Journal of Physics: Conference Series

Cosmic Rays Investigation by the PAMELA experiment

To cite this article: Beatrice Panico *et al* 2020 *J. Phys.: Conf. Ser.* **1342** 012017

XV International Conference on Topics in Astroparticle and Underground Physics IOP Publishing
Journal of Physics: Conference Series **1342** (2020) 012017 doi:10.1088/1742-6596/1342/1/012017

Cosmic Rays Investigation by the PAMELA experiment

Beatrice Panico[1]
INFN Napoli, I-80126 Naples, Italy
E-mail: `bpanico@na.infn.it`

D. Campana, G. Osteria
INFN, Sezione di Napoli, I-80126 Naples, Italy

G. C. Barbarino
University of Naples 'Federico II', Department of Physics, I-80126 Naples, Italy
INFN, Sezione di Napoli, I-80126 Naples, Italy

O. Adriani, M. Bongi, P. Spillantini, N. Mori
University of Florence, Department of Physics and Astronomy, I-50019 Sesto Fiorentino,Florence, Italy
INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Florence, Italy

P. Papini, E. Vannuccini
INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Florence, Italy

G. A. Bazilevskaya, A. N. Kvashnin, Y. I. Stozhkov
Lebedev Physical Institute, RU-119991, Moscow, Russia

R. Bellotti, A. Monaco
University of Bari, Department of Physics, I-70126 Bari, Italy
INFN, Sezione di Bari, I-70126 Bari, Italy

A. Bruno, F. Cafagna
INFN, Sezione di Bari, I-70126 Bari, Italy

M. Boezio, V. Bonvicini, E. Mocchiutti, R. Munini, G. Zampa, N. Zampa
INFN, Sezione di Trieste, I-34149 Trieste, Italy

---

[1] Speaker

A. Vacchi
INFN, Sezione di Trieste, I-34149 Trieste, Italy
University of Udine, Department of Mathematics and Informatics, I-33100 Udine, Italy

E. A. Bogomolov, S. Y. Krutkov, G. I. Vasilyev
Ioffe Physical Technical Institute, RU-194021 St. Petersburg, Russia

P. Carlson, M. Pearce
KTH, Department of Physics, and the Oskar Klein Centre for Cosmoparticle Physics,
AlbaNova University Centre, SE-10691 Stockholm, Sweden

M. Casolino
INFN, Sezione di Roma Tor Vergata, I-00133 Rome, Italy
RIKEN, Advanced Science Institute, Wako-shi, Saitama, Japan

G. Castellini
IFAC, I-50019 Sesto Fiorentino, Florence, Italy

C. De Santis, L. Marcelli, M. Mergé, P. Picozza, R. Sparvoli
University of Rome Tor Vergata, Department of Physics, I-00133 Rome, Italy
INFN, Sezione di Roma Tor Vergata, I-00133 Rome, Italy

V. Di Felice
INFN, Sezione di Roma Tor Vergata, I-00133 Rome, Italy
Agenzia Spaziale Italiana (ASI) Science Data Center, Via del Politecnico snc I-00133 Rome, Italy

A. M. Galper,A. V. Karelin,S. V. Koldashov,S. Koldobskiy,Y. T. Yurkin,V. Malakhov,A. Leonov,A. G. Mayorov,V. V. Mikhailov,S. A. Voronov
National Research Nuclear University MEPhI, RU-115409 Moscow

M. Martucci
University of Rome Tor Vergata, Department of Physics, I-00133 Rome, Italy
INFN, Laboratori Nazionali di Frascati, Via Enrico Fermi 40, I-00044 Frascati, Italy

W. Menn, M. Simon
Universitat Siegen, Department of Physics, D-57068 Siegen, Germany

M. Ricci
INFN, Laboratori Nazionali di Frascati, Via Enrico Fermi 40, I-00044 Frascati, Italy

S. B. Ricciarini
INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Florence, Italy
IFAC, I-50019 Sesto Fiorentino, Florence, Italy

