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## Study of deuteron spectra under radiation belt with PAMELA instrument

S A Koldobskiy<sup>1</sup>, O Adriani<sup>2,3</sup>, G C Barbarino<sup>4,5</sup>, G A Bazilevskaya<sup>6</sup>, R Bellotti<sup>7,8</sup>, M Boezio<sup>9</sup>, E A Bogomolov<sup>10</sup>, M Bongi<sup>2,3</sup>, V Bonvicini<sup>9</sup>, S Bottai<sup>3</sup>, A Bruno<sup>7,8</sup>, F Cafagna<sup>8</sup>, D Campana<sup>5</sup>, P Carlson<sup>11</sup>, M Casolino<sup>12,13</sup>, G Castellini<sup>14</sup>, C De Donato<sup>12,15</sup>, C De Santis<sup>12</sup>, N De Simone<sup>12</sup>, V Di Felice<sup>12,16</sup>, V Formato<sup>9,17,\*</sup>, A M Galper<sup>1</sup>, A V Karelin<sup>1</sup>, S V Koldashov<sup>1</sup>, S Y Krutkov<sup>10</sup>, A A Kvashnin<sup>6</sup>, A N Kvashnin<sup>6</sup>, A A Leonov<sup>1</sup>, V V Malakhov<sup>1</sup>, L Marcelli<sup>15</sup>, M Martucci<sup>15,18</sup>, A G Mayorov<sup>1</sup>, W Menn<sup>19</sup>, M Merge<sup>12,15</sup>, V V Mikhailov<sup>1</sup>, E Mocchiutti<sup>9</sup>, A Monaco<sup>7,8</sup>, N Mori<sup>3,20</sup>, R Munini<sup>9,17</sup>, G Osteria<sup>5</sup>, F Palma<sup>12,15</sup>, B Panico<sup>5</sup>, P Papini<sup>3</sup>, M Pearce<sup>11</sup>, P Picozza<sup>12,15</sup>, M Ricci<sup>18</sup>, S B Ricciarini<sup>3,14</sup>, R Sarkar<sup>8,\*\*</sup>, V Scotti<sup>4,5</sup>, M Simon<sup>19</sup>, R Sparvoli<sup>12,15</sup>, P Spillantini<sup>2,3</sup>, Y I Stozhkov<sup>6</sup>, A Vacchi<sup>9</sup>, E Vannuccini<sup>3</sup>, G I Vasilyev<sup>10</sup>, S A Voronov<sup>1</sup>, Y T Yurkin<sup>1</sup>, G Zampa<sup>9</sup>, N Zampa<sup>9</sup>

<sup>1</sup> National Research Nuclear University MEPhI, RU-115409 Moscow, Russia

<sup>2</sup> Department of Physics and Astronomy, University of Florence, I-50019 Sesto Fiorentino, Florence, Italy

<sup>3</sup> INFN, Sezione di Florence, I-50019 Sesto Fiorentino, Florence, Italy

<sup>4</sup> Department of Physics, University of Naples "Federico II", I-80126 Naples, Italy

<sup>5</sup> INFN, Sezione di Naples, I-80126 Naples, Italy

<sup>6</sup> Lebedev Physical Institute, RU-119991 Moscow, Russia

<sup>7</sup> Department of Physics, University of Bari, I-70126 Bari, Italy

<sup>8</sup> INFN, Sezione di Bari, I-70126 Bari, Italy

<sup>9</sup> INFN, Sezione di Trieste, I-34149 Trieste, Italy

<sup>10</sup> Ioffe Physical Technical Institute, RU-194021 St. Petersburg, Russia

<sup>11</sup> KTH, Department of Physics, and the Oskar Klein Centre for Cosmoparticle Physics, AlbaNova University Centre, SE-10691 Stockholm, Sweden

