

Measurements of cosmic-ray proton and helium spectra with the PAMELA calorimeter

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Abstract

We present a new measurement of the cosmic ray proton and helium spectra by the PAMELA experiment performed using the “thin” (in terms of nuclei interactions) sampling electromagnetic calorimeter. The described method, optimized by using Monte Carlo

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simulation, beam test and experimental data, allows the spectra to be measured up to 10 TeV, thus extending the PAMELA observational range based on the magnetic spectrometer measurement.

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1. Introduction

Despite of the long history of cosmic ray proton and helium measurements, few investigations have continuously covered the energy range from 1 to 10 TeV. Since the 1960s, when the first direct measurement was achieved by the PROTON satellite experiments (Grigorov et al., 1969), only a few balloon borne and only one satellite (SOKOL (Ivanenko et al., 1989)) experiments reported observations in that range. A new measurement of the cosmic ray proton spectrum up to 2 TeV and of the helium spectrum up to 300 GeV/nucleon, performed at balloon altitudes, was provided by Ryan et al. (1972) during November 1970. Almost 30 years after, the ATIC balloon experiment (Ahn et al., 2006) reported results for the energy spectra of protons and helium nuclei over the energy range from 100 GeV to 100 TeV. The first series of JACEE balloon flights (Asakimori et al., 1998) observed protons over the energy ranges 5–500 TeV and helium nuclei over 2–50 TeV/nucleon. Finally, the CREAM experiment (Seo et al., 2004) has recently published proton and helium data above 2.5 TeV (Ahn et al., 2010).

The measurements by the PROTON satellite series reported for the first time a steepening of the integral proton spectrum at an energy of about 1000 GeV. However, data from PROTON and from the Ryan group – where no steepening is visible – appear to be in agreement once the measurement uncertainties have been taken into account. The resulting spectral index is 2.75 ± 0.03 for 50 GeV–2 TeV protons and 2.77 ± 0.05 for helium nuclei in the range 20–600 GeV/nucleon. The Jacee flights 0, 1, 2 (Burnett et al., 1983) showed almost the same spectral indexes for both species as well (~ 2.8). From SOKOL measurements (Ivanenko et al., 1993) the power spectral index for protons was found to be -2.85 ± 0.14 for energy more 5 TeV and for helium -2.64 ± 0.12 for energy more 1 TeV/nucleon. The ATIC-2 results do indicate differences in spectral shape between protons and helium over the investigated energy range (Panov et al., 2009).

The CREAM group (Ahn et al., 2010) confirmed the ATIC-2 results, showing that the proton and the helium spectra can be described by power-law fits with indexes of -2.66 ± 0.02 for protons and -2.58 ± 0.02 for helium, respectively, in the range from 2.5×10^3 GeV to 2.5×10^5 GeV. All these results are assembled in Table 1 including the PAMELA calorimetric results.

PAMELA published already the proton and helium absolute energy spectra in the in the rigidity range 1 GV to 1.2 TV (Adriani et al., 2011), by spectrometric measurements. These measurements showed that the spectral shapes of these two species are different and cannot be described well by a single power law. A new measurement of the cosmic ray proton and helium nuclei spectra made by PAMELA in a wider energy range might provide very important constraints on the shape and the spectral indexes.

2. PAMELA experiment

The PAMELA experiment (Picozza et al., 2007) was put into a space on board of the Resurs DK1 satellite from the Baikonur Cosmodrome in June 2006. It was designed to study the composition and energy spectra of cosmic ray particles in a wide energy range in near-Earth space. The PAMELA instrument (a total mass is 470 kg) consists of several specialized detectors as shown in Fig. 1: a permanent magnet equipped with the silicon tracking system, a time of flight (ToF) system made of three double planes, an anticoincidence system, a neutron detector, a bottom shower scintillator detector and a tungsten/silicon sampling electromagnetic calorimeter (Boezio et al., 2002). The total calorimeter thickness is 16.3 radiation lengths and 0.6 nuclear interaction lengths. The calorimeter (see Fig. 2) is composed of 44 silicon layers (SSD) interleaved by 22 tungsten plates with a thickness of 0.26 cm thick. Each silicon plane is 380 μm thick and segmented in 96 strips with a pitch of 2.4 mm. 22 Planes are used for the X view and 22 for the Y view in order to provide topolog-

Table 1
The indices reported in different experiments.