Abstract. PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) is a satellite-borne experiment. It was launched on June 15th 2006 from the Baikonur space centre on board the Russian Resurs-DK1 satellite. For about 10 years PAMELA took data, giving a fundamental contribution to the cosmic ray physics. It made high-precision measurements of the charged component of the cosmic radiation challenging the standard model of the mechanisms of production, acceleration and propagation of cosmic rays in the galaxy and in the heliosphere. PAMELA gave results on different topics on a very wide range of energy. Moreover, the long PAMELA life gives the possibility to study the variation of the proton, electron and positron spectra during the last solar minimum. The time dependence of the cosmic-ray proton and helium nuclei from the solar minimum through the following period of solar maximum activity is currently being studied. Low energy particle spectra were accurately measured also for various solar events that occurred during the PAMELA mission. In this paper a review of main PAMELA results will be reported.

1. Introduction

PAMELA (Payload for Antimatter-Matter Exploration and Light-nuclei Astrophysics) was designed to study the charged component of the cosmic radiation, focusing on antiparticles. It was a space-based cosmic-ray detector hosted on the Russian Resurs-DK1 satellite. It was launched on June 15th, 2006, from the Baikonur cosmodrome (Kazakhstan).

PAMELA experiment was the results of the collaboration between Italian (Universities and Istituto Nazionale di Fisica Nucleare I.N.F.N. Structures), German (Universitt Siegen), Russian (Lebedev Physical Institute, Ioffe Physical Technical Institute, National Nuclear Research University MEPhI) and Swedish (KTH Royal Institute of Technology) institutes. Over the years, PAMELA has started other external collaborations with the North-West University in South Africa and the NASA Goddard Space Flight Center, New Mexico State University, University of New Hampshire in USA.

2. The PAMELA experiment

PAMELA experiment was in nearly continuous data-taking mode until January 2016 when downlink operations were terminated. The satellite orbit was quasi polar, elliptical, with a period of about 90 minutes and an inclination of about 70°. The altitude varied between 355 and 584 km; since September 2010, the orbit was changed to a nearby circular one, at an altitude of about 570 Km [1].

PAMELA has several goals:

- the search for antimatter to help solving the cosmological problem about the existence of the apparent asymmetry between matter and antimatter;
- the search for signatures of exotic processes connected to the Dark Matter problem;
- the study of cosmic-ray propagation, providing new high precision data about CR primary and secondary fluxes; this is useful to obtain constraints on current acceleration and diffusion models of cosmic rays in the Galaxy;
- the study of solar physics and solar modulation to investigate the heliosphere;
- the study of the terrestrial magnetosphere.

PAMELA is composed by different detectors, whose characteristics are described below.

- A **Time of Flight system**, which is composed by 6 layers of plastic scintillators arranged into 3 planes. It provides the main experimental trigger and can determine particle charge

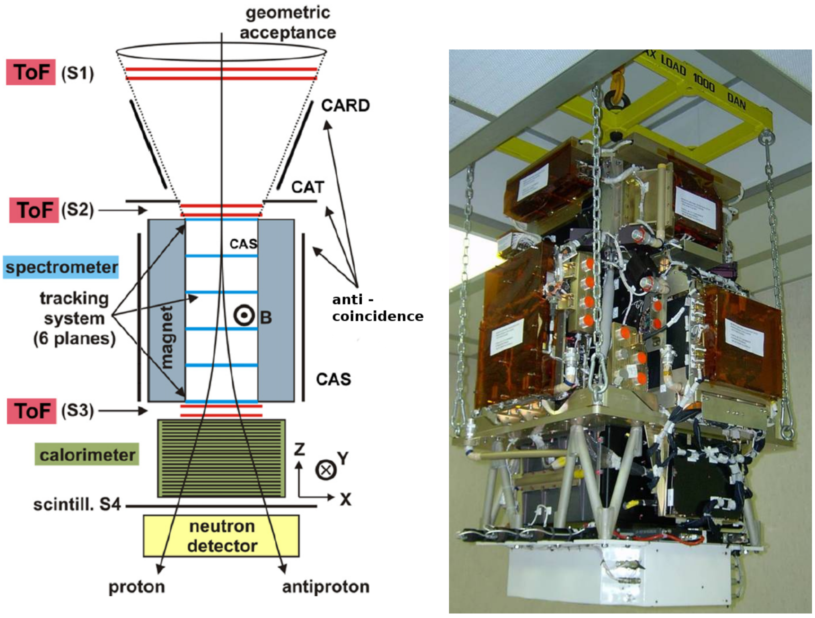

Figure 1. Pamela experiment

up to Z<8 by measuring ionization energy loss. It also measures the time of flight of particles in the crossed planes; this information is combined with track length information derived by the spectrometer to determine particle velocity. It allows the identification of albedo particles measuring the incoming particle direction.

