^{10}Be , for instance), which results in $\tau_R \approx 6 \times 10^6$ years. Having all the information, we can estimate the source power:

$$P_S = \frac{\rho_E V_D}{\tau_R} \approx 4 \times 10^{40} \text{ erg/s}. \quad (1.2)$$

Figure 3 – Chemical composition of the cosmic rays as measured at 1 AU from the Sun (solid line) compared to the abundances in the Solar System (dashed line) for elements from $Z = 1$ to $Z = 30$. Relative abundances are normalized to the Carbon abundance, arbitrarily set to 100.

Source: SIMPSON⁶

Taking into account the energy requirement mentioned above, an explanation with SNR as sources was proposed.⁷ Assuming a scenario where three SNR occur every century and an average released energy of $\sim 10^{51}$ erg/explosion, the total power released by these events is about 3×10^{41} erg/s. This makes the SNRs strong candidates for sources of GCRs.

The power budget is not the only argument to support SNRs as CR accelerators. In 1949, Enrico Fermi developed an acceleration mechanism able to predict the power-law shape and spectral index of the CR spectrum.⁸ Fermi originally proposed that slow moving magnetic clouds, from 10 to 100 times denser than the ISM could accelerate CRs. There are two versions of this mechanism: the *first order* and *second order*, depending on whether the energy gain is proportional to β or to β^2 , where $\beta = v/c$, being v the cloud's velocity and c the speed of light. In the case of a uniform magnetic field, the particles would simply invert their motion, similar to what happens with trapped particles inside the Earth's radiation belts. If the magnetic field is moving, however, the particles may gain energy: when the particle enters such clouds, it is scattered by random irregularities in the magnetic field that change the particle's momentum. The gain or loss of energy depends on the particle's momentum direction and the cloud velocity direction: when they are opposite, the particle gains energy. Since frontal collisions have higher probability, the overall effect is an energy gain of the GCRs. This mechanism is able to reproduce the CR

spectrum prior to the modification caused by propagation with no additional hypothesis. In addition, synchrotron radiation from electrons accelerated at the shock front of SNRs⁹ also support this scenario. These mechanisms are able to explain the acceleration of CRs up to the knee region; beyond that, other mechanisms are needed such as shocks in active galaxy nuclei jets, a scenario that received strong support from the recent observations of the IceCube experiment of a high energy neutrino emission from a blazar.¹⁰

1.2.2 Propagation

CR particles and nuclei traveling through the Galaxy interact with the ISM and the galactic magnetic field.¹¹ If the magnetic field was regular, the resulting motion would be a spiral trajectory with gyro-radius proportional to the particle's momentum. However, the magnetic field presents irregularities which scatter particles, randomizing their direction, turning the motion into a diffusive process. CRs undergo fragmentation and energy losses as a consequence for their journey through the ISM, mainly made of protons and helium nuclei. All these processes are described by the *transport equation*:

$$\frac{\partial \psi(\vec{r}, p, t)}{\partial t} = Q^{tot}(\vec{r}, p) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi_i) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_i - \frac{\partial}{\partial p} [p \psi_i - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi_i] - (\frac{1}{\tau_r} + \frac{1}{\tau_f}) \psi_i \quad (1.3)$$

where $\psi(\vec{r}, p, t)$ represents the density per total particle momentum unit p at space-time coordinates $(\vec{r}, t)$ for a CR species i . The remaining terms in the equation describe different phenomena in the propagation of CRs:

- $Q^{tot}(\vec{r}, p)$: represents every possible CR production mechanism for the species i , including production at the sources, decay contributions and spallation. In the case of primary sources, their distribution is assumed to be correlated with the known density of sources.
- D_{xx} and D_{pp} : the curvature of the trajectory of a charged particle in a magnetic field depends on its rigidity ($R = pc/Ze$), hence, particles with same R are equally affected. The galactic magnetic field can be described as the sum of a regular, average component, and random fluctuations. These fluctuations are responsible for the diffusive CR motion.¹¹ D_{xx} , proportional to R^α , is the diffusion coefficient. D_{pp} is also a diffusion coefficient, but in the momentum space, which is due to the fact that these interactions with the random fluctuations induce stochastic accelerations, in a phenomenon called *re-acceleration*.¹²

- $\vec{\nabla} \cdot \vec{V} \psi_i$: a wind, moving from the bulk to the halo, is present in the Galaxy. Composed of a stream of particles coming radially out of the Galaxy's bulk, with speeds growing with the distance from the galactic plane, this wind affects the motion of CRs.¹³ Generating adiabatic energy losses.
- τ_f and τ_r : these terms represent, respectively, the timescale for loss by fragmentation and radioactive decay. These processes influence the evolution of the density of parent and daughter CR species as they propagate.
- $\frac{\partial}{\partial p}(\dot{p} \psi_i)$: during their propagation, CRs lose energy due to interactions with the ISM. Electrons, for instance, lose energy by processes like bremsstrahlung, synchrotron radiation emission and inverse Compton scattering, while nuclei mostly lose energy via ionization.

In the context of propagation, the measurements of the fluxes of secondary CRs is of great importance, for in the case of unstable isotopes, such as ^{10}Be , they allow inference about the confinement time of CRs in the Galaxy, while in the case of stable species, they give information about the traversed matter from the source to Earth. One interesting way to study these phenomena is to measure secondary-to-primary ratios, such as B/C and $^3\text{He}/^4\text{He}$ because they factor out the unknown source spectrum of the progenitor.

1.2.3 Cosmic rays in the heliosphere

CRs entering the Solar System interact with the Sun and its environment, the heliosphere. CR traversing the heliosphere face the solar wind, a plasma made mostly of protons and electrons with energy between 0.5 and 10 keV, released from the Sun's upper atmosphere, the Corona. There is a magnetic field embedded in this plasma, called heliospheric magnetic field (HMF), which is dragged by the plasma. Combining this effect with the the Sun's rotation movement results in a spiral pattern for the magnetic field lines,¹⁴ as depicted in figure 4. Similar to what happens during the propagation in the ISM, charged particles entering the heliosphere go through a diffusion process. The result is a suppression of the GCR flux at energies below 10 GeV/n. Since the the intensities of the solar activity and wind are time-dependent, displaying an eleven-year cycle, the flux of low-energy GCRs is also time-dependent. This process is called *solar modulation*.¹⁵ The AMS-02 collaboration recently published time-dependent measurements of the proton, helium, electron and positron fluxes at low energies,^{16,17} showing the solar modulation's dependence on the particle's charge sign and its evolution during the solar cycle.

1.2.4 Cosmic rays in the magnetosphere

The last “barrier” CRs need to overcome in their journey to Earth is the magnetosphere, a region surrounding the planet where its magnetic field is dominant, rather than

Figure 4 – Schematic view of the heliosphere, its boundary regions and its effects on cosmic rays

Source: VUKCEVIC¹⁸

the heliospheric magnetic field. The movement of Earth's outer core, made of nickel and iron, is the source of the geomagnetic field, which can be modelled, to a great extent, as a dipole with moment $M = 8 \times 10^{17} \text{ Tm}^2$ inclined about eleven degrees from the Earth's rotation axis.^{19,20} As particles travel through this field, their motion is altered depending on the particle's rigidity. If it is not above a certain threshold value, the *cutoff rigidity*, the particle's trajectory cannot be extrapolated to outside the magnetosphere, hence if the particle is trapped inside the field is not of galactic origin, but atmospheric. Besides not having a uniform structure, the geomagnetic field is also distorted by the solar wind, thus the cutoff rigidity may not be the same for different locations, as shown in figure 5. In 1956, Stormer²¹ developed an analytic model to calculate the cutoff value for a particle in a given frame of reference:

$$R_C^\pm = \frac{M \cos^4 \lambda}{d^2 [1 + (1 \pm \cos^4 \lambda \cos \phi \cos \theta)^2]}, \quad (1.4)$$

where M is the dipole moment, d the distance from the dipole center, λ the latitude along the dipole, θ and ϕ the polar and azimuth angles from the local zenith, respectively. The plus and minus signs applies for positively and negatively charged particles, respectively. Satellites or balloons attempting to detect GCRs directly must know the geomagnetic location of the event detection and calculate the *cutoff rigidity* to ensure the detected

events are not from atmospheric origin.

Figure 5 – Contour maps of time averaged cutoff rigidities for a 450 km orbiting spacecraft. The cutoff values in displayed are in GV.

Source: SMART²²

1.3 Deuterium flux in cosmic rays

Deuterium is synthesized in stars by the reaction $p + p \rightarrow d + e^+ + \nu$. The destruction occurs mainly via its consumption in the second step of the proton-proton chain reaction, $d + p \rightarrow \gamma + {}^3\text{He} + E$, where $E = 5.49$ MeV,²³ which dominates the fusion processes in stars with masses similar to the Sun. In stars with larger mass, the CNO cycle is thought to be the predominant cycle, and it does not produce deuterium in any step. Hence, deuterium is mainly a secondary species, thus it carries information about the mean amount of matter traversed by CRs during their propagation. In the current models, the main mechanism of deuterium production in CRs is the interaction of primaries with the ISM, being the main channel the spallation of ${}^4\text{He}$ and ${}^3\text{He}$.²⁴ The interaction $p + p \rightarrow \pi + d$ also plays an important contribution, but less than the aforementioned, as can be seen in figure 6, showing that the interactions with He have higher cross-sections.