The experiment	The energy range	Protons	Helium
PROTON	0.07–0.8 TeV; 1–1000 TeV	2.65 ± 0.05	
SOKOL	5–100 TeV (p); 1–50 TeV/n (He)	2.85 ± 0.14	2.64 ± 0.12
Ryan	0.05–2 TeV (p); 0.02–0.6 TeV/n (He)	2.75 ± 0.03	2.77 ± 0.05
JACEE-1,2,3	5–500 TeV (p); 2–50 TeV/n (He)	2.81 ± 0.13	2.82 ± 0.20
CREAM	2.5–250 TeV	2.66 ± 0.02	2.58 ± 0.02
PAMELA CALO	0.05–15 TeV (p); 0.05–3.5 TeV/n (He)	2.70 ± 0.05	2.47 ± 0.07

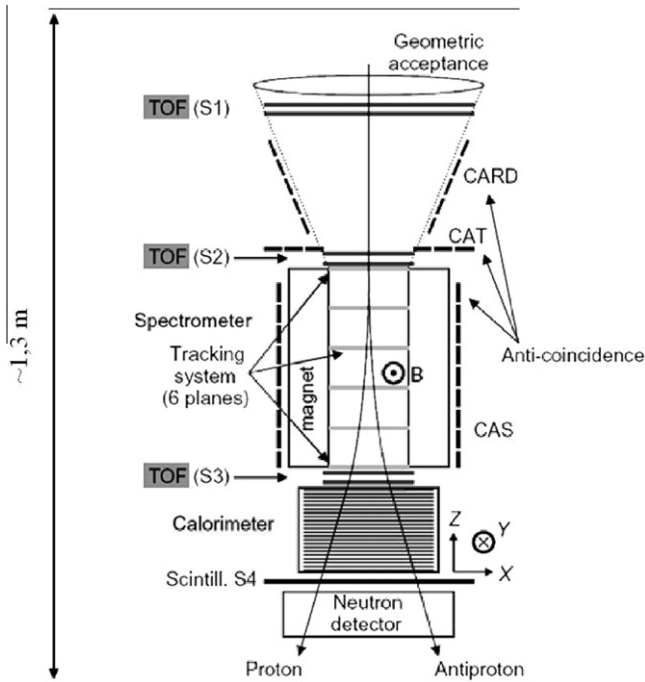


Fig. 1. The PAMELA instrument.

ical and energetic information about the showers produced inside the calorimeter. The front-end is a developed version of a 16 channels CR1 chip with a peaking time of 2 ms, a linear dynamic range between 0.4 and 1200 MIPs, a sensitivity of 5 mV/MIP and a counting rate of 30 kHz. The total number of channels is 4416. The calorimeter has a mass of 110 kg and a total power consumption of 75 W. The calorimeter allows to reconstruct the energy of the electromagnetic shower, providing a measurement of the energy of the incident electrons up to several hundred GeV with a resolution of the order of 5.5%. The ToF system (Osteria et al., 2004) comprises six layers of fast plastic scintillators arranged in three planes (S1, S2 and S3). Each detector layer is segmented into strips, placed in alternate layers orthogonal to each other. The distance between S1 and S3 is 77.3 cm. The magnetic spectrometer allows the energy of incident protons and helium nuclei to be precisely measured up to about 1 TeV/nucleon. However, the mea-

surement of the spectra can be extended to higher energies by using the calorimeter information.

3. Data analysis

The method presented in this paper is based on simulations, flight data and beam test data. Both GEANT3 (Brun et al., 1984) and GEANT4 (Agostinelli et al., 2003) packages were used in the proton analysis, while only the latter was involved in the analysis of helium nuclei. The cross-check between data samples allowed the procedure to be tested, providing an estimate of the systematic uncertainties on the measurements. All events were collected in the normal acceptance of PAMELA (see Fig. 1 which is 21.5 cm² and is defined by the acceptance of tracking system.

