MEASUREMENT OF THE ISOTOPIC COMPOSITION OF HYDROGEN AND HELIUM NUCLEI IN COSMIC RAYS WITH THE PAMELA EXPERIMENT

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ABSTRACT

The satellite-borne experiment PAMELA has been used to make new measurements of cosmic ray H and He isotopes. The isotopic composition was measured between 100 and 600 MeV/n for hydrogen and between 100 and 900 MeV/n for helium isotopes over the 23rd solar minimum from 2006 July to 2007 December. The energy spectrum of these components carries fundamental information regarding the propagation of cosmic rays in the galaxy which are competitive with those obtained from other secondary to primary measurements such as B/C.

Key words: astroparticle physics – cosmic rays

Online-only material: color figures

1. INTRODUCTION

Hydrogen and helium isotopes in cosmic rays are generally believed to be of secondary origin, resulting from the nuclear interactions of primary cosmic-ray protons and 4He with the interstellar medium, mainly through spallation of primary 4He nuclei or through the reaction $p + p \rightarrow ^2\text{H} + \pi^+$. These isotopes can be used to study and constrain parameters in propagation models for galactic cosmic rays (GCRs; Strong et al. 2007; Tomassetti 2012; Coste et al. 2012). $^2\text{H}$ and $^3\text{He}$ are the most abundant secondary isotopes in GCRs and have peculiar features: $^2\text{H}$ is the only secondary species (apart from antiprotons) that can also be produced in proton–proton interactions and $^3\text{He}$ is the only secondary fragment with a A/Z significantly different from two (A and Z being, respectively, the mass and charge number).

The importance of light isotopes has been known for about 40 yr, when the first measurements became available (Garcia-Munoz et al. 1975a, 1975b; Mewaldt et al. 1976; Leech & O’Gallagher 1978). Measurements require very good mass resolution, a challenge for instruments deployed in space. With the exception of the results from AMS-01 (Aguilar et al. 2011) most of the measurements were performed using stratospheric balloons (Wang et al. 2002; Reimer et al. 1998; Wefel et al. 1995; Webber et al. 1991; Beatty et al. 1993), where the residual atmosphere above the instrument caused a non-negligible background of secondary particles. The atmospheric background estimation is subject to large uncertainties (e.g., the limited knowledge of isotope production cross sections). Due to these limitations, experimental errors are generally very large and the focus of measurements therefore shifted to other secondary species, like boron or sub-iron nuclei (Strong & Moskalenko 1998).

The light-isotope quartet offers an independent unique way to address the issue of “universality in GCR propagation,” which
The apparatus was optimized for the study of antimatter with respect to previous experiments. To reach this goal the apparatus was modified by adding several detectors to measure the trajectory of incoming particles. The spatial resolution is ∼3 μm in the bending view (also referred to as the x-view) and ∼11 μm in the non-bending view (also referred to as the y-view). The main task of the magnetic spectrometer is to measure particle rigidity \( \rho = p c / Z e \) (\( p \) and \( Z e \) being, respectively, the particle momentum and charge, and \( c \) the speed of light) and ionization energy losses (\( dE/dx \)).

The time-of-flight (ToF) system comprises three double layers of plastic scintillator paddles (S1, S2, and S3, as shown in Figure 1) with the first two placed above and the third immediately below the magnetic spectrometer. The ToF system provides 12 independent measurements of the particle velocity, \( \beta = v / c \), combining the time of passage information with the track length derived from the magnetic spectrometer. By measuring the particle velocity the ToF system discriminates between particles moving downward and splash albedo particles moving upward thus enabling the spectrometer to establish the sign of the particle charge. The ToF system also provides six independent \( dE/dx \) measurements, one for each scintillator plane.

A silicon-tungsten electromagnetic sampling calorimeter made of 44 single-sided silicon microstrip detectors interleaved with 22 plates of tungsten absorber (for a total of 16.3 \( X_0 \)) mounted below the spectrometer is used for hadron/lepton separation with a shower tail catcher scintillator (S4). A neutron detector at the bottom of the apparatus helps to increase this separation.

