# The method and some results of high energy primary proton and light nuclei measurements with the PAMELA calorimeter

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**Abstract:** This method is based on using the sampling electromagnetic PAMELA calorimeter to measure energy of proton and nuclei. This makes it possible to extend the energy range which available for PAMELA measurements by the tracker. As a nuclei energy resolution for the calorimeter is poor a spectrum deconvolution procedure was applied. The scintillator detectors of the PAMELA instrument were used to separate species of nuclei. The results of the method are demonstrated in the case of Cosmic-ray proton and helium spectra.

**Keywords:** Calorimeter, Protons, Helium, PAMELA.

## 1 Introduction

PAMELA [1] – the instrument abroad the Resurs-DK1 satellite was launched into Earth's orbit in June 2006. The satellite orbit is elliptical and semipolar with an inclination of 70.4°. It is designed to study the composition and energy spectra of cosmic ray particles in the wide energy range in the near-Earth space. The PAMELA instrument consist of several specialized detectors: a magnetic spectrometer with the silicon tracking system, a time of flight system with three double planes, an anti-coincidence system, a neutron detector, a bottom shower scintillator detector and a tungsten/silicon sampling electromagnetic calorimeter [2]. The incident hadron energy measurements by a determination of a declination angle value in a magnetic field inside the magnetic spectrometer is possible just up to the total energy ~ 1 TeV, while for the energy range more than 1 TeV such ability is available for the calorimeter only. The total calorimeter thickness is 16.3 radiation lengths. The calorimeter 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 Y view in order to provide topological and energetic information of the shower development inside the calorimeter. The whole described method is based on simulated GEANT data, flight data and beam test data. These data sets were compared between each other in different energy regions to verify a reliability and an accuracy of the obtained results.

## 2 The charge particle determination

Due to the fact that the measurements take place in space first of all it is necessary to discriminate incoming particles into groups according to their charges. The method of multiplied responses was applied to resolve this problem. The ToF system [3] comprises six layers of fast plastic scintillators arranged in three planes (S1, S2, S3). Each scintillator layer of the ToF system is comprised of paddles. The PMT R5900 is on each edge of every paddle. The PMT responses in either edge in a paddle are following:

$$A_i = a_i \times \frac{Z^2}{\beta^2} \times \exp\left(-\frac{L-X}{\lambda}\right) \quad (1)$$

where $a_i$ is a peak value of a response from $i$ edge of the paddle, $Z$ is a particle charge, λ - an attenuation length, β - a particle velocity ~ 1, $L$ is a length of the paddle, $X$ - a cross position of a particle in the paddle.
The PMT responses in another edge - $j$ of the same paddle:

$$A_j = a_j \times \frac{Z^2}{\beta^2} \times \exp\left(-\frac{X}{\lambda}\right) \quad (2)$$

By multiplication of $Ai$ and $Aj$ the new parameter $S$ comes. $S$ depends on a particle charge only.

$$S = a_i \times a_j \times \exp\left(-\frac{L}{\lambda}\right) \times Z^4 \approx Z^4 \quad (3)$$

Events with just one hit paddle in a single layer were selected. The S3 layer was out of the procedure due to the worst resolution in comparison with resolutions of S1 and S2. The S3 is right above the calorimeter thus there is a back scattering of secondary particles that arises

when an initial particle generates a shower inside the calorimeter.
The charge histogram for this method is shown on figure 1.

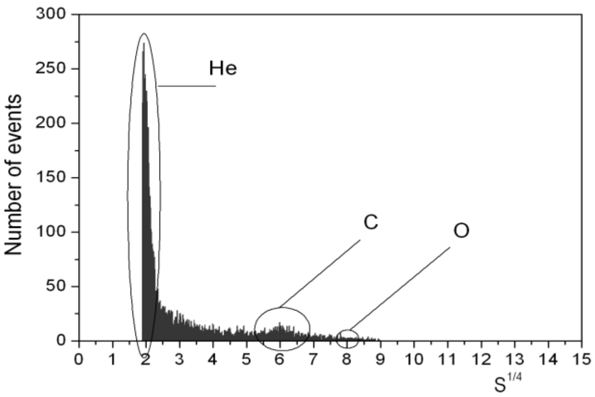


Figure 1. The charge histogram of events (with a shower inside the calorimeter) obtained by the multiplied responses method. Experimental data

# 3 The spectrum reconstruction

All criteria which are used for the event's preselection by calorimeter data are described somewhere else, for example see [4, 5]. The efficiencies for all applied selections were obtained from the simulated data. Instead of the value of total energy release *Etot* to estimate primary hadron energies, as it is usually used to be in previous measurements [6], in this work another parameter was found. The PAMELA calorimeter is rather thin for the hadronic interaction. Furthermore it detects only 1-3 % the primary hadron energy due to a high value of a non-registered energy part in tungsten layers. In order to eliminate high energy tails existing in *Etot* distributions at different hadron energies the shower topology inside the calorimeter in the total number of hit strips form was involved into the analysis. So a ratio between the total energy release and hit strips number was used to reconstruct the primary hadron energy. Nevertheless the distributions of the new parameter remain significantly spread that lead to a poor value of the energy resolution.
The multidimensional unfolding method based on the Bayes theorem [6] was used to adjust this problem by an iteration procedure where the spectrum obtained from the first iteration is assumed as initial one to obtain the second spectrum and so on.
A simulated energy spectrum of particles is used to calculate probability that an event with energy $E$ might be identified with the energy $E'$.
Making the hypothesis that the spectrum in reality has a certain shape, it is possible to get probability $P(E_i|E_j')$ that a particle has the energy $E_i$ while it was reconstructed as $E_j'$:

$$P(E_i \mid E_j') = \frac{P(E_j' \mid E_i) P_0(E_i)}{\sum_l P(E_j' \mid E_l) P_0(E_l)} \qquad (4)$$