The measurement of the deuterium-to-hydrogen and deuterium-to-helium flux ratio is therefore of great interest, since it allows to constrain the propagation models.¹ Figure shows the available deuteron measurements in the GeV range⁷. It is a very difficult measurement above 0.1 GeV/n because the instrument requires an excellent mass resolution to be able to identify the deuterium events among the extremely large proton background, what explains the limited number measurements above 1 GeV.

Recently, the SOKOL satellite provided the first deuterium measurement in CRs above 100 GeV/n,²⁶ yielding results much higher than expected from the production of

Figure 6 – Cross-section data for deuterium production from ^4He -p, ^3He -p, and p-p collisions.

Source: TOMASSETTI²⁴

Figure 7 – Compilation of deuterium-to-hydrogen flux ratio measurements of different experiments.

Source: MAURIN et al.²⁵

deuterium via interaction of primaries with the ISM. Figure 8 shows the SOKOL data compared to the other experiments and also two possible scenarios of propagation: the solid green line is constrained with B/C ratio measurements of AMS-02²⁷ and the dashed red line is assuming that SNRs can act as sources of secondary species. In view of these tensions, it is clear that measurements with AMS-02 could provide valuable information to solve this puzzle. In this work, measurements of the deuterium-to-hydrogen ratio measured

with AMS-02, from 0.6 GeV/n to 10 GeV/n , will be presented.

Figure 8 – Deuterium-to-helium ratio of several experiments, including SOKOL, with predictions from two different propagation scenarios: 1) SNRs as sources of secondary species (dashed red line) and 2) constrained with B/C data from AMS-02 (solid green line)

Source: TOMASSETTI²⁴

2 THE ALPHA MAGNETIC SPECTROMETER

The Alpha Magnetic Spectrometer (AMS-02) is a large (0.45 sr^2) acceptance cosmic ray detector equipped with state-of-the-art particle physics detectors technology, taking data aboard the International Space Station (ISS) since May 2011, where it will operate until the end of the ISS mission, currently expected to end in 2024. The ISS follows a Low Earth Orbit, approximately 400 km above Earth's surface, an ideal location to detect cosmic rays before they interact with the atmosphere. The experiment was developed aiming to measure the fluxes of charged cosmic rays with high precision in the GeV to TeV energy range.

A schematic view of the detector is shown in figure 9. The silicon tracker measures the particle's trajectory and absolute charge $|Z|$ by measuring the coordinates and energy loss in each of its nine layers. Together with the 0.14 T permanent magnet, the tracker measures the particle's charge sign and rigidity ($R = pc/Ze$). The Transition Radiation Detector (TRD) is used to identify electrons and positrons among the huge proton background. The Time of Flight (TOF) is composed by two segmented scintillator planes placed at both ends of the magnet. They provide measurements of the particle's velocity and charge and also work as a trigger for the experiment. The Anti-Coincidence Counter (ACC) provides the veto signal for particles passing through the detector outside its geometric acceptance. The Ring Imaging Cherenkov detector (RICH) also measures the particle's charge and velocity. Finally, the Electromagnetic Calorimeter (ECAL) is used for lepton-hadron separation and the measurement of the particle's energy.

In this chapter, a detailed description of the sub-detectors that compose AMS-02 will be given.

2.1 Transition Radiation Detector

Particles traversing the interface between two materials with two different dielectric constants have a probability of emitting transition radiation (TR), which is proportional to the particle's Lorentz factor $\gamma = \frac{E}{m}$, where E is its energy and m its mass.²⁹ Light particles with a high Lorentz factor, such as electrons, emit TR in the X-ray range. The TRD in AMS-02³⁰ is located on top of the detector, between the first layer of the tracker and the first layer of the Time of Flight, and was designed mainly to separate protons and positrons, as well as measure the charge of light nuclei.

This detector is composed of 328 modules arranged in 20 layers along the vertical coordinate. Each module is made of 20 mm of polyethylene/polypropylene fiber fleece with density 0.06 g/cm^3 and 16 6 mm straw tubes filled with a Xe:CO₂ (90% 10%) gas mixture.

Figure 9 – Schematic view of AMS-02.

Source: KOUNINE²⁸

When the TR produced by the particle passes through these tubes, a ionization avalanche is started, converting the X-rays into electric signals. Unlike protons and nuclei electrons and positrons produce X-rays, allowing to identify and separate leptons from hadrons.

Figure 10 – The AMS-02 TRD. Top: one module with 16 tubes. Bottom: The complete detector, with the fiber fleece radiator for the topmost layer visible.

Source: WENG³¹

2.2 Time of Flight

The AMS-02 Time of Flight (TOF) detector³² is made of 4 layers of scintillator planes, placed in pairs above (Upper-TOF) and below (Lower-TOF) the magnet. Each of

these planes contain, from top to bottom, 8, 8, 10 and 8 scintillator paddles, which are made of 1 cm thick polyvinyl-toluene. Both ends of each paddle are coupled to photomultiplier tubes (PMTs) by means of plexiglass light guides. In each pair of layers, paddles are oriented in both x and y directions, to provide a two-dimensional measurement with $12 \cdot 12 \text{ cm}^2$ resolution. When a charged particle passes through the scintillator, it causes the fast emission ($\tau \approx 10^{-8} \text{ s}$) of fluorescent light. The photons collected by the PMTs provides a very precise hit time measurement and an estimation of the deposited energy, what allow the charge to be evaluated, since the energy loss by ionization is proportional to Z^2 .

The TOF is used to measure the particle's velocity ($\beta = v/c$) and charge, and it is also used as a trigger for the whole experiment. The timing resolution is $\approx 180 \text{ ns}$ for particles with $Z = 1$ and $\approx 100 \text{ ps}$ for particles with $Z \geq 2$. The resulting β resolution is $\Delta\beta/\beta \approx 4\%$ at $\beta = 1$ for $Z = 1$ and $\approx 1\%$ for particles with higher Z .

Figure 11 – Left: Time of Flight planes disposition for the Upper-TOF (left) and Lower TOF (right). Right: Scintillator, light guides and PMT of a paddle.

Source: QUADRANT³²

2.3 Permanent magnet

The AMS-02 permanent magnet³³ is made of 64 sectors, with each of them made of 100 high-grade Nd-Fe-B blocks. They are assembled in a 0.8 m long toroidal structure, with an inner diameter of 1.15 m, as seen in figure 12. This arrangement creates a dipole magnetic field of 0.15 T at the center, with a negligible magnetic dipole moment outside ($\sim 10^{-2} \text{ T}$). The AMS coordinate system is aligned with the magnet's center, such that the X axis is parallel to the field line in the center and the Y axis describes the bending direction. This choice of reference frame makes the bent trajectories of all charged particles to be contained in the Y-Z plane.

Figure 12 – AMS-02 permanent magnet. Left: Permanent magnet’s magnetic field orientation and intensity. Right: scheme of the magnet (dimensions in mm).

Source: AGUILAR et al.³³

2.4 Silicon tracker

The silicon tracker³⁴ is made of 2264 double-sided silicon micro-strip sensors, with dimension $72 \times 41 \times 0.3 \text{ mm}^3$, totaling 6.4 m^2 of detection area. They consist of high resistivity ($6 \text{ k}\Omega/\text{cm}$) n-doped silicon wafers, with metallic strip implants running in perpendicular directions in each face of the sensor, allowing two-dimensional measuring for each sampling. On the p-side, p^+ strips are placed with a (readout) implantation pitch of (110) $25.5 \mu\text{m}$. On the opposite side, the n-side, n^+ strips are placed with a (readout) implantation pitch of (208) $104 \mu\text{m}$, with direction orthogonal to the other side’s strips. The sensors are grouped in ladders, each having a variable number of silicon sensors (from 10 to 15). In total there are 192 ladders, disposed along 9 layers: each of the first eight layers contains around 22 ladders, while the last layer contains only 16. These layers are placed along the height of the AMS-02 detector: layer 1 is on top of the TRD, layer 2 is below TOF, just above the magnet, while layer 9 is located on top of the ECAL. The other layers, from 3 to 8, are placed in pairs inside the magnet (3-4, 5-6, 7-8), mounted on a cylindrical carbon fiber structure.

When a charged particle passes through the detector, electron-hole pairs created along the trajectory induce electric signals at the nearest strips, allowing the identification of the traversing particle’s coordinate. The finer pitch p-side measures the bending coordinate (y) and the n-side measures x. The coordinate resolution is estimated to be better than $10 \mu\text{m}$ in the bending direction for protons. The Maximum Detectable Rigidity (MDR) depends on the number and location of used hits. It is measured to be around 200 GV for

Figure 13 – Arrangement of the tracker ladders in one layer.

Source: DURANTI³⁵

tracks using only layers 2 to 8 and up to 2 TV using all layers.

2.5 Anti-Coincidence Counter

The Anti-Coincidence Counter (ACC)³⁶ is composed of 16 scintillator paddles arranged on a cylinder that surrounds the permanent magnet. Light coming from the scintillators is collected by wavelength shifter fibers of 1 mm diameter and then sent to 16 PMTs (8 in the magnet's upper part and 8 in the lower), similar to the ones used in the TOF.

