PAMELA and indirect dark matter searches

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Abstract. We present a review of the experimental results obtained by PAMELA in measuring the \((p, \bar{p})\) and \(e^\pm\) abundance in cosmic rays. In this context, we discuss the interpretation of the observed anomalous positron excess in terms of the annihilation of dark matter particles as well as in terms of standard astrophysical sources. Moreover we show the constraints on dark matter models from \(\bar{p}\) data.

1. A historical introduction

About one hundred years ago cosmic rays (CR) offered a means to study physical processes at energies exceeding by more than three orders of magnitude those available from natural radioactivity. The structure of the nucleus could be investigated, mesons were discovered and studied, and ‘particle physics’ was born. It took four decades of technological efforts to reproduce CR energies with accelerators and to compete in intensity. Three additional decades later the technical development of particle detectors allowed the study of CR with energies largely exceeding those supplied by accelerators, and CR again became a useful instrument for elementary particle physics and astrophysics. In the 1970s the revolutionary newly developed
space transportation system (STS) provided a means for transporting large detectors to space. The USA National Academy of Sciences (NAS) elaborated a plan for great observatories [1, 2] and a new CR research program [3, 4]. In the decade 1985–1995 a CR research program based on ground experiments and theoretical studies—complemented by facilities in space—was developed. This program aimed to assure a permanent presence in orbit of instruments for continuous monitoring the electromagnetic and ionizing particle radiation coming from the Universe.

Fundamental pieces of the CR program in space were: (a) the advanced composition explorer (ACE) for studying low energy CR (up to a few GeV nucleon\(^{-1}\)) that cannot penetrate the Earth’s magnetosphere; (b) the superconducting magnetic spectrometer ASTROMAG [5, 6], to be used as a facility for CR research up to energies beyond a PeV nucleon\(^{-1}\); (c) the heavy nucleus collector (HNC) [7] for studying composition of highly charged (up to actinides) CR. ASTROMAG and HNC were planned for the FREEDOM Space Station (FSS) that was under construction and was planned to go into service in 1992 to celebrate the 200th anniversary of the Independence of the USA.

In the CR program in space envisaged by NASA, the observation of the energy spectra of antiparticles and the search for antinuclei was considered of fundamental importance. This was considered particularly exciting after (a) the first observations of antiprotons in balloon-borne experiments by Golden \textit{et al} [8] and Bogomolov \textit{et al} [9] suggesting a \(\bar{p}/p\) ratio higher than foreseen by secondary production of CR on interstellar matter (ISM), and (b) a bump in gamma-ray spectrum at 1–10 MeV, suggesting abundant \(\pi^0\) production by \(\bar{p}–p\) annihilation shortly after matter-radiation decoupling and subsequently red-shifted to the 1 MeV region by the expansion of the Universe.

The first experiment selected for the ASTROMAG facility, nicknamed WIZARD [10, 11], was proposed by an international team gathered around an Italian–USA collaboration and was dedicated to the study of antiparticle spectra and search for antinuclei. Concerning electromagnetic observations, the great observatories (CGRO, AXAF(CXO+XMM), HST, and SIRTF) were all constructed and launched. Also the ACE explorer for the study of low-energy CR outside the magnetosphere was realized and launched in 1999, and its instruments are producing a rich harvest of valuable data. For the HNC and ASTROMAG facilities the final fate was different. The tragic explosion of the Challenger shuttle in 1986, the Gulf war, as well as the end of the USA–Russian competition of the ‘cold war’ period, slowed down the FSS program, which was terminated in 1991. Collaborations that had gathered around the programmed facilities were partially disbanded or had to rescale their projects. The WIZARD collaboration started a program of balloon-borne experiments. Several Russian institutions joined this collaboration to form the Russian Italian Mission (RIM) program. This collaboration, after several experiments on satellite and on the space stations MIR and ISS for life science and solar CR, constructed and launched the PAMELA (a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) project [12], dedicated to antiparticle studies up to hundreds of GeV.