Protons and helium nuclei represent the most abundant cosmic ray components: they account for about 89% and 9% of the cosmic radiation respectively, while electrons are nearly 1%. Since the calorimeter does not allow the particle charge-sign to be determined, the selected proton sample includes electrons too. As shown in simulations, the response of the detector to the showers produced by the two particle species can be quite similar at high energies. Therefore, despite of their relative abundance, electrons introduce some contamination in the sample of protons which interact in the calorimeter.

To distinguish between protons and helium nuclei, a method using the geometrical mean S of the measurements at each end of the scintillator paddles was applied:

$$S \approx Z^2 \tag{1}$$

Such kind of approximation can be used just for low-charge relativistic particles, like those considered here, for which the light output of the scintillator is close to linear. Events with only one hit paddle for each ToF layer were selected. The S3 scintillators, placed just above the calorimeter, were not involved in the procedure since affected by the backscattering of secondary particles from showers produced in the calorimeter. The charge histogram of events selected by plane S11 in framework of this method is shown in Fig. 3 (flight data). The total efficiency of

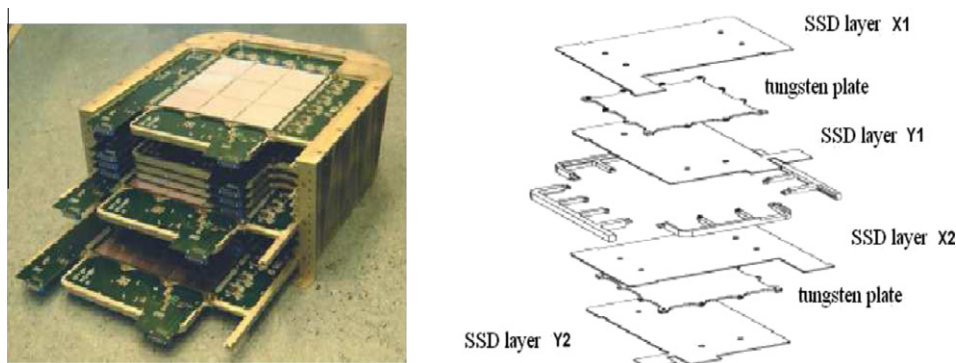


Fig. 2. The PAMELA calorimeter.

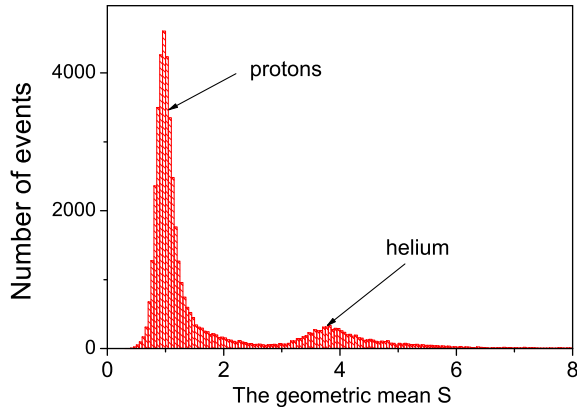


Fig. 3. The charge histogram of events for S11 plane selection. Flight data.