The best quality measurements come from particles which pass the detector from top to bottom. In the case of particles coming sideways, they may interact with the detector and cause spurious triggers and affect the measurements. The purpose of the ACC is to provide a veto signal to these particles, as shown in figure 14. The measured efficiency of this veto is better than 10^{-5} .

2.6 Ring Imaging Cherenkov Detector

The Ring Imaging Cherenkov Detector (RICH)³⁸ is placed below the lower TOF and is used to measure the particle's velocity with high precision. This work is based on the Cherenkov radiation emission, produced by a charged particle with velocity greater than the electromagnetic field's phase velocity in the medium. A cone of Cherenkov radiation is emitted along the particle's trajectory. The cone's opening angle is related to the particle's velocity inside a medium with refractive index n as:

$$\beta = \frac{1}{n \cos \theta} \quad (2.1)$$

Figure 14 – Left: Particle entering the detector from the side, giving a signal in the ACC but not in the TOF. These kinds of events are rejected. Center: particle traversing the detector from top to bottom. Although interactions may occur, the ACC veto is disable for these particles. Right: Particles passing through ECAL may produce *backsplash* particles, which may hit the ACC. In this case, the trigger is provided by TOF and not more than ACC paddles fired.

Source: GRAZIANI³⁷

for a particle with charge Z , the number of radiated photons per radiation length and distance is given by

$$\frac{d^2 N}{d\lambda dx} = \frac{2\pi}{\lambda^2} \alpha Z^2 \sin^2 \theta \quad (2.2)$$

where α is the fine-structure constant. Hence, the emission of Cherenkov light also allows the charge to be measured.

This detector is composed of a radiator plane, a conical mirror and a photon detection plane as seen in figure 15. The detector plane has an empty area of $64 \cdot 64 \text{ cm}^2$ in its center to match the active area of the calorimeter below. The radiator is made of an array of 2.7 cm thick aerogel tiles with refractive index between 1.03 and 1.05, which surrounds an area of $35 \cdot 35 \text{ cm}^2$ in the center, which is made of 5 mm thick sodium fluoride (NaF). This design, with a material with higher refractive index in the center, was chosen in order to make the Cherenkov cones of particles passing through that region broader, therefore optimizing the counter acceptance ($0.4 \text{ m}^2\text{sr}$), because the photons will then fall within the detection area. The detection plane is made of 680 4×4 multi-anode PMTs which are arranged to cover the circular 134 cm diameter surface at the basis of the mirror. The radiators and the detection plane are on top and below, respectively, of a conical mirror of height 47 cm. The mirror increases the acceptance by reflecting high inclination photons. The RICH measures the particle's β with resolution $\sigma_\beta/\beta \sim 0.1\%/Z$.

It can also identify nuclei up to Fe ($Z = 26$) with charge confusion lower than 10%.

Figure 15 – The AMS-02 RICH exploded view. The components are the radiator plane (a); the conical mirror (b); detection plane (c).

Source: LIU et al.³⁸

2.7 Electromagnetic Calorimeter

When a high energy $e^\pm$ or γ passes through a high Z material, such as lead, an electromagnetic shower is generated, caused mainly by two phenomena: the bremsstrahlung, the electromagnetic radiation produced by the deceleration of a charged particle when deflected by another particle's electric field, and pair production, the creation of a particle and its anti-particle from a photon. The shower ends when the energy of the photons is below the pair production threshold or the produced particles escape the calorimeter. Protons, on the other hand, are less likely to interact inside the ECAL, as show in 16. The difference between the interactions of leptons and hadrons inside the ECAL allows the separation of these particles.³⁹

The AMS-02 Electromagnetic Calorimeter (ECAL)⁴⁰ is a fine-grained lead-scintillating fiber sampling calorimeter. Its active volume is composed of 9 super-layers (SL) consisting of 11 grooved 1 mm lead foils interleaved by 1 mm plastic scintillating fibers. In each super-layer the fibers run along the same direction, making necessary to stack super-layers with fibers alternatively parallel to the Y-axis and X-axis. This arrangement yields a density of 6.8 g/cm^3 , with the total calorimeter thickness corresponding to approximately 17 radiation lengths, including almost all the electromagnetic shower generated by incident electrons or positrons. The fibers are read out by 324 PMTS, each with 4 anodes with an

Figure 16 – Schematic view of the passage of an electron and a proton through the ECAL.

Source: VAGELLI³⁹

area of $0.9 \times 0.9 \text{ cm}^2$, allowing an accurate 3D imaging-sampling of the longitudinal shower profile.

Figure 17 – ECAL active volume. The 9 super-layers piled alternatively, with the scintillating fibers running in perpendicular directions, are seen. There are 50,000 fibers of 1 mm each, resulting in a volume of $68.5 \times 68.5 \times 16.7 \text{ cm}^3$.

Source: VAGELLI³⁹

3 EVENT RECONSTRUCTION IN AMS-02

When passing through AMS-02, the CRs leave signals in each sub-detector they interact with. The first step to identify CRs is to use the signals of the appropriate sub-detectors to extract the necessary information for the identification. In the case of isotopes, two properties are essential: the charge and mass.

In AMS-02, these measurements are performed by different sub-detectors:

- **Charge:** measured simultaneously by the TRD, RICH, 9 layers of the tracker and 4 layers of the TOF.
- **Mass:** the rigidity measured by the tracker combined with the velocity measured by RICH or TOF allows the particle's mass to be calculated.

The methods of reconstruction of these properties will be presented in this chapter.

3.1 Charge reconstruction

The measurement of the charge in AMS-02 is done by several sub-detectors, using complementary detection techniques, based on different physical processes: the energy loss by charged particles traversing a given layer of matter and the Cherenkov effect. In this section, these techniques will be described.

3.1.1 Measurements based on energy loss: the tracker, TOF and TRD

When a charged particle penetrates matter, it undergoes a series of collisions, leading to excitation and ionization of the atoms in the material. Each interaction leads to an energy loss, $-dE$. The mean energy loss normalized by the path length, $\langle \frac{dE}{dx} \rangle$ for a relativistic, heavy particle is well described by the Bethe-Bloch formula,⁴¹

$$-\langle \frac{dE}{dx} \rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right], \quad (3.1)$$

where $K \approx 0.307 \text{ MeV g}^{-1} \text{ cm}^2$; Z , I and A are the atomic number, mass number and mean excitation energy; z , β and T_{max} are the incoming particle charge, velocity and maximum transferable energy in collisions with an electron; $\delta(\beta\gamma)/2$ is a density correction; and x is amount of traversed material in g/cm^3 . The Bethe-Bloch equation can be approximated as

$$-\langle \frac{dE}{dx} \rangle \approx H Z^2, \quad (3.2)$$

being H the energy loss for a Minimum Ionizing Particle (MIP). Hence, if a detector measures the energy deposition, the charge can also be estimated. The tracker measures the deposited energy in each layer, while the TRD does the same in each tube, therefore the charge can be readily measured with them.^{42,43} In the case of the TOF, what is measured is the scintillation light coming from the particle traversing the paddle; however, the amount of light produced in the paddle is related to the deposited energy by the Birsk-Chou formula,⁴⁴

$$L = \frac{AdE/dx}{1 + BdE/dx + C(dE/dx)^2}, \quad (3.3)$$

where A , B and C are constants determined experimentally. Their numerical values for the AMS scintillators are: $A \approx 10$, $B \approx 0.01$ and $C \approx 10^{-5}$. Since A is much larger than the other coefficients, the scintillation light is approximately proportional to Z^2 , therefore the charge can also be accurately measured with the TOF³²; however, there are saturation effects in the scintillators which degrade the charge separation for $Z \geq 10$.

3.1.2 Measurement based on the Cherenkov effect: the RICH

The charge reconstruction in the RICH is different as the charge measurement is not done using the deposited energy, but the number of photons emitted in the Cherenkov cone. This number depends on the particle's charge and β , as stated in equation 2.2 in the previous chapter. Naming N_{exp} the expected number of photons in the cone of a $Z = 1$ particle, the incoming particle's charge can be readily obtained from a simple equation:

$$Z = \sqrt{\frac{N_{tot}}{N_{exp}}}, \quad (3.4)$$

where N_{tot} is the total number of photons emitted in the cone. The calculation of N_{exp} uses the RICH reconstructed β and the parameters of the tracker's track as it entered the radiator. An integration of equation 2.2 is done over the path of the emitted photon and over the Cherenkov light spectrum⁴⁵:

$$N_{exp} = \int d\lambda dx 2\pi\alpha \frac{q(\lambda)}{\lambda^2} \sin^2 \theta_C(n, \beta) \epsilon(x, \lambda) f(x, \lambda), \quad (3.5)$$

where λ is the emitted photon's wavelength, n the medium refraction index, $q(\lambda)$ the quantum efficiency, $\epsilon(x, \lambda)$ the detection efficiency and $f(x, \lambda)$ the term accounting for photon losses. Like the tracker and the TRD, the RICH can distinguish particles with charges up to and beyond Iron.

Figure 18 shows a comparison of the charge resolution between the mentioned sub-detectors for particles with $Z = 1$. The tracker and the TOF clearly are more precise in this case, however, charge measurements by the TRD and the RICH are also useful.

Being located in different regions within the AMS-02, namely on top of the instrument and above the ECAL, their charge measurements provide valuable information on the interaction of nuclei inside the detector, allowing for the identification and rejection of the background coming from these events.

