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2015 J. Phys.: Conf. Ser. 632 012014

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Measurement of electron-positron spectrum in high-energy cosmic rays in the PAMELA experiment

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Abstract. At present the existing data on the cosmic ray electron energy spectra in the high energy range are fragmented, and the situation is exacerbated by their small number. In the satellite PAMELA experiment measurements at high energies are carried out by the calorimeter. The experimental data accumulated for more than 8 years of measurements, with the information of the calorimeter, the neutron detector and the scintillation counters made it possible to obtain the total spectrum of high-energy electrons and positrons in energy range 0.3-3 TeV.



1. Introduction

Study of the cosmic ray energy spectrum, obtained in direct measurements on board satellites, is one of the priority tasks in modern astrophysics.

Fluxes of cosmic electrons with energies greater than 10 GeV contain important information about the sources of their generation and the processes that occurred during their propagation inside the Galaxy. Due to significant loss in energy during propagation, unlike with protons and helium nuclei, electrons cannot propagate far from their sources. To date, measurement of electron and positron fluxes are carried out only in three satellite experiments. They are PAMELA [1], FERMI [2], the AMS-02 [3]. In previous years, in ground-based experiments measuring electron energy spectra a dramatic change in the spectrum at energies above a few hundreds of GeV was detected. It was associated with a significant decrease of electron-positron number in this energy range of the spectrum [4, 5]. However, the results obtained in the FERMI [6] and AMS-02 [7] satellite experiments, do not indicate a significant spectrum break at these energies.

Thus, the use of the calorimeter in the PAMELA experiment, providing the capability to achieve a higher energy limit, helps to clarify the current situation with the previous and current observations.

2. The PAMELA experiment

The PAMELA magnetic spectrometer is designed for high-precision measurements of the particle spectra in a wide energy range. The apparatus consists of the following detectors: scintillation time-of-flight system, TOF, magnetic spectrometer, anticoincidence system, electromagnetic calorimeter, shower scintillation detector C4 and neutron detector. The geometric factor of the PAMELA apparatus defined by the magnetic spectrometer aperture is $21.6 \text{ cm}^2\text{sr}$. A detailed description of both the entire PAMELA apparatus as a whole and of its separate detectors and measurement conditions is given in [1].

To increase the geometric factor and improve the statistical reliability of the results a combination of the calorimeter and the C4 detector were used. Let us consider the design of the calorimeter in more detail.

Calorimeter [8] consists of 44 (x, y) layers of silicon strip detectors, between which 22 tungsten layers ($Z = 74$, $A = 183.85$, $\rho = 18.1 \text{ g/cm}^3$, $X_0 = 0.3735 \text{ cm}$) each 2.6 mm thick are located. Each detector layer includes a set of 96 strips with a pitch of 2.2 mm. It allows measuring particle coordinates in two planes and thus obtaining spatial distribution of secondary particle cascade developed in the calorimeter. The total thickness of the calorimeter is 0.6 of nuclear interaction length or 17 radiation lengths.

3. Measurement of electron-positron spectrum

A set of data stored in the memory while registering the particles at any trigger action of the PAMELA apparatus is called an event. Calorimeter and C4 triggers run when only a certain value of the energy is released inside the calorimeter or C4, which corresponds to the occurrence of a secondary particle cascade in the calorimeter by particles interacting within the apparatus, mainly that of the calorimeter.

The dominant background consideration for charge one particles are protons. Given that protons vastly outnumber electrons in cosmic rays, the task is to adequately separate electrons from protons, and even more challenging positrons from protons.

The contamination by nuclei in the selecting events was suppressed using scintillation detectors, when events with a particle charge more than one were selected by ionization losses. The contamination by these particles appeared to be less than 1%.

All selection conditions described below and their efficiencies were tested and optimized by Monte-Carlo simulation, beam-test data and by inter-comparing with the magnetic spectrometer data where it was possible.

The initial event selection criterion for the particle spectrum construction was exceeding of some value of the total energy release in the calorimeter that is higher than a trigger threshold. This criterion made possible the separation the high-energy particles (more than tens of GeV).

Next event selection criterion was a choice of the events with well measured direction of the primary particle along the shower axis in the calorimeter. Direction measurement in the calorimeter is possible for particles coming at an angle of not more than 75° to the vertical. To determine the shower axis direction an iterative approach was used, which is based on the least squares fit method, and yet for calculating the shower axis coordinates only those strips are used that are the closest to the shower axis, that considerably improves angular resolution [9].

Events that do not cross the calorimeter at angles greater than 15 degrees to the vertical were selected.

One of the parameters used for the selection of electrons associated with the transverse shower development is the “RMS root mean square deviation” parameter. It is an expression of the standard deviation of energy release at a certain distance from the shower axis from the energy value on the shower axis.

Besides information about the transverse shower development in the PAMELA calorimeter, information about its longitudinal profile was also used for stronger proton suppression.

Additionally, one of the criteria, that made it possible to highlight the electron component, was energy release in the region along the shower core. So the information only from strips nearest to shower axis was used while for the RMS transverse selection the information from all strips in whole plane was used.

