The Russian-Italian Project PAMELA - investigation the antiparticle flux in the galaxy cosmic rays

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Abstract

On the 15th of June 2006 the Resurs DK 1 satellite was successfully launched from the Baikonur cosmodrome on board was mounted the Pamela magnetic spectrometer. With the launch of the Pamela apparatus a main stage of realization of the International Russian-Italian RIM-Pamela project was complete and with the participation of Swedish and German scientists, they aimed to measure cosmic galactic ray fluxes and first of all antiparticle fluxes (antiprotons and positrons). The report contains information about the main scientific purposes of the project, along with the description of the equipment and the preliminary results.

1 Scientific tasks of the PAMELA project

a) There is no doubt about that the nature of dark matter is among the main problems of cosmology, elementary particle physics, cosmic-ray physics at which a lot of scientific groups aim their efforts today. Almost 25% of all potential energy of the Universe is concentrated in the form of dark matter![1].

The result of a lot of theoretical studies shows that dark matter consists of some particles [2, 3]. But there are not any known particles (including neutrino) which could be the particles of dark matter. These are absolutely new hypothetical particles. They could either be much lighter than electrons (they are called axions) or much heavier than nucleons (they are called WIMPs (WIMP - weakly interacting massive particle))(Fig. 1).

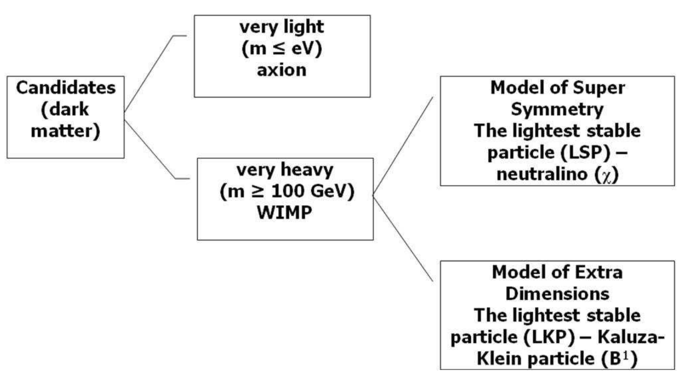

Fig. 1. Possible candidates to be dark matter .

Practically all the theoretical models suppose that particles which are the components of dark matter appeared at the early stage of the Universe development. t the moment they

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are supposed to be cooled (with law energies) relict particles. The model of supersymmetry, (SUSY) where a supersymmetric particle denoted by χ and having the properties of WIMPs which mass is from a hundred to a thousand times bigger than the proton mass appears, have had a special development. Another model (Kaluza-Klein theory - KK), based on the idea of multidimensional space also supposes the existence of supersymmetric particles B_{kk} (kk-stimulations) which mass is $\geq 5 \cdot 10^2$ proton masses. The interaction of B_{kk} and $\overline{B_{kk}}$, as well as the interaction of kk and kk can result the annihilation of WIMPs with the appearance of usual particles(fig.2).

Detect WIMP *annihilation* process:

$$B^1 + B^1 \rightarrow e^+ + e^-,\ \gamma + \gamma,\ \ldots.$$

$$\chi + \chi \rightarrow b\overline{b},\, t\overline{t},\, \tau^+\tau^-,\, Z^0Z^0,\, Z^0\gamma,\, W^+W^-,\, HH \rightarrow$$

$$\rightarrow \gamma + \ldots,\ e^{\pm} + \ldots,\ p\overline{p} + \ldots,\ d\overline{d} + \ldots,\ \ldots$$

Fig. 2.The resul of WIMP annihilation

This process is assumed as a basis of the χ and $_{kk}$ search in the Rome-Pamela project. It is known that primary cosmic rays generally protons and nuclei during transition in space interact with interstellar gas. As a result, the nuclear fragmentation takes place and the production of elementary particles including antiparticles $\overline{p}$, e^+. If the source of χ and $_{kk}$ annihilation process also with the production of $\overline{p}$ and e^+ add to this source of antiprotons and positrons, the energy spectrum of antiparticles registered in circumterrestrial space has special features reflecting the WIMP annihilation process. This peculiarity also appears in energy distribution of ratio $\frac{\overline{p}}{p}$ and $\frac{e^+}{e^- + e^+}$. As the mass of WIMPs is much bigger than the antiproton mass, the peculiarities should appear at the energies more than several tens of billions electronvolt. Precision measurements of antiproton and positron fluxes to find some peculiarities in the particle spectra is the main scientific task of the Rome-Pamela project- to find out the nature of dark matter.