- A **magnetic spectrometer**, which allows the determination of the sign of the charge and the rigidity of particles. It is composed by a permanent magnet equipped with six double-sided micro-strip silicon sensors. Inside the cavity a quasi-dipolar magnetic field is produced; it is rather uniform and mostly concentrated along the Y axis (the X and Z components are less than 10% of the Y component). The magnet is enclosed by a ferromagnetic shielding to prevent any interference with satellite instruments and navigation systems.
- An **anticoincidence system**, which consists of nine plastic scintillators acting as a veto shield. It allows the identification, during off-line data analysis, of the events originating fake triggers, mainly due to the interaction with the mechanical structure of the experiment.
- An **electromagnetic calorimeter**, which is composed by 44 silicon planes and 22 plates of tungsten for a total of 16.3 radiation lengths. It provides a direct measurement of the energy for electrons and positrons and allows the discrimination between hadrons and leptons through the analysis of the shower topology.
- A **neutron detector**, which improves the lepton/hadron discrimination.

In Fig.1 a photo of the experiment and a schematic view of PAMELA apparatus are shown.

3. PAMELA results

PAMELA results span over 4 decades in energy while the measured fluxes extend over 12 orders of magnitude. The most relevant results have been summarized in [2, 3]. In the following paragraphs we will revise the most important ones. Thanks to the big amount of collected data, PAMELA can explore different items. In particular we have results on:

- the absolute fluxes of primary cosmic rays;

- the fluxes of light nuclei and the determination of isotope ratio;
- the fluxes of antiparticles;
- the cosmic ray electron and positron anisotropy;
- solar modulation of proton and helium nuclei;
- solar modulation of the electron flux;
- solar events.

3.1. Cosmic ray fluxes

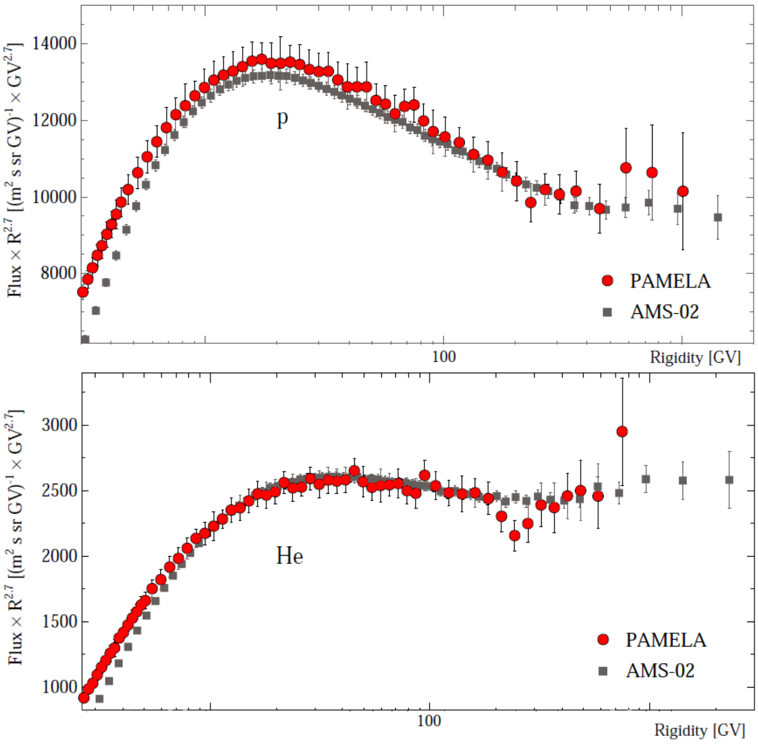

Figure 2. Top: Proton fluxes measured by PAMELA [4] and AMS-02 [5]. Bottom: Helium fluxes measured by PAMELA [4] and AMS-02 [6].