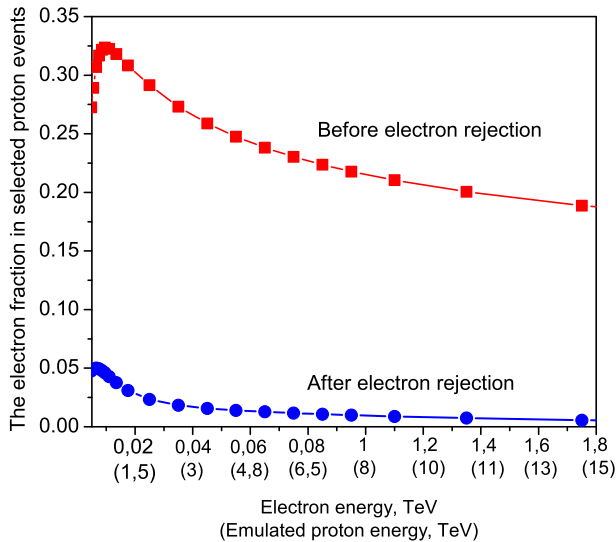


Fig. 4. The electron contamination before and after cut. Simulated data. The emulated proton energy is the approximate energy of a proton that would deposit the same energy in the calorimeter as the electron.

selection for S11, S22, S21, S22 planes taken in the lump is about 98%. The helium contamination in the selected proton sample does not exceed 0.5%, while the proton contamination in the helium sample is 4% maximum.

The electron rejection was performed by using the information from the first layers of the calorimeter, where approximately 95% of electrons produce a shower. To characterize the showers, the amount of energy released inside a cylinder of one Moliere radius around the shower axis reconstructed in the calorimeter was considered. Events with a value larger than 8 MIPs were identified as electromagnetic showers and excluded from the analysis. The fractions of contaminating electrons before and after this calorimeter selection are reported in Fig. 4 (simulated data). This cut allows to eliminate about 90% of electrons but simultaneously about 30% of protons are lost due to this selection.

The information about the shower axis was also used to select only events that pass through the main acceptance of

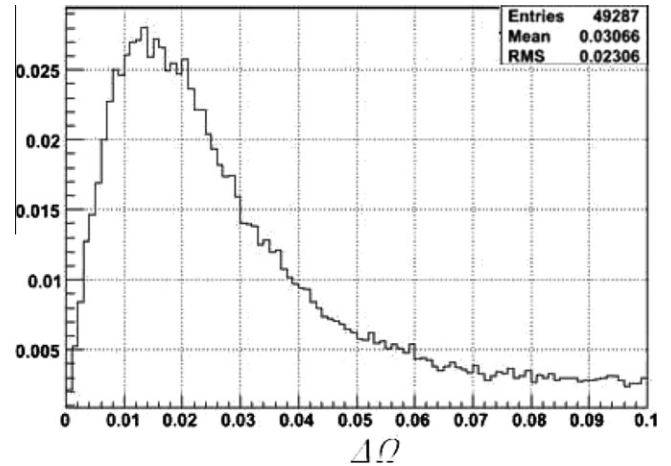


Fig. 5. The $\Delta\Omega$ distribution for 1 TeV protons. Simulated data.

PAMELA. The particle direction was reconstructed by considering the position of the centers of gravity of the deposited energy in each layer of the calorimeter. This method was verified on simulated data. The position of the shower axis in a single layer was obtained using the calorimeter segmentation into strips.

An estimate of the uncertainties in the shower axis reconstruction was obtained by analyzing the variable Ω in the simulated data, defined as:

$$\Delta\Omega = \sqrt{\Omega_x^2 + \Omega_y^2} \quad (2)$$

where Ω_x and Ω_y are the differences between the reconstructed shower axis projections and real shower axis ones. Ω distribution defines the accuracy of the axis reconstruction (see Fig. 5). Events with values larger than 0.5 were excluded (Borisov et al., 2010).

Since the total calorimeter thickness corresponds to only 0.6 interaction lengths, a good energy resolution was achieved by selecting only well contained hadron showers. In order to optimize the selection efficiency, while minimizing the energy leakage from the calorimeter, events with a shower started before the 12th tungsten layer and with a core not closer than 1 cm to the lateral sides of the calorimeter were selected. The layer where the particle shower was initiated was identified by requiring an energy difference of 50 MIPs with respect to the previous layer. In order to cut the showers with an imprecisely reconstructed axis, events which had a high value of the χ^2 (a standard quality of fit parameters) were discarded. This value was defined by simulated data.

