ISSN 1062-8738, Bulletin of the Russian Academy of Sciences. Physics, 2015, Vol. 79, No. 3, pp. 302–305. © Allerton Press, Inc., 2015.
Original Russian Text © E.A. Bogomolov, G.I. Vasilyev, S.Yu. Krut'kov, W. Menn, N.N. Nikonov, V. Formato on behalf of the PAMELA Collaboration, 2015, published in Izvestiya Rossiiskoi Akademii Nauk. Seriya Fizicheskaya, 2015, Vol. 79, No. 3, pp. 334–337.

H, He, Li, and Be Isotopes in the PAMELA Space Experiment, According to the Flight Data of 2006–2008

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Abstract—The results from measurements of the isotopic composition of nuclei from hydrogen to beryllium in galactic cosmic rays observed in the orbital experiment near the solar activity minimum in 2006–2008 by analyzing the loss of nucleus ionization with the rigidity known from measuring the trajectories for particles passed through the device without nuclear interaction in the multilayer calorimeter of the PAMELA magnetic spectrometer are presented. The results from measurements are compared to existing experimental and calculated data.

DOI: 10.3103/S1062873815030120

INTRODUCTION

Knowledge of the energy dependence of the isotopic composition of galactic cosmic rays (GCRs) yields information for investigating the processes and parameters of the GCR propagation in the Galaxy. The experimental situation in measuring H and He isotopes in GCRs during different phases of solar activity can be judged from the set of data in the energy region of up to ~2 GeV/nucleon [1, 2] with a wide statistical and methodological errors and separate measurements in the region of higher energies [3] found mainly in stratospheric experiments and using the AMS-01 cosmic magnetic spectrometer [4]. The calculated data, which generally agree with the experimental data, also have a considerable mistakes [5–7] due to the inaccuracy of our knowledge of the processes and propagation parameters of GCRs and cross sections of nuclear reactions.

The ^{7}Li/^{6}Li ratio for isotopes of Li nuclei was measured in the VOYAGER and ACE cosmic experiments at energies of up to ~0.1–0.2 GeV/nucleon, while other data in the stratosphere have been measured at energies of up to ~2 GeV/nucleon, particularly in the ISOMAX98 [98] and AMS-01 experiments in 2010–2011 [9, 10]. The isotopic composition of Be nuclei in GCRs was measured with an error of ~10% for the ^{7}Be/^{9}Be and ^{10}Be/^{9}Be ratios in the VOYAGER, ULYSSES, and ACE experiments at energies of up to ~0.1–0.2 GeV/nucleon, while the separate ISOMAX98 and AMS-01 measurements were made at energies of up to ~1–2 GeV/nucleon with a large errors.

Orbital measurements using the PAMELA magnetic spectrometer allow us to improve the statistical and methodological accuracy of measuring the isotopic composition of H and He nuclei in GCRs, investigate the solar modulation of the isotope ratio for the flight time of a device and the generation of isotopes during solar flares, and measure the isotopic composition of Li and Be nuclei more exactly in the almost uninvestigated energy region of up to ~1 GeV/nucleon. Compared to stratospheric experiments, an additional advantage of the new measurements is that there is no need to correct the results from measuring the contribution of the residual atmosphere.

METHOD OF ANALYSIS

Isotopes of H and He nuclei in the rigidity range of ~1–4 GV in the PAMELA international space experiment [11] are selected using the data from measuring their trajectories in the field of the device's magnet to determine the rigidity of the nuclei, and by analyzing the time-of-flight (TOF) of the nuclei from their input into the device to the output from the spectrometer magnet. The limits of detection according to rigidity are associated with the loss of nuclei ionization in the device's material to the output from the magnet bore (5 g cm^{-2}) and the device's temporal resolution (~0.2 ns). In separating isotopes of nuclei from hydrogen to beryllium in GCRs at nuclei rigidities of up to ~5 GV when analyzing the data of the PAMELA experiment, the method of analyzing the limited loss of nuclei ionization with the rigidities known from trajectory measurements in the multilayer calorimeter of