One of the most important results is the measurement of proton and helium nuclei spectra published in [4]. It was the first high-statistics and high-precision measurement over three decades in energy. The high resolution of the spectrometer and the information given by different detectors allowed to determine the spectra up to ∼1 TV. At energies of about 230 - 240 GV it can be clearly see a deviations from a single power law. Particularly, there is a spectral hardening at this energies with a variation for the spectral index of about 0.2. The single power law spectrum is rejected at 98% of confidence level. The break is also visible in the ratio between proton and helium spectra as a function of the measured rigidity. In [5, 6] AMS-02 confirmed PAMELA results, publishing the final spectra of proton and helium nuclei.

Proton and helium spectra measured by PAMELA are shown in Fig.2. In the same plot recent measurements from AMS-02 are reported. The agreement is at the order of few percent, except for the low energies. The disagreement at low energies is due to the fact that the two experiments took data into different period of the solar cycle, indeed they undergo different solar modulation conditions.

3.2. Antiparticles

A fundamental result of PAMELA is reported in [7, 8]. The analysis on the data collected between July 2006 and February 2008 showed that the ratio of positron flux to the sum of electron and positron fluxes increases sharply for energies greater than 10 GeV. Differently from the previous measurements, PAMELA results cover a wide energy range of energies, from 1.5 to 100 GeV, with an high statistics. They cannot be explained with current models for the secondary positron production, but the rise can be explained as the evidence of a primary source for positrons. Several models have been developed, addressing questions about the nature and distribution of particle sources in the Galaxy, the interaction of cosmic-ray nuclei with the interstellar gas and the presence of dark matter into the Galaxy. In [9] AMS-02, with a larger statistics, confirmed PAMELA results. In Fig.3 the cosmic ray positron fraction measured by PAMELA is reported, together with AMS-02 and Fermi measurements.

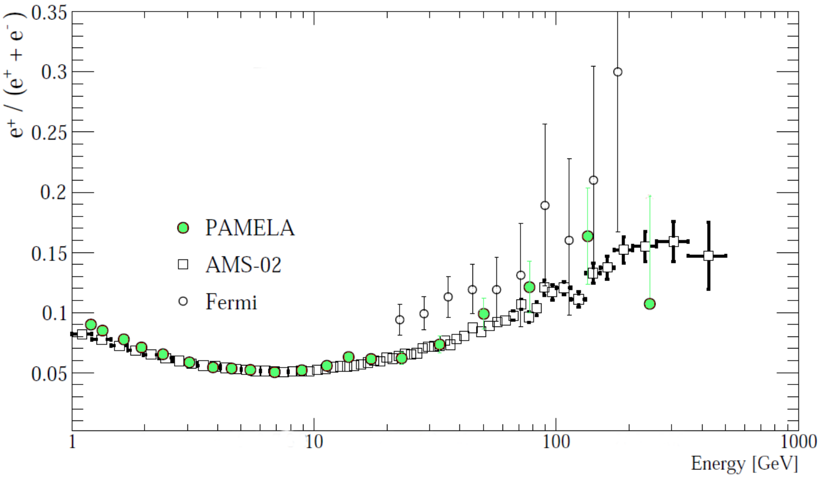

Figure 3. Cosmic ray positron fraction measured by PAMELA [8], AMS-02 [9] and Fermi [10]. Only statistical errors are shown.

Information on possible deviations from standard positron and electron production can be found into the spectrum of the individual particles. In [2] the spectrum of electrons and positron have been reported. While the electrons mostly follow a power-law trend, the positron spectrum rise above 20 GeV, producing the same rise seen into the positron fraction. Also the flux of antiproton and its ratio with protons can give important constraints to the propagation models. PAMELA detector can discriminate antiprotons with a negligible contamination of protons up to 200 GV. Results are reported in [11, 12] and are in excellent agreement with recent AMS-02 data.

