Boron Isotopes in the PAMELA Experiment

E A Bogomolov and G I Vasilyev on behalf of the PAMELA Collaboration

Ioffe Institute, 26 Polytechnicheskaya, St. Petersburg 194021, Russian Federation

E-mail: edward.bogomolov@gmail.com

Abstract. Analysis of the isotopic composition of nuclei in galactic cosmic rays (GCR) in the PAMELA orbital international experiment allows us to study the problems of the origin and propagation of cosmic rays in the Galaxy. Due to the high statistical and methodical accuracy, the PAMELA magnetic spectrometer data provided significant progress in the study of the isotopic composition of the light nuclei from H to Be in the GCR in the energy region of ∼0.1–1 GeV/nucleon and, for the first time, made it possible to estimate the contribution in GCR from local (∼100 pc) recent (∼10^6 years) interstellar sources (LS) from supernova explosions. An isotopic analysis of boron (B) nuclei in the GCR has so far been carried out only in the energy region ∼0.08–0.17 GeV/nucleon in the space experiments Voyager, Ulysses, ACE. In this work using the PAMELA data 2006-2014 about the rigidities of the detected nuclei and their speed (time of flight analysis (TOF) and ionization losses in a multilayer calorimeter) for the first time was made an attempt to determine the ^{11}B/^{10}B ratio in the energy range of ∼0.1–1.0 GeV/nucleon. The new PAMELA data are consistent with existing measurements and those expected from modeling, but the statistical and methodological accuracy of measurements does not allow us to separate the contribution of local boron sources to GCR. The results of the isotope analysis of boron nuclei in the GCR (spectra ^{10}B, ^{11}B and ^{11}B/^{10}B ratio depending on the rigidity and energy of the nuclei) in comparison with the existing measurement data and calculations will be presented.

1. Introduction

In the international space experiment PAMELA a flux of positrons exceeding those expected in a theory was first discovered [1]. This excess at energies above several GeV is probably due to the existence of local sources at a distance of ∼100 pc. Such sources may be recent (∼10^6 years) supernova remnants in which electron-positron pairs are born. At 100 GeV, the excess is 3 times. Measurements in the AMS-2 experiment at 300 GeV showed an excess of 10 times [2]. The contribution of local sources (LS)of the electronic component with energy above tens of GeV becomes the main one. With regard to the possible contribution of local sources to the nuclear component, it is convenient to use in the search for data from observations of the isotopic composition of light nuclei in cosmic rays. Due to a short distance of ∼100 pc, the ^{2}H and ^{3}He isotopes are practically not generated. On the short path ^{7}Be practically does not meet the electrons necessary for the K-capture and is stored. On the short path ^{7}Be does't practically meetis preserved, since on the short path, it practically does not meet electrons for the K-capture reaction and ^{7}Li is not produced. ^{10}Be with a half-life $1.39{\cdot}10^6$ years saved. All these effects were probably detected [3] in the isotopic analysis of the PAMELA flight data collected in 2006–2014. In the present work an attempt is made of isotopic analysis of boron nuclei in the GCR. The generation of isotopes of Li, Be, B nuclei in cosmic rays is mainly of a secondary nature and occurs in the nuclear reactions of protons and alpha particles of cosmic rays on C, N, O nuclei of interstellar matter. Due to the shorter path from local sources as compared to GCR, in the case of the contribution of local sources to GCR, the isotope fluxes should generally decrease in comparison with LS absence.

Before the PAMELA experiment fluxes ^{10}B and ^{11}B isotopes were measured in the Voyager, Ulysses and ACE space experiments in the energy range of $\sim$0.08–0.17 GeV/nucleon [4]. The dE/dx-E technique was used in these measurements. The PAMELA orbital magnetic spectrometer data makes it possible to extend the range of analysis of the B isotopic ratio up to $\sim$1 GeV/nucleon.