<sup>12</sup> INFN, Sezione di Rome Tor Vergata, I-00133 Rome, Italy

<sup>13</sup> RIKEN, Advanced Science Institute, Wako-shi, Saitama, Japan

<sup>14</sup> IFAC, I-50019 Sesto Fiorentino, Florence, Italy

<sup>15</sup> Department of Physics, University of Rome Tor Vergata, I-00133 Rome, Italy

<sup>16</sup> Agenzia Spaziale Italiana (ASI) Science Data Center, Via del Politecnico snc, I-00133 Rome, Italy

<sup>17</sup> Department of Physics, University of Trieste, I-34147 Trieste, Italy

<sup>18</sup> INFN, Laboratori Nazionali di Frascati, Via Enrico Fermi 40, I-00044 Frascati, Italy

<sup>19</sup> Department of Physics, Universitt Siegen, D-57068 Siegen, Germany

<sup>20</sup> Centro Siciliano di Fisica Nucleare e Struttura della Materia (CSFNSM), Viale A. Doria 6, I-95125 Catania, Italia

\* now at INFN, Sezione di Perugia, I-06123 Perugia, Italy

\*\* now at Indian Centre for Space Physics, 43 Chalantika, Garia Station Road, Kolkata 700084, West Bengal, India

E-mail: koldobskiy@gmail.com



**Abstract.** This paper presents the results of measurements of proton and deuteron fluxes of albedo radiation in the Earth vicinity, obtained in the PAMELA experiment. PAMELA is an international experiment meant to study cosmic rays. PAMELA is carried out on board the satellite Resurs-DK1. High-precision equipment of the experiment allows registration and identification of cosmic ray particles of different varieties in a wide energy range. The albedo deuteron spectrum and albedo deuteron-to-proton fluxes ratio in the energy range 70 – 600 MeV/nucleon at altitude of 350 – 600 km for different geomagnetic latitudes is presented.

## 1. Introduction

Albedo radiation is a product of the interaction of primary cosmic rays (PCR) with the nuclei of the residual atmosphere by different processes. After their generation secondary deuterons move in the magnetic field of the Earth forming albedo fluxes under the radiation belt. The composition of atmosphere and cosmic rays are well known. Therefore the different mechanisms of deuteron generation can be studied by measuring the deuteron spectrum. In addition, knowing of the albedo deuteron flux is necessary for evaluating the radiation conditions at low altitudes in space.

The Earth's radiation belt and albedo radiation were discovered in 1957 by American scientist James Van Allen [1] and Soviet scientist S. N. Vernov [2]. It has been found that particles of albedo are predominantly protons [3, 4, 5]. Events, corresponding to heavier nuclei and electrons were detected as well in subsequent experiments. In [6] it was mentioned the registration of deuteron albedo radiation for the first time, in [7] the results of the unique attempt to measure the spectrum of deuterons under radiation belt in the AMS-01 experiment was presented. These results were compared with the calculated models described in [8, 9].

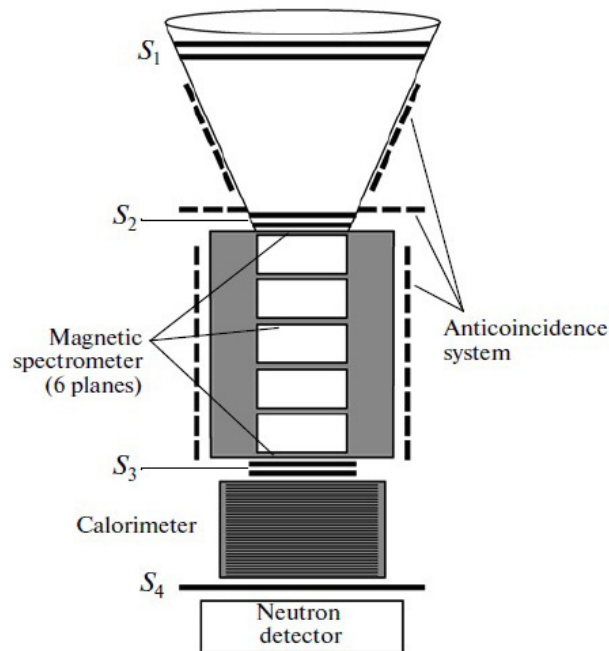
Results of the experiment AMS-01 [7] do not coincide with the computational model, which is based on the predominance of deuteron generation by means of nuclear reactions of the incident cosmic ray particles with the nucleons of the atmospheric nuclei. In view of the paucity of data on the measurement of deuteron fluxes under radiation belt new measurements, as well as verification and refinements, are undoubtedly required. In addition, these measurements are needed to precisely estimate the radiation environment in near Earth orbits.