The anticoincidence (AC) system comprises four scintillators surrounding the magnet (CAS), one surrounding the cavity entrance (CAT) and four scintillators surrounding the volume between S1 and S2 (CARD). The system is used to reject events where the presence of secondary particles generates a false trigger or the primary particle suffers an inelastic interaction.
Events were selected requiring:
1. A single track fitted within the spectrometer fiducial volume where the reconstructed track is at least 1.5 mm away from the magnet walls.
2. A positive value for the reconstructed track curvature.
3. Selected tracks must have at least four hits on the x-view and at least three hits on the y-view to ensure a good rigidity reconstruction.
4. A maximum of one hit paddle in the two top planes of the ToF system.
5. The hit paddles in S1 and S2 must match the extrapolated trajectory from the spectrometer.
6. A positive value for the measured ToF. This selection ensures that the particle enters PAMELA from above.
7. For the selection of the hydrogen sample no activity in the CARD and CAT scintillators of the anticoincidence system is required.

The anticoincidence selections on the hydrogen sample were necessary since most secondary particles that entered the PAMELA fiducial acceptance were by-products of hadronic interactions taking place in the aluminum dome or in the S1 and S2 scintillators. Such particles were generally accompanied by other secondary particles which hit the anticoincidence detectors. For the selection of the helium sample there were no anticoincidence requirements since contamination by secondary helium coming from heavier nuclei spallation is negligible.

3.1.2. Galactic Particle Selection

The Resurs-DK1 satellite orbital information was used to estimate the local geomagnetic cutoff, G, in the Störmer approximation (Shea et al. 1987) using the IGRF magnetic field model (MacMillan & Maus 2005) along the orbit. The maximum zenith angle for events entering the PAMELA acceptance was 24° with a mean value of 10°. To select the primary (galactic) cosmic ray component particles were binned by requiring that \( \rho_m > k \times G \), where \( \rho_m \) is the lowest edge of the rigidity interval and \( k = 1.3 \) is a safety factor required to remove any directionality effects due to the Earth’s penumbral regions. Galactic particles losing energy while crossing the detector may be rejected by this selection. This effect is accounted for using Monte Carlo simulations.

3.1.3. Charge Selection

Particle charge identification relies on the ionization measurements provided by the magnetic spectrometer. Depending on

\[ \beta = \left(1 + \frac{m^2}{Z^2 \rho^2}\right)^{-1/2} \]  

as shown in Figure 3 for events in the \((\beta, \rho)\) plane.

Isotope separation as well as the determination of isotope fluxes was performed in intervals of kinetic energy per nucleon. Since the magnetic spectrometer measures the rigidity of particles, this implies different rigidity intervals according to the isotope under study. For example, Figure 4 shows the \(1/\beta\) distributions used to select \(^1\)H (top panel) and \(^2\)H (bottom panel) in the kinetic energy interval 0.329–0.361 GeV/n corresponding
to 0.85–0.9 GV for $^1$H and 1.7–1.8 GV for $^3$H. Particle counts were subsequently extracted from a Gaussian fit to the $1/\beta$ distribution in each rigidity range as shown by the solid lines in Figure 4.

Separation between $^3$He and $^4$He was obtained in a similar way. Figure 5 shows the $1/\beta$ distributions used to select $^3$He (bottom panel) and $^4$He (top panel) in the kinetic energy interval 0.312–0.350 GeV/n corresponding to 1.24–1.32 GV for $^3$He and 1.65–1.76 GV for $^4$He.

It should be noted that, because of the large proton background, an additional selection, based on the lowest energy release among the 12 measurements provided by the tracking system (often referred as truncated mean), was used to produce the $1/\beta$ distributions in the $^3$H case. Figure 6 shows this quantity for $Z = 1$ particles. The solid line indicates the condition on the minimum energy release used for the selection.

The selected number of hydrogen and helium events are summarized in the second and third column of Tables 1 and 2.

3.3. Flux Determination

The procedure described in the previous section was used to estimate the number of $^1$H and $^2$H events in the $Z = 1$ sample and the number of $^3$He and $^4$He events in the $Z = 2$ sample.
To derive each isotope flux the number of selected events had to be corrected for the selections efficiencies, particle losses, contamination, and energy losses. These corrections were obtained using a Monte Carlo simulation of the PAMELA apparatus based on the GEANT4 code (Agostinelli et al. 2003) and from the flight data. The simulation contains an accurate representation of the geometry and performance of the PAMELA detectors. The measured noise of each silicon plane of the spectrometer and its performance variations over the duration of the measurement were accounted for. The simulation code was validated by comparing the distributions of several significant variables with those obtained from real data. Hadronic interactions for all the isotopes under study were handled via the QGSP_BIC_HP physics list.