2. Antiparticle spectra and the search for antimatter and dark matter

Although theoretical arguments based on constraints from gamma-ray sky surveys [13, 14] argue that the distance to any hypothetical domains of antimatter must be roughly comparable to the horizon scale, the apparent baryon asymmetry in the Universe can be probed by searching
for antihelium in the cosmic radiation since this is not thought to be produced in secondary processes. The detection of antinuclei with \( Z > 2 \) in CR would provide, instead, direct evidence of the existence of antistellar nucleosynthesis in antimatter domains or lumps (e.g. \([15]\)). The pioneering experiments of Golden \([8]\) and Bogomolov \([9]\) were followed by many others performed on balloons mainly by the WIZARD, BESS and HEAT collaborations, and onboard the Space Shuttle by the AMS-01 collaboration. The first historical results concerning an antiproton excess were not confirmed and antihelium was not observed. The search for antimatter resulted in a better understanding of the backgrounds posed by secondary positrons and electrons. These CR antiparticles also became a tool in their own right for the study of hypothesized dark matter particle annihilations and primordial black hole evaporation.

Now we have come to realize that the energy budget of the Universe is shared among baryonic matter (4\%), dark matter (23\%) and dark energy (73\%). The nature of the dark matter is still unknown. The favorite candidates for the non-baryonic component are electrically neutral weakly interacting massive particles (WIMPs) with a mass in the range between 10 s of GeV to TeV \([16]\). They would naturally appear as one of the thermal leftovers from the early Universe and their presence is predicted in several classes of extension of the standard model of particle physics. The most studied WIMP is the neutralino, a combination of supersymmetric partners of the neutral gauge bosons of the standard model. Neutralinos are Majorana fermions that can annihilate with each other in the halo of the Galaxy, resulting in the symmetric production of particles and antiparticles, the latter providing an observable signature. Another interesting candidate, among the many proposed, is the lightest Kaluza–Klein (KK) particle in the Universal Extra Dimension framework. The search for excess fluxes of antiparticles due to dark matter annihilations has become a focus of CR studies. An excess of antiparticles in our Galaxy could be a signature of dark matter annihilations. However, these contributions are mixed with a background of secondary particles produced by the interaction of CR with the ISM. Hence, they would appear as a distortion of the energy spectra of the secondary produced antiprotons, positrons and gamma rays. The available data, mostly collected by balloon-borne experiments, are not sufficiently statistically significant and do not extend enough to high energies to effectively constrain the dark matter models. Furthermore, better knowledge of additional astrophysical sources and influence of the solar activity are necessary.

In June 2006 the satellite experiment PAMELA was launched in orbit by a Soyuz-U rocket from the Bajkonur cosmodrome in Kazakhstan, with the aim of answering these fundamental questions.

3. The PAMELA experiment

The PAMELA apparatus is composed of the following sub-detectors, arranged as in figure 1, from top to bottom:

- a time-of-flight system (TOF \((S1,S2,S3)\));
- an anticoincidence system (CARD, CAT, CAS);
- a magnetic spectrometer;
- an electromagnetic imaging calorimeter;
- a shower tail catcher scintillator \((S4)\);
- a neutron detector.
Figure 1. Schematic overview of the PAMELA apparatus. The detector is approximately 1.3 m high, has a mass of 470 kg and an average power consumption of 355 W. The magnetic field lines inside the spectrometer cavity are oriented along the $y$-direction. The average value of the magnetic field is 0.43 T.

The TOF system comprises six layers of fast plastic scintillators arranged in three double planes (S1, S2 and S3). It provides a fast signal for triggering the data acquisition and measures the TOF and ionization energy losses ($dE/dx$) of traversing particles. The measured TOF resolution of $\sim 300$ ps allows $e^{-}(e^{+})$ to be separated from $\bar{p}(p)$ up to 1 GeV $c^{-1}$. Albedo particles can also be rejected with a significance of $\sim 30$ standard deviations.