Figure 18 – Charge resolution for $Z = 1$ particles in different sub-detectors, estimated using Monte Carlo simulations of proton events.

Source: By the author

3.2 Rigidity and charge sign reconstruction

In AMS-02 the measurement of the particle's rigidity and charge sign are performed by the tracker together with the permanent magnet: the nine silicon layers register the hit's coordinates (x, y) in each layer, enabling the particle's trajectory to be reconstructed. The rigidity of a particle with momentum p and charge Ze in a magnetic field B is related to the curvature radius r

$$R = \frac{p}{Ze} = Br, \quad (3.6)$$

therefore, if the particle's trajectory as well as the magnetic field are well known, the rigidity can be measured.

In the case of a detector consisting of several planes of detection such as the AMS-02 tracker, the rigidity can be measured by the sagitta method as schematically shown in figure 19, where S represents the sagitta, L the distance between the outermost planes, θ the circular sector's angle, B the magnetic field and r the curvature radius. From the figure it is easy to see that, using the small angles approximation

Figure 19 – Scheme of the sagitta method for the calculation of the rigidity using three detection planes: S is the sagitta; L the distance between the external planes; θ the circular sector's angle; r is the trajectory's curvature radius; and B the magnetic field.

Source: OLIVA⁴⁵

$$L = 2r \sin \frac{\theta}{2} \approx r\theta \quad (3.7)$$

and

$$S = r \left(1 - \cos \frac{\theta}{2} \right) \approx r \frac{\theta^2}{8}. \quad (3.8)$$

Finally, combining equations 3.6 to 3.8 yields a relation between the sagitta S , the known magnetic field B and the rigidity R

$$S = \frac{BL^2}{8R}, \quad (3.9)$$

From this equation, the rigidity can be readily calculated. The error related to this measurement can also be calculated. For the simplest case, consisting of three points: x_1 , x_2 and x_3 , S is given by

$$S = x_2 - \frac{x_1 + x_3}{2}, \quad (3.10)$$

being the uncertainty given by

$$\sigma_s = \sqrt{\frac{3}{2}} \sigma_x. \quad (3.11)$$

Hence, from equation 3.9 R and S have the same relative error, thus

$$\frac{\sigma_R}{R} = \frac{\sigma_S}{S} = \sqrt{\frac{3}{2}} \frac{8R}{BL^2} \sigma_x, \quad (3.12)$$

so the error relative to the rigidity is directly related to the error in determining the hit's coordinates (σ_x) as well as the distance between the outermost hits. The AMS-02 tracker has 9 layers, thus different combinations can be used to measure the rigidity balancing precision against the acceptance and thus the available statistics: events passing through all layers are less likely than the ones crossing only the layers inside the magnet. Each of these combinations is called *span*. Figure 20 shows the rigidity resolution for different *spans* as a function of rigidity. The degradation of the resolution at low energies is related to multiple Coulomb scattering,⁴¹ while at high energies the degradation occurs due to the fact that the bending of the particle's trajectory by the magnetic field is smaller, therefore the curvature radius is measured with less precision.

Figure 20 – Tracker rigidity resolution for protons (left) and helium (right) as estimated from Monte Carlo simulation. Each curve represents a different tracker span. Black: inner tracker (L2 to L8); green: inner tracker and layer 9; red: inner tracker and layer 1; and blue: all layers.

Source: ZUCCON³⁴

3.3 Velocity reconstruction

In AMS-02 the velocity measurement is performed by the RICH and the TOF systems. The former, whose measurement is based on the detection of Cherenkov light, has a better resolution than the TOF; however, since there is a velocity threshold for Cherenkov emission, not all events can be measured by the RICH, whereas the TOF measures the velocity of particles with $\beta < 1$, even at the lowest velocities. In this analysis, the RICH is used to measure the velocity in two different ranges, according to the radiator used: $0.78 \leq \beta < 0.96$ with NaF and $0.96 < \beta \leq 0.996$ with aerogel, while the TOF is used

to cross-check the measurements of the RICH. The methods of reconstruction of both detectors will be presented in this section.

3.3.1 TOF

The 4 layers of the TOF are grouped in two pairs, above and below the magnet. When a particle passes through the upper and lower scintillators, the time taken, Δt , is registered; the particle's trajectory length in the magnetic field, L , is obtained with the reconstructed tracker information. Given the time and distance, the velocity is simply given by

$$\beta = \frac{1}{c} \frac{\Delta t}{L}; \quad (3.13)$$

the largest error source on the TOF measurement is the time resolution

$$\frac{\sigma_\beta}{\beta} = \frac{\beta c}{L} \sigma_{\Delta t}, \quad (3.14)$$

where Δt accounts for different error sources: the number of emitted photons; light attenuation between the scintillation site and the PMT; and electronic noise. Figure 21 shows the β resolution as a function of the charge.

Figure 21 – TOF β resolution as a function of the charge Z .

Source: QUADRANI³²

3.3.2 RICH

The velocity reconstruction in RICH is using the image formed by the Cherenkov cone at the PMT plane. The shape of the ring formed by the cone at the PMT plane strongly depends on the incidence point at the radiator. Hence, the RICH reconstruction algorithm uses information from the tracker to get the incidence point and direction. With

this information, the β value is estimated for each detection cell over threshold, then the algorithm selects the cells with similar β to reconstruct the shape of the ring and the β measurement is the average value of this distribution.

The number of Cherenkov photons is given by the integrating equation 2.2:

$$N = N_0 Z^2 L \sin^2 \theta, \quad (3.15)$$

where L is the radiator length and N_0 the detector response, including acceptance, efficiency and transmittance. The uncertainty on the number of photons is given by

$$\frac{\sigma_N}{N} = 2\sigma_\theta \frac{1}{\tan \theta}. \quad (3.16)$$

Equation 2.1 states that $\beta = 1/(n \cos \theta)$, hence

$$\frac{\sigma_\beta}{\beta} = \tan \theta \sigma_\theta = \frac{\tan^2 \theta \sigma}{2} \frac{\sigma_N}{N}, \quad (3.17)$$

but the number of photons follows a Poisson distribution, so $\sigma_N/N = 1/\sqrt{N}$, hence

$$\frac{\sigma_\beta}{\beta} = \frac{\tan^2 \theta \sigma}{2\sqrt{N}}, \quad (3.18)$$

thus the resolution improves with the charge, as $N \propto Z^2$, as shown in figure 22. Since deuterium and protons have unitary charge, their measurement is the most challenging scenario for the RICH reconstruction: $\sigma_\beta/\beta \approx 0.1\%$ for $Z = 1$ while $\sigma_\beta/\beta \approx 0.01\%$ for heavier nuclei.

3.4 Mass reconstruction

The mass reconstruction is performed by using the particle's velocity and momentum, since

$$m = \frac{RZ}{\beta\gamma}, \quad (3.19)$$

where R is the rigidity; Z the charge; β the velocity divided by the speed of light; and γ the Lorentz factor. The error relative to the mass is then

$$\left(\frac{\Delta m}{m}\right)^2 = \left(\frac{\Delta R}{R}\right)^2 + \gamma^4 \left(\frac{\Delta \beta}{\beta}\right)^2, \quad (3.20)$$

hence, it is clearly dependent on the rigidity and on the velocity; however, due to the γ^4 factor, the contributions of those two variables to the mass resolution can be

Figure 22 – RICH β resolution as a function of the charge Z .

Source: LANCIOTTI⁴⁶

studied separately: at low rigidities, the resolution is dominated by R , whereas at high rigidities $\beta \approx 1$, hence γ^4 is very large, therefore the mass resolution is dominated by β .

Figure 23 – The mass resolution $1/m$ for data and Monte Carlo simulations for helium in three kinetic energy regions: TOF, from 0.5 to 1.5 GeV/n; RICH-NaF, from 1.0 to 5.0 GeV/n; and the RICH-Aeogel, from 3.0 to 10.0 GeV/n. Filled symbols represent real data and open symbols represent Monte Carlo simulations.

Source: XIA et al.⁴⁷

Figure 23 shows the mass resolution for three different ranges (TOF, RICH-NaF and RICH-aerogel) for both data and Monte Carlo (MC) simulations of CR helium events

detected by AMS-02. In this work, a similar study was done for the case of protons and deuterons^{*}. The procedures and results will be shown in the next chapter.

^{*} Deuteron is the atomic nucleus of a deuterium atom. Although in CRs deuterons can be found but not deuterium, the terms deuteron and deuterium are used interchangeably in this text.

4 IDENTIFICATION OF DEUTERONS WITH AMS-02

The goal of this work is to perform the measurement of the CR deuteron flux using the data collected by the AMS-02 experiment on the ISS between May 2011 and May 2015. Information of all sub-detectors of AMS-02 are combined to identify deuterons. The first step towards the measurement of CR deuteron consists of a selection of events that is performed to remove most of the background, then MC simulations are used as reference spectra to identify the species present in data. This step, however, requires that the simulations reproduce well the data, therefore this must be checked and corrected if necessary. This chapter introduces the MC simulations used in AMS-02, then the event selection used to ensure the quality of the event reconstruction and mitigate the background of the search for deuterons is presented, followed by a comparison between data and MC in terms of mass resolution. Finally, the method for counting deuterons is presented, followed by a discussion about the data and MC comparison.

