H, He, Li, and Be Isotopes in the PAMELA Experiment

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Abstract—The results from measuring the isotope composition of nuclei from hydrogen to beryllium in Galactic cosmic rays are presented. Data is gathered near the minimum of solar activity in the years 2006–2008 in the orbital experiment by analyzing in the multilayer calorimeter of the PAMELA magnetic spectrometer the ionization losses of nuclei with a rigidity known from trajectory measurements passing through the unit without nuclear interactions. The measurement results are compared to the available experimental and theoretical data.

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INTRODUCTION

Knowledge of the energy dependence of the isotopic composition of nuclei of Galactic cosmic rays (GCRs) provides information for studying the processes and distribution parameters of GCRs in the Galaxy. The experimental situation with measurements of H and He isotopes in GCRs in different phases of solar activity is now represented by a number of data in the energy range up to ~2 GeV/nucleon [1, 2] with a wide statistical and methodological spread and individual measurements at higher energies [3], obtained mostly in stratospheric experiments and AMS-01 cosmic magnetic spectrometer [4]. The calculated data, which are generally consistent with the experimental data, also have significant variations [5–7] due to the inaccuracy in our knowledge of processes, distribution parameters of GCR, and cross sections of nuclear reactions.

The ACE ratio of $^7\text{Li}/^6\text{Li}$ was measured at energies of up to ~0.1–0.2 GeV/nucleon for isotopes of Li nuclei in Voyager cosmic experiments, and individual data were obtained at energies of up to ~2 GeV/nucleon in the stratosphere, particularly in the ISOMAX98 experiment [8], along with the AMS-01 data in 2010–2011 [9, 10]. The isotopic composition of Be nuclei in GCRs was measured with an accuracy of ~10% for the ratio of $^9\text{Be}/^8\text{Be}$ and $^{10}\text{Be}/^9\text{Be}$ in the experiments of Voyager, Ulysses, ACE, at energies of up to ~0.1–0.2 GeV/nucleon and the individual measurements of ISOMAX98 and AMS-01 were performed with a wide spread at energies of up to ~1–2 GeV/nucleon.

Orbital measurements with the PAMELA magnetic spectrometer allow us to improve the statistical and methodological precision of measurements of the isotopic composition of H and He nuclei in GCRs, to study the solar modulation of the isotope ratios for the flight time of the unit, the generation of isotopes during solar flares, and to perform more accurate measurements of the isotopic composition of Li and Be nuclei in the virtually unexplored energy range up to ~1 GeV/nucleon. An additional advantage of the new measurements over the stratospheric experiments is there is no need to correct the measurement results for the contribution from the residual atmosphere.

METHOD OF ANALYSIS

The isotopes of H and He nuclei in the range of rigidity values of ~1.0–2.5 GV in the PAMELA international cosmic experiment [11] are selected by using the data from trajectory measurements in the field of the unit’s magnet that yield the rigidity of nuclei, and analyzing the time of flight (TOF) of nuclei from the time they enter the unit until they exit the spectrometer magnet. The registration limits on rigidity are associated with ionization losses of nuclei with rigidity known from trajectory measurements passing through the unit without nuclear interactions. The measurement results are compared to the available experimental and theoretical data.

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detectors is registered for each event described by Landaub distribution, and of the 44 resulting signals, half are chosen in the range of low energy losses, allowing us to increase the accuracy of measuring ionization losses and improve the efficiency of the separation of isotopes with different rates at equal rigidity due to differences in mass and different ionization losses, respectively [12].