b) The next task is the search for antihelium nuclei in cosmic rays. The probability of production of antihelium nuclei during the interaction of primary cosmic rays with circumterrestrial space is very small and the experimental detection of such particles could allow us to affirm that there is region in our Galaxy full of antimatter. Even the identification of the upper boundaries for the ratio $\frac{\overline{He}}{He}$ is a very important scientific task of the Rome-Pamela project- the study of nature of the baryonic asymmetry of the Universe.

c) The precision measurements of energy spectra of known particles (protons, electrons, positrons, and isotopes of light nuclei) carried out within the bounds of the Rome-Pamela project are necessary to find out the mechanism and the physical conditions of generation and acceleration of cosmic rays in galactic sources, the mechanism of propagation of cosmic rays in the Galaxy, heliosphere and Earth magnetosphere and are of a great scientific interest. So they form a large branch of the Rome-Pamela scientific program- physical processes of generation and propagation of cosmic rays in the Galaxy.

d) The tasks connected with the physics of accelerating processes during solar flares, propagation of cosmic rays in heliosphere and Earth magnetosphere, the study of different charge sign particle modulation also should be mentioned.

e) Finally, the study of composition, spatial characteristics of the particles in circumterrestrial space (albedo, captured particles in radiation belt of Earth) is a very important scientific task of the Rome-Pamela project which also have an applied aspect.

2 The PAMELA magnetic spectrometer

The PAMELA magnetic spectrometer was developed and created to be used in the program of measurements by Russian (MEPhI, Lebedev Institute, Ioffe Institute), Italian(INFN), Swedish(KTH of shcool) and German(Ziegen University) scientists [4]. The physical scheme of the instrument is shown in fig. 3.

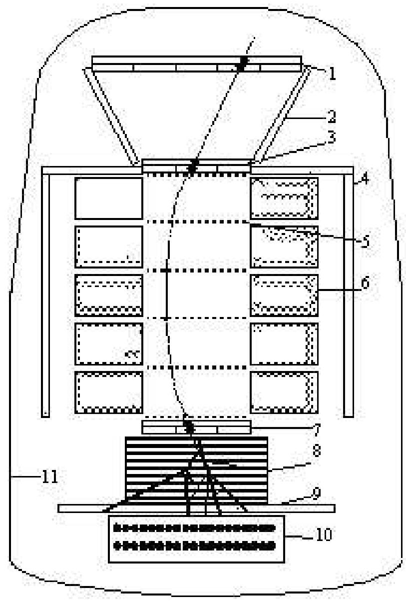

Fig. 3. The magnetic spectrometer PAMELA. 1,3,7 - time of flight system; 2,4 - anticoincidence system; 5 - silicon strip tracker (6 double plates); 6 - magnet (5 sections); 8 - silicon strip imaging calorimeter; 9 -bottom scintillator S4; 10 - neutron detector; 11 - pressurized container.

Physically the magnetic system consists of six double silicon strip detectors (tracker) placed into field of five-section constant magnet. The strip system used allows to measure the coordinates of the particle while passing through magnetic field up to several microns ($\sim$ 3.5 mk). The magnetic field value in the center of magnetic system is $\sim$ 0.48 T where detectors are disposed; the inner sizes of magnetic field are $160 \times 140 \times 450 mm^3$. With these magnetic system performances we can measure momentum of a particle up to 700 MeV/c. The precision of momentum measuring within the range of $0.1 \div 300$ GeV is about 5%.

The Time of Flight system consists of three two-layer scintillation counters (S1, S2, S3), each of them consists of separate paddles being observed by photomultipliers from both ends. The Time of Flight system has time resolution $0.4 \cdot 10^{-9}$ s, that assures reliable measuring of velocity and direction of particle movement.