2. Isotope analysis method

Selection of nuclei isotopes from hydrogen up to boron in the rigidity range of $\sim$1–5 GV in the PAMELA international space experiment carried out by measuring the trajectory in a magnetic field with strip detectors and on measuring the time of flight (TOF). A method, based on measuring of the ionization losses of nuclei in Si layers of the silicon-tungsten multilayer calorimeterer, giving information on speed of nuclei, is also used for selection of nuclei isotopes [5]. The nuclear charge is determined from the instrument scintillation telescope data. The lower limits of the registration of isotopes by rigidity in TOF analysis are associated with the ionization losses of nuclei in the material of the device before the magnet gap leaves $\sim$5 g/cm^2. The upper limits of isotope selection $\sim$2 GV for TOF analysis are associated with the time resolution of the instrument ($\sim$0.08 ns for nuclei B) and at higher rigidity are determined by the resolution of the distributions of the ionization losses of nuclei isotopes in Si strip detectors PAMELA calorimeter. (Si - 44 layers, thickness 0.38 mm; W - 22 layers, thickness 0.38 mm). In the isotope analysis particle that pass through the device without nuclear interactions, are selected. Additional selection by 2D-analysis of the distributions of the ionization losses of nuclei in strip detectors was used to exclude a slight background due to nuclear interactions in the calorimeter. In events with particle rigidity greater than $\sim$2 GV, the TOF method does not allow the separation of isotopes. In each analyzed event, from 1 to 44 signals appear in the calorimeter (depending on the particle energy). We used a truncating method similar to that used to identify relativistic particles on accelerators. The distribution of ionization losses in silicon layers is not symmetric (Landau distribution) and has a large half-width. After ranging of signals on amplitude and uses of a half of signals with minimum amplitudes distribution becomes more narrow and approaches Gaussian. The best resolution of isotopes is obtained under the condition of selecting events in which particles pass without nuclear through the entire calorimeter. There are relatively few such events. Therefore, to improve the statistical confidence, events are used in which particles pass through top half part of the calorimeter with the 22 Si layers without nuclear interactions. To improve event statistics and reduce the lower energy limit of the calorimeter data analysis, in this work, we used data selection with analysis of 50 % of the minimum energy loss in Si detectors along the nuclear trajectories in the calorimeter (qtrack selection). With this selection the separation efficiency of isotopes is somewhat reduced. The number of events in the passage of each isotope with the rigidity measured in the magnet gap was determined. The range 0.7–2.3 GV was divided into intervals in increments of 0.2 GV for the TOF analysis. Results were compared with the GEANT4 simulation. In the analysis of model data, the expected isotope ratios from various versions of the theory [4] were used. For each interval the modeling data were normalized to the experimental total number of events. In a separate interval of rigidity the energy distributions of isotopes overlap. In the area of overlap of the isotope distributions, the limit of $1/\beta$ (or ionization losses in the case of analyzing calorimeter data) was determined (where from the simulation data the number of events of the analyzed isotopes in the region of overlapping distributions was the same). The number of expected events in the overlap region of

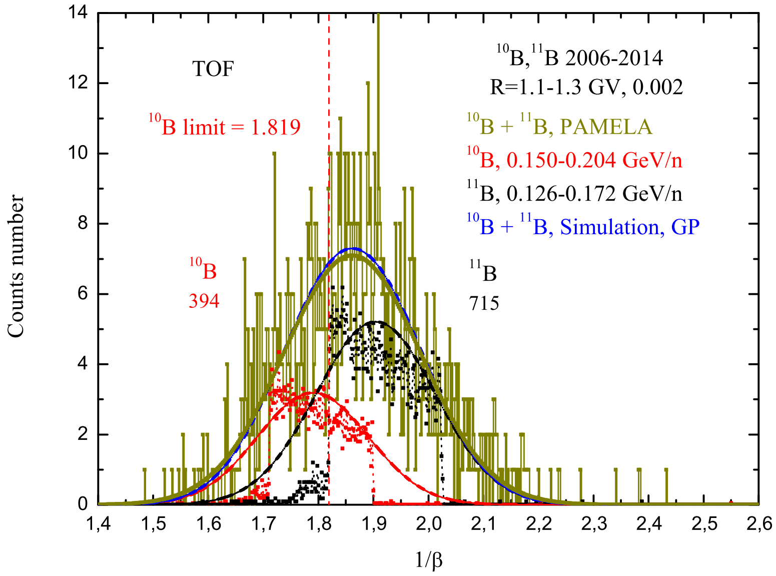

Figure 1. Analysis example of $1/\beta$ distribution of the TOF for boron.