Fig. 1. (a) Experimental data for the ratio $^{2}\text{H}/^{1}\text{H}$: (■) Pamela calorimeter; (◇) AMS-01, 1998, 600 MV [4]; (◇) BESS97, 1997, 490 MV [1]; (●) BESS98, 1998, 600 MV [2]; (◇) TOF PAMELA; (◇) PTI, 1975, ~500 MV [16]. Calculations, solar minimum (500 MV): dotted-and-dashed line, Seo E.S. et al. (1994) [5]; dotted line, Seo E.S., Pushkin V.S. (1994) [6]; solid line, Wang J.Z. et al., (2002) [1]. (b) Experimental data for the ratio $^{3}\text{He}/^{4}\text{He}$: (■) Pamela calorimeter; (◇) AMS-01, 1998, 600 MV [4]; (◇) BESS97, 1997, 490 MV [1]; (◇) TOF PAMELA. Calculations, solar minimum (500 MV): dotted-and-dashed line, Seo E.S. et al. (1994) [5]; solid line, Moskalenko I.V. et al. (2003) GCR [7]; dotted line, Moskalenko I.V. et al. (2003) local sources [7]. (c) Experimental data on the ratio of $^{2}\text{H}/^{4}\text{He}$: (■) Pamela calorimeter; (●) IMP-8, 400 MV [17]; (◇) AMS-01, 1998, 600 MV [10]; (◇) BESS97, 1997, 490 MV [1]; (◇) NH balloon; (◇) IMAX92 balloon. Calculations, solar minimum (500 MV): dotted line, Coste B. et al., (2012) [17]; solid line, Strong A.W. et al. (1998) GCR [18]; dotted-and-dashed line, Strong A.W. et al. (1998) local sources [18].

A necessary condition for the separation of isotopes in the above method is the selection of the nuclei that enter the aperture of the unit without nuclear interactions in the material of the magnetic spectrometer until they exit the calorimeter. These events do not have to produce signals in the top and side shields of the scintillation detectors, which protect them against nuclear interactions in the unit’s material until they enter the calorimeter, and signals in the silicon detectors at the entrance and exit of the calorimeter must remain without appreciable changes for the analyzed event, which protects against nuclear interactions in the calorimeter. An additional condition for selecting nuclear interactions is the number of tripped strips and the absence of a signal in the neutron detector of the unit. The good statistics on events for H and He nuclei from July to the end of 2006 allowed the use of all these methods of selection. Due to the limited statistics on Li and Be nuclei, in analyzing them we must limit ourselves to using only some protective measures against nuclear interactions.

**MEASUREMENT RESULTS**

The dependence of the ratio of isotopes of H nuclei on rigidity was analyzed from July 7 to October 31, 2006. In the 1.1–3.5 GV range of rigidities of H nuclei measured by stripped detectors in the magnet gap, 52377 events were selected that occurred in the aperture of the unit without nuclear interactions. The iso-
topic composition of H nuclei in the 1.7–3.9 GV range of rigidities was similarly analyzed from July 7 to December 31, 2006, for 69,562 events. The spectra of limited ionization losses in the silicon strip detectors of the calorimeter were constructed in the studied range of rigidities with a step of 0.2 GV, and normalized to a single layer for the vertical cross section of the calorimeter with allowance for the trajectories of detected nuclei. The experimental spectra of energy release were compared to the results from GEANT4 simulation of the registration of nuclei using a detailed computer model of the unit, which can also adjust the data for the nuclei entering it.

Using the PAMELA data on the rigidity of H and He spectra [14, 15], the measured $^2\text{H}/^1\text{H}$ and $^4\text{He}/^4\text{He}$ ratios allowed us to obtain spectra depending on the rigidity, the energy of isotopes, and the dependence of the ratio of isotopes on energy, respectively. The results from measurements of the $^2\text{H}/^1\text{H}$, $^4\text{He}/^4\text{He}$ and $^2\text{H}/^4\text{He}$ ratios depending on energy and compared to the characteristic calculations [5–7, 17] for the minimum of solar activity (parameter of solar modulation, ~500 MV) are presented in Fig. 1.

The ratios of $^7\text{Li}/^6\text{Li}$, $^7\text{Be}/^9\text{Be}$ and $^{10}\text{Be}/^{9}\text{Be}$ are now being analyzed for the flight of the unit in 2006–2008. The total number of events for Li nuclei in the range of rigidity values of 1.7–4.1 GV was 1392; for Be nuclei with rigidity values of 2.3–4.3 GV, the number was 696. The $^7\text{Li}/^6\text{Li}$, $^7\text{Be}/^{9}\text{Be}$ and $^{10}\text{Be}/^{9}\text{Be}$ ratios obtained depending on the rigidity of nuclei have been converted to the ratios that depend on the energy of isotopes and are compared with the calculations of [7] in Fig. 2.

CONCLUSIONS

The preliminary data obtained in the PAMELA experiment from analyzing the isotope composition of nuclei from hydrogen to beryllium in GCRs allow us to refine the distribution parameters of GCR in the Galaxy further.

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