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Carbon Isotopes in the PAMELA Experiment

E A Bogomolov¹, G I Vasilyev¹ and W Menn² on behalf of the PAMELA Collaboration

¹ Ioffe Institute, 26 Polytechnicheskaya, St. Petersburg 194021, Russian Federation

² University Siegen, FB Physic, Walter-Flex-Str. 3, Siegen 57068, Germany

E-mail: edward.bogomolov@gmail.com

Abstract. An analysis of the isotopic composition of nuclei in galactic cosmic rays (GCR) in the orbital experiment of the PAMELA collaboration allows us to study the problems of the origin and propagation of cosmic rays in the Galaxy. Due to the high statistical and methodological accuracy, the data of the PAMELA magnetic spectrometer provided significant progress in studying the isotopic composition of 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 of local sources from close ones to the GCR (~ 100 pc) of recent ($\sim 10^6$ yrs) supernova explosions. To date, the isotopic composition of carbon nuclei in the GCR has been measured only for the $^{13}\text{C} / ^{12}\text{C}$ ratio in the energy region ~ 0.05 -0.13 GeV / nucleon in the VOYAGER 1.2 space experiment and the upper limit for the $^{14}\text{C} / ^{12}\text{C}$ ratio was estimated in the ACE / CRIS experiment for energies 0.12-0.43 MeV / nucleon. In this work, using PAMELA flight data 2006-2014, on the rigidity of the detected nuclei and their speed (time-of-flight analysis and ionization losses in the multilayer calorimeter of the device), an attempt was made to determine the isotopic composition of carbon nuclei in the energy region of ~ 0.1 -1 GeV / nucleon. The half-life of ^{14}C nuclei is 5730 years and can be detected in the case of a supernova explosion in the last $\sim 5 \cdot 10^4$ years at a distance of ~ 100 200 pc. The results of isotope analysis of carbon nuclei in GCR (spectra ^{12}C , ^{13}C , ^{14}C and $^{14}\text{C} / ^{12}\text{C}$ - ratio depending on the rigidity and energy of the nuclei) in comparison with the existing measurement data will be presented.

1. Introduction

In the international space experiment PAMELA, in the study of primary cosmic radiation, sources of high-energy positrons associated with the generation of electron-positron pairs in the remnants of recent ($\sim 10^6$ yrs) close (~ 100 pc) supernova explosions were first discovered [1]. Positron data were confirmed in orbital observations of the AMS-02 collaboration [2]. When analyzing the isotopic composition of light nuclei from hydrogen to beryllium, probable evidence was also first obtained for detecting the contribution of local sources of light nuclei in galactic cosmic rays [3]. PAMELA data statistics collected by boron isotopes ^{10}B and ^{11}B prevented reliably distinguish the contribution of local sources [4]. Relatively high intensity of carbon nuclei in cosmic rays and the half-life of 5730 yrs, an unstable isotope ^{14}C allows, according to estimates, to conduct a search for local sources of carbon nuclei from supernovae explosions close over the past $\sim 5 \cdot 10^4$ yrs at distances up to ~ 100 -200 pc. The data on the isotopic composition of carbon nuclei in cosmic rays are currently limited by observations of $^{13}\text{C} / ^{12}\text{C} = 6.29 \pm 0.33\%$ on VOYAGER 1, 2 probes in 1976-1994. at energies of 48–126 MeV / nucleon [5] and the upper limit for $^{14}\text{C} / ^{12}\text{C} + ^{13}\text{C}$ at $2.3 \cdot 10^{-4}$ at energies of 120–430 MeV / nucleon measured in the ACE / CRIS space experiment in 1997 1999. [6]. According to the



calculations, the expected $^{13}\text{C} / ^{12}\text{C}$ ratio during propagation in the Galaxy is $\sim 8\%$, and in stars $\sim 1\%$ [7]. At times characteristic of the propagation of cosmic rays in the Galaxy ($\sim 10^6$ yrs) the ^{14}C nuclei completely decay and their detection indicates a local origin. An analysis of PAMELA data on the registration of carbon nuclei in cosmic rays was undertaken with the aim of searching for ^{14}C nuclei and expanding the energy range of observations of the $^{14}\text{C} / ^{12}\text{C}$ ratio to ~ 1 GeV / nucleon.