3.3. Light nuclei and isotopes

PAMELA results on cosmic ray spectra changed the standard paradigm of cosmic-ray propagation and acceleration. Important information on the parameters of the propagation model can be obtained by the secondary-over-primary ratios of nuclear species. Secondaries are due to the inelastic interactions of heavier cosmic ray nuclei with the insterstellar medium while primary nuclei are produced and accelerated into physical sources. The relative abundance of secondary to primary nuclei is uniquely related to propagation processes and can be used to tune the parameters of the cosmic ray propagation models. In [13, 14] the analysis on hydrogen and helium isotopes has been reported. Both of them are produced by fragmentation of 4He, which is mostly of primary origin, indeed they can be used to test the propagation process of He. Other information have been obtained by the ratio B/C, as B is mostly produced from the fragmentation of C. Results are reported in [15].

3.4. Anisotropies

An additional source is the most probable explanation for the positron anomaly described before. It can be represented by an astrophysical source, as supernova remnants or pulsars, or a contribution from dark matter decay or annihilation. In both case we expect an anisotropy in the arrival distribution of cosmic ray electrons because these sources need to be nearby. Indeed, due to the synchrotron radiation emission and inverse Compton collisions with low-energy photons of the interstellar radiation field, high energy cosmic-ray electrons and positrons lose rapidly their energy.

For this analysis, the arrival distribution of positrons with rigidities greater than 10 GV in the period June 2006 - January 2010 has been considered [16]. To take into account the effect of galactic magnetic field, particles are backtraced in the space until ~20 radius of the Earth using the IGRF model. To compare the experimental distribution with the background a reference map is constructed starting from proton data. The comparison has been done for different integration radius to highlight the anisotropy signal. Results are compatible with the expectations. In Fig.4(left) the significance map for positrons with an integration radius equal to 30° is reported. The analysis has been done also selecting a sample of electrons with rigidities greater than 10 GV [17]. There is no excess in the significance maps for any integration radius. Fig.4(right) shows the significance map for electrons with an integration radius of 30°.

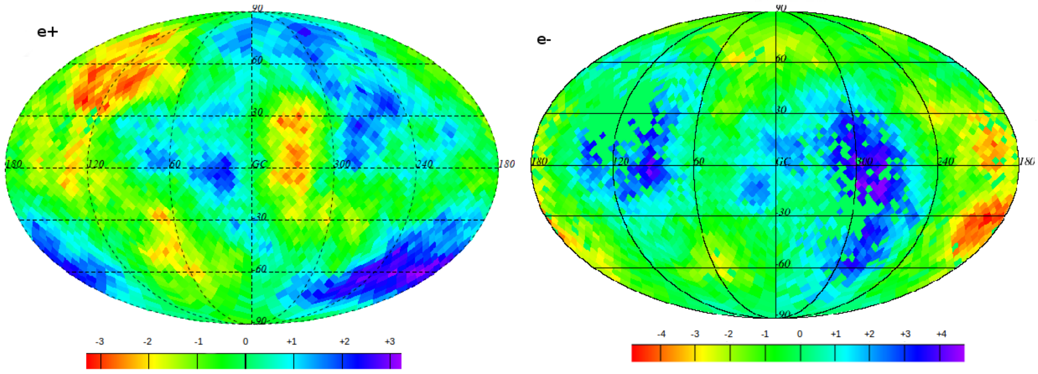

Figure 4. Significance maps for positrons (left) and electrons (right) for 30° integration radius. The analysis is reported in [16].

Information on the angular scale of the anisotropy can be obtained expanding the cosmic ray intensity in spherical harmonics. The angular power spectrum has been calculated as a function of the multi-pole for the positron signal over the proton background. Results are consistent with the expectations within 5σ C.L. and the upper limit for the dipole amplitude has been set at δ=0.166 with a 95% of C.L. [16].