4.1 AMS-02 Monte Carlo simulations

The simulation of events detected by the AMS-02 experiment is based on the GEANT4⁴⁸ package, that accurately reproduces the detector and interactions of incoming particles with the matter that constitutes the AMS material. The events are generated with a spectrum roughly proportional to R^{-1} , which is different from the actual CR spectrum of about $R^{-2.7}$. This is done to allow the generation of a statistically significant sample also at the highest energies. In order to be sure that no discrepancy between data and MC arises from their differences in the shape of the flux, the MC used in this work is re-weighted according to the proton flux. Figure 24 shows the rigidity distribution of simulated deuteron events before and after the re-weighting.

4.2 Event selection

The first step of the analysis is to establish criteria to identify the signal candidates and reject the background. There are two main sources of background in the search for CR deuterons:

- **Heavier nuclei fragmentation:** Nuclei with $Z \geq 2$ (mainly helium, given its abundance) may interact and fragment inside the detector, leaving spurious signals of $Z = 1$ particles. This effect does not affect significantly the hydrogen signal, given its overwhelming presence in CRs, on the other hand, the deuteron signal can be affected as they are about 100 times less abundant than protons.

Figure 24 – MC rigidity spectrum before and after the re-weighting.

Source: By the author

- **Protons with mis-reconstructed mass:** Due to the finite resolution of the detector, it is expected that a fraction of the detected protons have their mass mis-reconstructed. Given the overabundance of protons in CRs, this is a relevant source of background, while mis-reconstructed deuterons do not significantly affect the proton measurements.

Aiming at keeping an high efficiency on the signal, while reducing the background from protons and heavier nuclei, a set of event selection criteria were established by using simulated events of deuterium, hydrogen and helium. The criteria can be grouped in categories, as follows:

- **Basic selection:** Events with positive charge sign, triggered by the TOF, whose velocity is sufficient to pass through the inner tracker from top to bottom ($\beta > 0.3$) are accepted.
- **Charge selection:** Since this analysis is focused on single charged particles, the signals collected by the tracker, the TRD, the RICH and the TOF are used to ensure the events have a Z measurement compatible with 1. Since the TOF and the tracker have a better resolution, tighter requirements are applied on the charge estimator based on the signals from these detectors. Moreover, events whose charge is reconstructed to be lower than 1.4 by the RICH and the TRD are accepted.
- **Tracker quality selection:** Events that produced only a single, well reconstructed track in the tracker are allowed. This is assured by using a cut on the normalized χ^2

of the track fitting on both on the bending plane (y) and the non-bending plane (x). Only events with $\chi_{x,y}^2 < 5$ are selected.

- **TOF quality selection:** Only events detected by the four scintillation planes are allowed; also, a cut on the normalized χ_{TOF}^2 of the particle's trajectory as detected by the TOF is applied, selecting events with $\chi_{TOF}^2 < 10$.
- **RICH quality selection:** To ensure the quality of the β reconstruction, the following criteria are used:
 1. Good tiles: A few RICH radiator tiles are known to have operational problems. Events passing not passing through known bad tiles are selected
 2. Fraction of photons used in the reconstruction: Events reconstructed using at least 50% of the detected photons are selected.
 3. Number of PMTs used in the reconstruction: Since the reconstruction algorithm uses the average value of the β measured in each PMT, the more PMTs used, the more precise the measurement. Only events with at least 3 PMTs used to reconstruct the particle's β are selected.
 4. Velocity consistency check: The measured β values by the RICH and the TOF are allowed to have a maximum difference of 5%, removing events which were mis-reconstructed by the RICH.
 5. Komolgorov probability test: A consistency check can be done between the reconstructed ring and the actual measured ring, that is, the one given by the position of the fired PMTs: a Komolgorov probability test is performed; this value is uniformly distributed in the interval $(0, 1]$ in the case of correctly reconstructed rings. In the case of incorrectly reconstructed rings this value peaks at zero. Hence, only events with this parameter greater than 0.01 are allowed.
- **Galactic CRs selection:** In order to ensure that the CR events being studied are of galactic origin, thus discarding particles produced by the interactions of CRs with the outer layers of the Earth's atmosphere. It is required that the rigidity of each event is above a given threshold. This threshold is defined as 1.2 times the cutoff rigidity at the geomagnetic location where the event was detected, as calculated by the Stoermer model presented in the first chapter. Since this analysis is done in velocity bins, this cut is applied using the cutoff rigidity (R_C) calculated with the measured β and assuming the proton mass, that is, $R_C = m_p \beta \gamma$, where m_p is the proton mass.

4.3 Mass resolution: data and MC comparison

As discussed in chapter 3, the mass resolution is given by:

$$\left(\frac{\Delta m}{m}\right)^2 = \left(\frac{\Delta R}{R}\right)^2 + \gamma^4 \left(\frac{\Delta \beta}{\beta}\right)^2. \quad (3.20)$$

The study of this quantity is of great importance, not only because it gives information about the capability of separating the isotopes up to a given energy range, but also because during this study it is possible to compare the mass, β and rigidity resolutions in data and MC. As already mentioned in chapter 3, due to the γ^4 factor, the contributions of the rigidity and β to the resolution can be studied separately using independent data samples in different ranges of these variables. The mass resolution study is done in three steps:

1. β resolution: In a high rigidity sample (above 50 GV), where the particles velocities are relativistic ($\beta \approx 1$) the mass resolution is dominated by β .
2. R resolution: Once the β effects have been understood and any possible data and MC discrepancies have been fixed, the rigidity resolution can be studied over the entire analysis range. This work aims to detect deuterons in the energy range from 0.6 to 10 GeV/n. The corresponding range in rigidity, given by $R = m\beta(E_K - 1)$, goes between ≈ 1 GV and ending at ≈ 22 GV: the mass resolution in this interval is mostly affected by the rigidity rather than the velocity.
3. Mass resolution: Once the β and rigidity resolutions have been studied, the mass resolution in data and MC can be estimated and compared.

4.3.1 Velocity resolution

To study the β resolution, protons events with rigidity between 50 and 100 GV (measured by the inner tracker) are used both on MC and ISS data. Deuteron MC is not needed, as both species are expected to behave the same way in this rigidity range: at high energies the probability of interaction with detector material is low, hence the signals protons and deuterons leave in the detector are mostly charge dependent, therefore their behavior is similar. The distributions of β for ISS data and MC are built with the selected events: a fit to a Gaussian is performed in a range of β including 90% of the events. This restriction is imposed due to the fact that a simple Gaussian cannot fit the whole distribution: other physical processes such as multiple scattering and energy loss play a role, making the distribution non-Gaussian, especially at the tails. Figure 25 shows examples of these fits in the NaF range.

(a) Distribution of particles β for high rigidity simulated protons events.

(b) Distribution of the particles β for high rigidity proton events detected by AMS-02 on the ISS.

Figure 25 – Gaussian fits performed on high rigidity β distributions of events measured by the RICH in the NaF range

Source: By the author

(a) β resolution RICH-NaF and RICH-Aerogel as estimated from data and MC simulations.

(b) The β resolution ratio, $\frac{\sigma_{ISS}}{\sigma_{MC}}$ for RICH-NaF and RICH-Aerogel.

Figure 26 – Data and MC ratios of the obtained resolutions for each detector.

Source: By the author

The results of this study are shown in figure 26: the top panel shows the resolution σ_β/β for ISS data (blue squares) and MC (red dots) for the two ranges, while the bottom panel shows the ratio between the width of the β distributions (σ parameters) for data and MC, for the two ranges. As expected, the RICH has shown good precision when measuring the velocities of particles with high β ; however, the most striking feature of these results is the difference between data and MC resolutions, reaching values as high as 10% in RICH-NaF, used in this analysis. With the aim of fixing these discrepancies, a correction is applied on the reconstructed β in every Monte Carlo event:

$$\beta_{MEAS} = \beta_{GEN} + (\beta_{MEAS} - \beta_{GEN}) \frac{\sigma_{ISS}}{\sigma_{MC}}, \quad (4.1)$$

where β_{MEAS} is the reconstructed β value, β_{GEN} the generated velocity (from MC), σ_{ISS} and σ_{MC} are the resolutions as estimated from data and MC, respectively. This equation enhances or diminishes the detector response, by a factor corresponding to the difference between data and MC, adjusting the width of the distribution. The results obtained after this correction are shown in figure 27, where the improvement with respect to the initial situation can be observed: the β resolution estimated from the ISS data is now compatible with MC.

Figure 27 – Data and MC ratios of the obtained resolutions for each detector after MC correction.

Source: By the author

4.3.2 Rigidity resolution

The rigidity resolution is estimated using both ISS data and MC: however, given the results of the previous section, the corrected β will be used. Moreover, based on the

actual CR composition, a mixture of simulated protons and deuterons is used to take into account the fact that deuterons can be misidentified as protons. This study is performed by dividing the events in bins of kinetic energy per nucleon, based of their reconstructed β value. The weights used in the mixture of protons and deuterons are arbitrary, based of the deuteron-to-proton flux ratio measured by previous experiments.²⁵

Figure 28 – Normalized inverse mass distribution for simulated protons and deuterons with $1.482 < E_k/n < 1.695$ GeV/n. Deuterons can fragment into protons and neutrons inside the detector, being misidentified as protons, explaining the tail in the proton region.