To measure the primary particle energy, we introduced a variable that is the ratio between the total energy E_{tot} released by the particle and the number N_{hit} of hit strips inside the calorimeter. Since the calorimeter is able to measure only a portion of the showering particle energy, the total energy released in the calorimeter results to be asymmetric, with a tail at high energy, therefore it does not ensure a reliable evaluation of the particle energy leading

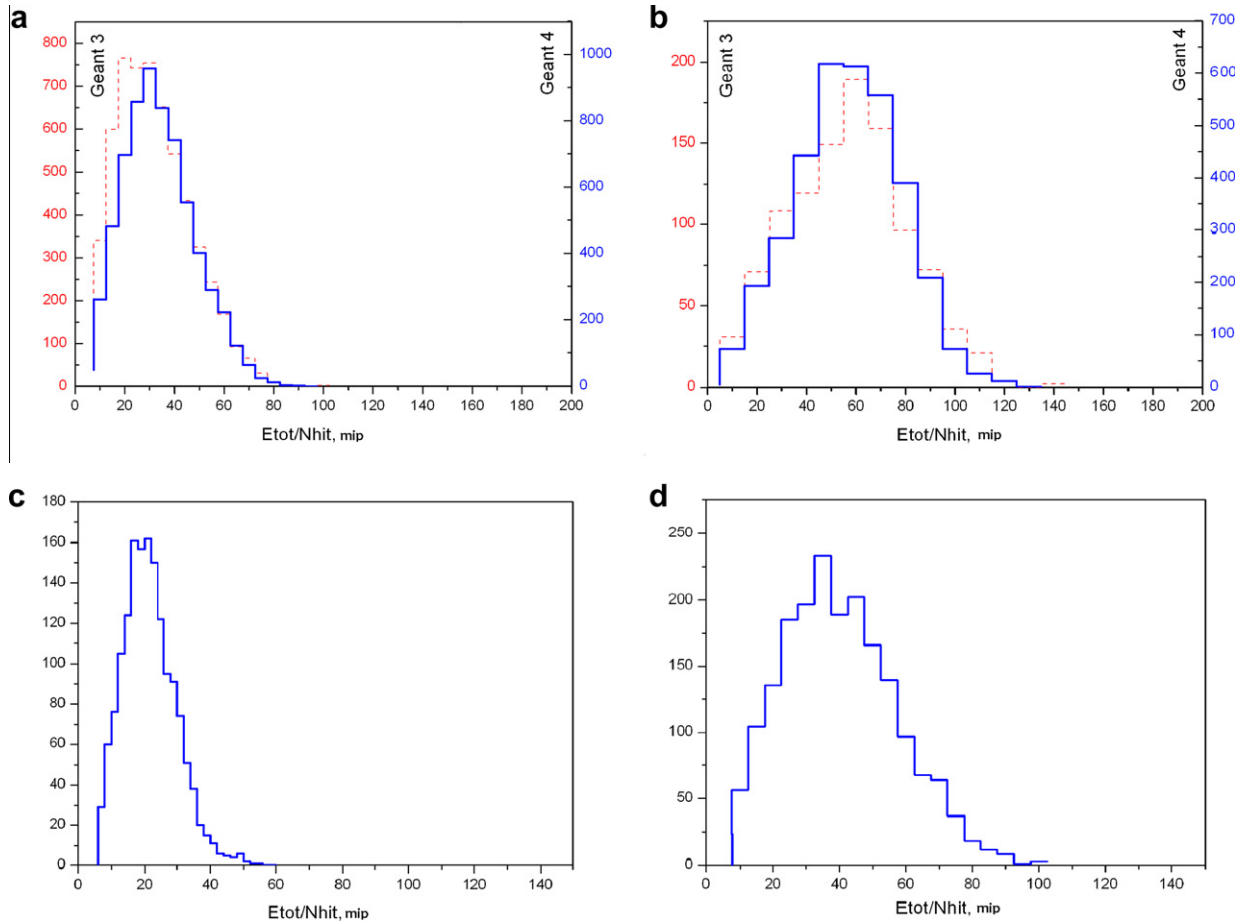


Fig. 6. The distribution of E_{tot}/N_{hit} for 1 TeV simulated (a) protons, (c) helium, and 3 TeV simulated (b) protons and (d) helium. The GEANT 4 data is blue line, the GEANT 3 data is red dash-line. (For interpretation of reference to color in this figure legend, the reader is referred to the web version of this article.)