3.5. Solar modulation

Traversing the heliosphere, cosmic rays are scattered by the turbulent heliospheric magnetic field embedded into the solar wind. As a consequence, cosmic rays undergo a temporal variation in their intensity and in their energy as a function of the position inside the heliosphere. This process depends on the solar cycle and is known as the solar modulation of cosmic rays [18]. It has large effects for energy less than few GeV but decreases rapidly with increasing energies, until it becomes negligible for energies above few tens of GeV. The modulation is clearly visible in the spectra of cosmic rays. To have a complete description of the propagation effects, precise measurements of cosmic-ray spectra over a wide rigidity range and over a long period of time are needed. PAMELA took data from June 2006 to the beginning of 2016, covering a long part of the last solar cycle. This gives the possibility to study the influence of the solar modulation in different conditions with a unique detector on a wide range of energy.

PAMELA results on the time variation of the proton spectrum during the 23rd solar minimum, from July 2006 to the end of 2009, have already been published [19]. Besides protons, PAMELA measured the time-dependent electron fluxes between 70MeV and 50GeV during the 23rd solar minimum [20]. Since electrons represent only 1% of the cosmic radiation, the collected statistics allowed the fluxes to be measured only for a six months time interval. Data about the solar modulation of proton and helium nuclei up to 2014 are currently under analysis.

4. Conclusions and acknowledgments

PAMELA has been in orbit and studied cosmic rays for almost 10 years, obtaining a lot of fundamental results. Other studies are in progress, from the primary and secondary-nuclei abundance (up to Oxygen), to the long-term flux variation and charge-dependent effects. Also several new solar events are under study to cover the energy gap between particles detected in space (below few hundreds of MeV) and particles detected at ground level (above few GeV).
The Italian authors acknowledge the partial financial support from the Italian Space Agency (ASI) under the program ‘Programma PAMELA - attività scientifica di analisi dati in fase E’.

References

[1] Picozza, P., Galper A., Castellini, G., Astropart. Phys. (2007) 27, 296
[2] Adriani, O., Barbarino, G.C., Bazilevskaya, G.A. et al., Phys. Rep. (2014) 544, 4
[3] Adriani, O., Barbarino, G.C., Bazilevskaya, G.A. et al., Il Nuovo Cimento (2017) 10, 473
[4] Adriani, O., Barbarino, G.C., Bazilevskaya, G.A. et al., Science (2011) 332, 6025
[5] Aguilar, M., Aisa, D., Alpat., B., et al., Phys. Rev. Lett. (2015) 114, 171103
[6] Aguilar, M., Aisa, D., Alpat., B., et al., Phys. Rev. Lett. (2015) 115, 211101
[7] Adriani, O., Barbarino, G.C., Bazilevskaya, G.A. et al., Nature (2009) 458
[8] Adriani, O., Barbarino, G.C., Bazilevskaya, G.A. et al., Phys. Rev. Lett. (2013) 111, 081102
[9] Aguilar, M., Aisa, D., Alpat., B., et al., Phys. Rev. Lett. (2013) 110, 141102
[10] Ackermann, M., Ajello, M., Allafort, A. et al., Phys. Rev. Lett. 108 (2012) 011103
[11] Adriani, O., Barbarino, G.C., Bazilevskaya, G.A. et al., Phys. Rev. Lett. (2010) 105, 121101
[12] Adriani, O., Barbarino, G.C., Bazilevskaya, G.A. et al., Phys. Rev. Lett. (2009) 102, 051101
[13] Adriani, O., Barbarino, G.C., Bazilevskaya, G.A. et al., ApJ (2013) 770, 2
[14] Adriani, O., Barbarino, G.C., Bazilevskaya, G.A. et al., ApJ (2016) 818, 68
[15] Adriani, O., Barbarino, G.C., Bazilevskaya, G.A. et al., ApJ (2014) 791, 93
[16] Adriani, O., Barbarino, G.C., Bazilevskaya, G.A. et al., ApJ (2016) 811, 21
[17] Panico, B. for the PAMELA collaboration, PoS(ICRC2015) (2015) 410
[18] Potgieter, M.S., Living Rev. Sol. Phys. (2013) 10, 3, doi:10.12942/lrsp-2013-3
[19] Adriani, O., Barbarino, G.C., Bazilevskaya, G.A. et al., ApJ (2013) 765, 91
[20] Adriani, O., Barbarino, G.C., Bazilevskaya, G.A. et al., Phys. Rev. Lett. (2015) 810, 142