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The Proton and Helium cosmic ray spectra from 50 GeV to 15 TeV

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Abstract. To date, very little has been done in the field of research of the nuclei cosmic ray spectra in the energy range between 1 and 10 TeV per nucleon and especially there were even fewer direct measurements in space. The PAMELA experiment (Casolini et al., 2008) has a possibility to make progress in this range. The method of the measurement of the helium and proton cosmic ray spectra with the energy higher than 50 GeV/nucleon was developed mainly with the use of the PAMELA calorimeter. This analysis method and the results obtained based on 3 years of measurements are presented.

1 Introduction

The idea that the protons and helium are produced in the cosmic rays due to different processes in the Galaxy and that the spectrum of protons has a break in the energy area near 1 TeV appeared in 1960s. During that period of time, the first direct measurements of the high energy proton cosmic ray spectrum were performed on board of the PROTON satellite (Grigorov et al., 1969). In the past, the attention of research groups was mainly directed to the lower energy range (below 1 TeV) or the higher range (above 10 TeV). The studies in the energy range between 1 and 10 TeV per nucleon are based on measurements from a few ground based (Antoni et al., 2004) and balloon experiments. Moreover any difference between the proton and the helium nuclei spectrum, such as spectrum breaks, lead to important conclusions concerning fundamental phenomena in space. The analysis method and the results for the helium and the proton spectra in the framework of the PAMELA experiment are presented in this work.

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2 PAMELA

PAMELA is a satellite-born experiment that has operated on a near-polar orbit since 15th of June 2006. The experiment was designed to measure cosmic ray particles and antiparticles fluxes in a wide energy range. The PAMELA apparatus (Casolini et al., 2008) consists of the following sub detectors: a magnetic spectrometer with a silicon tracking system; a time of flight (ToF) system with three double scintillator planes in which each detector layer is segmented in strips, with alternate layers strips are oriented orthogonally to each other; an anticoincidence system; a neutron detector; a bottom shower scintillator detector and a tungsten/silicon sampling electromagnetic calorimeter. The calorimeter is composed of 44 silicon layers interleaved by 22 tungsten plates 0.26 cm thick. Each silicon plane is segmented in 96 strips. 22 planes are used for the X view and 22 for the Y view in order to provide topological information about a shower development inside the calorimeter. The total calorimeter thickness is about 0.6 nuclear interaction lengths.

3 The spectra measurement

The instrument of the PAMELA experiment has a magnetic spectrometer that allows precise measurements of the particles rigidity and the charge sign, in the best case up to 1 TeV. In order to provide measurements in the higher energy range the use of the calorimeter is needed. The calorimeter is rather thin for the hadron interactions. Thus a preselection of well contained hadron showers is the first demand, otherwise the results would appear with a poor energy resolution. For this reason the events with a shower that started before the 12^{th} tungsten layer and had a core not closer than 1 cm to the lateral sides of the calorimeter were selected. It was found that such conditions are optimal to achieve a rather high ef-

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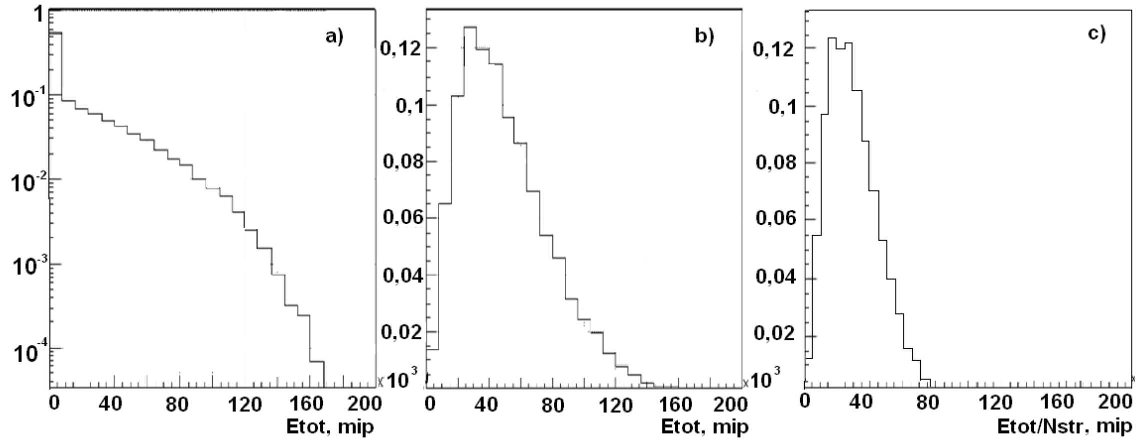

Fig. 1. **(a)** The Etot distribution before the selection **(b)** The Etot distribution after the selection **(c)** The Etot/Nstr distribution after the selection (1 TeV simulated protons were used in all cases)

ficiency of the selection together with a minimization of an energy leakage from the calorimeter (Karelin, 2009).

