Boron Isotopes in the PAMELA Experiment

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Abstract—Analysis of the isotope composition of nuclei in galactic cosmic rays (GCR) in the PAMELA orbital international experiment allows studying the problems of cosmic-ray origin and propagation in our Galaxy. PAMELA magnetic spectrometer data provided the significant progress in the study of the light nuclei isotope composition of GCR from H to Be in the energy range ~0.1–1 GeV/nucleon. This makes it possible to estimate the contribution of local (~100 pc) young (~10^6 years) interstellar sources (LISS) into GCR fluxes from supernova explosions. The analysis of boron (B) isotope fluxes in the GCR has so far been carried out only in the energy range ~0.08–0.17 GeV/nucleon in the space experiments Voyager, Ulysses, ACE. In the present contribution the attempt was done to determine the 11B/10B ratio in the energy range ~0.1–1.0 GeV/nucleon for the first time on the base of 2006–2014 PAMELA data using the measurements of the detected nuclei rigidities, velocities and ionization losses in a multilayer calorimeter. The new PAMELA results are consistent with existing as experimental data and those expected from simulations. However the statistical and systematic measurement uncertainties do not allow to separate the local boron source contributions into GCR fluxes. The preliminary results of the boron isotope flux analysis in GCR (10B, 11B spectra and 11B/10B ratio dependences on the rigidity and energy) are presented as well as the existing measurement data and simulation results.

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INTRODUCTION

In the frame work of the international space experiment PAMELA when observing positrons with energies above several GeV an excess of positrons in cosmic rays was reliably detected for the first time [1]. It is probably of local nature and associated with the generation of electron–positron pairs in the remnants of young (~10^6 years) and close (~100 pc) supernovae. At the energy of ~100 GeV the effect exceeds the expected intensity of galactic cosmic rays by ~3 times and at ~300 GeV according to the new observations of AMS-02 [2] it increased up to ~10 times. This means that the contribution of local sources into the electron–positron component with an energy more than some tens of GeV is the main one. With regard to the possible contribution of local sources to the nuclear component of GCR it is convenient to use the data of observations of the light nuclei isotope composition in cosmic rays because 2H and 3He isotopes are practically not generated at short distances of ~100 pc, 7Be is preserved as at the short path and it practically does not meet electrons for the K-capture reaction, 10Be isotopes decay a little and 7Li is not produced with 7Be decay... All these effects were probably detected in the isotope analysis of the PAMELA flight data collected in 2006–2014 [3].

The present contribution describes an attempt of analysis of boron isotope fluxes in the GCR. The Li, Be, B isotopes in cosmic rays are mainly of secondary nature and are generated in the nuclear reactions of cosmic-ray protons and alphas with C, N, O nuclei of interstellar matter. Due to the short path from local sources as compared with GCR in the case of the local source contribution into GCR, the isotope fluxes have to decrease generally in comparison with LISS absence.