to a distortion of the reconstructed spectrum shape. Another parameter approximately depending only on the particle energy is the total number of hit strips. Its distribution does not contain tails, but the distributions of its mean values results to be more non-linear than that obtained by the total energy release. To minimize such effects we considered the ratio between the total energy release E_{tot} and the number N_{hit} of hit strips inside the calorimeter (see Fig. 6). This parameter takes into account differences between highly fluctuating hadron showers.

The E_{tot}/N_{hit} distribution was found to be the more symmetric than the one of E_{tot} . The index A related to the distribution asymmetry:

$$A = \frac{(\langle x \rangle - x_0)}{\sigma} \quad (3)$$

where $\langle x \rangle$ is the mean value of a distribution, x_0 is the position of a center distribution, σ is the standard deviation, is equal to 0.026 for the E_{tot}/N_{hit} ratio and to 0.25 for E_{tot} . While the use of the E_{tot}/N_{hit} parameter does not result in an improvement in the reconstructed energy of the incident particle, it provides the better spectral resolution. The use of E_{tot} without any corrections leads to a significant distortion

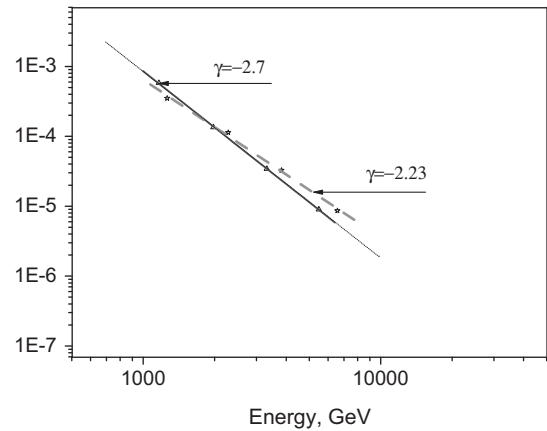


Fig. 7. The plot of reconstructed simulated proton spectrum (the dot line) using E_{tot}/N_{hit} (the solid line) compared to reconstruction using E_{tot} (the dash line).

of an reconstructed spectral index. This effect is demonstrated in Fig. 7. The GEANT4 simulated proton spectrum in the energy range of 700–10,000 GeV and with the spectral index -2.7 has been reconstructed using E_{tot}/N_{hit} and E_{tot} . In case of E_{tot}/N_{hit} the index was obtained

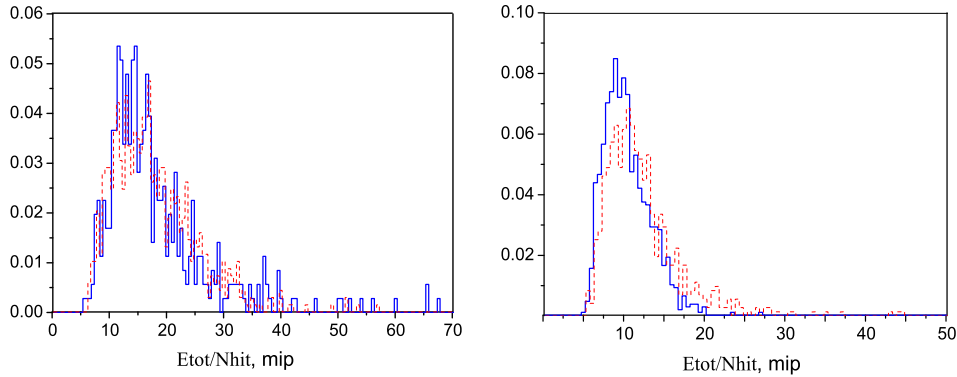


Fig. 8. The distribution of E_{tot}/N_{hit} for 300 GeV (left panel) and 200 GeV (right panel) protons. The flight data is blue line, the GEANT 3 data is red dash-line. (For interpretation of reference to color in this figure legend, the reader is referred to the web version of this article.)

correctly but by using E_{tot} it is more on 0.5 due to an event's shift from lower energy to higher.