The following corrections to the number of selected events were applied:

1. **Selection efficiencies.** The redundant information provided by PAMELA allowed most of the selection efficiencies to be estimated directly from flight data. For example, the efficiency of the charge selections was evaluated on a sample of events selected with the ToF $dE/dx$ measurements in the same way as described in Section 3.1.3 for the charge misidentification study. The efficiency of the tracking system was, however, obtained from the Monte Carlo simulation. The decrease in efficiency from 2006 to 2007 is due to the failure of some of the front-end chips in the tracking system. This situation was included in the Monte Carlo simulation, as discussed in Adriani et al. (2013). The efficiencies of the various selections are reported in Table 3.

2. **Hadronic interactions.** Helium and hydrogen nuclei may be lost due to hadronic interactions in the 2 mm thick aluminum pressurized container and the top scintillator detectors. The correction to the flux due to this effect was included in the PAMELA geometrical factor as follows:

$$G(E) = [1 - b(E)] \text{G_F}$$

where $G(E)$ is the effective geometrical factor used for the flux determination, $b(E)$ is a correction factor which accounts for the effect of inelastic scattering, $G_F$ is the nominal geometrical factor which is almost constant above 1 GeV.
ρ (GV) 0.5 1 1.5 2 2.5 3

***Figure 7.*** The nominal geometrical factor $G_F$ as a function of rigidity (solid line). The filled bands represent the effective geometrical factor $G(E)$ for each isotope with the associated uncertainty.

(A color version of this figure is available in the online journal.)

and slowly decreases by $\sim 2\%$ to lower energies, where the particle trajectory in the magnetic field is no longer straight. The requirement on the fiducial volume corresponds to a geometrical factor $G_F = 19.9 \text{ cm}^2 \text{ sr}$ above 1 GV. The correction factor $b(E)$ is different for each isotope and has been derived from the Monte Carlo simulation, being $\sim 6\%$ for protons, $\sim 10\%$ for deuterium, and $\sim 13\%$ for both helium isotopes. The nominal geometrical factor and the effective geometrical factor for each isotope are shown in Figure 7.

3. Contamination. The contribution to $^2\text{H}$ from $^4\text{He}$ inelastic scattering was evaluated from the simulation (Figure 8) and subtracted from the raw $^2\text{H}$ counts (see Column 4 of Table 1). The contamination in the $^3\text{He}$ sample from $^4\text{He}$ fragmentation was also evaluated and it was estimated to be less than 1%. This was included in the systematic uncertainty of the measurement.

4. Energy loss and resolution. The finite resolution of the magnetic spectrometer and particle slowdown due to ionization energy losses results in a distortion of the particle spectra. A Bayesian unfolding procedure, described in D’Agostini (1995), was used to derive the number of events at the top of the payload (see Adriani et al. 2011).

The flux was then calculated as follows:

$$\Phi_{\text{ToF}}(E) = \frac{N_{\text{ToF}}(E)}{TG(E)\Delta E}$$

(3)

where $N_{\text{ToF}}(E)$ is the unfolded particle count for energy $E$, also corrected for all the selection efficiencies (see Tables 1 and 2, rightmost two columns), $\Delta E$ is the energy bin width, and $G(E)$ is the effective geometrical factor. The live time, $T$, as evaluated by the trigger system, depends on the orbital selection as described in Section 3.1.2 (e.g., see Bruno 2008). The live and dead time are cross-checked with the total acquisition time measured by the on-board CPU to remove possible systematic effects in the time counting.

3.4. Systematic Uncertainties

The possible sources of systematic uncertainties considered in this analysis are listed below and are also included in Tables 4 and 5 and in Figures 9–11.

1. Quality of the $1/\beta$ fit. The quality of the Gaussian fit procedure was tested using the truncated mean of the energy deposited in the electromagnetic calorimeter to select pure samples of $^1\text{H}$ and $^2\text{H}$ from non-interacting events. The two samples were then merged to form a control sample for the fitting algorithm. The number of reconstructed events from the Gaussian fit was found to agree with the number of events selected with the calorimeter, so no systematic uncertainty was assigned to this procedure.