The experimental situation with 10B and 11B isotopes data in the GCR before the PAMELA experiment was limited by measurements of Voyager, Ulysses, ACE space experiments in the energy range of ~0.08–0.17 GeV/nucleon [4] when dE/dx – E technique was used. Orbital measurements with PAMELA magnetic spectrometer made it possible to
nuclear interactions the 2D analysis of the ionization losses was done for nuclei energy deposition in strip detectors of the tracker and the calorimeter as well as the time of flight between scintillation detectors (more precisely 1/\(\beta\) where \(\beta\) is the ratio of the particle velocity to the velocity of light). For the rigidity of the analyzed events over \(\sim 2\) GV the measurement of nucleus velocities by TOF method does not allow to separate isotopes and the data of ionization losses in calorimeter detectors were used for isotope selection. The calorimeter consists of 22 layers of tungsten (2.6-mm thick) enclosed between strip detector planes (Si, thickness 0.38 mm). For each event in the PAMELA multilayer calorimeter an ionization loss distribution arises (from 1 to 44 amplitudes). Then one half of the smaller amplitudes is selected (truncating method) from the ionization loss distribution (asymmetric Landau distribution) and the resulting one approaches the Gaussian one with the smaller width. The best resolution for isotopes was obtained for nuclei passing through the entire calorimeter without nuclear interactions. Unfortunately, for all events in the instrument aperture nuclei pass only through not more than \(\sim 1.4\) Si layers. The form of the calorimeter is not a truncated pyramid (Fig. 1)\[6\] and some of the nuclei do not pass through the entire calorimeter. This reduces the efficiency of isotope selection. In our analysis the selection of flight data with using 50\% of the smaller energy loss in Si detectors along the trajectories was used for the nuclei that passed through the 11–44 planes of the calorimeter and the 23–44 planes. According to the simulation results when data are selected in planes 23–44 of the calorimeter it was expected increasing of the isotope selection efficiency by \(\sim 1.5\) times with some loss of statistics and an increase in the lower energy limits of the calorimeter data analysis. The aim of this work was to study this effect. To determine the number of \(^{10}\)B and \(^{11}\)B events in the rigidity intervals selected with a step of 0.2 GV measured by PAMELA magnetic spectrometer and different from the rigidities at the entrance into the instrument the TOF analysis was compared with the GEANT4 simulation in the 0.7–2.3 GV range. In the analysis of the simulation data the expected isotope ratios for the given rigidities expected from different versions of the theory [4] were used. Then the simulation data were normalized to the experimental total number of events. In the overlap area of the isotope distributions the boundary of 1/\(\beta\) value (or ionization losses in the case of calorimeter data) was determined where from the simulation data the numbers of events of the analyzed isotopes in the area of overlapping distributions was the same. The number of expected events in the overlap area of the 1/\(\beta\) distributions was additionally included for estimation of the statistical errors

**Fig. 1.** Scheme of the PAMELA instrument.
of the resulting isotope ratios. Examples of analysis of the TOF data and ionization loss distributions in the calorimeter are shown in Figs. 2 and 3. The obtained experimental values of the isotope ratios corrected using the GEANT4 modeling data to the instrument entrance are almost the same for the various theoretical models of GCR propagation in the Galaxy used (GP—GALPROP) or generation of nuclei in local sources (LISS). For verification of the isotope selection results the additional data analysis was car-
ried out using the iterative method. The method of used isotope selection was implemented to obtain the preliminary data on the ratio of isotopes depending on their rigidity. The standard maximum likelihood method gives close final results for the $^{7}\text{Li}/^{6}\text{Li}$ and $^{7}\text{Be}/({}^{9}\text{Be} + {}^{10}\text{Be})$ isotopes but does not yet allow to determine the $^{10}\text{Be}/{}^{9}\text{Be}$ ratio [5] unlike the presented method. When analyzing H and He isotopes with
RESULTS OF MEASUREMENTS

As a result of PAMELA flight data analysis the flux ratios of $^{11}\text{B}/^{10}\text{B}$ were obtained for the first time depending on the rigidity of the nuclei up to $\sim 3.5$ GV. Good event statistics without fluctuation problems both methods gave almost identical results.

GEANT4 simulation data were used for the transition from the instrumental results to outer space. The $^{11}\text{B}/^{10}\text{B}$ ratios depending on the nuclei rigidity using the PAMELA data on the spectrum of boron nuclei [7, 8] were transformed into the rigidity and energy spectra of $^{11}\text{B}$ and $^{10}\text{B}$. After this the obtained rigidity and energy spectra of boron isotopes at the input to
the instrument were transformed into $^{11}$B/$^{10}$B ratios depending on the isotope energy. The comparisons with calculations [4] and existing experimental data are presented in Figs. 4 and 5. The rigidity and energy spectra of $^{10}$B and $^{11}$B nuclei in the GCR in comparison with those expected from the calculations are presented in Figs. 6 and 7.

CONCLUSION

The preliminary results of the analysis of the isotope composition of boron nuclei in cosmic rays in the energy range of $\sim$0.1–1.0 GeV/nucleon are presented for the first time. The data were obtained in the PAMELA experiment during measurements in 2006–2014. They are consistent with the expected results of calculations [4] and measurements with the space experiments Voyager, Ulysses, ACE at energies $\sim$0.1 GeV/nucleon. Because of the statistical uncertainties it is not possible to separate the contribution of local interstellar sources (LISS) of boron isotopes into the GCR.

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