The central part of the PAMELA apparatus is the magnetic spectrometer, consisting of a 0.43 T permanent magnet and a silicon tracking system. The tracking system comprises six equidistant planes of double-sided microstrip silicon detectors (made of six 300 $\mu$m thick, $5.3 \times 7.0$ cm$^2$ wide sensors), each providing two independent impact coordinates. The dimensions of the permanent magnet define the geometrical factor of the PAMELA experiment to be $21.5$ cm$^2$ sr. The spectrometer measures the rigidity (momentum divided by charge) of charged particles and the sign of the electric charge through their deflection (defined as the inverse of rigidity) in the magnetic field. During flight the spatial resolution is observed to be $3$ $\mu$m, corresponding to a maximum detectable rigidity (MDR) exceeding 1 TV.
Table 1. Design PAMELA performance.

| Particle             | Energy range               |
|----------------------|---------------------------|
| Antiprotons          | 80 MeV–190 GeV            |
| Positrons            | 50 MeV–300 GeV            |
| Electrons            | up to 500 GeV             |
| Protons              | up to 700 GeV             |
| Electrons + positrons| up to ∼1 TeV (from calorimeter) |
| Light nuclei (He/Be/C)| up to 200 GeV nucleon \(^{-1}\) |
| Antinuclei search    | sensitivity of \(3 \times 10^{-8}\) in anti-He/He |

Ionization losses are measured in the TOF scintillator planes, the silicon planes of the tracking system and the first silicon plane of the calorimeter, allowing the absolute charge (Z) of traversing particles to be determined at least up to \(Z = 8\).

The spectrometer is surrounded by a plastic scintillator veto shield, aiming to identify false triggers and multiparticle events generated by secondary particles produced in the apparatus. Additional information to reject multiparticle events comes from the segmentation of the TOF planes in adjacent paddles and from the tracking system.

The sampling electromagnetic calorimeter comprises 44 single-sided silicon planes (made of nine 380 \(\mu\)m thick, 8 × 8 cm\(^2\) wide sensors) interleaved with 22 plates of tungsten absorber. The total depth of the calorimeter is 16.3 \(X_0\) (0.6 nuclear interaction lengths). The main task of the calorimeter is to select \(e^+\) and \(\bar{p}\) from the background of \(p\) and \(e^-\), respectively. The longitudinal and transverse segmentation of the calorimeter, combined with the measurement of the particle energy loss in each silicon strip, allows a high identification (or rejection) power for electromagnetic showers against interacting and non-interacting hadrons.

A plastic scintillator system mounted beneath the calorimeter aids in the identification of high–energy electrons and is followed by a neutron detection system. This neutron counter is made of 36 \(^3\)He proportional counters, surrounded by a polyethylene moderator enveloped in a thin cadmium layer. It complements the electron–proton discrimination capabilities of the calorimeter, by detecting the increased neutron production associated with hadronic showers compared to electromagnetic ones in the calorimeter. Furthermore, the calorimeter can also operate in self–trigger mode to perform, in combination with the neutron detector, an independent measurement of the lepton component up to ∼1 TV.

More technical details about the entire PAMELA instrument and launch preparations can be found in [17]. The apparatus was installed inside a pressurized container attached to the Russian Resurs DK1 Earth-observation satellite and launched into space in a semi-polar (70°) elliptical (350–610 km) orbit by a Soyuz-U rocket from the Baikonur cosmodrome in Kazakhstan on 15 June 2006. The mission is foreseen to last at least until the end of 2011.

4. PAMELA science

PAMELA aims to measure in great detail the CR component at 1 AU (Astronomical Unit). Its quasi–polar elliptical orbit makes it particularly suited to study particles of galactic, heliospheric and trapped origin. The performance of the PAMELA instrument, as illustrated in table 1, allows high-precision spectral measurement of antiprotons and positrons and a search for antinuclei,
over a wide energy range. As discussed previously, antiparticles can provide hints of new physics, since they can be produced from exotic sources such as primordial black holes (e.g. see [18]), annihilation of supersymmetric particles (e.g. see [19]) or KK particles (e.g. see [20]). Moreover, PAMELA is extending the observational limit in the search of antihelium to the $\sim 10^{-8}$ level in the antihelium-to-helium fraction and it is searching for exotic matter in the Universe, e.g. strangelets.

Besides the primary objective to study cosmic antimatter, the instrument set-up and the flight characteristics allow many additional scientific goals to be pursued. Light nuclei can be identified at least up to $Z = 8$. This provides complementary data, besides antimatter abundances, to test models for the origin and propagation of galactic CR. In addition, the low-cutoff orbit and long-duration mission allows low-energy particles (down to 50 MeV) to be studied and the long-term time variation of the radiation intensity and transient phenomena to be evaluated. This allows the measurements to be extended down to the solar-influenced energy region, providing data about spectra and composition of solar energetic particles and allowing solar modulation of galactic CR over the minimum between solar cycles 23 and 24 to be studied. Finally, the satellite orbit spans over a significantly large region of the Earth’s magnetosphere, making possible a study of its effect on the incoming radiation. A more detailed overview of PAMELA's scientific goals can be found in [17, 21].