the $1/\beta1$ distributions was additionally included in the statistical errors of the resulting isotope ratios. Examples of analysis of the TOF data and ionization loss distributions in the calorimeter are shown in Fig. 1, 2.

The obtained experimental values of the isotope ratios, corrected using 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 CR sources (LS). To control the results of the isotope selection carried out, additional data analysis was carried out using the iteration method. The method of isotope selection was used to obtain preliminary data on the ratio of isotopes, depending on their rigidity. Using the standard maximum likelihood method gives close final results for the ^{7}Li/^{6}Li and ^{7}Be/(^{9}Be+^{10}Be) isotopes, but does not yet allow us to determine the ^{10}Be/^{9}Be ratio [5], unlike our method. When analyzing H and He isotopes with good event statistics without fluctuation problems, both methods gave almost identical results.

3. Measurement result

As a result of analyzing the PAMELA flight data, the ratios of ^{11}B/^{10}B were obtained for the first time, depending on the rigidity of the nuclei up to $\sim$3.5 GV. GEANT4 simulation data was used during the transition from instrumental results to outer space. The ^{11}B/^{10}B ratios depending on the nuclei rigidity using the PAMELA data on the spectrum of boron nuclei [6] were transformed in the rigidity and energy spectra of ^{11}B and ^{10}B and after it obtaining the rigidity and energy spectra of boron isotopes at the input to the instrument were transformed in ^{11}B/^{10}B ratios depending from the isotopes energy. Comparison with calculations [4] and existing limited experimental data is presented in Fig. 3, 4.

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 Fig. 5, 6.

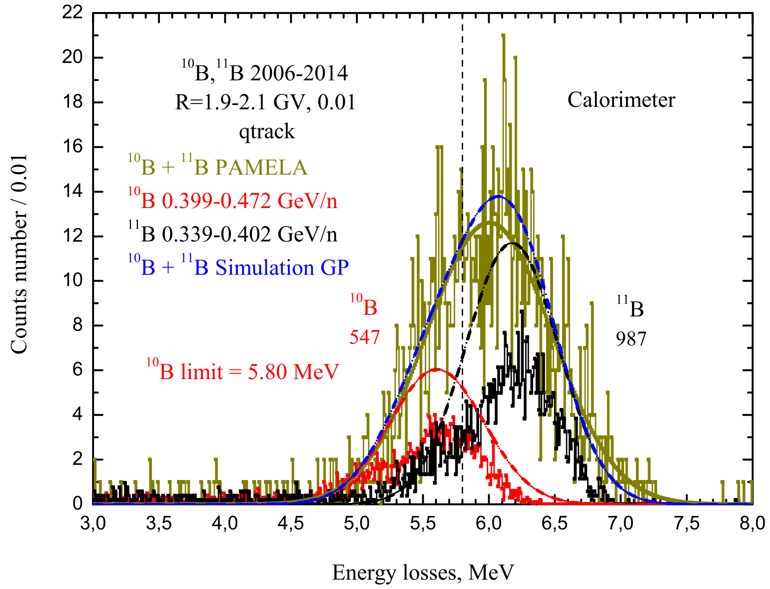

Figure 2. Analysis example of truncated mean dE/dx of the calorimeter for boron.