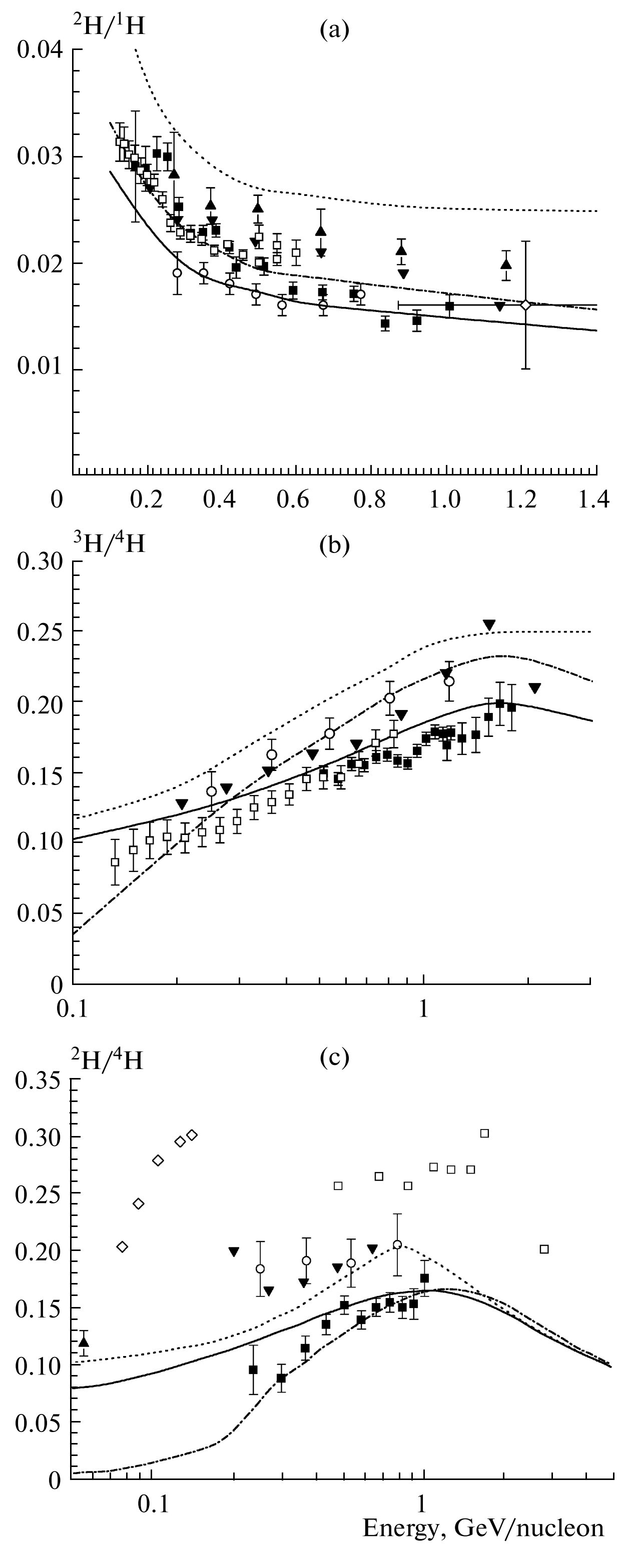

Fig. 1. (a) Experimental data for the $^2H/^1H$ ratio: ■ PAMELA calorimeter; ○ AMS-01, 1998, 600 MV [4]; ▼ BESS97, 1997, 490 MV [1]; ▲ BESS98, 1998, 600 MV [2]; □ TOF PAMELA; ◇ Ioffe Institute, 1975, ~500 MV [16]; calculations, solar minimum (500 MV): dashed line, E.S. Seo et al. (1994) [5]; dashed-and-dotted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

the PAMELA magnetic spectrometer, which consists of 22 tungsten layers and 44 layers of thin (380 μm) silicon strip (step, 2.4 mm) detectors was proposed and used for the first time at the Ioffe Institute. The distribution of the ionization loss in silicon detectors during the flight of nuclei through the calorimeter is detected for each event. This distribution is described well by the Landau distribution, and half of the signals are sampled in the regions of low energy loss before interaction (from ~20 to 44). This allows us to improve the accuracy of measuring ionization losses, and the efficiency of separating isotopes with different velocities as a result of the difference between their masses (and thus different ionization losses with equal rigidity) [12]. A similar truncation method for identifying particles according to mass using precision measurements of the limited ionization loss of particles was successfully used earlier in high-energy accelerators when operating with gas multilayer proportional chambers [13]. Preliminary GEANT4 simulations of ionization loss measurements in the silicon strip detectors of a calorimeter with tungsten layers showed that separating the nuclei of isotopes from hydrogen to beryllium has promise.

