The high energy electrons with the PAMELA calorimeter

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Abstract: The PAMELA magnetic spectrometer, being the main part of the equipment, has a finite size and consequently the upper limit of energy measurements. Nevertheless the PAMELA calorimeter has the possibility to significantly increase the statistics, by involving in an analysis the events with trajectories outside the magnetic spectrometer aperture. It has made it possible to measure the electron cosmic ray spectrum in the energy range 300 - 1200 GeV with sufficient accuracy. In addition a electrons track reconstruction inside the calorimeter, that includes tracks with large angles, was used to obtain west-east and a north-south intensity asymmetry for the high energy electrons.

Keywords: PAMELA, electrons, calorimeter, asymmetry.

1 The PAMELA experiment

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 particle and antiparticle fluxes in a wide energy range. The PAMELA apparatus [1] 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 layer's 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. This work has been made on the base of the calorimeter data. 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.

2 The basic selection and the shower axis reconstruction procedure

We have considered events that came within a "wide" aperture. The "wide" aperture is defined not by the magnetic spectrometer opening angle but by the calorimeter size. For the "wide" aperture particles can penetrate through the calorimeter from any direction and the only limit was that an angle between vertical and a particle direction has not to be larger than 75°. The first step as the basic cut was the threshold for a total energy release inside the calorimeter - Etot. This value is measured by mips - 1 mip is the energy that released when a minimum ionization particle crosses a single detector layer. Such criterion allows extracting the events corresponding to the high energy particles generating a shower inside the calorimeter. The certain amount of energy release doesn't correspond to the identical values of primary energies for protons, electrons and nuclei. The GEANT simulation [3] has shown that the certain energy release could correspond to certain electron energy or few times higher proton energy as well. The next selection criterion was sampling of events that had a well distinguishable track inside the calorimeter. Otherwise if there were no tracks the events were discarded. Most probable the last type of events has been generated by particle interaction with the Pamela magnetic system or with the structure of the satellite and these primary particles didn't penetrated into the calorimeter. In case of registration of the high energy particle (more than 10 GeV) the strip with maximum energy release is situated close to the particle trajectory $r \leq R$ (R depends on total energy release). This takes place within all calorimeter layers when the primary particle crosses them. When the particle energy is low as well as there is no primary particle penetrated into the calorimeter the particle cascade has the large fluctuations and value of r exceeds R significantly. The direction reconstruction algorithm consists of multi-step resolving of the shower axis equation. The first step is calculating of centers of gravity within the clusters for a set of X and Y layers. The cluster is defined as a group of strips with energy release more than 0.1 mip. Next 3 steps are the recalculations of the positions of centers of gravity. With the new positions a new iteration of least square linear fit of the trajectory is performed. Such procedure helps to exclude side distorted clusters and determine the better positions of centers of gravity by using only strips from core of the shower. However some types of events require an additional procedure. They are "abutting" to the sides of the calorimeter. In this case the track disappears in the calorimeter side but the layers that have no energy release nevertheless have an influence on the reconstructing trajectory. To avoid this effect all the planes that are lower the last layer where a cluster border is 0 or 96 and have the weight (for a least square fit procedure) lower than 0,7 of this last layer weight were excluded from analysis. As a result the track can be reconstructed for "abutting" events as well. The more precise explanation for this method can be found in [2].

3 The high-energy electron-positron spectrum

The shower axis reconstruction procedure, that defines the primary particle direction inside the calorimeter, is a crucial stage of the electron-proton separation method. In this method all parameters used are closely related to the shower axis. The GEANT simulation has been used to estimate the values of parameters corresponding to protons and electrons. One of these parameters RMS (root mean square) associated with a lateral development of the shower. RMS represents the roof-mean-square deviation of energy release at some distances from the shower axis from energy release straight at the shower axis. RMS indicates the transversal density of the shower inside the calorimeter and is defined by:

$$RMS_l^2 = \frac{\sum_l^i E_l^i (X_i - X_l^c)^2}{\sum_l^i E_l^i}, \qquad (1)$$

where l - the number of the calorimeter plane, i - the plane strip number, E - the energy release, X - the shower axis coordinate, X - the strip coordinate. The value of RMS depends on the shower shape in the certain calorimeter. In case of the PAMELA calorimeter, E_l^i has to be taken squared that corresponding to the simulation results of the electromagnetic interaction inside the PAMELA calorimeter. The longitudinal development of the shower is also important to separate electrons from protons. To calculate longitudinal RMS strips have been changed on planes while the summation has been made within the whole calorimeter. The energy release along the shower axis is another parameter. According to Molier shower development theory 90 % of the shower energy is concentrated within 1 Molier radius around the shower axis. This parameter has been used for different planes of the calorimeter. By this method the proton rejection was achieved at the level 10^{-3} for protons with energies within 0.1-8 TeV and 10^{-4} for protons with the energies within 8-20 TeV. The more detail description of this method one can find in [4]. The electron energy has been obtained from the Etot. But the dependence of Etot on electron energy is not linear at high energies. To estimate this effect caused by a strip saturation the experimental flight data has been used. The acceptance and selection efficiency have been obtained by GEANT simulation. To calculate proton contamination the proton spectrum with -2.7 slope index has been simulated. On the base of the experimental data within the period 2006-2009 the electron-positron spectrum has been obtained (See Fig.1). The errors are statistical. One can see the good agreement with the experimental results of PAMELA that has been obtained with magnetic analysis [5] and with FERMI results [6]. The last value in the energy range 900-1500 TeV seems to be higher then other points. That might be caused by the underestimated proton contamination in this region. In what follows the period 2009-2013 will be involved into this analysis an and extra check in the region 900-1500 TeV for protons will be made.

4 The east-west effect

The east-west effect [7] is when one can measures more positive particle in the West and less on the East and otherwise for negative particles. The Fig.2 shows the Ne/Nw ratio of selected according to the section 2 events (it is mainly a mixture of protons and electrons). The number of events that has arrived from East Ne is more than from

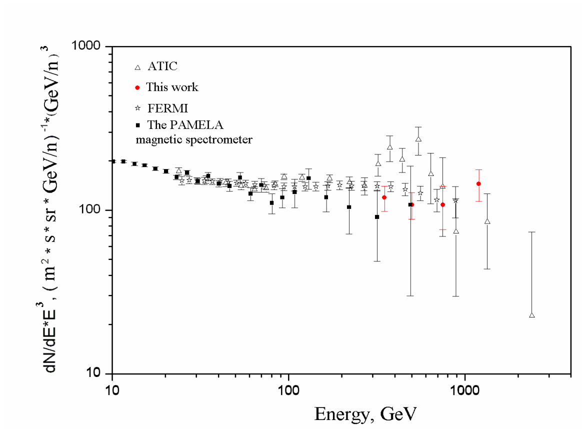

Fig. 1: The electron-positron energy spectrum.

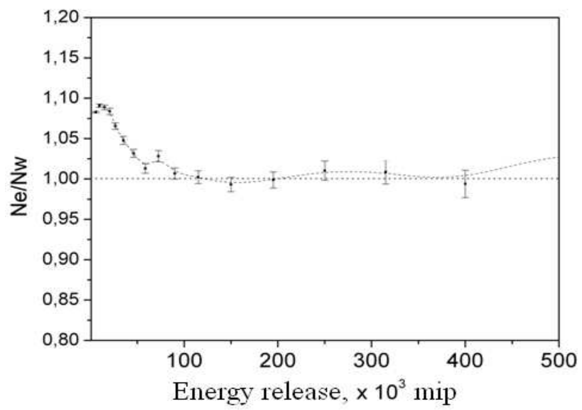

Fig. 2: Ne/Nw as a function of the total energy release inside the calorimeter.

West Nw. This asymmetry exists in the range 4000 mip - 100000 mip in terms of Etot. The prevalence of events from East upon events from West means that among selected events the electrons (negative charge particles) are the significant part. It is well known that electron-proton ratio in cosmic rays is about 1:100. However in the calorimeter as it was said before protons deposit less energy than electrons and just partially generate showers while electrons generate showers in almost 100% cases. So the number of electrons among selected events is significantly higher than in cosmic rays. To prove the connection of obtained asymmetry with the east-west effect the Ne/Nw ratio was measured at different L shells. The more is L the weaker is influence of the Earth magnetic field. The obtained asymmetry decreases with the increase of L. This confirms the nature of that asymmetry. As it could be seen on Fig.2 the Ne/Nw is rising up to 12000 mip and than the decrease begins. Etot=12000 mip corresponding to the shower that is initiated by 75 GeV electrons or 200-250 GeV protons. To estimate the significance of the obtained east-west asymmetry the following approximation has been used. The selected events are positive and negative particles. The suggestion is that in the Etot range which starts from 12000 mip the negative charged particle are shifted by the Earth