2. Selection efficiencies. The estimation of the selection efficiencies is affected by a statistical error due to the finite size of the sample used for the efficiency evaluation. This error was considered and propagated as a systematic uncertainty. For the efficiency of the ToF and AC selections this uncertainty is 0.21% at low energy (120 MeV/n)
and drops to 0.14% at high energy (600–900 MeV/n). For the tracker selections the uncertainty is 0.3% at low energy increasing to 0.4% at high energy.

3. **Galactic particle selection.** The correction for particles lost due to this selection has an uncertainty, due to the size of the Monte Carlo sample, which decreases from 6% to 0.07% as the energy increases from 120 MeV/n to 900 MeV/n.

4. **Contamination subtraction.** The subtraction of the contamination results in a systematic uncertainty on the $^{2}\text{H}$ flux of 1.9% at low energy dropping below 0.1% at 300 MeV/n.
due to the finite size of the Monte Carlo sample. To test the validity of the Monte Carlo simulation the $^3\text{H}$ component, identified as the additional cluster of events at low $\beta$ in the hydrogen sample visible in Figure 4, was used. The $^3\text{H}$ events are created by $^4\text{He}$ spallation in the top part of the apparatus since no tritium of galactic origin should survive propagation to Earth. The observed number of $^3\text{H}$ events was used to test that the Monte Carlo simulation correctly inferred the number of $^2\text{H}$ events coming from $^4\text{He}$ fragmentation. For example, for the 2006 data set in the rigidity range between $1.17$ GV and $1.18$ GV the flight data sample contains $136 \pm 17$ tritium events, while $110 \pm 15$ events are expected according to the Monte Carlo simulation (Figure 4). Simulation and flight data were in agreement within a 10% tolerance. This discrepancy was treated as an additional systematic uncertainty on the estimated number of contamination events. The 10% systematic uncertainty on the $^2\text{H}$ contamination translates in an additional 1% uncertainty on the number of reconstructed $^3\text{H}$ events.

5. Geometrical factor. The uncertainty on the effective geometrical factor as estimated from the Monte Carlo simulation is almost independent of energy and amounts to 0.18%.

6. Unfolding procedure. As discussed in Adriani et al. (2011), two possible systematic effects have been studied regarding the unfolding procedure: the uncertainty associated with the simulated smearing matrix and the intrinsic accuracy of the procedure. The former was constrained by checking for compatibility between measured and simulated spatial residuals and found it to be negligible. The latter was estimated by folding and unfolding a known spectral shape with the spectrometer response and was found to be 2%, independent of energy.

4. RESULTS

Figures 9 and 10 show hydrogen and helium isotope fluxes (top) and the ratios of the fluxes (bottom). The results are also reported in Tables 4 and 5. Figure 11 shows the $^2\text{H}/^4\text{He}$ ratio as a function of kinetic energy per nucleon, compared to previous measurements (Aguilar et al. 2011; Wang et al. 2002; Reimer et al. 1998; Wefel et al. 1995; Webber et al. 1991; Beatty et al. 1993). The error bars show statistical uncertainty while shaded areas show systematic uncertainty.
et al. 1993). It is worth noting that flux ratios (in particular the $^3\text{He}/^4\text{He}$ ratio), if modulated using the force-field approximation (Gleeson & Axford 1968), show very little dependence on solar activity and can therefore be used to discriminate between various propagation models of GCR in the Galaxy.

The PAMELA results are the most precise to date. Considering the relatively large spread in the existing data, PAMELA results agree with previous measurements, in particular with BESS results for $^2\text{H}$ and IMAX results for $^3\text{He}$. Previous measurements are affected by large uncertainties and, for $^3\text{He}$ where more measurements are available, there is a large spread between data. All the measurements displayed in Figures 9–11, except AMS-01, are from balloon-borne experiments and are affected by a non-negligible background of atmospheric secondary particles.

A high precision measurement of the H and He isotope quartet abundances represents a significant step forward in modeling the origin and propagation of GCRs. The constraints on diffusion-model parameters set by the quartet ($^1\text{H}$, $^2\text{H}$, $^3\text{He}$, and $^4\text{He}$) were recently revisited (Coste et al. 2012). It was found that the constraints on the parameters were competitive with those obtained from the $\text{B}/\text{C}$ flux ratio analysis and available data supported the universality of GCR propagation in the Galaxy. The tightest constraint was obtained when the He flux was included in the fit. This is because at energies of a few GeV about 10% of He is from fragmentation of heavier nuclei, which is a non-negligible amount given the precision (1% statistical) of the PAMELA He data (Adriani et al. 2011).

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