A necessary condition for separating the isotopes in this method is the selection of nuclei passing through the device's aperture without nuclear interaction in the magnetic spectrometer's material. Such events should not produce signals the in top and side guard scintillation detectors, which protect against nuclear interaction in the device's material before the particles enter the calorimeter. The signals in the silicon detectors when particles enter the calorimeter and before interaction should display no appreciable variation for an event. A 2D analysis of the distributions of limited ionization losses in a calorimeter depending on the flight time (1/beta) between the scintillation detectors is used to select additional background events of nuclear interaction inside the calorimeter. This virtually eliminates the need to use the modeling data except for transforming the data on the ratios between isotopes and cosmic space, measured inside the device, when selecting isotopes of H and He nuclei. Our analysis of observations of fluxes of ^3H nuclei generated in the device's material before they entered the calorimeter demonstrated the

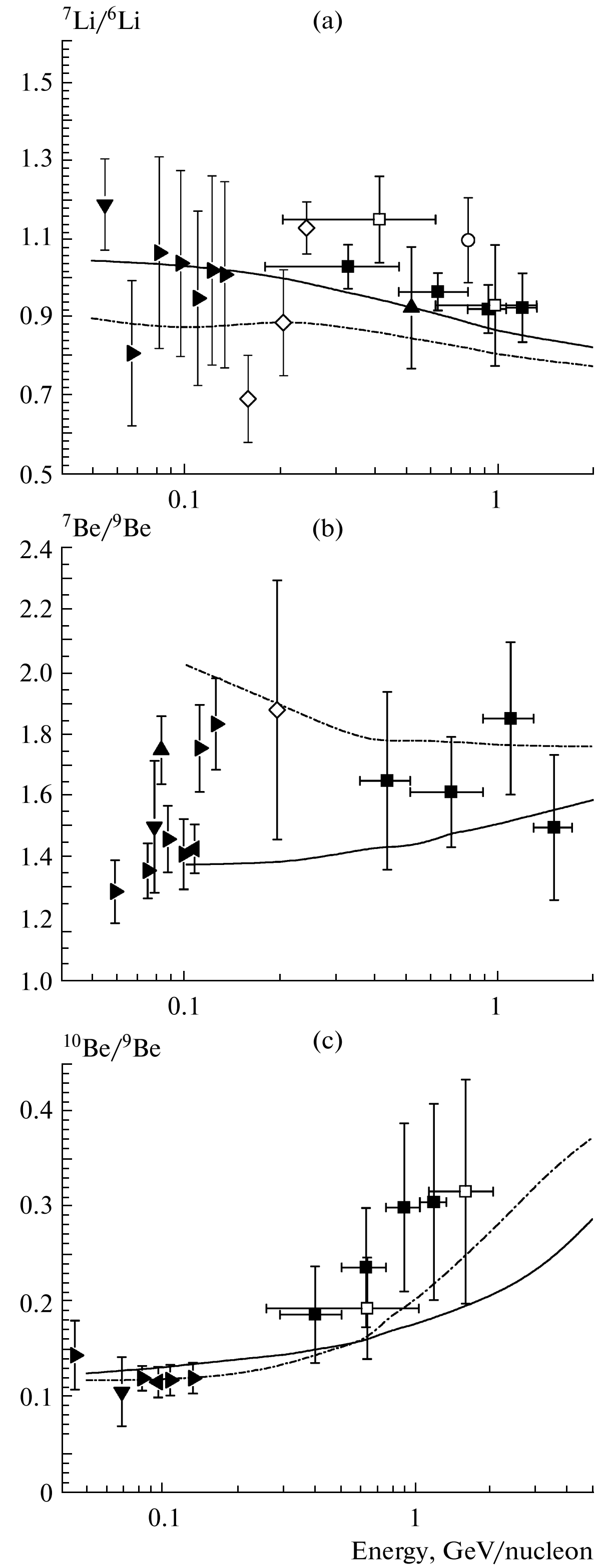

Fig. 2. (a) Experimental data for the ^{7}Li/^{6}Li ratio: ■ PAMELA calorimeter; ► CRIS (ACE); ▼ VOYAGER; ○ AMS-01, 1998, 600 MV [4]; ◇ NH, balloon; ▲ UC, Berkley, balloon; □ ISOMAX98, 1998, balloon [8]; calculations, solar minimum (500 MV): solid line, I.V. Moskalenko et al. (2003) GCR [7]; dashed-and-dotted line, I.V. Moskalenko et al. (2003), local sources [7]. (b) Experimental data for the ^{7}Be/^{9}Be ratio: ■ PAMELA calorimeter; ► CRIS (ACE); ▲ IMP-7,8; ▼ VOYAGER; ◄ ULYSSES; ○ AMS-01, 1998, 600 MV [4]; ◇ NH, balloon; calculations, solar minimum (500 MV): solid line, I.V. Moskalenko et al. (2003) GCR [7]; dashed-and-dotted line, I.V. Moskalenko et al. (2003), local sources [7]. (c) Experimental data for the ^{10}Be/^{9}Be ratio: ■ PAMELA calorimeter; ► CRIS (ACE); ▼ VOYAGER; ◄ ULYSSES; □ ISOMAX98, 1998, balloon [8]; calculations, solar minimum (500 MV): solid line, I.V. Moskalenko et al. (2003) GCR [7]; dashed-and-dotted line, I.V. Moskalenko et al. (2003), local sources [7].

high efficiency of the methods used to shield against the interaction background in the top part of the device and their negligible contribution to the detection of ^{2}H and ^{3}He nuclei. Similar methods were used to analyze Li and Be nuclei.