The calorimeter consists of 22 tungsten plates with a thickness 0.74 of radiation length, each of which is disposed between 2 silicon strip detectors directed perpendicular to each other with strip width of 2.2 mm. Such a position-sensitive calorimeter allows it to register spatial development of shower generated by through-passing particles interaction with matter of detector; to measure energy of particles of showers; and to distinguish the showers generated by electrons or positrons from the showers created by protons and nuclei.

The shower scintillator detector (S4) is placed just under the calorimeter. The sizes of S4 override the sizes of calorimeter low plane. Therefore there is opportunity to detect particles coming out from the lower part of calorimeter and to measure the part of the energy carried away with them. Moreover, S4 can be included in trigger that allows it to register events with high energy deposit inside the calorimeter.

The neutron detector consists of two-layer gas neutron counters filled with He_2^3 isotope and a three-layer polyethylene moderator. The interactions of electrons and positrons inside the calorimeter are different form interactions of nuclei by shower form and large number of neutrons. generated in hadron shower, as well. Then neutrons are slowed down to thermal energy by polyethylene moderator and then are registered by the helium counters. This is one more method for the separation of electrons and positrons on the proton background.

Finally, the system of scintillation counters surrounding the Time of Flight system registers particles passing from sides through detectors during appearance of trigger signal.

Practically all detectors of the instrument allow the measurement of the energy lost by a cosmic particle while passing through them. The knowledge of energy losses gives the additional information about energy and value of electrical charge of a particle.

Mode of operation of the PAMELA spectrometer is the following: while a cosmic particle is passing through the instrument, i.e. through the counters S1, S2 and S3, the trigger signal is produced that gives a command to pick up information from all detectors of the spectrometer, namely from the strips of the tracker, from the strips of the calorimeter, from the shower counter S4, from the neutron detector, from the counters of anticoincidence system. Then this information is recorded into the spectrometer mass memory of 4 GBytes. The trigger system is blocked during time of information read-out and its recording into the memory of the instrument. The mean size of recorded information within a separate registered event is $\sim 5 \cdot 10^3$ byte; the dead time is from 2 till 10 milliseconds. The properly sized and mass, thermal, technological and flight models of the instrument were created during the process of development and creation of the equipment. A total cycle of autonomous tests including the tests of instrument systems in accelerator beams were carried out. Then the complex tests inside the spacecraft were fulfilled.

The main physics performances of the instrument were obtained by the Monte-Carlo method and calibrated in the CERN accelerator and in vitro on cosmic muons. In table 1 physics and technical performances of the spectrometer are presented.

Table 1

Geometric Factor	21 sm^2sr
Energy range of measurements:	
protons	0.1 $\div$ 1000 GeV
antiprotons	0.1 $\div$ 150 GeV
electrons	0.05 $\div$ 300 GeV
positrons	0.05 $\div$ 300 GeV
nuclei	0.1 $\div$ 200 GeV/nuc
antinuclei	0.1 $\div$ 200 GeV/nuc
The size of one event	5 kB
Power consumption	350 W
Linear dimensions	$90 \times 90 \times 120$ sm^2
Mass	450 kg

During the processing of the received information on Earth the main characteristics of a registered particle like sign and value of charge, mass, velocity, momentum and energy are determined.

It is significant to note that this is the first time the scientific equipment like the magnetic spectrometer "PAMELA" onboard of this spacecraft has been used which has the capability of the registration of various types of particles with so high energy resolution with the energy range more than three decades.

3 Measurement Performance, Information Reception

The "RESURS DK1" N^o1 spacecraft (Fig. 4 has been designed for the photographing of the Earth's surface with a high spatial resolution. The satellite was shipped onto an elliptic orbit with perigee 350 km and apogee 600 km. The orbit inclination was 70.4^o. The planned life time is three years. The precise magnetic spectrometer "PAMELA" was installed aboard the same spacecraft as an additional scientific load.

