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Splash and Re-entrant albedo fluxes measured in the PAMELA experiment

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Abstract

This work devoted to the description of the method for splash albedo protons identification in the satellite-born experiment PAMELA. In contrast to the reentrant albedo particles, which enter into the main aperture of the instrument, the direct albedo particles enter from the opposite direction, so they pass a few detectors, including calorimeter, before being register by the magnetic spectrometer. The developed method take into account the influence of these detectors on the selection of events and measurements of their characteristics. To test this method the energy spectrum of reentrant albedo protons in various regions of the near-Earth space reconstructed; it is in a good agreement with the classical measurements in the main aperture. Therefore, this method can be useful to obtain a new physical data about fluxes of splash albedo protons in the PAMELA experiment, which, unlike the reentrant albedo, can be study even at high geomagnetic latitudes.

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Keywords: PAMELA, splash albedo

1. Introduction

The albedo component of cosmic rays is a charged particles flux formed by interactions of high-energy primary cosmic rays with atomic nuclei of the residual atmosphere, and went into the near-Earth space. There are several ways of classifying albedo particles today, and one of them based on the mechanism of their motion in the magnetic field of the Earth. So-called splash albedo moves along a field force line in the direction from the point of generation to the geomagnetic equator, i.e. from the Earth. Another one, so-called re-entrant albedo – moves the opposite direction, i.e. to the Earth (Treiman S.B. et al. [1], K. Wang [2]).

Van Allen [3, 4] and F. Singer [5] discovered the albedo particles in 1949 in experiments on cosmic probe-rockets designed to study the upper atmosphere. The most active period of study the particle fluxes of splash and reentrant albedo is 50-70th of last century with the scientific equipment installed on probe-rockets and balloons, for example N.L.*Grigorov*[6], A.E. Golenkov *et al. [7],* S.D. Verma[8], K.P Wenzel et al. [9]. However, methods of such kind are allow carrying out researches in limited regions of the near-Earth space, and a high level of background due to production of secondary particles in the residual atmosphere leads to deterioration of the measurements quality. In 1990 years a new series of experiments, which gave the possibility to measure a different kinds of particles including albedo, were carry out on spacecraft and orbital stations. Among them known experiments are NINA, NINA-2 (V. Bidoli et al. [10]), AMS-01 (J. Alcaraz et al. [11]) that measured the differential energy spectrum of albedo protons with energies of 10-50 MeV (NINA) and more than 200 MeV (AMS-01) in various regions of the near-Earth space.

Due to a whole set of experimental data it is known today that electrons, positrons and protons are dominating component of albedo, but a light nuclei are also presented. Among them, the electromagnetic component is most studied (A.J. Tylka [12]). Strangely enough, such important characteristics of albedo fluxes, as their intensity and angular distributions in different regions of the near-Earth space for nuclear components, in particular, for protons, are poorly studied (A.J. Tylka [12]). There are contradictions between the different experiments and disagreement with the theoretical predictions of the energy spectra and angular distributions (C.R. Pennypacker et.al. [13], K. Wang, A. Huang [14], P. Lipari [15], G. Battistoni et al. [16], O. Adriani et al. [17]) of albedo protons.

From June 2006 to present days the PAMELA magnetic spectrometer successfully working in the near-Earth orbit. Except of main scientific tasks of the experiment, it measure the fluxes of albedo particles with high accuracy for energies more than ~80 MeV(O. Adriani et al. [17]).Some time ago, the paper about re-entrant albedo proton fluxes measured by the PAMELA were published (O. Adriani et al. [18]).

In this work, the method of splash albedo protons identification with the PAMELA spectrometer is considered.

2. The PAMELA spectrometer

Since June 2006, the PAMELA experiment (O. Adriani et al. [17]) carried out on the Resurs-DK1 satellite. The main aim of this experiment is to study galactic cosmic ray flux with the focus on antiparticles, including the search for antiparticles. The layout of the instrument, based on a magnetic spectrometer, shown in Fig. 1. It includes the following detector systems:

- The time-of-flight system (ToF); it consists of six layers of scintillation counters, which are separated into strips and are grouped pairwise into three planes so that the strips in each pair are mutually perpendicular. The time-of-flight system makes it possible to determine the arrival direction and to measure the particle velocity β and serves as a trigger to begin obtaining information from all detector systems.
- The coordinate track system (tracker) consists of six two-sided (X and Y projections) planes of silicon coordinate-sensitive strip detectors located between sections of a permanent magnet, creating a field with an average of 0.43 T. The tracker makes it possible to measure the coordinates of a particle trajectory in two projections and to determine rigidity R (momentum-to-charge ratio) of the passing particle.
- The coordinate-sensitive calorimeter consists of tungsten plates and coordinate strip detectors between them. It makes it possible to measure the energy of the particles interacting in it and simultaneously used to identify them.
- The anticoincidence system designed to exclude from analysis events arriving beyond the aperture of the instrument.
- The lower scintillation avalanche detector used as a trigger for the interaction of high-energy particles in the calorimeter.
- The neutron detector used to detect neutrons appearing in the interactions in the calorimeter and, as a consequence, to separate leptons and hadrons.
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All the detectors, except for the neutron one, allow the measurement of ionization losses. This set of detectors is sufficient to determine the sign and magnitude of the charge, velocity, mass, and energy of particles.

3. Method

The PAMELA instrument on board the Russian spacecraft Resurs-DK1 located such that its main axis directed to the zenith. The particle direction (let it be d) determined relative to this axis, therefore, can be distinguish by two cases: "top-down" moving (or so-called down-going particles) and "bottom-up" moving (or so-called up-going particles). Then for the reentrant albedo moving toward the Earth, d=+1, and for the splash albedo moving away from Earth, d=-1. The PAMELA spectrometer can separate opposite directions using the sequence of operation of the Time-of-Flight detectors S1-S2-S3. In work of A.G. Mayorov et al. [19] it is shown that the characteristics of ToF system allow to do it with high reliability.

The first results of the PAMELA experiment about measurements of the reentrant albedo proton fluxes presented in O. Adriani et al. [18].Events selection criteria used in this work described in Adriani O. et al. [20, 21].

However, this set of criteria is not enough for selection of splash albedo particles because they are enter into the track system, where the energy measured, only after passing through the several detectors including the thin calorimeter. Therefore, the low-energetic nuclei will stop there and electrons/positrons will produce electromagnetic showers. Nevertheless, the nuclear component of splash albedo having enough energy to get through all the bottom detectors of instrument will be registers. The additional criteria for identification of splash albedo protons needed to be create. Therefore, particles passing through the spectrometer without interactions except of ionization losses must be select.

Namely, next additional calorimeter-based criteria was apply:

- Non-zero energy release in all of the 44 planes, i.e. particle passes through detector.
- Energy release in the upper and lower halves does not differ by more than 10% (considering the fluctuations of energy losses in single planes).
- No energy release on the edges of the calorimeter (3 strips from the edge for all 44 planes).
- The number of strips with non-zero energy release in each of the 44 planes is not more than three.

- The single trajectory in calorimeter has been successfully restore.
- The ratio of total energy release in cylinder with radius of four strips around particle trajectory to the total energy release in detector is greater than 0.95.

To calculate the characteristics of the PAMELA spectrometer with respect to the proposed selection the Monte Carlo simulation based on Geant4wasuse. We simulate monoenergetic up-going and down-going protons in a wide energy range.

Firstly, based on simulation data it were obtained a correction to the measured by magnetic spectrometer energy of particles associated with the energy losses in the material below the tracking system. Fig. 1 shows the dependence of simulated rigidity versus measured rigidity.

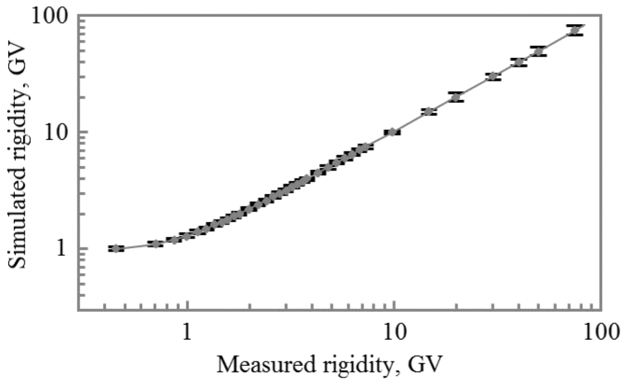

Fig. 1. Dependence of simulated rigidity versus measured rigidity (Monte-Carlo simulation data).

Energy losses in detectors below tracker for high-energy protons are negligible, so measured and simulated rigidities are approximately equal. With the decrease of the particles energy, relative losses in the calorimeter has increases, therefore measured rigidity is low than simulated. Protons with energy less than 1 GV cannot pass through the calorimeter and stop therein.