MEASUREMENT RESULTS

The dependence between rigidity and the isotope ratio of H nuclei has so far been analyzed for the period from July 7, 2006 to December 31, 2007, in the 1.1–3.5 GV range of H nuclei rigidity measured by strip detectors in the magnet gap as particles entered the device's aperture without nuclear interaction. The isotopic composition of He nuclei in the rigidity range of 1.1–3.9 GV has similarly been analyzed for the period from July 7, 2006 to December 31, 2007. The spectra of truncated energy loss in the calorimeter's silicon strip detectors, normalized for each layer and the vertical cross section of the calorimeter using the trajectories of detected nuclei, were constructed in the investigated ranges of rigidity with steps of 0.2 GV. The experimental spectra of energy loss were compared to the results from the GEANT4 simulation of nuclei detection using a detailed computer model of the device that also allowed us to correct the data on the nuclei entering the device.

Ratios ^{2}H/^{1}H and ^{3}He/^{4}He, measured depending on rigidity using the PAMELA data on the rigidity spectra of H and He nuclei [14, 15], allowed us to obtain spectra depending on rigidity and isotope energy, and thus the dependence between the isotope ratio and the energy. The results from measuring ratios ^{2}H/^{1}H, ^{3}He/^{4}He, and ^{2}H/^{4}He depending on energy, compared to the calculations in [5–7, 17, 18] for the minimum of solar activity (a solar modulation parameter of ~500 MV), are presented in Fig. 1.

Ratios ^{7}Li/^{6}Li, ^{7}Be/^{9}Be, and ^{10}Be/^{9}Be are currently being analyzed for the device's flight of 2006–2008. The total number of events for Li nuclei in the rigidity range of 1.1–4.1 GV was 4774, while the number for Be nuclei with rigidities of 1.5–5.1 GV was 2473. Ratios ^{7}Li/^{6}Li, ^{7}Be/^{9}Be, and ^{10}Be/^{9}Be found from nuclei rigidity, transformed in the ratios depending on the isotope energy and compared to the calculations in [7], are presented in Fig. 2.

CONCLUSIONS

The preliminary data from analyzing the isotope composition of nuclei from hydrogen to beryllium in GCRs, obtained in the PAMELA experiment in 2006–2008 and presented in this work, allow us to further refine the parameters of GCR propagation in the Galaxy.

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research, project no. 13-02-00298.

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Translated by N. Korovin