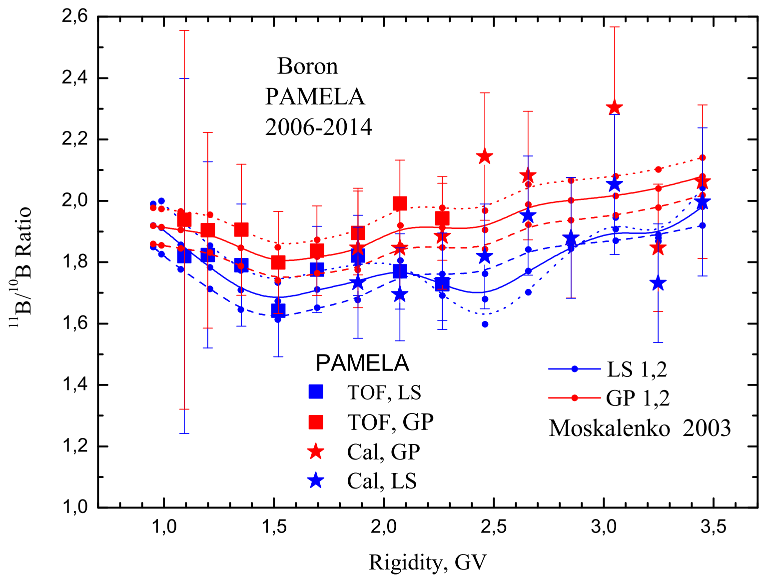

Figure 3. $^{11}B/^{10}B$ ratio depending on rigidity from the TOF (squares) and the calorimeter (stars) data at top of payload.

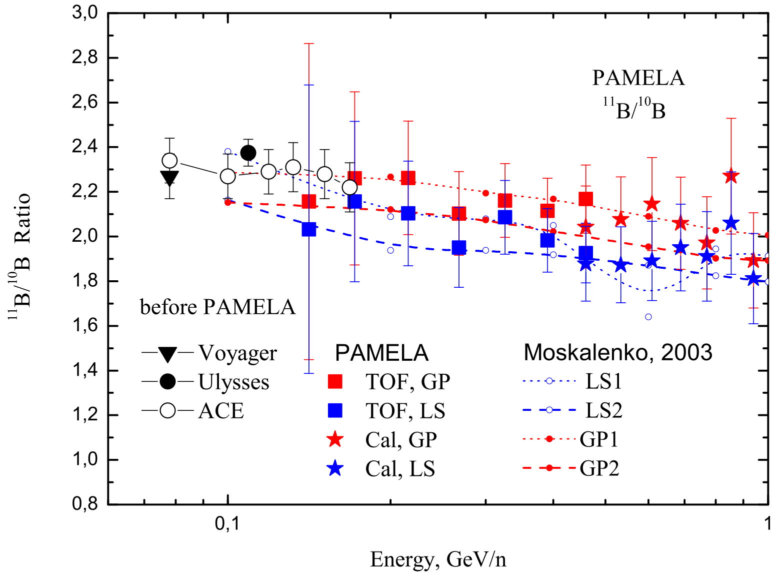

Figure 4. $^{11}B/^{10}B$ ratio depending on energy from the TOF (squares) and the calorimeter (stars) data at top of payload in comparison with Voyager, Ulysses and ACE measurements.

