Light Nuclei and Isotope Abundances in Cosmic Rays.
Results from AMS-01

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Observations of the chemical and isotopic composition of light cosmic-ray nuclei can be used to constrain the propagation models. Nearly 200,000 light nuclei ($Z > 2$) have been observed by AMS-01 during the 10-day flight STS-91 in June 1998. Using these data, we have measured Li, Be, B and C in the kinetic energy range 0.35 - 45 GeV/nucleon. In this proceeding, our charge and isotopic composition results are presented and discussed.

Keywords: cosmic rays — charge composition — isotopic composition

1. Introduction

Cosmic rays detected on Earth with kinetic energies from 100 MeV to 100 GeV per nucleon are believed to be produced by particle acceleration mechanisms occurring in galactic sites such as supernova remnants. Most of our knowledge on the interstellar propagation of the galactic cosmic rays comes from the study of secondary species, i.e. spallation products of C-N-O and Fe nuclei that are almost absent in the cosmic ray (CR) sources.

The relation between secondary CRs and their primary progenitors allows us to determine the propagation parameters, such as the diffusion coefficient and its energy dependence [1]. Among the ratios B/C and Sub-Fe/Fe, it is of great interest to determine the propagation history of the lighter nuclei Li, Be, and their isotopes, which are mostly of spallogenic origin. Their abundances depend not only on interactions of the primary species C, N and O, but also on tertiary contributions like Be$\rightarrow$Li or B$\rightarrow$Li. Therefore the Li/C and Be/C ratios may provide further restrictions on propagation models [2].

AMS-01 observed cosmic rays at $\sim$380 km of altitude during a period
close to the solar minimum, providing data free from atmospheric-induced background and little influenced by the solar modulation. Using these data, we present a measurement of the ratio Li/C, Be/C and B/C.

2. Instrument

The AMS-01 precursion mission of the Alpha Magnetic Spectrometer (AMS) project [3] operated successfully during the 10-day flight STS-91 onboard Discovery.

The AMS-01 spectrometer was composed of a cylindrical permanent magnet (analyzing power $BL^2 = 0.14$ Tm$^2$), a silicon microstrip tracker (six layers of double sided silicon sensors with resolution of 10 $\mu$m in the bending coordinate), four time of flight (TOF) scintillator planes (time resolution of $\sim 90$ psec for $Z > 1$ ions) an aerogel Cerenkov counter (threshold velocity $\beta=0.985$) and anti-coincidence counters [4].

The detector response was simulated with GEANT3 [5]. The effects of energy loss, multiple scattering, nuclear interactions and decays were included in the code, as well as efficiencies, resolutions and reconstruction algorithms. Further simulations have been performed using GEANT4 [6] and FLUKA [7] within the framework of the Virtual MC tool-kit [8].

3. Data Analysis

The identification of a cosmic-ray particle with the AMS-01 spectrometer was performed through the combination of independent measurements provided by the various sub-detectors. The particle rigidity $R$ (momentum per unit charge $p/Z$) was provided by the deflection of the reconstructed particle trajectory. The velocity $\beta = v/c$ was measured from the particle transit time between the four TOF planes along the track length. The particle charge magnitude $|Z|$ was obtained by the analysis of the multiple measurement of energy deposition in the four TOF scintillators (up to $Z = 2$ [4]) and the six silicon layers (up to $Z = 8$ [9]). Figure 1 shows the charge histogram of CR particles with $Z > 2$ obtained with the silicon tracker. The particle mass was then determined from the resultant charge $Z$, velocity $\beta$ and rigidity $R$:

The differential energy spectrum of the $Z$-charged particles measured by AMS-01 in the energy bin $E$ of width $\Delta E$ is related to the measured counts $\Delta N^Z$ by:

$$\Phi^Z(E) = \frac{\Delta N^Z(E)}{A^Z(E) \cdot \Delta T^Z(E) \cdot \Delta E}$$
where $\Delta T^Z(E)$ is the effective exposure time and $A^Z(E)$ is the detector acceptance. In order to compute bin-to-bin ratios, all the elemental fluxes were determined in a common grid of kinetic energy per nucleon $E$, obtained by the rigidity measurements performed by the tracker. The relation between the measured energy of detected particles and their true energy were studied using unfolding techniques [10]. Most of systematic uncertainties arising from many steps of the analysis are suppressed in the ratios. Differences in the trigger efficiencies of the two species are present, as expected, from the charge dependence of delta ray production and fragmentation effects in the detector material. This study was performed through extensive simulations employing the transport codes GEANT3, GEANT4 and FLUKA. Uncertainties of 2-10 % were estimated for the trigger efficiency. The spill over from adjacent charges also produces net effects on the measurements, leading to errors of up to 5 %. The MC determination of the acceptance gave a statistical uncertainty of $\sim$1–3 %, increasing with energy.

Fig. 1. Charge spectrum of the selected $Z > 2$ data. The velocity-dependent signal amplitudes of are equalized to $\beta \equiv 1$ and shown in units of charge. Different nuclear species fall in distinct charge peaks of widths 0.1–0.16 charge units.
4. Results and Discussions

Figure 2 shows the isotopic ratio $^{7}\text{Li}/^{6}\text{Li}$ as a function of the rigidity. Ongoing measurements of other isotopic fractions of H, He, Li, Be and B will be discussed during the conference. Results for the Li/C, Be/C and B/C ratios are presented in Figure 3 with the existing experimental data [11–16]. The error bars in the figure represent the sum in quadrature of statistical errors with the systematic uncertainties.

Our B/C ratio measurement agrees well with the results from the first flight of CREAM in 2004 [15] and with the data collected by HEAO-3-C2 [14] from October 1979 and June 1980. The Be/C ratio is consistent, within errors, with the HEAO data, but not with balloon data [12]. Our Li/C data have unprecedented accuracy in a poorly explored energy region. In comparison with balloon data from Ref. [12], our data indicate a quite different trend in the high energy part of the Li/C ratio. In these ratios,
the main progenitors of boron nuclei are primary cosmic rays (CNO). On the contrary, the abundances of Li and Be depend also on secondary progenitors Be and B through tertiary contributions like B→Be, Be→Li and B→Li. However, the observed shapes of the measured ratios Li/C and Be/C suggest their suitability in constraining the propagation parameters: their decreasing behaviour with increasing energy is a direct consequence of the magnetic diffusion experienced by their progenitors, while the characteristic peak around ~1 GeV/n is a strong indicator of low energy phenomena like stochastic reacceleration or convective transport with the galactic wind.

To describe our results, we make use GALPROP\textsuperscript{a}, a numerical code that incorporates all the astrophysical inputs of the CR galactic transport. In thus proceeding, we use the latest version GALPROP~v54 through the web-based interface WebRun [22]. We describe the propagation in the framework of the diffusive-reacceleration model, that has been very successful in the description of the cosmic ray nuclei fluxes.

\textsuperscript{a}http://galprop.stanford.edu
Our results for the B/C ratio, the Li/C ratio and the $^7\text{Li}/^6\text{Li}$ isotopic ratio of Figure 2 are described quite well within the uncertainties. It is difficult, however, to accommodate the Li and B description with the Be/C ratio by only means of astrophysical parameters. Beryllium appears to be overproduced in the model by a factor $\sim 10^{-15}\%$. This discrepancy is also apparent in the previous measurements. It should be noted that spallation processes of light nuclei over interstellar medium are not well understood quantitatively. The lack of cross section measurements limits the model predictions to uncertainties of $\sim 10^{-20}\%$ in the Li/C and Be/C ratios [2].

Cosmic rays are expected to be measured with high precision in the near future. Understanding fragmentation is a key factor in establishing final conclusions concerning cosmic ray propagation.

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