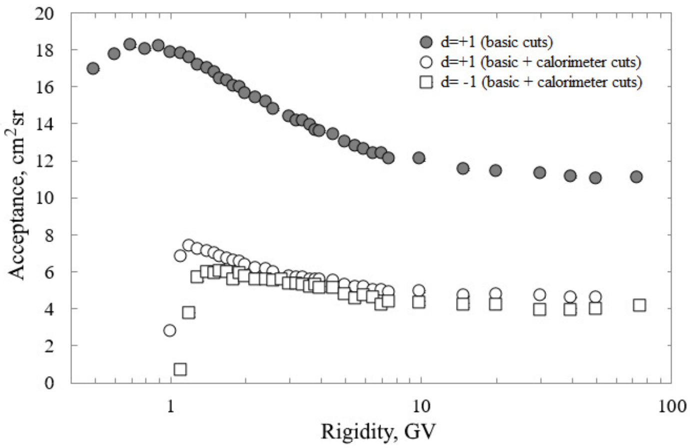

Fig. 2. Dependence of the acceptance of proton selection on its rigidity. (Errors are within the points.)

Second, the acceptance of PAMELA for our selection criteria were calculated. Fig. 2 shows the dependence of the acceptance on the simulated particles rigidity for three cases: 1) the standard selection that used in O. Adriani et al. [18] (filled circles) 2) selection with additional criteria applied to protons moving from top to down (open circles), and 3) selection with additional criteria applied to protons flying from bottom to up (open squares).

4. Results and discussion

The experimental data from the PAMELA spectrometer during four months of observations (August-November 2006) was processed with proposed method. The splash and re-entrant albedo protons selected and their differential energy spectra in different ranges of geomagnetic latitudes were determined. They are show in Fig. 3: left side – for the region of the geomagnetic equator 0<| θ_M |<0.2 and right side– for the near polar region 0.9<| θ_M |<1.

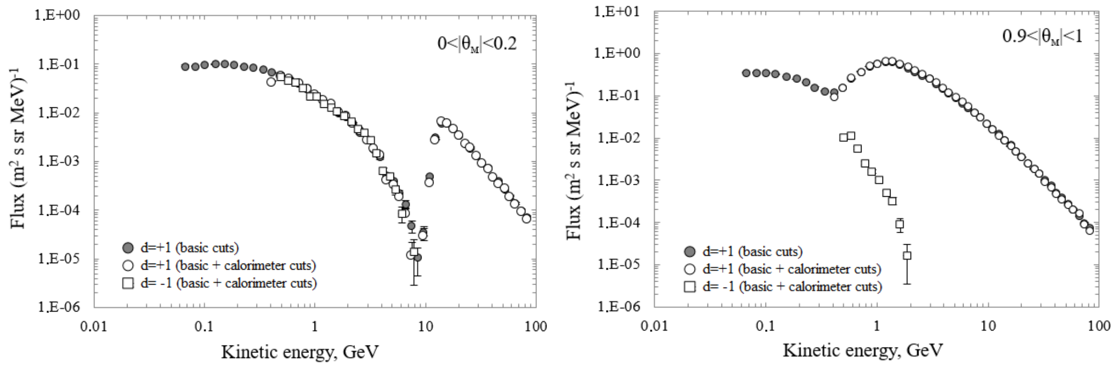

Fig. 3. Differential energy spectra of direct and return albedo protons (and GCR at energies above the geomagnetic cutoff rigidity) in the equatorial (0<|θ_M|<0.2) and near-polar regions (0.9<|θ_M|<1) with the PAMELA experiment.

The energy spectra of the re-entrant albedo protons restored in the main aperture (O. Adriani et al. [18]) (filled circles) and with proposed method (open circles) are in a good agreement. This testifies the correctness of the calculation of the PAMELA characteristics for the albedo particle selection discussed here.

Fig. 3shows that in the PAMELA experiment we can study the splash albedo flux (hadronic component) even at high geomagnetic latitudes. The down-going particles, entering into the instrument from above, include both galactic cosmic rays from interplanetary space and re-entrant albedo. With increasing of geomagnetic latitude the geomagnetic cutoff rigidity reduced, therefore it is difficult (or impossible) to distinguish the re-entrant albedo on the background of the dominant galactic flux in the polar region. At the same time, in the direction from the Earth's atmosphere only up-going splash albedo particles move, which observed experimentally (open squares).

5. Conclusion

The paper presents the criteria for the selection of splash albedo in cosmic rays in the PAMELA experiment. It shown that in comparison with re-entrant albedo, which can be study only in regions with high geomagnetic cutoff rigidity, PAMELA can explore the splash albedo with high accuracy in a wide range of geomagnetic latitudes.

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