2. Method of analysis

The selection of carbon nucleus isotopes in the rigidity range of ~ 1 -5 GV in the international space experiment PAMELA is carried out using trajectory measurements in the tracker from strip detectors in the magnet field of the device, giving the rigidities of the nuclei, analysis of the time of flight (TOF) of the nuclei from their entrance to the device exit from the spectrometer magnet and measurements of ionization loss of nuclei in the PAMELA calorimeter [8]. The nuclear charge is determined from the scintillation telescope data of the device. The lower limits of rigidities isotope registration in TOF analysis are associated with ionization losses of nuclei in the material of the device before the magnet leaves the gap (~ 5 g / cm^2). The upper limits of isotope selection (~ 2 GV) in TOF analysis are related to the time resolution of the device (~ 0.08 ns for C nuclei), and at higher rigidities they are determined by the resolution of the distribution of ionization losses of nuclear isotopes in strip calorimeter detectors. During isotope analysis in the PAMELA experiment, events that passed through the device without nuclear interactions are selected. For additional selection of the insignificant contribution of background events from nuclear interactions, we used a 2D- analysis of the distribution of ionization losses of nuclei in the strip detectors of the tracker and PAMELA calorimeter depending on the time of flight (more precisely, from $1 / \beta$ - the ratio of the speed of light to the speed of the nucleus) between scintillation detectors. For rigidities of the analyzed events above ~ 2 GV, the TOF measurement of nuclear velocities does not allow separation of isotopes and to select isotopes are used ionization data of nuclei losses in Si strip detectors of the calorimeter consisting of 22 layers of tungsten (thickness 2.63 mm) enclosed between the planes of strip detectors (Si, thickness 0.38 mm). For each event in the PAMELA multilayer calorimeter, a distribution of ionization losses occurs (from 1 to 44 signals). By analogy with the analysis of data from identifiers of relativistic particles from gas proportional chambers at high-energy accelerators, to improve the resolution of isotopes from the total distribution of ionization losses (asymmetric Landau distribution), half of the minimum signals (clipping method) are selected and the signal distribution approaches the Gaussian distribution with a better half-width. The best resolution of isotopes is obtained by selecting events that have passed (without nuclear interactions) through the entire calorimeter, but to preserve statistics, the criterion for passing (without nuclear interactions) the upper half of the calorimeter and analyzing the distribution of ionization losses from 20 layers of strip detectors is used. To increase the statistics of events and lower the lower energy limit of the analysis of the calorimeter data, we used data sampling with analysis of 50% of the minimum energy loss in Si detectors along the nuclear paths in the calorimeter (qtrack selection). With this selection of calorimeter data, some decrease in the efficiency of isotope selection is possible.

To determine the number of events ^{12}C , ^{13}C , and ^{14}C in the rigidities intervals selected with a step of 0.2 GV, measured in the gap of the PAMELA magnet and differing from the rigidities at the entrance to the device, the TOF analysis in the range of 0.7–2.3 GV compared the experimental $1 / \beta$ distributions with the results GEANT4 simulation. Currently, the GEANT4 software package allows, unfortunately, to simulate only electromagnetic interactions of carbon nucleus isotopes at the intersection of PAMELA material. Due to the insufficient resolution of the ^{12}C and ^{13}C isotopes, the ratio $^{13}\text{C} / ^{12}\text{C} = 0.06$ was used, which is consistent with the observations of VOYAGER 1, 2 and does not contradict the calculated data, and to estimate the ratio $^{14}\text{C} / ^{12}\text{C}$, the differences in the distributions of experimental data and the results of modeling the sum of the distributions of ^{12}C and ^{13}C . A similar procedure was used to analyze the calorimeter data in the range of measured core rigidities of 1.7–3.5 GV. The preliminary results obtained at a level of $^{14}\text{C} / ^{12}\text{C} \sim 0.02$ led to the conclusion that the Gaussian model distributions used for ^{12}C and ^{13}C nuclei do not sufficiently take into account the effects of nuclear scattering in the PAMELA material. To solve the problem of