Source: By the author

The rigidity resolution estimation is done with a Gaussian fit performed around the inverse rigidity proton peak, in a range containing 95% of the events, as shown in figure 29. The inverse rigidity is used instead of R because as described in chapter 3, the tracker measures the sagitta, therefore $1/R$ is the measured quantity.

The results are shown in figure 30. As expected, the resolution increases at low energies, where the multiple Coulomb scattering becomes more relevant; the obtained values are compatible with the ones shown in figure 20, in chapter 3. There are discrepancies between data and MC, but the differences are smaller: at most 5% in the majority of bins.

The following correction is applied to the inverse reconstructed rigidity

$$\frac{1}{R_{MEAS}} = \frac{1}{R_{GEN}} + \left(\frac{1}{R_{MEAS}} - \frac{1}{R_{GEN}} \right) \frac{\sigma_{ISS}}{\sigma_{MC}}, \quad (4.2)$$

where $1/R_{MEAS}$ is the inverse reconstructed rigidity and $1/R_{GEN}$ the inverse generated rigidity; σ_{MC} and σ_{ISS} are the rigidity resolutions as estimated from simulations and data, respectively. Since the resolution changes in every bin, this correction has a

(a) Inverse rigidity distribution of a bin in the Aerogel range of simulated proton and deuteron events.

(b) Inverse rigidity distribution of a bin in the Aerogel range of experimental data.

Figure 29 – Gaussian fits performed around the proton peaks in inverse rigidity distributions of simulated and experimental data.

Source: By the author

(a) Rigidity resolution as estimated from experimental data and simulations for the NaF and Aerogel ranges.

(b) Data and MC rigidity resolution ratio for the NaF and Aerogel ranges.

Figure 30 – Gaussian fits performed around the proton peaks in inverse rigidity distributions of simulated and experimental data.

Source: By the author

energy dependence that is already included in the values of σ_{MC} and σ_{ISS} , as opposed to β , where the correction is the same for every event in the same radiator range. The results are shown in figure 31, indicating the ratio is now compatible with 1, hence the rigidity resolution in data and MC are matching. The same correction was applied to deuterons, assuming they behave the same way as protons.

Figure 31 – Data and MC rigidity resolution ratio for the NaF and Aerogel ranges after the MC correction.

Source: By the author

4.3.3 Mass resolution

Once the rigidity and β resolutions have been estimated and the discrepancies between data and MC have been fixed, the mass resolution can be studied. The procedure is the same as the one for rigidity: a mixture composed of 2% simulated deuterons and 98% protons is used and a Gaussian fit is performed on the proton peak in a range containing 95% of the events. Results are shown in figure 32. Overall, the mass resolution varies from around 9% to around 17% and the simulations are in good agreement with data within the uncertainties.

4.4 Event counting method

The number of signal and background events are estimated by means of a template fit method. The reference spectra are fit to the data by varying the normalization of the signal and background. These spectra are determined by simulated deuterons, protons

Figure 32 – Mass resolution for $Z = 1$ particles as estimated from MC and experimental data. Open red symbols represent MC, while blue filled symbols represent data.

Source: By the author

and helium *. The fit is performed in each kinetic energy per nucleon bin, yielding the number of events per each one of the components discussed above.

The reference spectra for the signal and the background are obtained using the following classes of simulated events

- Protons;
- Deuterons;
- Helium: composed of 15% ^3He and 85% ^4He in order respect the isotopic composition of He in CRs as measured by previous experiments.²⁵

Examples of these fits in the NaF and Aerogel range are shown in figure 33, where it is possible to see a good agreement between the fitted MC distributions and data.

However, in the region between ≈ 0.9 and ≈ 3 GeV/n, where β is measured by the NaF, there is a tail of low inverse mass (or high mass) events which is not well reproduced in MC, affecting the robustness of the counting method as can be seen in figure 34, where the green curve fails to be adjusted to the black dots when $1/m < 0.4$ GeV/n. The causes of these tails will be discussed in the following section.

* 15% ^3He and 85% ^4He ²⁵

(a) Template fit in NaF region

(b) Template fit in aerogel region

Figure 33 – Examples of template fits in the NaF **(a)** and aerogel **(b)** regions. The blue curve represents deuterons, the red represents protons, magenta represents helium and the green the sum of all contributions. The data is represented by black dots. The box in the top right indicate the number of events of each species with the respective uncertainties. $ndeut$ is the number of deuterons, nhe the number of helium events and $nprot$ the number of protons.

Source: By the author

Figure 34 – Template fit of the inverse mass distribution in the NaF region of events in the energy interval $1.184 < E < 1.316$ GeV/n. The blue curve represents deuterons, the red represents protons, magenta represents helium and the green the sum of all contributions. The data is represented by black dots. The box in the top right indicate the number of events of each species with the respective uncertainties. $ndeut$ is the number of deuterons, nhe the number of helium events and $nprot$ the number of protons.

Source: By the author

4.5 Sources of high mass tails in the NaF region

The first step to investigate the physical processes that cause the high mass tails in the NaF region was to determine which sub-detector contributes the most to this tail during the mass reconstruction. In order to understand whether the bigger source of discrepancy was coming from the rigidity measurement or from the velocity, simulated proton events for which generated rigidity is known were used. The test consisted of reconstructing the particle mass using the generated rigidity, therefore excluding the possibility that the tails are due to the tracker reconstruction. In this case, issues with the velocity reconstruction would be the only option to explain the presence of tails in the high mass range. Figure 35 shows the results of this exercise. It is clear that the distribution of the mass using the true rigidity still has a large high mass tail, albeit the core of the distribution is smaller. Spurious hits in single charge events with mis-reconstructed β are mainly due to CR interactions inside the detector material. A more detailed discussion about the sources of noise will be given in the following.

4.5.1 Interactions as the source of the high mass tails

The official AMS-02 analysis framework, used in this work, allows the tracking of simulated events. Making use of simulated proton events, it is possible to track down the

Figure 35 – Inverse mass distributions calculated with the true rigidity (red) and reconstructed rigidity (blue), as obtained from simulated proton events.

Source: By the author

sources of this interactions by following the generated particle as it traverses the detector: once it interacts inelastically inside the detector, a flag is generated in the software, hence, it is possible to know the Z of the coordinates of the point where the particle stopped, and in particular the vertical coordinate of the stopping point, Z_{min} . The Z coordinate in AMS-02 is defined with its value being zero at the middle of the magnet: positive values of Z are above it and negative are below. As an example, the first layer of the tracker is located at $Z \approx 200$ cm and the bottom of the ECAL at $Z \approx -160$ cm. A plot of Z_{min} versus the inverse mass can reveal where the interactions that contribute more to the tail occur inside the detector. Figure 36 reveals most of these interactions take place in the lower part of the detector.

Table 1 – Z_{min} intervals that contribute the most to the high mass tails together with the corresponding sub-detector regions.

Z interval [cm]	Region of interaction
[-61, -65]	Lower TOF
[-69.5, -70.5]	Between RICH radiator and TRK L9
[-135.5, -135.5]	Between L9 and top of ECAL
[-142.5, -143.5]	ECAL
[-159, -158]	Remaining material or no interaction

Source: By the author

Table 1 indicates in which part of the detector these interactions take place. Figure 36 shows that the interactions occurring in ECAL are the most relevant to the tails. A comparison of inverse mass distributions of particles with their trajectories passing through

Figure 36 – Particles stopping point Z_{min} as a function of the inverse mass, for simulated proton events whose velocity is measured by the NaF. The color gradient indicates the number of events in each pixel. Blue pixels contain few events, while red pixels contain over one hundred events.

Source: By the author

ECAL and other of particles not passing through it is shown in figure 37. An explanation for this is that the calorimeter is right below the RICH PMT detection plane: when a particle interacts inside the calorimeter, it may produce *backsplash* particles, that is, particles that are emitted backwards. Hence, they traverse the PMT plane, generating signals which are erroneously identified as Cherenkov photons, thus the algorithm recognizes these events have a more intense signal, thus they are reconstructed with higher β and therefore higher mass.

Besides the interactions happening inside ECAL, there are the interactions occurring between the lower TOF and the top of ECAL as shown in table 1. Inside this region are whole RICH apparatus and also the lower TOF. Unlike the ECAL, there is no way to compare inverse mass distributions of particles traversing and not traversing this region to determine if a interaction occurred or not; however, in MC it is possible to determine if the incoming particle interacted by search for particles other than the generated species: since this work is done using simulated proton events, if a particle other than a proton is present in the simulation, it means an interaction took place. The AMS-02 software enables access to information about the generated particles in the MC simulations, not only their type but also the direction and coordinates in which they were generated. Since the energy loss or particles traversing particles in this velocity regime is mostly due to ionization, in order to study the effect of the interactions happening in the interval $-135.5 < Z_{min} < -61$ cm, a check for down-going electrons within this interval was

Figure 37 – Inverse mass distributions of simulated proton events whose track is traversing (red curve) and not traversing (blue curve) the ECAL fiducial volume.

Source: By the author

performed. A comparison of inverse mass distributions of events with secondary electrons present and absent is shown in figure 38. As expected, interaction happening in this region of the detector influence the β reconstruction: if additional charged particles are produced before or inside the radiator, the amount of Cherenkov light detected is different and so is the reconstruction. If produced after the radiator, the produced particles may traverse the PMT planes and produce the same effect as described for the backplash particles.