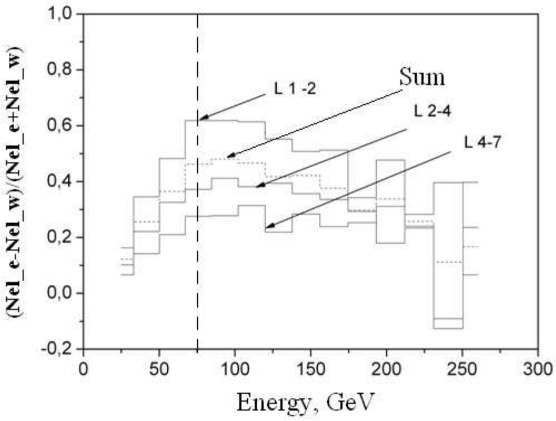

Fig. 3: The estimated (Nel_*e*-Nel_*w*/(Nel_*e*+Nel_*w*) for electrons as a function of the electron energy. The dotted line shows where an influence of protons can be neglected.

magnetic field while protons are not. Then Ne and Nw number of particles might be written as follows:

$$Nw(Etot) = N(Etot) + Nel\_w(Etot) \quad (2)$$

$$Ne(Etot) = N(Etot) + Nel\_e(Etot) \quad (3)$$

where N(Etot) - the background of positive particles, Nel_*e* , Nel_*w* - East and West electrons number, Etot - the total energy release inside the calorimeter. With knowledge of the electron flux from [5], the acceptance, the measurement time and the selection efficiency the number of electrons was estimated as Nel(Etot).

$$Nel(Etot) = Nel\_e(Etot) + Nel\_w(Etot) \quad (4)$$

So here we have the combined equations that have to be resolved for N, Nel_*e* and Nel_*w*. The result in terms of (Nel_*e*-Nel_*w*/(Nel_*e*+Nel_*w*) for different L shells is demonstrated on 3. One can see the slow decrease from 75 GeV to 250 GeV. So for energies more than 250 GeV asymmetry couldn't be tracked. In the range lower than 75 GeV for electrons the positive particles have energies less than 250 Gev and are shifted by magnetic field as well as electrons and make ratio (Nel_*e*-Nel_*w*/(Nel_*e*+Nel_*w*) lower. But at energies more than 75 GeV just electrons are responsible for a measurable effect. At energy 75 GeV and L = 1-2 the ratio (Nel_*e*-Nel_*w*/(Nel_*e*+Nel_*w*) is about 0.6. It means that a count rate (the number of events per second) of electrons is in 4 times more intensive from the East than from West.