The E_{tot}/N_{hit} simulation distributions were compared to the ones from flight data (see Fig. 8), where the energy was defined by the tracking system information.

The distribution width and the deviation from linearity of the dependence of mean value of distribution on the particle primary energy – at high energy – lead to a poor energy resolution. For this reason a multidimensional method based on the Bayes theorem (D'Agostini, 1995) was applied to unfold the obtained distributions. The procedure required a simulated spectrum with spectral index close to real one and then the number of measured events inside each energy bin was corrected according to calculated probabilities. Two sets of simulated data for protons and helium were used to corroborate the experimental spectra after the Bayesian approach. One set contains spectra with index equal to -2.7 (the experimental proton index within the framework of the Bayesian approach) and another one with index -2.5 (the experimental helium index within the framework of the Bayesian approach). The comparison of the E_{tot}/N_{hit} distributions (see Fig. 9) shows an agreement between the flight data and the results

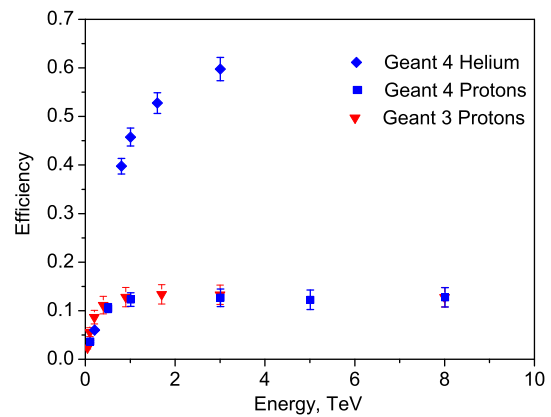


Fig. 10. The efficiency after all cuts. The differences in comparison between flight and simulated data are put as errors.

of the Bayesian method. The selection efficiencies were estimated by means of the official PAMELA simulation, based on GEANT3 and GEANT4 packages (see Fig. 10). This simulation accurately reproduces the full geometry of the instrument: electronics effects like noise, strip saturation and so on are taken into account. Events were simulated within the geometrical acceptance of PAMELA. The

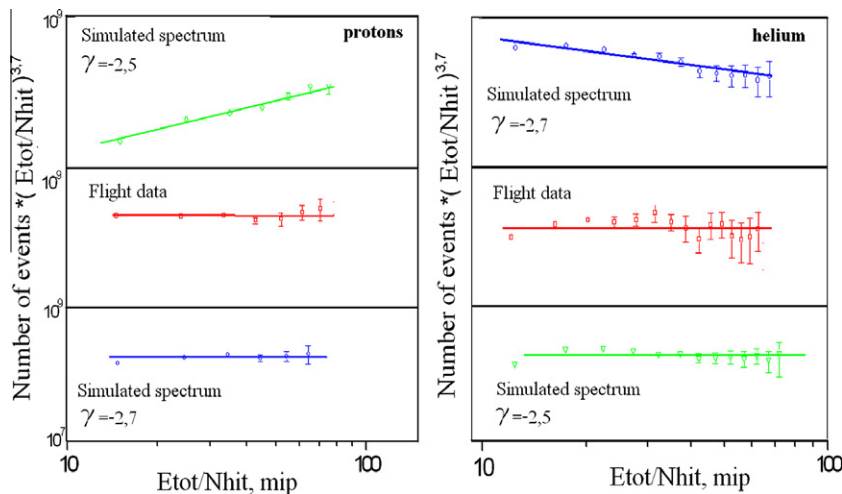


Fig. 9. The distribution of E_{tot}/N_{hit} for the simulated and flight spectra. The lines are simple power law fits.