3.1 The shower axis reconstruction

For an exclusion of extra-aperture events and for a calculation of shower topological variables it is necessary to find the incoming particles direction which is calculated as a shower axis in the calorimeter. The calculation algorithm uses centres of gravity of energy releases in a shower for a set of planes of the calorimeter. A linear least-square fit of these points is performed. The detailed description of the axis reconstruction algorithm is presented in the previous work (Borisov et al., 2010). In order to cut the showers with the imprecisely reconstructed axis, events which had a high value of the χ^2 (a standard quality of fit parameters) were discarded. To obtain the selection efficiency a GEANT 3 simulation was used, which reproduces a full geometry of the instrument, detectors and electronic effects as well for events within the geometrical factor of the PAMELA instrument. A reduced acceptance angle limit, based on the angular resolution of the shower axis measurement, was used to insure that the all events collected inside the aperture of the instrument, and thus to guard against possible distortion of the measured spectrum.

3.2 The particle identification

The crucial problem of the cosmic ray measurements is the determination of particle type. Protons and helium are the most abundant components of cosmic rays. For their identification the energy deposit measurements in the scintillator detectors of the ToF system were used. Such kind of separation is possible due to the fact that the helium and protons have different charge value. However protons and electrons cannot be separated by this method because they have the same charge value.

Though the electron fraction in the common cosmic ray flux is only 1%, since electrons produce shower more easily than nuclei, the fraction can increase among the selected showers. Moreover, electrons of certain energy could be reconstructed as protons with a higher energy. The largest amount of electrons generates the electromagnetic shower in the first 2 tungsten layers of the calorimeter so the information in this part of the calorimeter could be used for a proton/electron separation. A cylinder of 5 strips radius (2 Moliere radius or 12 mm) along the reconstructed shower axis in silicon planes before the third tungsten layer was checked for any strips with energy release greater than 8 mip (mip – minimum ionizing particle) which would idicate that the shower has started. The electron contamination to the proton spectrum after this cut does not exceed 5%.

3.3 The Flux measurement

The energy release distribution for 1 TeV simulated protons is presented in Fig. 1. In Fig. 1**(a)** the distributions of simulated protons before the selection in Sect. 3.1 and 3.2 is shown while in Fig. 1**(b)** this distribution refers to data after the selection. The use of the ratio between a total energy release Etot and a total number of hit strips Nstr as a parameter for energy measurements provides more symmetric and narrow distribution than the first one (Fig. 1**(c)**). However, the distribution width and at high energy the deviation from linearity of the dependence of mean value of distribution on the particle primary energy lead to the poor energy resolution. The multidimensional unfolding method based on the Bayes theorem (D'Agostini, 1995) was used to adjust this problem by an iteration procedure where the spectrum obtained from the first iteration is used as initial one to obtain the second spectrum and so on. This procedure requires the

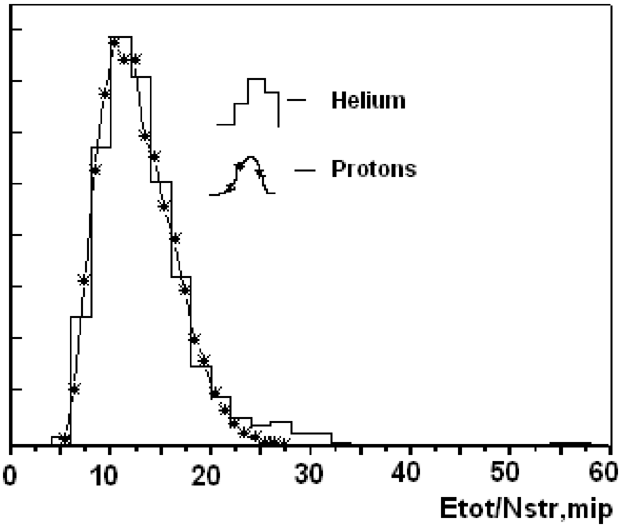

Fig. 2. The comparison between the 100 GV rigidity helium distribution (the histogram) and the 150 GV rigidity proton distribution (the black line).