estimating the $^{12}\text{C} + ^{13}\text{C}$ background during the search for ^{14}C nuclei, the experimental distributions of $^{10}\text{B} + ^{11}\text{B}$ nuclei were used with the necessary modification to analyze the TOF and calorimeter data. The use of the analysis of mass distributions of isotopes, which use data on the stiffness of the nucleus and its speed to determine masses, made it possible to slightly reduce the statistical measurement errors in comparison with the analysis of time-of-flight distributions. As a result of applying the new approach, the background of nuclear scattering completely excluded events with ^{14}C nuclei and the upper limits for the $^{14}\text{C} / ^{12}\text{C}$ ratios were determined by the statistics of ^{12}C nuclei and statistical errors of the analysis method used. Mass analysis data and calorimeter data analysis are in good agreement.

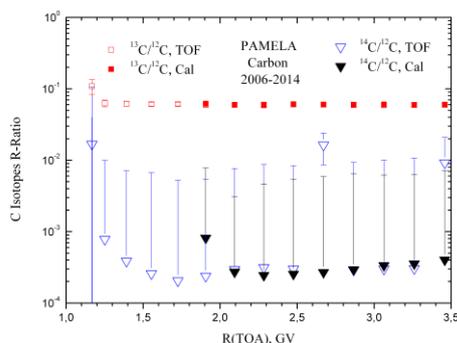


Figure 1. $^{13}\text{C}/^{12}\text{C}$ and $^{14}\text{C}/^{12}\text{C}$ ratio depending on rigidity from the TOF and the calorimeter data at top of payload.

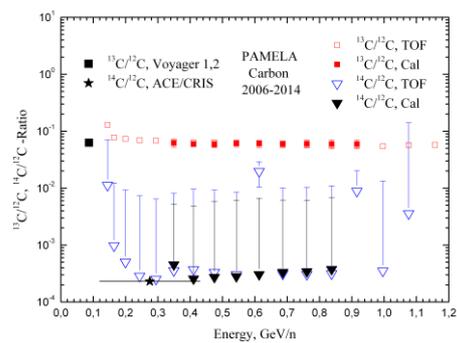


Figure 2. $^{13}\text{C}/^{12}\text{C}$ and $^{14}\text{C}/^{12}\text{C}$ ratio depending on energy from the TOF and the calorimeter data at top of payload in comparison with VOYAGER 1, 2 and ACE/CRIS measurements.

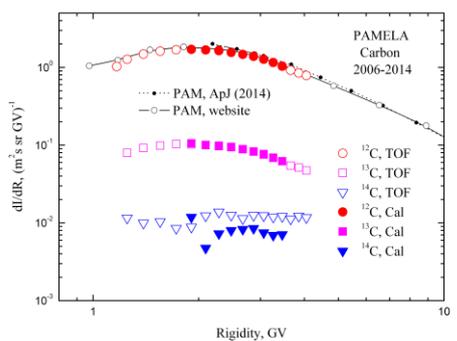


Figure 3. C, ^{12}C , ^{13}C and ^{14}C (upper limits) rigidity spectra at top of payload.

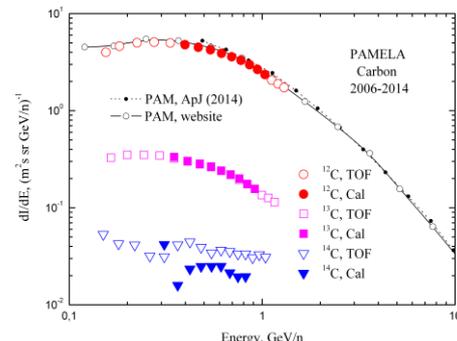


Figure 4. C, ^{12}C , ^{13}C and ^{14}C (upper limits) energy spectra at top of payload.