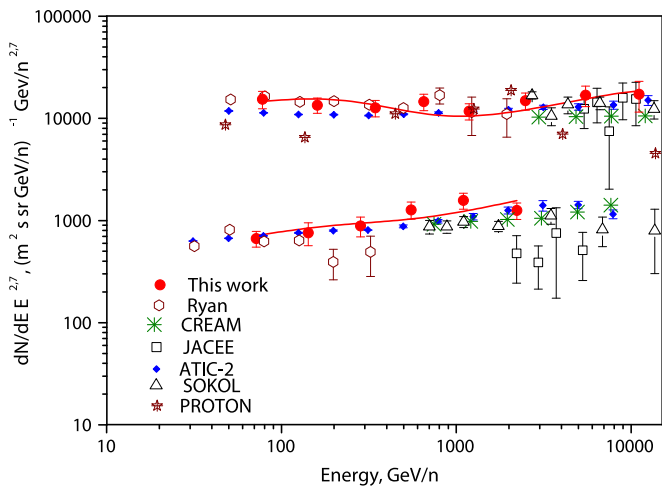


Fig. 11. Proton and He spectra. Red line reproduces a three component model fit. (For interpretation of reference to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Parameters for three classes of sources.

Class	α	R_{max} (GV)	γ	γ_k
I	2.3	5×10^4	2.63	8
II	2.1	4×10^6	2.43	4.5
III	2.5	3×10^2	2.83	4.5

results of simulation were supported and cross-checked by comparing flight and beam test data. The systematic errors on the efficiencies determination was estimated not to exceed 10%. The contamination of protons by electrons and helium by protons was taken into account.

4. Results

The proton and helium spectra measured by the PAMELA calorimeter are shown in Fig. 11. The sample used for the analysis includes data recorded during the first four years of the experiment. The presented results are compared with data by the other experiments: ATIC-2 (Panov et al., 2009), Ryan (Ryan et al., 1972), CREAM (Ahn et al., 2010), JACEE-1,2 (Burnett et al., 1983), SOKOL (Ivanenko et al., 1989), PROTON (Grigorov et al., 1969). The error bars include both statistical and systematic uncertainties. The PAMELA results are in general agreement with the previous balloon measurements. Due to the large uncertainty, no significant structures can be recognized in the spectra, as it was the case for the spectrometric measurements. However, the calorimetric measurement has the advantage of extending the energy range up to 10 TeV for protons, thus providing and independent cross-check of the high-energy slope.

A three-component model (Zatsepin and Sokolskaya, 2006) was used to fit obtained data. According to this model the structure of proton and helium spectra is due to a superposition of three types of sources. The spectrum of each source is:

$$Q^{(i)}(R) \approx R^{-\alpha^{(i)}} \left[1 + (R/R_{max}^{(i)})^2 \right]^{(\gamma - \gamma_k^{(i)})/2} \quad (4)$$

where $i = I, II, III$ is the class of the source, $\alpha^{(i)}$ is the index of the source spectrum, $\gamma = \alpha^{(i)} + 0.33$ is the spectral index in the region of effective acceleration, γ_k is the spectral index after termination of effective acceleration, R is the particle rigidity, and $R_{max}^{(i)}$ is the “termination rigidity”. The parameters of the components are presented in Table 2. It should be noticed that parameters used for III class are different respect to those used in work (Zatsepin and Sokolskaya, 2006). A fit to the spectra with a power law above 200 GeV gives a spectral index of 2.64 ± 0.01 (stat) and 2.43 ± 0.02 (stat) for H and He, respectively, which is consistent with values found from the spectrometer measurements.

5. Conclusion

A new method to measure the cosmic ray proton and helium energy spectra with the electromagnetic calorimeter of the PAMELA instrument was developed. This method uses the value of the total energy deposited in the calorimeter and the total number of hit strips. The particle charge identification is done by using scintillator detectors. All events were collected inside the normal acceptance of PAMELA. To estimate the level of uncertainties the flight, simulated and beam test data were brought into comparison. The obtained spectra is consistent with the previous PAMELA measurements and with those from other experiments.

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