In this paper we present the first results of data analysis for measuring the albedo deuteron spectra and d/p ratio for different geomagnetic latitudes. Data of the PAMELA experiment for period from 2006 till 2008 were used.

## 2. PAMELA experiment

PAMELA instrument [10] (Fig. 1) is a magnetic spectrometer (MS), composed by a permanent magnet hosting a tracking system and equipped with a time-of-flight system (ToF) and the calorimeter. The tracking system consists of six double-sided micro-strip silicon sensors. MS allows to measure the particle charge and rigidity (momentum over charge) with high precision. The time of flight system consists of three planes of double-layer plastic scintillators ( $S_1$ ,  $S_2$  and  $S_3$ ) and serves for precise measurements of particle velocity and energy losses. It provides the main trigger for the experiment. PAMELA apparatus also includes a tail shower scintillation detector  $S_4$  and neutron detector. The magnet is surrounded by scintillation counters operating in the anticoincidence mode (AC) used to select events with particles entering the spectrometer in its field of view.

Detailed description of the scientific equipment PAMELA detectors can be found in [10, 11, 12, 13].



**Figure 1.** The schematic view of PAMELA experiment.

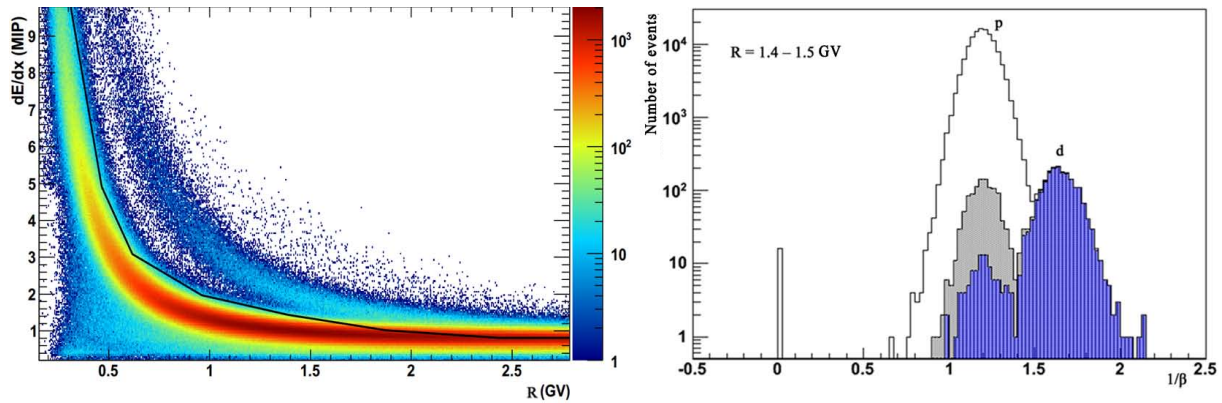
### 3. Particle identification

At the first stage of data analysis the selection of "good" events was carried out because only events with correct detector signals were used for subsequent event identification procedure. For this purpose, the analysis of the event characteristics was done to identify hydrogen isotopes in the energy range from 60 MeV/nucleon to 2 GeV/nucleon. The special set of criteria for implementing the so-called "basic" selection has been developed. Events that passed "basic" selection had no signals from anticoincidence detectors, corresponded to particle arriving inside the aperture of apparatus, with no interactions in the detector material, and characterized by well approximated trajectory in MS.