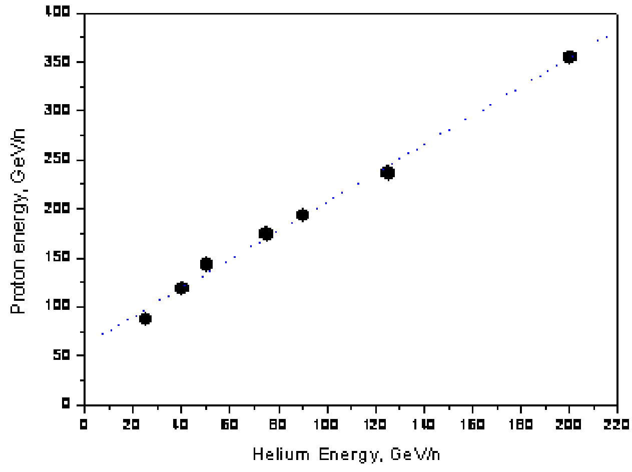

Fig. 3. The relation between proton and helium response in the calorimeter.

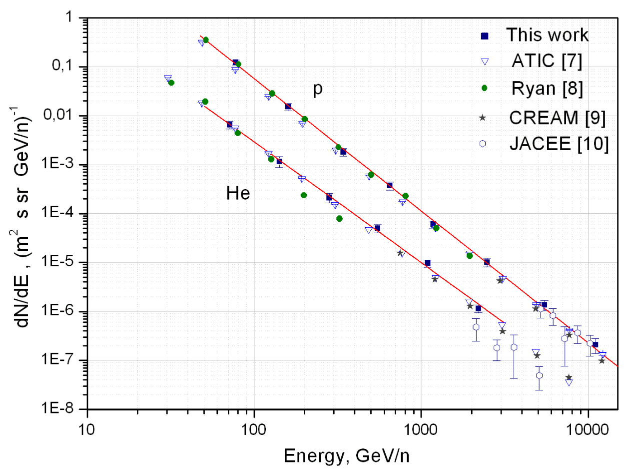

Fig. 4. The obtained proton and helium spectra. The power law lines with the spectral indices 2.7 for protons and 2.47 for helium are shown by red lines.

knowledge about the probabilities that the certain energy is reconstructed as other energy values. It is achieved by simulating of a spectrum with the index in a range $+/-30\%$ from the real one.

In Fig. 2 the obtained from experimentally measured helium distribution of Etot/Nstr for the 100 GV rigidity is shown. In the same figure the 150 GV rigidity proton simulated distribution is presented as well for a comparison. The response of protons at certain energy gives a similar Etot/Nstr distribution as helium at different energy. Such correlation is traceable in the flight data for the energy range up to 400 GeV/nucleon which is measurable by the magnetic spectrometer (Fig. 3). It also was confirmed up to 800 GeV/nucleon by GEANT 4 simulation data. The correlation was extrapolated for higher energies to use the proton simulated data in the framework of helium analysis.

To restore spectra, the efficiencies are needed for all applied selections. They were obtained from the proton simulated data in whole energy range and from helium flight data at low energies. At high energies the proton efficiency was multiplied by factor 2.5 that corresponds to increasing of the strong interaction cross section for helium. The proton efficiency increases from few percents at 50 GeV to 14% at 1 TeV and at higher energies it remains constant.

4 Results and discussion

The proton and helium spectra are shown in Fig. 4. These spectra were obtained by an application of the described above procedure to the 3.5 year observation experimental data of PAMELA. The presented results have been compared with ones, which have been measured by the balloon experiments in the energy range $1-10$ TeV. The statistical errors of the presented results are put together with systematic ones. Formers were estimated from the comparison of flight, beam-test and simulation data. The obtained differential proton spectrum was fitted by a power law with the spectral index 2.70 ± 0.05. The helium spectrum was approximated by a power law as well with the index 2.47 ± 0.07. In the previous article (Karelin et al., 2011) preliminary results with low statistics were published. No significant breaks of the spectra shape have been found.

5 Conclusions

The PAMELA instrument allows measurements of high energy cosmic ray proton and helium spectra from 50 GeV/nucleon to 15 TeV/nucleon and from 50 GeV/nucleon to 3.5 TeV/nucleon respectively. Such measurements have been done with the use of the calorimeter and the scintillators of the ToF system to identify a particles type and measure its energy. They are the first direct cosmic ray proton and helium spectra measurements performed on satellite in this energy range since the sixties.

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