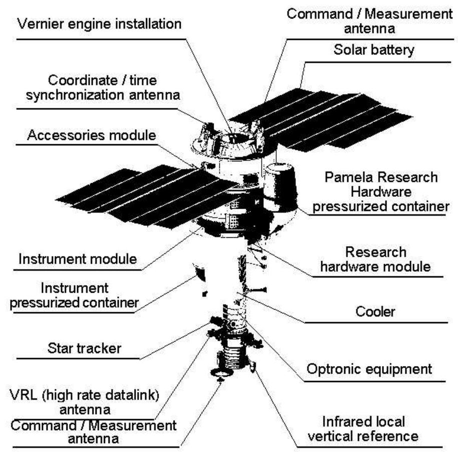

Fig. 4. The schematic of placement spectrometer "PAMELA" at spacecraft "RESURS DK1" 1

As the optical system of the satellite is directed on subsatellite point (nadir) most of time and axis of magnetic spectrometer mounted in a pressurized container is directed on local zenith, there is opportunity to realize practically permanent registration of primary cosmic rays fluxes.

After the launch of spacecraft "RESURS DK1" 1 the following order of the cosmic-ray fluxes measured by magnetic spectrometer was determined:

1) Measurements are carried out permanently;

2) The transmission of stored information from memory of the spectrometer to the on-board memory is executed once every three hours;

3) The information from the spacecraft "RESURS DK1" 1 is downloaded 3-4 times per day to the ground receiving station at the Scientific Center of Operational Monitoring of Earth (NTs OMZ) placed in Otradnoe (Moscow);

4) The information from spectrometer PAMELA is extracted at the NTs OMZ from the full data stream and delivered to ground segment PAMELA placed at NTs OMZ ;

5) Express-analysis of the received information is performed at ground segment PAMELA during 30-40 minutes after each transmission session with satellite, solutions about the continuation of measurements or necessity to send commands to satellite about changing of routine of spectrometer's work is assumed on the basis of the results of express-analysis;

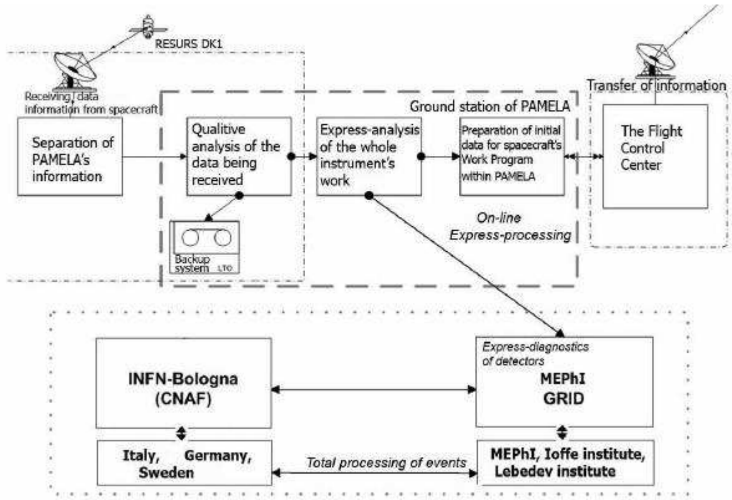

Fig. 5. The scheme of information spreading between participants of collaboration RIM-PAMELA

6) In parallel with carrying out of the express-analysis "raw" data is delivered to MEPhI (Main organization from Russian side) where the bank of raw data is formed;

7) By using the international scientific net GRID the scientific information from MEPhI is transferred to Russian Ioffe Institute and Lebedev Institute (participants in the project) and to the scientific information center of INFN (CNAF, Bologna) where easy access to this information is provided for all foreign participants of collaboration "PAMELA";

8) The every day work of the PAMELA spectrometer gives about 14.6 GB of "raw" data.

9) The physics treatment and analysis of the obtained results are accomplished by all the fellows of "PAMELA" collaboration together.

10) The full volume of raw information by 1 May 2008 is about 9 TBytes.

4 The Physical Conditions of Measurement Performance

In fig. 6 the rate of the appearance of trigger signals (counting rate of instrument) is shown. It can be seen in particular that this counting rate reaches a maximal possible value of about 100 Hz while the spacecraft is passing through the region of the South Atlantic magnetic anomaly. However, there is an opportunity for investigation of not only particles trapped in radiation belt, but also galactic particles even in that case.