The most important and complex task was authentic identification of deuterons on the huge background of protons with similar detector signals. For the identification of detected particle nature, as well as the recovery of its energy the multivariate correlation analysis of the signals from the PAMELA detectors was used. The procedure of event identification was applied using values of particle rigidity  $R$ , measured by MS, its velocity  $\beta$ , measured by ToF and multiple measurements of the energy losses of ToF and tracker detectors. Multiple measurements of energy losses were used to suppress the proton background in  $1/\beta$  distributions where deuteron amount obtaining was implemented by direct counting for energies below 300 MeV/nucleon or by distribution approximation by two Gaussians for higher energies (examples of steps in particle identification procedure are in Fig. 2). Employment of this identification procedure allowed to distinguish deuterons in energy range from 100 to 600 MeV/nucleon.

Verification of particle identification procedure and selection efficiencies were fulfilled by comparing of flight data with Monte Carlo simulation results. The simulation was performed by means of the software package GEANT [14].

More detailed description of particle identification procedure can be found in [13, 15]



**Figure 2.** Left panel: Mean energy losses in MS versus rigidity distribution for protons and deuterons mix; black line is a cut used for proton suppression. Right panel:  $1/\beta$  distributions for narrow rigidity bin  $1.4 < R < 1.5$  GV without proton suppression (white distribution), using proton suppression with energy losses in MS (grey distribution) and in MS and ToF (blue distribution).

#### 4. Albedo deuteron spectra

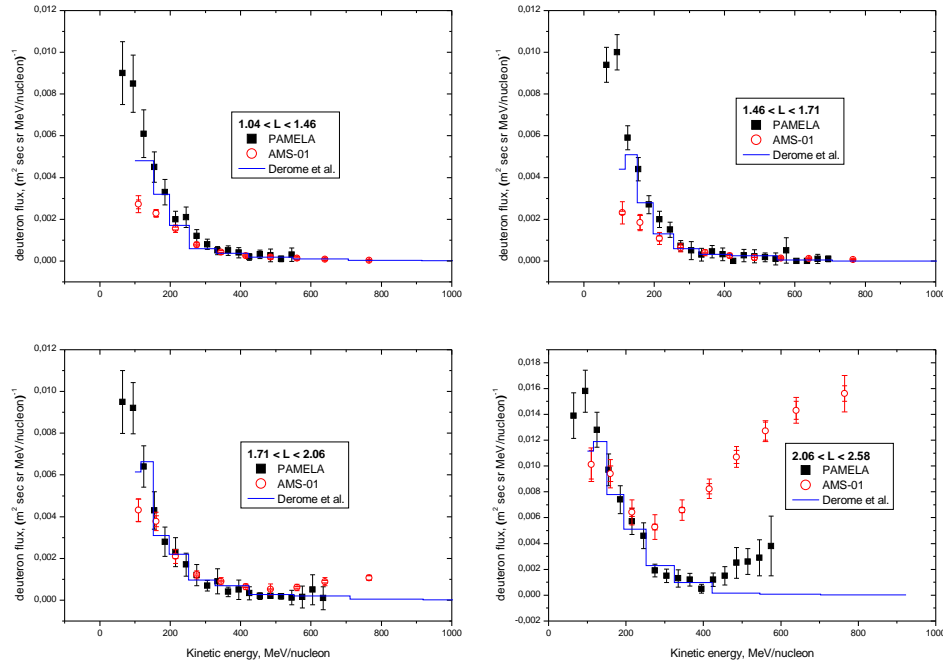
The deuteron spectrum in each narrow energy interval  $\Delta E$  for different geomagnetic coordinate intervals were calculated as follows:

$$\frac{dJ}{dE} = \frac{N(\Delta E, E)}{\Delta E \times \Gamma(E) \times \varepsilon(E) \times t_{live}},$$