3. Measurement results

As a result of the analysis of PAMELA flight data, only the upper limits were obtained for the $^{14}\text{C} / ^{12}\text{C}$ ratio, depending on the stiffness of the nuclei up to ~ 4 GV. In the transition from instrument results to outer space, the data of GEANT4 modeling were used. Estimates of $^{13}\text{C} / ^{12}\text{C}$ ratios and upper limits of $^{14}\text{C} / ^{12}\text{C}$ obtained depending on the rigidities of the nuclei in the GCR using PAMELA data on the spectrum of carbon nuclei [9] are converted after obtaining the rigidities and energy spectra of carbon isotopes at the input to the device, depending on the isotope energy. Comparison with existing limited experimental data [5, 6] is presented in Fig. 1-2. Estimates of the stiffness and energy spectra of ^{12}C , ^{13}C , and ^{14}C nuclei in the GCR are presented in Fig. 3-4.

4. Conclusion

The preliminary data presented in this work for the analysis of the isotopic composition of carbon nuclei in cosmic rays in the energy range of ~ 0.1 -1.0 GeV / nucleon, obtained in the PAMELA experiment during measurements in 2006-2014, are consistent with the measurement data on Voyager 1, 2 spacecraft and ACE / CRIS, expand the energy range of measurements and methodological errors of the PAMELA by ~ 3 times less. Estimating the ratios of ^{14}C isotopes with a half-life of 5730 years (taking into account the Lorentz-factor in the PAMELA measurement range of ~ 6500 -12100 yrs) and stable ^{13}C isotopes of less than ~ 0.01 , taking into account the process of nuclear diffusion from a possible source at a diffusion coefficient of $\sim (12-15) 10^{28} \text{ cm}^2 \text{ s}^{-1}$ [10], we can conclude that a possible source of nuclei ^{14}C could not be closer than 100-200 pc and the birth of a supernova could not have happened earlier $\sim 5 \cdot 10^4$ years ago. The co-authors of the work are naturally members of the PAMELA collaboration [8, 9], who provided initial flight information.

References

- [1] Adriani O, Barbarino G C, Bazilevskaya G A et al. An anomalous positron abundance in cosmic rays with energies 1.5-100 GeV 2009 *Nature* **458** 607
- [2] Aguilar M, Alberti G, Alpat B 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 from Flight Data for 2006-2014 2019 *Bull. Russ. Acad. Sci.: Phys.* **83** 967
- [4] Bogomolov E A and Vasilyev G I Boron Isotopes in the PAMELA Experiment 2019 *J. Phys: Conf. Ser.* **1400** 022039
- [5] Webber W R, Lukasiak A, McDonald F B and Ferrando P New High-Statistical-High-Resolution Measurements of the Cosmic-Ray CNO Isotopes from a 17 year Study using the VOYAGER 1 and 2 Spacecraft 1996 *Ap J* **457** 435
- [6] Yanasak N E, Wiederbeck M E, Mewald R A et al. Measurement of the Secondary Radionuclides ^{10}Be , ^{26}Al , ^{36}Cl , ^{54}Mn , and ^{14}C and Implications for the Galactic Cosmic-Ray Age 2001 *ApJ* **563** 768
- [7] Strong A W and Moskalenko I V Models for Galactic Cosmic-Ray Propagation 2001 *astro-ph/0101068*
- [8] Picozza P, Galper A M, Castellini G et al. PAMELA - A payload for matter antimatter exploration and light-nuclei astrophysics 2007 *Astropart. Phys.* **27** 296
- [9] Adriani O, Barbarino G C, Bazilevskaya G A et al. Measurement of Boron and Carbon Fluxes in Cosmic Rays with the PAMELA Experiment 2014 *Ap J* **791** 93
- [10] Cummings A C, Stone E C, Heikkila B C et al. Galactic Cosmic Rays in the Local Interstellar Medium: VOYAGER 1 Observations and Model Results 2016 *ApJ* **831** 18