As an outcome of the study presented in this section, the conclusion is that high mass events that are not well reproduced by the simulations are mainly due to the interactions taking place in different parts of the detector, especially the calorimeter. Given that the source of the high mass tails are interactions taking place in different parts of the detector, a deep investigation of the models and parameters used in MC simulations should be carried out in order to discover why they fail to reproduce these effects, however this is out of the scope of this work. Instead, other efforts to fix the current simulations were implemented and will be presented in the next sections.

4.6 MC re-weighting according to RICH signals

Since the interactions that affect the RICH reconstruction are not well reproduced by MC, it means the simulations have less noise in the PMT plane. It is possible to verify this by comparing the signals detected by the RICH in data and MC: the number of hits on the PMT plane that were used (N_{used}) and the number of hits that were not used

Figure 38 – Comparison between inverse mass distributions for simulated proton events which have (red curve) and not have (blue curve) secondary electrons produced during their propagation inside the detector.

Source: By the author

(N_{unused}) in the reconstruction is registered for every event. A two-dimensional histogram with N_{used} in one axis and N_{unused} in the other was made for data and MC samples and their ratio was calculated, resulting in an histogram containing a the ratio between data and MC in every bin.

Figure 39 shows such a histogram for events with $2.409 < E_K/n < 3.113$. The histogram is not homogeneous, with a peak in a region with $N_{used} < 10$ and $N_{unused} > 15$. In other words, the peak is in a region dominated by noise as the number $N_{unused} > 15$ is large; since it is a ratio plot, this means the MC has fewer events in this region. This is not unexpected: as shown before the high mass tails are due to interactions inside the detector that generate noise in the PMT plane. The information in this kind of histogram can, however, be used to adjust the MC to better match the data in a re-weighting process. The same kind histogram was made for every velocity bin being analyzed and was used as a re-weighting function in the process of filling the inverse mass histograms: the ratio between data and MC was obtained for every event in MC by using its values of N_{used} and N_{unused} and interpolating the histogram. This ratio value was then used as a weight to fill the inverse mass distribution of MC events in every bin, thus events where the discrepancies between data and MC are larger have larger weights, therefore the MC distribution should have a better agreement with data.

Figure 40 shows an example of template fit performed with the re-weighted MC.

Figure 39 – Ratio between data and MC histograms of the number of RICH hits used versus unused in the reconstruction of the Cherenkov ring.

Source: By the author

Although the agreement between data and MC is better, the simulations of high mass events is still not reproducing accurately the data. This comes from the fact that even though the charged particles produced by the interactions that cross the PMT plane increase N_{used} and N_{unused} , the signals they generate inside the PMTs are usually different from those produced by photons: charged particles may leave signals in more than one channel of the same PMT. Hence, the number of detected photons is also important for the correction. A method for identifying and counting these interaction events was developed and is discussed in the following subsection.

4.7 Fitting the high mass tails: template of interactions

Although the MC simulations are unable to reproduce the high mass tails, it is possible to identify the interactions using experimental data: selection criteria can be developed to select only these events, then they can be used to produce a reference spectra for the the event counting method. This allows the identification and counting of such events, hence their contribution can discarded when computing the flux. Figure 41 shows the behavior of the inverse mass with the increase of the number of hits in the ECAL; above 150 hits, the inverse mass distribution starts to be dominated by high mass events, hence, the number of ECAL hits can be used as a tool to identify the events composing the tails; however the number of ECAL hits cannot be used alone to identify particles interacting inside the calorimeter, since these particles do not necessarily produce backplash particles

Figure 40 – Template fit performed after MC re-weighting.

Source: By the author

that distort the β measurement: they may interact inside the ECAL and do not produce any particles that pass through the PMT plane. In order to guarantee the selected sample is composed of backplash events, a cut on the number of photoelectrons collected by the PMTs is also applied: when charged particles traverse them, they leave signals as if a photon was detected, so the number collected photoelectrons increases.

Figure 41 – Inverse mass versus the number of hits in the ECAL.

Source: By the author

The reference spectra that describes the events undergoing interactions inside the detector is built using events with large number of hits in the ECAL and a large number of collected photoelectrons in the NaF, namely the selection requires:

- Number of ECAL hits > 120 .
- Number of collected photoelectrons > 20 .

An example of inverse mass histogram in the NaF region with this selection is shown in figure 42. The selected events are in the expected region, however, due to the very strict criteria, statistical fluctuations are too big to use this histogram as a reference spectra. To overcome this issue, a fit of a Landau distribution was performed on the histogram, and the output distribution was used to generate another histogram, with more events, to be used as a template. This process was repeated in every other bin in the NaF region between 0.598 and 3.113 GeV/n.

Figure 42 – Histogram of experimental data after the selection of interaction events. A fit of a Landau distribution is performed in order to generate a smoother histogram to be used as a template.

Source: By the author

The results of this procedure are shown in figure 43, where it is possible that including an additional contribution that describes the effects of the interactions, the reference spectra based on simulated events is in good agreement with the data.

Figure 43 – Template fit in the NaF region using a template of interaction events. The blue curve represents deuterons, the red represents protons, magenta represents helium, the cyan represents the events with interactions, while the green line is the sum of all contributions. The data is represented by black dots.

Source: By the author

5 DEUTERIUM FLUX MEASUREMENT

The flux of deuterons in cosmic rays in the kinetic energy per nucleon bin E_K with width ΔE_K is given by

$$\phi_D(E_K, E_K + \Delta E_K) = \frac{N_D(E_K)}{A(E_K)T(E_K)\Delta E_K}, \quad (5.1)$$

where N_D is the number of deuterons detected in the kinetic energy per nucleon interval $[E_K, E_K + \Delta E_K]$, $A(E_K)$ the detector acceptance and $T(E_K)$ the exposure time. A measurement of the deuterium flux in cosmic rays will be presented in this chapter, along with a measurement of deuterium-to-hydrogen flux ratio. The results were obtained using four years of data collected by AMS-02, from May 2011 to May 2015.

5.1 Exposure time

The exposure time T present in equation 5.1 corresponds to the time AMS-02 is able to trigger the data acquisition. Since the event selection requires events to have a rigidity above the geomagnetic cutoff, which varies according to the detector's geomagnetic location, the exposure time is rigidity dependent and it must be calculated for every bin. Each event detected by AMS has an associated live time, defined as the fraction of a second where the detector's trigger was not busy. All events triggered in the same second have the same live time, therefore the total exposure time is given by the sum of all registered live times.

Figure 44 – Exposure time as a function of the energy for NaF and Aerogel.

Source: By the author

Figure 44 shows the exposure time as function of the kinetic energy per nucleon.

5.2 Acceptance

The detector's geometry, as well as the interactions particles undergo while traversing the material must be considered while calculating the real flux of particles. The acceptance correction is given by relating the number of measured particles to their flux at the top of the instrument. A_{eff} , the corrected acceptance is defined as

$$A_{eff}(E_K) = A_{MC}(1 + \delta(E_K)), \quad (5.2)$$

where A_{MC} is the acceptance calculated using MC simulations and $(1 + \delta(E_K))$ a correction factor to take into account possible differences between data and simulations. A_{MC} is given by

$$A_{MC}(E_K) = \frac{N_{sel}(E_K)}{N_{gen}(E_K)} G, \quad (5.3)$$

where N_{sel} is the number of simulated events which passed the selection, N_{gen} is the total number of events generated and $G = \pi l^2$ is a geometrical factor representing the surface in which particles were generated. The MC sample used in this work was generated in a square box of side $l = 3.9$ m, resulting in $G \approx 47.78$ m² sr. Results for A_{MC} are shown in figure 45.

Figure 45 – Acceptance from MC as a function of energy for deuterons (blue) and protons (red).

Source: By the author

The MC simulations, however, do not reproduce data perfectly as discussed before, hence a correction must be applied to this acceptance in order to remove any possible

discrepancy. For each and every criterion used in the event selection, as discussed in the previous chapter, a correction $C_i(E_K)$ was calculated:

$$C_i(E_K) = \frac{\epsilon_{i,data}(E_K)}{\epsilon_{i,MC}(E_K)}, \quad (5.4)$$

where $\epsilon_{i,data}(E_K)$ represents the efficiency of the i^{th} selection criterion as estimated from experimental data and $\epsilon_{i,MC}(E_K)$ represents the same for proton MC simulations. Since it is not possible to compare data and MC in the case of deuterons, these corrections were obtained for protons and assumed to be the same for deuterons. In order to make a fair comparison between data and MC, the efficiency of all the selection criteria was calculated using events which have $1/m$ larger than 1, where the data is dominated by protons. Aiming to avoid possible correlations between selection criteria of the same detector, when a criterion of a sub-detector was being studied, no other selection based in other variable of the same sub-detector was used. Figure 46 shows an example of efficiency calculated for data and simulations: the differences will be taken into account as discussed in the following.

Figure 46 – Efficiency of the tracker χ^2 selection for data (red) and MC (blue) in the NaF and Aerogel regions.