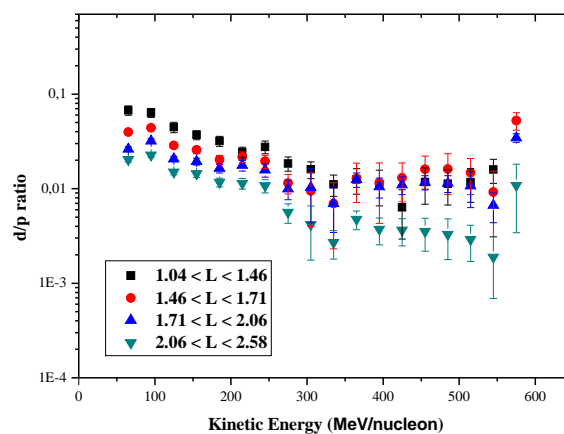
where  $N(\Delta E, E)$  – the number of particles with energy  $E$  registered in the energy interval  $\Delta E$ ,  $\Gamma(E)$  – the geometric factor of the instrument,  $\varepsilon(E)$  is the total efficiency of the event selection and  $t_{live}$  – “live” time of the spectra measurements. The cut on magnetic field value  $B < 0.23$  G was implemented to exclude radiation belt particles from analysis. Figure 3 shows the measured spectra of albedo deuterons for different geomagnetic latitudes  $\phi_M$ . Following geomagnetic latitude bins are considered:  $0.2 - 0.6$ ;  $0.6 - 0.7$ ;  $0.7 - 0.8$ ;  $0.8 - 0.9$  (radians), which correspond to the  $L$ -coordinate intervals  $1.04 < L < 1.46$ ;  $1.46 < L < 1.71$ ;  $1.71 < L < 2.06$ ;  $2.06 < L < 2.56$ . In the same figure the results of calculations made in [9] as well as the results of the experiment AMS-01 [7] are shown. Figure 4 presents the measured deuteron-to-proton albedo fluxes ratio for the same intervals of geomagnetic latitude.

As mentioned above, in the area under radiation belt deuterons are born as a result of interaction of cosmic ray particles with the nuclei of the residual atmosphere. In Fig. 3 solid line corresponds to a model where the coalescence is the dominant reaction of albedo deuterons generation [9]. PAMELA experiment data are well agreed with the calculation in the entire energy range. At low energies, where there is no calculation result deuteron spectrum has an indication to be flatter. For energy above 200 MeV/nucleon PAMELA data are in good agreement with AMS-01 results [7]. In the range of  $L$ -coordinate  $2.06 - 2.58$  the contribution of galactic deuterons in the obtained albedo spectrum becomes noticeable. The different galactic deuteron contribution in AMS-01 and PAMELA spectra can be explained by the difference of the mean geomagnetic cutoff in the measurement areas and by different apertures of instruments.

The radiation belt zone was investigated as well and the deuterons were registered in the wide energy range from 100 MeV/nucleon to 600 MeV/nucleon. However it was not possible to reconstruct the spectrum due to sharp flux anisotropy and low statistics for different angles. Nevertheless, if one can suppose the equal selection efficiencies for protons and deuterons it is



**Figure 3.** The deuteron albedo spectrum obtained in the PAMELA experiment for different  $L$ -geomagnetic coordinate intervals and geomagnetic field less than 0.23 G (black squares). Red circles represent AMS-01 data [7]. Blue solid lines shows the theoretical calculation results [8, 9].



**Figure 4.** The albedo deuteron-to-proton fluxes ratio obtained in the PAMELA experiment for magnetic field value  $B < 0.23$  G and different  $L$ -values.

possible to get rude evaluation of deuteron-to-proton ratio of order 0.02 for energy range 120 – 350 MeV/nucleon.

## 5. Conclusion

As a result of this work the spectrum of deuterons and deuteron-to-proton ratio under radiation belt in the energy range 70 – 600 MeV/nucleon is measured with PAMELA experiment. The measured spectra are agreed with the theoretical model results, where it is assumed that deuterons under radiation belt are generated mainly by nuclear fusion reactions of the incident cosmic ray particles and nucleons of the nuclei of the atmosphere and consequent movement in the Earth's magnetic field.

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