5 The north-south asymmetry

To compare count rates Nn - at North, and Ns - at South, it was decided to limit the regions where the satellite was inside the polar areas and where the geomagnetic conditions of measurements are similar. In this regards the zones in North and South with L shell interval 4-15 was chosen. Thus the geomagnetic cutoff conditions were the same in the regions where count rates were compared and this was vital in regards to attaining asymmetry. The studied events were taken for the time period June 2006 - May. 2009. However some events inside the selected zones had the trajectories that were bent by the geomagnetic field. Initially these particles travel to low latitude areas but arrived in high latitudes due to the geomagnetic field. To eliminate this effect additional selection was implemented. The particle directions in the equatorial system were used. Declination measures the angular distance of an object perpendicular to the celestial equator, positive to the North, negative to the South. Right ascension measures the angular distance of an object as well as the celestial equivalent of longitude. For the additional selection the particles travels northward and southward were taken by such a way that the declination had to be in ranges (-60°- - 80° South) and (60° - 80° North). To describe the asymmetry the value (Nn-Ns)/(Nn+Ns) has been used. The (Nn-Ns)/(Nn+Ns) time dependence is shown in Fig4. The time interval was 90 days, it started from the satellite launch time and the first data transfer (it was 187th day of 2006). The data was analyzed since the 180 day of flight because before it there were trigger adjustments that could influence on the count rate. The PAMELA turn-off in bin 9 caused the (Nn-Ns)/(Nn+Ns) drop. Looking at Fig4 one can make a conclusion that (Nn-Ns)/(Nn+Ns) doesn't change significantly during the observation period and the north count rate is higher 3-4 % during all time. The Fig5 represents the (Nn-Ns)/(Nn+Ns) dependence on total energy release inside the calorimeter. The decrease of this value is traced from 4000 mip up to 30000 mip, the last value corresponding to 100 GeV electrons. As it was said before, a certain Etot corresponds to certain energy of proton and a lower energy of electron. For example 4000 mip matches with 50 GeV proton and 10 Gev electron. It results in the fact that the portion of electrons was higher between selected events than it was in primary cosmic rays. In other words electrons have lower energy then protons for certain energy release Etot and as a consequence it was more probable that these electrons are responsible for north-south asymmetry, which is higher for lower Etot. To confirm this statement East-West effect was used. This result confirms the significant portion of electrons inside the set of events. The comparison of the East-West effect for North and South arriving particles that cross the calorimeter with high angles (for such type of events the East-West effect is more visible) gives that Nw/Ne= 0.927±0.001 in South region while Nw/Ne= 0,908±0.001 in North one. In addition the neutron detector of PAMELA instrument selecting the electron like events provided an increase of a count rate in North region. To avoid the influence of the unknown registration efficiency and exposure, irregularity of background effects and so on the method of the "isotropy map" [8] has been used to get north-south asymmetry. The method of the isotropy map creation is to randomize the reconstructed directions of events. In case the direction distribution of the cosmic ray flux is ideally isotropic, a time-independent intensity should be detected when looking at any given instrument direction. Possible time variation of the intensity would be due only to changes in the operating conditions of the instrument. A set of isotropic simulated events can be built by randomly coupling the times and the directions of real events in local instrument coordinates. The randomization is implemented starting with the position of a given event in the PAMELA frame and exchanging it with the direction of another event, which was selected randomly from the data set with a uniform probability. Starting with this information, the sky direction is reevaluated for the simulated

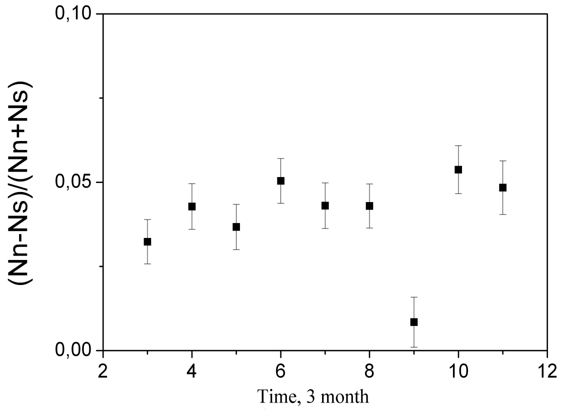

Fig. 4: (Nn-Ns)/(Nn+Ns) as a function of the time.

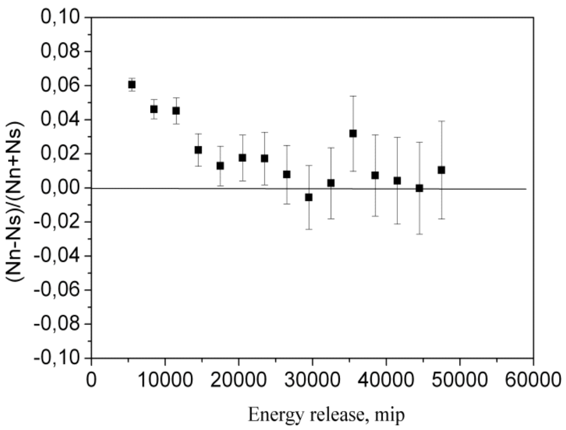

Fig. 5: (Nn-Ns)/(Nn+Ns) as a function of the total energy release inside the calorimeter.

events. The random coupling maintains the exposure and the total number of events. By this construction, the simulated data set preserves exactly the energy and angular distributions (with respect to the PAMELA reference frame), and also takes into account the detector dead times. The significance map is obtained from the experimental events and isotropy map. As the results for particles that have declination $\geq 60^\circ$ significance was higher. It was calculated that to achieve the obtained excess of events on North it is needed that electron flux was 3-5 % higher in the North region.

6 Conclusions

For 2006-2009 time period in the PAMELA experiment on the base of the calorimeter analysis were obtained results for the electron energy spectrum at high energies, East-West and North-South asymmetries. These results can be used for understanding of processes that happen with particles when they cross interstellar medium, geomagnetic field and heliosphere.

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