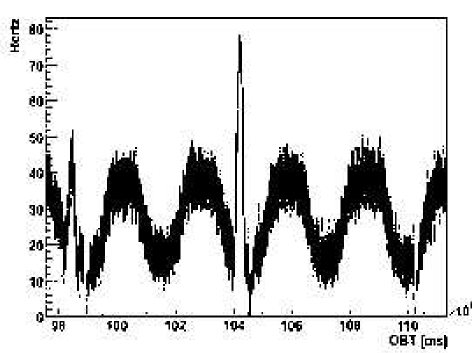

Fig. 6 -The counting rate along the orbit of the spacecraft.

As the orbit of the satellite has big inclination (70^0) there is opportunity for measurements of galactic cosmic particles fluxes with law energy at high geographic latitudes where geomagnetic cutoff is not high. In this case the minimum registrated energy depends on solar modulation and the energy a particle should have for time-of-flight (counters S1, S2 and S3), signals of which form trigger. On the other hand, speaking about the opportunity of registration of particles with the maximum energy it is should be taken into account that the intensity of cosmic particles rapidly decreases while energy increases. So the highest energy of the registered particles depends on the light-gathering power of the instrument and observation time. Of course, it is necessary to have other opportunities to measure energy and other characteristics of particles with such energies.

5 Processing of Scientific Information

By the first stage of information processing the data bank "Level0" is formed, where the scientific information is divided into separate files, each of them represents one of the information transmissions from the PAMELA instrument to on-board memory of "RESURS DK1" 1. Then the data bank "Level1" which consists of the files corresponding to daily information. The next stage is the forming of the "Level2" data bank. Here the readings of each system of the PAMELA instrument for each event (trigger shifting) are processed and recorded. Throughout the process, the information about the calibrations of the system in accelerator and in flight are recorded.

So, the main physical characteristics of particles are determined in the "Level2" data bank: particle speed, charge and a sign of the charge of a particle, rigidity (momentum), energy of a particle and mass.

Then with the use of a special library the orbital position (latitude, longitude, altitude) for each event and direction of telescope axis (and, consequently, direction of coming of a particle) is determined.

At the next stage the selection of the events depending on different characteristics takes place, ie: depending on charge, mass and momentum. Individual and general characterisrics of cosmic-ray fluxes are studied [5].

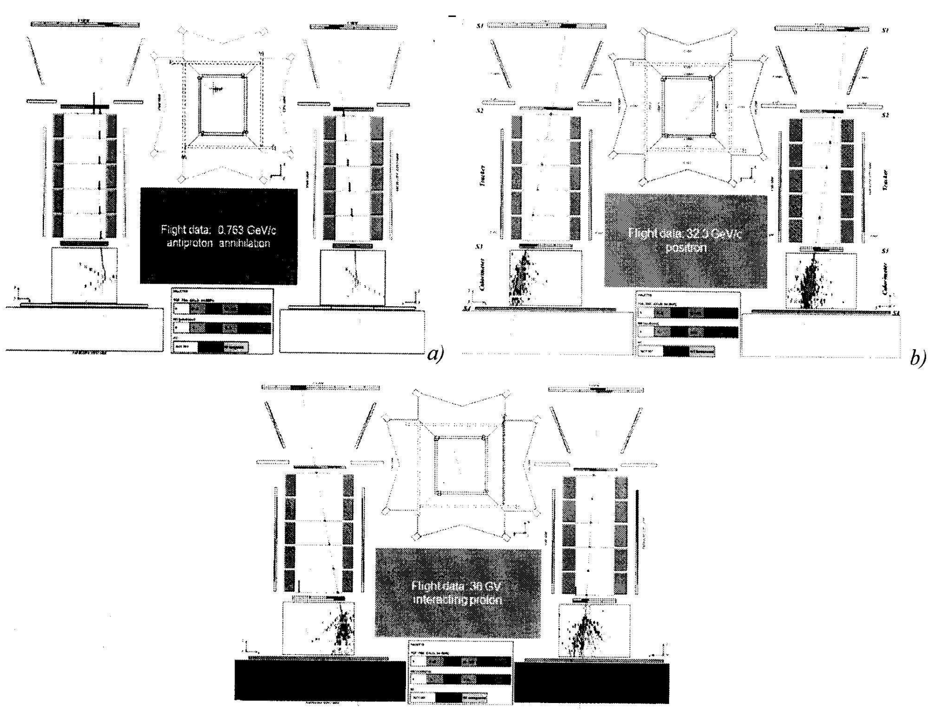

Fig. 7. The reproduction of the passing of particles through the instrument.