Source: By the author

Once all C_i have been calculated, the total correction is given by their product

$$1 + \delta(E_K) = \prod_{i=1} C_i(E_K). \quad (5.5)$$

A plot of the overall correction is shown in figure 47. In order to avoid possible fluctuations, a cubic spline interpolation is used to calculate the value for this correction in every bin to obtain A_{eff} .

Figure 47 – $(1 + \delta(E_K))$ correction for the acceptance as a function of the energy for Aerogel (blue circles) and NaF (red circles). The cubic splines are also shown for NaF (red line) and Aerogel (blue line).

Source: By the author

5.3 Results

5.3.1 Deuteron flux

Using equation 5.1 the flux can be calculated in every bin. The results are shown in table 2. The results are in good agreement with previous measurements such as PAMELA,⁴⁹ BESS (00),⁵⁰ IMAX92⁵¹ and CAPRICE94.⁵² The obtained flux is in good agreement with the measurements of other experiments. Above 1 GeV/n all measurements follow the same trend: the flux decreases with the energy. The obtained results are also in agreement with another ongoing analysis in the AMS-02 collaboration. Most importantly, these are the first measurements of the deuteron flux above 4 GeV/n, hence, they are of great value for the study of CR propagation.

5.3.2 Deuteron-to-proton flux ratio

Since the number of protons is also determined with great precision in every bin, the flux of protons and hence the deuteron-to-proton flux ratio can be calculated. Table 3 shows the results. As before, they are well compatible with the previous experiments, following the same trend. This result is of great value, because it provides measurements in a previously unexplored region, with very low statistical uncertainties, up to 10 GeV/n, and will allow CR propagation models to be better constrained.

Table 2 – Deuteron flux measurements made with the NaF and Aerogel, along with the statistical errors and the energy intervals.

NaF		
Interval [GeV/n]	Flux [m ² sr GeV/n] ⁻¹	σ_{STAT} [m ² sr GeV/n] ⁻¹
0.598 - 0.635	8.659	0.646
0.635 - 0.677	17.616	0.687
0.677 - 0.724	21.172	0.538
0.724 - 0.777	24.084	0.421
0.777 - 0.836	27.476	0.350
0.836 - 0.904	23.824	0.257
0.904 - 0.983	22.815	0.191
0.983 - 1.075	17.791	0.135
1.075 - 1.184	13.423	0.096
1.184 - 1.316	11.235	0.067
1.316 - 1.482	8.397	0.0461
1.482 - 1.695	5.882	0.030
1.695 - 1.985	4.658	0.021
1.985 - 2.409	1.712	0.007
Aerogel		
Interval [GeV/n]	Flux [m ² sr GeV/n] ⁻¹	σ_{STAT} [m ² sr GeV/n] ⁻¹
2.571 - 2.679	0.9887	0.0470
2.679 - 2.798	0.8790	0.0101
2.798 - 2.931	0.7337	0.0043
2.931 - 3.078	0.6399	0.0029
3.078 - 3.245	0.4667	0.0017
3.245 - 3.434	0.3854	0.0014
3.434 - 3.653	0.3091	0.0012
3.653 - 3.909	0.2593	0.0007
3.909 - 4.215	0.2113	0.0005
4.215 - 4.587	0.1751	0.0003
4.587 - 5.055	0.1239	0.0002
5.055 - 5.669	0.09032	0.0001
5.669 - 6.522	0.06209	0.0001
6.522 - 7.825	0.03619	0.0001
7.825 - 10.19	0.019340	0.00001

Source: By the author

Table 3 – Deuteron-to-proton flux measurements made with the NaF and Aerogel, along with the statistical errors and the energy intervals.

NaF		
Interval [GeV/n]	Flux ratio	σ_{STAT}
0.598 - 0.635	0.03042	0.00227
0.635 - 0.677	0.03017	0.00118
0.677 - 0.724	0.02977	0.00076
0.724 - 0.777	0.03011	0.00053
0.777 - 0.836	0.02720	0.00035
0.836 - 0.904	0.02489	0.00027
0.904 - 0.983	0.02700	0.00023
0.983 - 1.075	0.02464	0.00019
1.075 - 1.184	0.02269	0.00016
1.184 - 1.316	0.02309	0.00014
1.316 - 1.482	0.02180	0.00012
1.482 - 1.695	0.02007	0.00010
1.695 - 1.985	0.01792	0.00008
1.985 - 2.409	0.01571	0.00007
Aerogel		
Interval [GeV/n]	Flux ratio	σ_{STAT}
2.571 - 2.679	0.010679	0.000548
2.679 - 2.798	0.013481	0.000171
2.798 - 2.931	0.013149	0.000086
2.931 - 3.078	0.012522	0.000065
3.078 - 3.245	0.010791	0.000044
3.245 - 3.434	0.010342	0.000042
3.434 - 3.653	0.009646	0.000041
3.653 - 3.909	0.009650	0.000031
3.909 - 4.215	0.009579	0.000025
4.215 - 4.587	0.009777	0.000020
4.587 - 5.055	0.008672	0.000020
5.055 - 5.669	0.008101	0.000017
5.669 - 6.522	0.007485	0.000016
6.522 - 7.825	0.006632	0.000015
7.825 - 10.19	0.006829	0.000016

Source: By the author

6 CONCLUSION

The measurement of the fluxes of secondary CRs is imperative for the study of propagation processes of CRs in the galaxy. This is commonly done using the boron-to-carbon ratio, a well measured quantity; however, in the present times there are experiments able to measure the fluxes of CRs with great precision, enabling the study of propagation processes with different species, testing the universality of such processes. Recent measurements of high energy deuterons are in tension with the expectations from conventional astrophysical mechanisms, in which deuterons are purely secondary particles, whose flux should be a decreasing function of energy. Due to the technical challenges, measurements by previous experiments are mostly limited to energies below 1 GeV/n, with large uncertainties. Hence, precision measurements up to higher energies are of great interest as they provide information that could help the understanding the propagation processes that connect the current measurements and the ones performed by SOKOL. AMS-02, built with state-of-the-art particle physics technology and operating aboard at the International Space Station, collecting data since 2011, has the capability of measuring deuterons with great precision and hence provide the needed results.

The precise measurement of the CR deuteron flux between 0.6 and 10 GeV/n has been performed in this work, analyzing data collected by the AMS-02 experiment between May 2011 and May 2015. The deuteron-to-proton flux ratio was also measured over the same range. The analysis have been carried out using both simulated and actual CR events detected on the ISS, using the official analysis pipeline of the AMS-02 collaboration. In particular, the data are transferred from the ISS to CERN where they are stored on the CERN computer cluster and later calibrated and reconstructed.

The first step of this work was to study how the detector and the event reconstruction algorithms work and establish a quality selection to suppress most of the background and ensure the quality of the measurements. Afterwards, the mass, velocity and rigidity resolutions were studied, aiming to understand the limitations of the detector in terms of mass separation, as well as how each of the variables used to reconstruct the mass affects this resolution. This step was also very important to verify if the MC simulations, essential for this work, were thoroughly reproducing the data. As a result of this study, a correction was applied to MC in order to mitigate the discrepancies with data.

A strategy for counting events using template fits, based on the simulations, was implemented. This procedure worked quite well for the RICH-Aerogel range, however in the RICH-NaF region, above ≈ 1 GeV/n, the MC was underestimating the number of high mass events. In order to fix this issue, the possible sources of these tails were studied using MC, by checking the regions inside AMS-02 where interactions were more likely to

take place as well as regions in which secondary particles were produced. Most of these discrepancies were found to be due to particles interacting inside the calorimeter that produce additional particles that traverse the RICH PMT plane, mimicking the signal of Cherenkov photons and thus increasing the particle's measured mass. Once the origin of the interactions was known, strategies had to be developed to overcome this problem: namely the MC re-weighting and the creation of an additional reference spectra of the interacting particles. These results are of great importance, not only because they improve robustness of the template fit results, but also because they provide valuable information to the collaboration about the flaws in the current MC simulations.

In possession of the number of events, the exposure time, acceptance and its corrections were calculated to obtain the deuterium flux in CRs. The results are in good agreement with previous experiments, showing a similar behavior as a function of the energy. Besides that, precision measurements between 4 and 10 GeV/n were provided for the first time. In similar fashion, the deuteron-to-proton ratio is well compatible with the previous experiments and the measurements between 4 and 10 GeV/n are available to the first time, showing the ratio continues to decrease after 4 GeV/n. Our results are also in good agreement with respect to similar ongoing analyses ongoing with the AMS-02 collaboration.

Although this work had several interesting results, the complete analysis of the deuteron flux is not yet completed. In particular, we provide in the following a list of possible future developments:

- Study of the systematic uncertainties. The some of the sources of these uncertainties are: the correction parameters applied in MC; the event selection; the cross sections used in MC simulations; and the composition of the reference spectra.
- Further study the differences between data and MC. This is important because the understanding the origin of these discrepancies will enable the MC simulations to be corrected, producing more reliable reference spectra that do not need any additional correction.
- Optimize the identification of events which interacted inside the detector by using the deposited energy in ECAL along the particle's trajectory and information about the individual channels of each PMT in RICH. This would allow the identification of interaction events to be done more efficiently, what would help to obtain reference spectra of these particles with more statistics.
- Use multivariate analysis techniques aiming to assess the quality of the reconstruction of the rigidity and velocity. This would help the events with mis-reconstructed mass to be suppressed more efficiently.

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