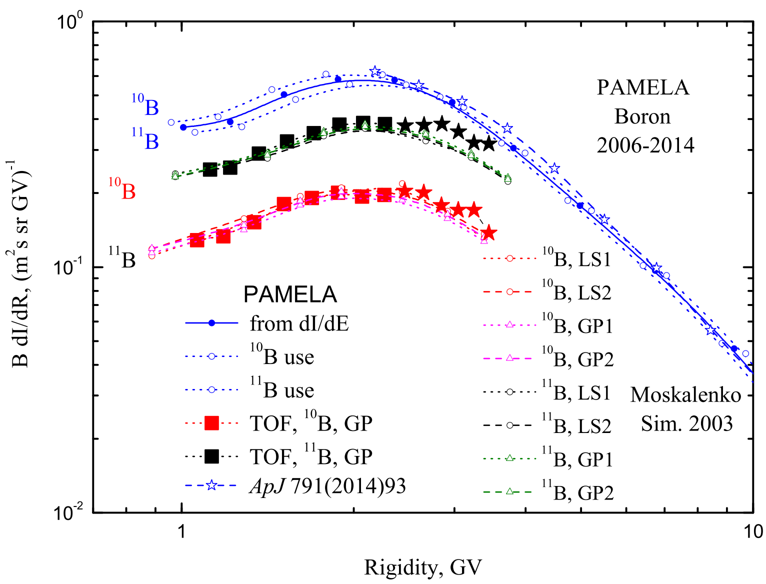

Figure 5. ^{11}B and ^{10}B rigidity spectra at top of payload

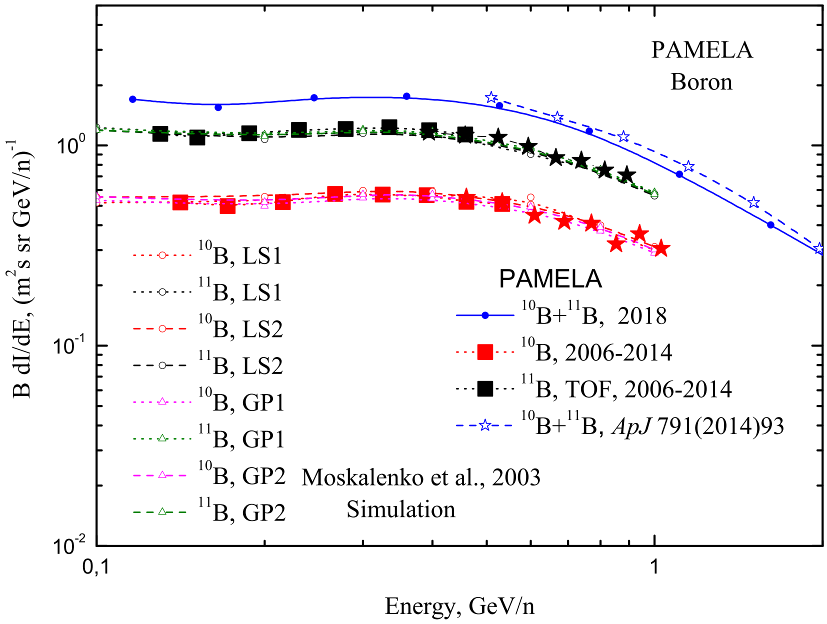

Figure 6. ^{11}B and ^{10}B energy spectra at top of payload

4. Conclusion

Presented for the first time in this work, preliminary data on the analysis of the isotopic composition of boron nuclei in cosmic rays in the energy region of ∼0.1–.0 GeV/nucleon, obtained in the PAMELA experiment during measurements in 2006–2014, are consistent with the expected results of calculations [4] and measurements on the spacecraft Voyager, Ulysses, ACE at energies ∼0.1 GeV/nucleon. Due to the statistical accuracy of the measurements, it is not possible to isolate the contribution of local interstellar sources (LS) of boron isotopes in the GCR. The co-authors of the work are naturally the members of the PAMELA collaboration [5], who obtained the initial flight information used in this analysis.

References

[1] Adriani O et al. An anomalous positron abundance in cosmic rays with energies 1.5-100GeV 2009 *Nature* **458** 607

[2] Aguliar M et al. First Result from the Alpha Magnetic Spectrometer on the International Space Station: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-350 GeV 2013 *Phys. Rev. Lett.* **110** 141102

[3] Bogomolov E A and Vasilyev G I Li and Be Isotopes in the PAMELA Experiment 2019 *Bull. Russ. Acad. Sci.: Phys.* **83** 967

[4] Moskalenko I V, Strong A W, Mashnik S G and Frank C J Propagation of Light Elements in the Galaxy 2003 *astro - ph/0306349*

[5] Menn W et al. Lithium and Beryllium Isotopes with the PAMELA Experiment 2018 *ApJ* **862** 141

[6] Adriani O et al. Measurement of Boron and Carbon Fluxes in Cosmic Rays with the PAMELA Experiment 2014 *ApJ* **791** 93