The diagrams of the passing for various particles through the instrument are presented in fig. 7. Also an example of an event that has appeared beyond the aperture of instrument is also shown. Such relative seldom events but with big energy-release in the calorimeter are registered by the instrument as well.

In this case the PAMELA instrument turns to be a separate system composed of the calorimeter, bottom shower scintillator and neutron detector, geometric factor of which is 400 $\frac{cm^2}{sr}$. This system allows it to extend the range of registered energies. Real opportunities of the discrimination of particles depending on mass is shown in fig.8, where energy losses of particles passing through the tracker are shown as a function of their rigidity. Antiprotons, isotopes of light nuclei are sufficiently and reliably singled out.

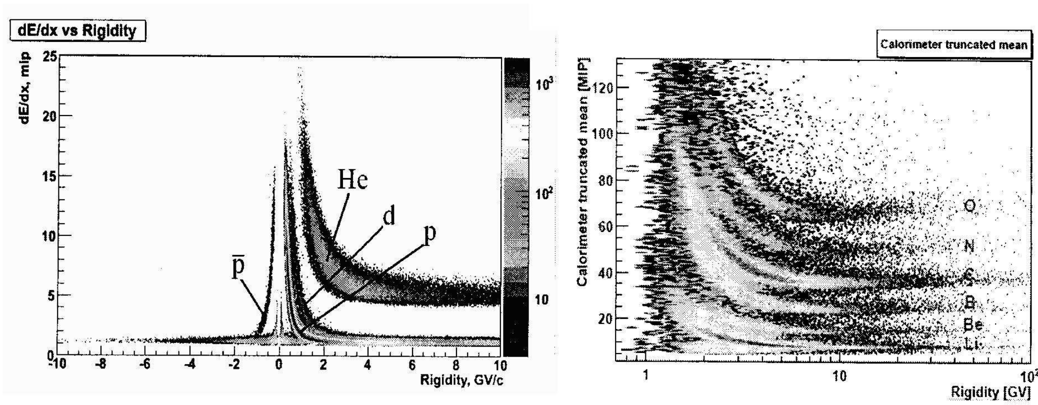

Fig. 8. The diagrams: the dependence of energy loss while passing of particles through tracker on their momentum (rigidity).

6 Prior observational results

Prior results were generally obtained by the processing and analysis of the data from the first year of measurements. By august 2007 there were analysed $\sim 2 \cdot 10^5$ electrons and $\sim 2 \cdot 10^4$ positrons ranging from 200 MeV to 200 GeV, by the 1st of march 2008 there were analysed $\sim 10^7$ protons and $\sim 10^3$ antiprotons ranging from 100 MeV to 100 GeV, $\sim 10^6$ nuclei with the charge > 2.

6.1 The measurement of the energy spectra of the protons and helium nuclei

The intensities of these particles are represented in the figure 9. The results were obtained by the processing of the several millions of protons and helium nuclei. They give the most precise values of the indices of energy spectra for today with the mistakes assignable by statistics.

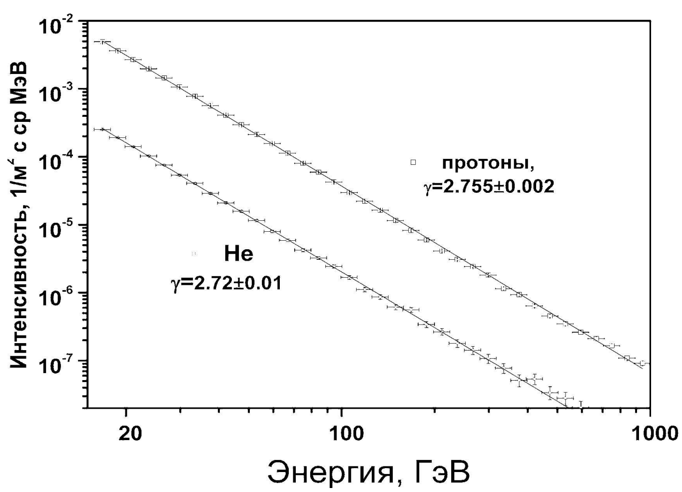

Fig. 9. The intensity of the galactic protons and helium nuclei.

