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Measurement of antiproton flux in primary cosmic radiation
with PAMELA experiment


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Abstract. The new method based on the classification algorithms was developed to separate antiprotons and electrons in the PAMELA experiment. Training samples based on Monte-Carlo simulation of particle’s interactions in the PAMELA imaging Si/W calorimeter were used to achieve rejection factor and to keep high antiproton efficiency. With comparison to the previous publication the number of events was increased 1.5 times. Information collected from the mission start in 2006 till January 2010 was used in the analysis. 2800 events were found in the energy range from 60 MeV to 350 GeV. The flux of antiprotons in galactic cosmic radiation obtained with new method is presented.
1. Introduction

For the first time antiprotons in cosmic rays were detected in the eighties of last century [1, 2]. The main reason of interest in their study was associated with the problem solution of the baryon asymmetry of the Universe. However, it soon became clear that the cosmic antiprotons are produced in interaction of high-energy nuclear component of cosmic radiation with interstellar gas (for example, [3]), and for study the problem of the baryon asymmetry more heavier antinucleus must be registered, or at least to set an upper limit on their flux [4].

At present time using a magnetic spectrometer PAMELA [7] (a Payload for AntiMatter Exploration and Light nuclei Astrophysics) precision measuring of antiparticles flux in the primary cosmic radiation are held. Launching of the satellite "Resurs-DK1" with the scientific instrument on board was in June 2006. It is located inside a pressurized container, and includes the following systems: a time-of-flight system (ToF), a coordinate-track system (tracker), a coordinate-sensitive calorimeter, an anticoincidence system, a shower tail catcher scintillator, a neutron detector. Such set of detectors allows determine the magnitude and sign of charge, rigidity, velocity, mass and energy.

In 2010 the energy spectra of galactic antiprotons and the energy dependence of the protons and antiprotons fluxes ratio in the range of energies from 60 MeV to 180 GeV, using information which was collected until the end of 2008 were published [8]. The data in this energy range are obtained for the first time. Analysis of the results shows that they are consistent with the calculations in GALPROP program without introducing of additional sources of antiprotons [9]. This means that the galactic antiprotons are secondary particles produced in interactions of high energy cosmic hadrons with interstellar matter. However, the statistical availability of results, especially near the upper energy limit is not enough to reliable exclusion of other sources. In this paper, in order to increase the statistics and get results at higher energies the selection of antiprotons with calorimeter has been optimized and the analysis of "spillover", that is errors in measuring the sign of the charge due to the finite spatial resolution of the spectrometer, or small-angle scattering in the inner planes of the tracker was held. Moreover, for analysis the information accumulated before January 2010 has been used.

2. Antiproton selection with Multivariate analysis

The main criteria for selection of events are similar to those used previously [4, 8 and 10]. Primary cosmic rays are distinguished by the condition \( R > 1.2 R_C \), where \( R_C \) is the local geomagnetic cutoff rigidity at the site of the event registry.

In order to exclude the electrons which content in the cosmic rays by 2-3 orders higher than that of the antiproton from the analysis, an additional selection related to the information from the calorimeter having a thickness of 0.6 nuclear and 16 electromagnetic lengths is needed. Electromagnetic and hadronic interactions differ by topology due to different nature of particle, which forming the showers. In order to characterize the showers the parameters that describe the longitudinal and transverse profiles, the initial point of interaction and energy deposition in different parts of the shower, were introduced. For example, \( Q_{\text{max}} \) - the maximum energy deposition in the calorimeter, \( Q_{\text{track}} \) - energy deposition along the reconstructed axes of shower and others. This parameters are described in detail in the works [8, 11] and in their references.

In our case there are a large number of parameters, therefore for separation of electrons and antiprotons the mathematical model of data classification that is a part of MVA (Multivariate analysis) algorithms was used [12]. In the work the classification of the training sample, based on modeling the passage of electrons and antiprotons through a spectrometer is used. At the same time a set of values of all parameters by which the classification is going for two classes (types of particles) is forming. Classification algorithms are implemented in MatLab environment. The result of it is a hypersurface in the space of dimension equal to the number of used parameters. The hypersurface divides the space into two parts: electronic events are concentrated in one part and antiprotons are in another one. The method can be illustrated on an example of parameters \( Q_{\text{max}} \) and \( Q_{\text{track}} \). The distribution of electrons and antiprotons by them for the rigidity of 8 GV is shown in Figure 1. Two methods of classification
shown of solid (Bayes classifiers) and dotted (Mahalanobis distances) lines have been used in this work.

Figure 1. Example of electrons and antiprotons classification in the case of $Q_{\text{max}}$ and $Q_{\text{track}}$.

In order to separate electrons and antiprotons at low energies ($|R|<2\text{GV}$) independent measurements of the ionization losses in the tracker planes and ToF counters have been used. From Monte-Carlo calculations electron rejection is better than $10^{-4}$ and the efficiency of antiprotons selection is higher 90% in all energy range. In this case the expected admixture of electrons will not exceed 1-2%.

As the energy increases "spillover", i.e. fraction of protons with the wrong sign of the charge is increasing too. In order to check it the following criteria of events selection are used [4]:

- coincidence of coordinates, measured by system of ToF counters, tracking system and calorimeter;
- check the coincidence of the measured rigidity using different parts of the trajectory tracker;
- constraints on the size of the clusters in tracker and on the number of signals that do not belong restored track;
- constraint on the measured rigidity $|R|<\text{MDR}/3$, where MDR - maximum detectable rigidity. It was calculated for each event, taking into account the topology of the track and measurement errors in the coordinates in each of the planes. The criteria allow us to extend the energy diapason up to 350-400 GeV in comparison with previous work [8].

Figure 2. The deflection distribution for selected antiprotons (shaded histogram) and protons.

The deflection distribution for selected negatively- and positively-charged particles is shown on figure 2. The shaded histogram corresponds to the antiprotons. The good separation between negatively charged particles and "spillover" protons is evident.
3. Results and conclusion

As a result of the analysis 2800 antiprotons in energy range from 150 MeV up to 180 GeV have been selected. In energy range from 60 MeV up to 150 MeV and from 180 GeV up to 350 GeV antiparticles have not been detected and upper limits on their fluxes have been fixed. In applying the optimized method an agreement with previous published results has been obtained [8] (figure 3), however, the statistics has been increased and energy range of measure has been widened.

![Figure 3. Antiproton to proton flux ratio: comparison of published results [8] and after optimization.](image)

Systematic uncertainties was estimated with different classification methods of antiproton-electron separation, test methods on different Monte-Carlo samples, analysis of "spillover" with different variety of using parameters and fuzzy logic. The final result is stable within the scope of 2-10% depends on energy.

Obtained in this work results allow to make a more detailed comparison with theoretical models. The method of events selection used in this work was effective, allowing to improve the experimental results that are of great interest.

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