However, events selected as a result of using the above criteria, contained not only the electrons and positrons, but also high fraction of background protons because of their, as it was mentioned above, vast number in the cosmic rays.

In order to restore the primary spectrum of electrons and positrons, it was necessary to estimate the fraction of background protons in each energy interval, which the range of measurement was divided into. This was done on the basis of cosmic-ray proton spectrum [10] experimentally measured with the PAMELA calorimeter and data on the proton fraction remaining after the selection, obtained in the simulation.

Thus, the number of protons N_p in each energy interval, which the range of the electrons and positrons spectrum measurement was divided into with the PAMELA calorimeter, was calculated according to the following expression:

$$N_p(E_1 \div E_2) = \int_{E_1}^{E_2} F(E)G\varepsilon(E)\Delta t dE$$

where E_1 , E_2 are boundary values of the proton energy intervals at which proton contribution into the given energy range of electrons spectrum cannot be considered negligible (calculated from the simulation), $F(E)$ is a differential energy proton spectrum, taken from [10], G is geometric factor that at high energies of the particles does not depend on the energy, $\varepsilon(E)$ is relative proton number left after the selection estimated in the simulation and Δt is time of measurement.

The value of $\varepsilon(E)$ obtained from simulation is verified by coincidence of the proton calorimeter spectrum, that had been obtained by means of simulation, and the results of proton spectrum measurements in the similar energy range by other experiments (see for example [11, 12]).

In the last highest energy intervals proton fraction exceeded 75%, and to increase reliability of the results obtained from electrons and positrons spectrum additional electron selection with the help of neutron detector was carried out.

The threshold cut for neutrons equals to 8 helped eliminate the proton background. If the number of neutrons less than 8 it is electron or proton with some probability, but if number of neutrons is large than 8 it is with high probability proton. The neutron detector rejection was applied for last three energy bins and it reduced proton contamination there to the level of 40% while it was not applied for two first energy bins where the level of proton contamination was 15 and 40 %, respectively.

Geometric factor and events selection efficiency were calculated by simulation. Energy was determined by measuring calorimeter total energy release. For the energy range 1500 - 3000 GeV, events satisfying to selection criteria were not found, and only upper limit for the total electron and positron flux was set.

Figure 1 and 2 show results obtained for electron-positron spectrum in the energy range of 300-3000 GeV in comparison with the experimental results of other authors (ATIC[13], AMS-02 [7], FERMI [6], HESS [4], Kobayashi [5]) and with the PAMELA magnetic spectrometer measurement [14]. Errors are related to the statistical uncertainty only.

Taking into account the uncertainty in the energy measurement amounting to 15% in the HESS experiment, it can be concluded that the results of the PAMELA calorimeter are closer to the ground based experiment results of HESS and Kobayashi [5] than to the satellite ones: FERMI [6] and AMS-02 [7]. Thus the new PAMELA results show a clear spectrum drop near 300-400 GeV, while the other two satellite experiments did not indicate the existence of a sharp spectrum change.