The index of difference spectrum for protons is $\gamma = 2.75 \pm 0.02$, and for helium nuclei is $\gamma = 2.72 \pm 0,01$. This data is of great interest from the point of mechanisms of the acceleration and expansion of particles within the Galaxy. Particularly, there appears a possibility to calculate more surely the flux of the secondary antiprotons and positrons, against the background of which one has to register antiprotons and positrons from different and more rare processes.

6.2 The ratio $\frac{\overline{p}}{p}$

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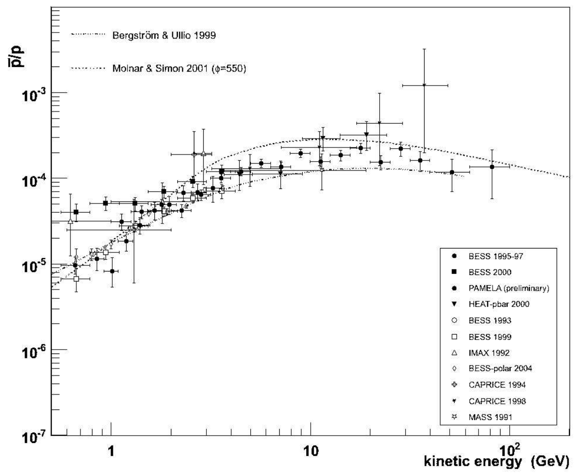

Fig. 10. Ratio $\frac{\overline{p}}{p}$ measured during the "PAMELA" experiment.

In figure 10 presented the dependence of the flux of antiproton to the flux of protons from energy [7]. In this figure also presents the results of calculations of this relationship based on the traditional model of interaction between protons and the nuclei of helium - the main component of the flux of high-energy cosmic rays - with the interstellar gas.

This figure shows that measured attitude coincides with the calculation. So there is not registered an additional flux of antiprotons.

6.3 The ratio $\frac{e^+}{e^+ + e^-}$

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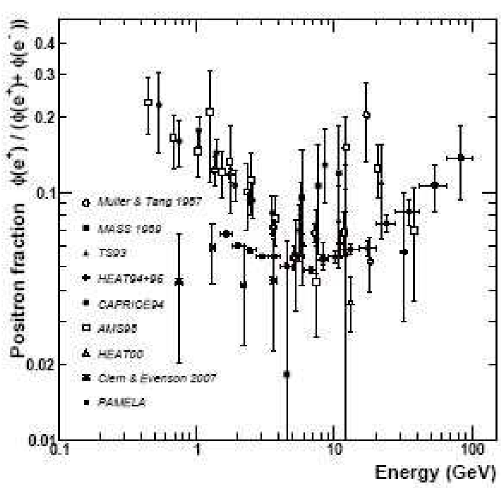

Fig. 11. Ratio $\frac{e^+}{e^+ + e^-}$ measured in the experiment "PAMELA". Comparision with calculations by Silk for WIMP with mass 50, 100, 300, 600 GeV and it's annigilation in to e^+e^- pairs.

In figure 11 presented flows of positrons to the total flow of electrons and positrons, measured in different experiments, including in the experiment PAMELA [8]. This figure shows the results of calculations of this relationship from the Moskalenko model [6]. The main outcome measurements - growth measured with the increase in energy tracer particles. So, in the experiment shows that since energies 5 GeV is an additional source of galactic positrons. The nature of his is not yet known, but presumably it could be annihilation of WIMP's, so manifestation of dark matter. Or any other reasons, such as the flux from pulsars, in an electromagnetic field that can generate pairs of electrons and positrons. Assuming as is done in the abcdef work, the source is WIMP's masses lies in the range of 100-250 GeV

7 Conclusion

The flight of the Resurs DK 1 satellite will be continued at least till 2009. So the measurements carried out on the unique PAMELA instrument will be continued.

8 Gratitude to

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