Where $P_0$ defines the initial spectrum according to the hypothesis.
The output spectrum is reconstructed using experimental data and $P(E_i|E_j')$.
In process of unfolding it is being checked that an output spectrum coincide with an income spectrum by the chi-square criterion. In the absence of the coincidence the initial spectrum is changed on an output one to run the next iteration. To illustrate this iteration procedure figure 2 is demonstrated.

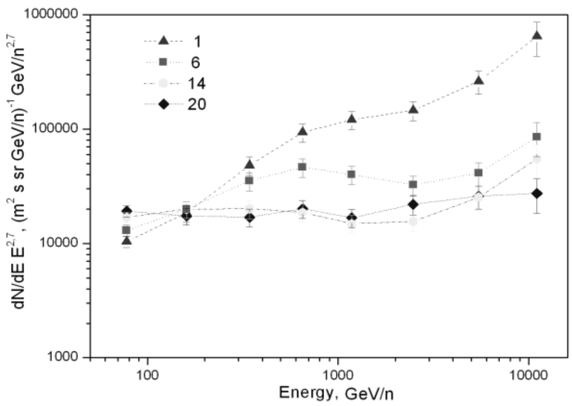


Figure 2. The iteration procedure of the proton spectrum reconstruction. The number of iteration is shown in the left side. Experimental data

# 4 Results of the helium and proton spectra reconstruction

The proton and helium spectra were obtained by an application of the described above procedure to the 4 year observation experimental data of PAMELA. 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. These results were interpreted within the bounds of three-component model [7] (figure 3). According to this model the structure of proton and helium spectra is caused by superposition of three types of sources. The spectrum of each source is:

$$Q^{(i)}(R) \approx R^{-\alpha(i)} \left[ 1 + \left( \frac{R}{R_{\max}^{(i)}} \right)^2 \right]^{(\gamma - \gamma_k^{(i)})/2} \qquad (5)$$

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, $\gamma_k$ is the spectral index after termination of effective acceleration, $R$ is a particle rigidity, $R_{max}$ is the "termination rigidity". The first class I is supposed to be exploded stars with masses from 8 to 15 of solar masses, the second class II – 15-25 solar masses stars exploding into their own stellar wind and third one III is believed to be nova stars.

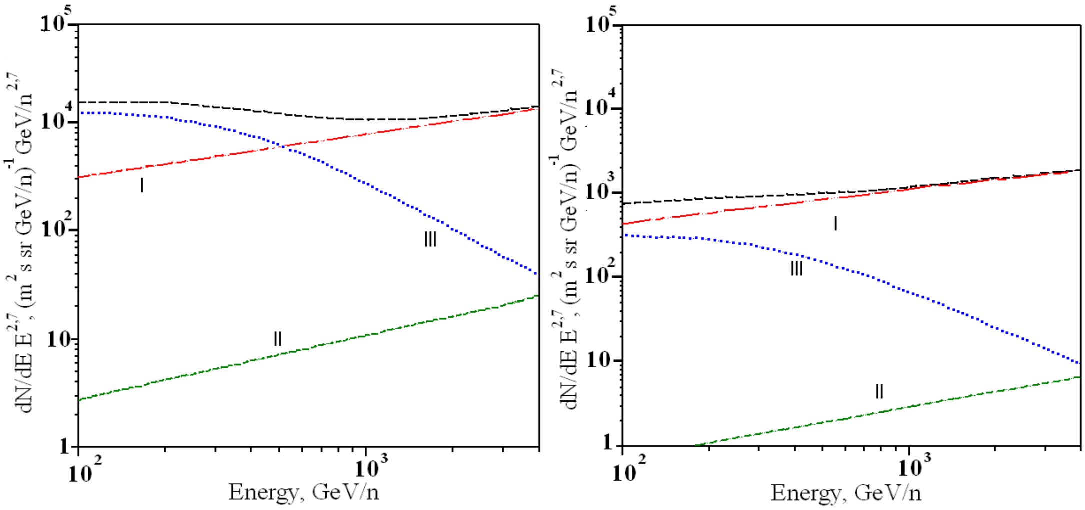


Figure 3. The composition of proton's and helium spectra in framework of the three-component model.

Based on results obtained we can conclude that the helium spectrum is mainly caused by I class sources in the energy range 100 – 3500 GeV/n. In the same region the proton spectrum includes issues of I and III classes simultaneously. As a result the proton and helium spectrum have different spectral slopes.

## 5 Conclusion

In framework of PAMELA experiment the method of reconstruction of high energy cosmic ray light nuclei spectra based on the calorimetric analysis was developed. First step includes the particle charge identification. It was done by using scintillator detectors and the simple method of multiplied responses. The second step consists of the calorimetric selection and the unfolding iteration procedure. This method results for helium and proton's spectra obtained from PAMELA experimental data are shown. The difference in spectra slope indexes depicts the various natures of proton's and helium sources. Considering three-component model it is possible to understand as such difference occurs.

## 6 References

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