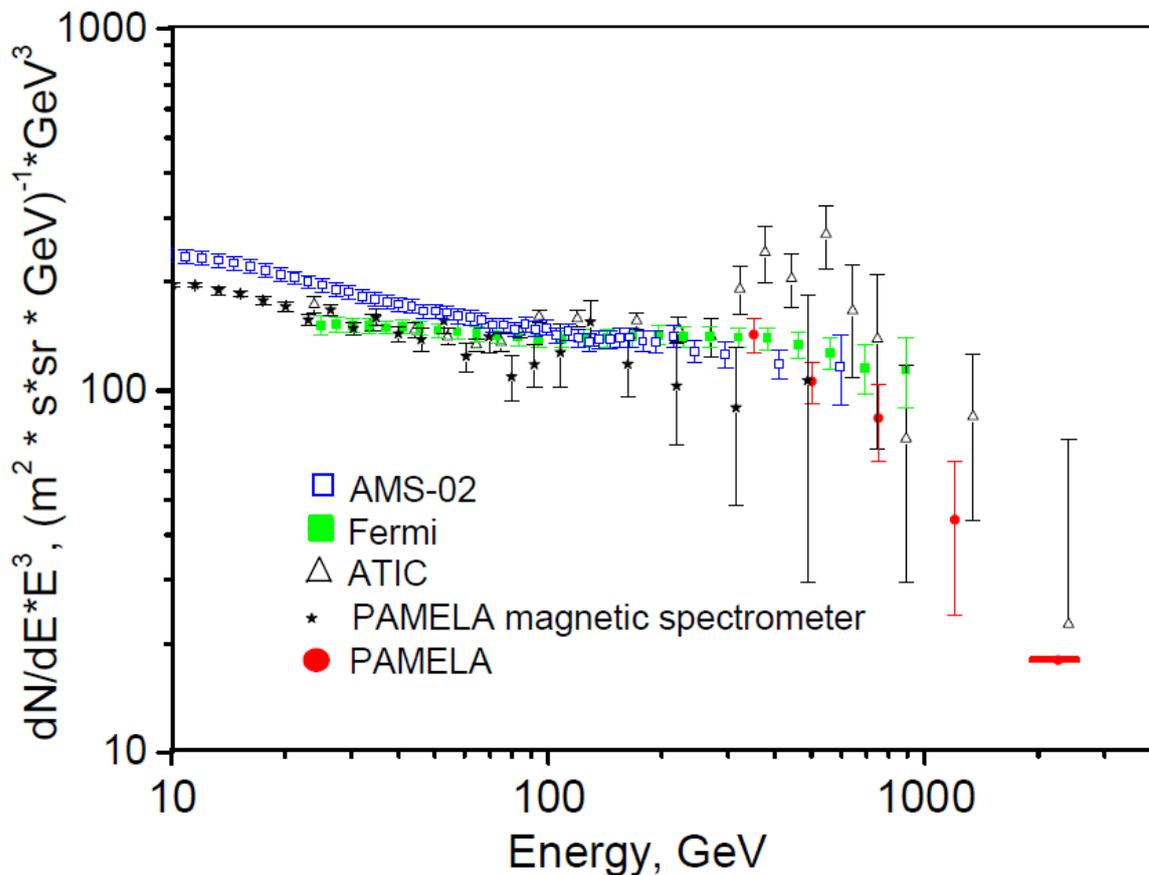


Fig.1 The obtained electron-positron spectrum in compare with direct measurements.

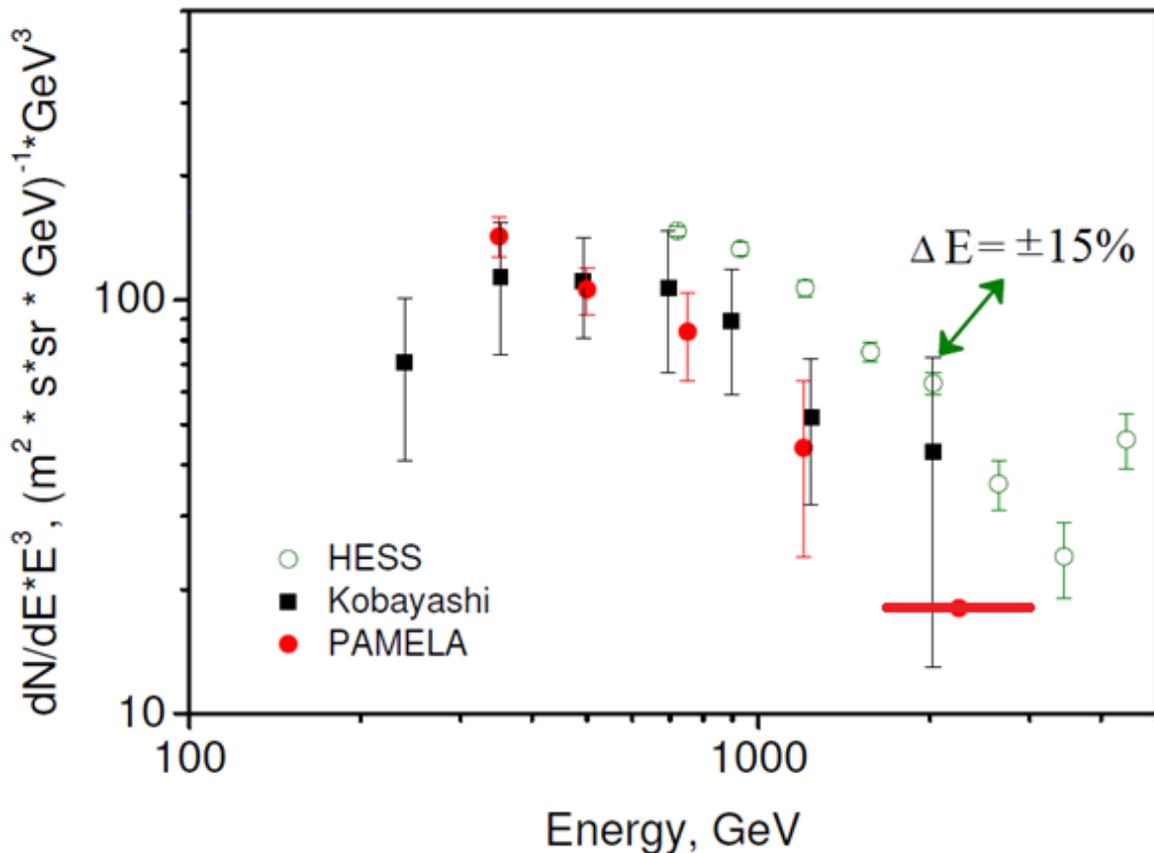


Fig.2 The obtained electron-positron spectrum in compare with ground-based measurements. The 15% for HESS measurements represents an upper limit for possible systematic energy shift.

4. Conclusion

New data obtained by the PAMELA calorimeter allowed comparison of results of the positron-electron spectra measurements with other ones in the high energy range. For the total positron-electron spectrum a sharp cutoff mentioned by HESS and Kobayashi is verified.

5. Acknowledgments

We are grateful to the Russian Science Foundation (grant no. 14-12-00373) and the President of the Russian Federation (grant no. MK-4599.2014.2) for support.

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