PAMELA was activated on 21 June 2006. After a brief period of commissioning, during which several trigger and hardware configurations were tested, PAMELA has been in a continuous data taking mode since 11 July 2006.

The average trigger rate of the experiment is $\sim 25$ Hz, varying from $\sim 20$ Hz at the equatorial region to $\sim 30$ Hz at the poles. The average fractional live time of the experiment is $\sim 73\%$. About 14 GB of data are transferred to ground via a few down-link sessions every day. The receiving station is located at the Research Center for Earth Operative Monitoring (NTs OMZ) in Moscow, Russia. After receiving the data, a dedicated computer facility unpacks and transfers them to various institutions for further data processing and analysis.

5. Scientific results

The PAMELA Collaboration has recently published results concerning the antiproton-to-proton flux ratio [22] and the positron fraction [23]. These results are based on the data-set collected by the experiment between July 2006 and February 2008. Details of the data analysis are provided below.

5.1. Data analysis methodology

Particle identification in PAMELA is based on a determination of the rigidity with the spectrometer and the properties of the energy deposit and interaction topology in the calorimeter. The analysis technique was validated using the PAMELA Collaboration’s official simulation program tuned using particle accelerator beam data. Figure 2 shows a $\sim 29$ GV negatively charged particle with a hadronic interaction in the calorimeter identified as an antiproton, whereas figure 3 shows a $\sim 92$ GV positively charged particle with a typical electromagnetic shower in the calorimeter identified as a positron. In these figures, different signatures in the electromagnetic calorimeter and neutron detector can be clearly seen.
Figure 2. The event display an ∼29 GV antiproton interacting in the calorimeter. The bending ($x$) and non-bending ($y$) views are shown on the left and on the right, respectively. A plan view of PAMELA is shown in the center. The signal as detected by PAMELA detectors is shown along with the particle trajectory (solid line) reconstructed by the fitting procedure of the tracking system.

One source of background in the antimatter samples comes from spillover (protons in the antiproton sample and electrons in the positron sample). This originates from incorrect determination of the charge sign due to the intrinsic deflection uncertainty in spectrometer measurements. This limits to the maximum rigidity up to which the measurements can be extended. Another source of background comes from the misidentification of like-charged particles (electrons in the antiproton sample and protons in the positron sample) due to the electron–hadron separation performance of the instrument.

5.2. Antiproton-to-proton ratio

In order to accurately measure antiprotons, the spillover was eliminated by imposing a set of strict selection criteria on the quality of the fitted tracks. Clean tracking position measurements (e.g. no accompanying hits from delta-ray emission) and a MDR, estimated for each event during the fitting procedure, 10 times larger than the reconstructed rigidity were required. The deflection ($1/\text{rigidity}$) distribution for positively and negatively charged down going particles, which did not produce an electromagnetic shower in the calorimeter, is shown in figure 4. A good separation between negatively charged particles and spillover protons is evident. Electrons
in the antiproton sample can be easily rejected by applying conditions on the calorimeter shower topology. The longitudinal and transverse segmentation of the calorimeter, combined with \(dE/dx\) measurements from the individual silicon strips, allows electromagnetic showers to be identified with very high accuracy. The resulting electron contamination was estimated to be negligible across the whole energy range of interest. The different—and momentum-dependent—interaction cross sections for protons and antiprotons and possible contamination from pions produced by CR interactions with the PAMELA payload were studied using both simulated and flight data. Additional details of the analysis can be found in \[22\].

The measured \(\bar{p}/p\) ratio is shown in figure 5 compared with theoretical calculations assuming pure secondary production of antiprotons during the propagation of CR in the galaxy. The ratio increases smoothly from about \(4 \times 10^{-5}\) at a kinetic energy of 1 GeV and levels off at about \(1 \times 10^{-4}\) for energies above 10 GeV. The \(\bar{p}/p\) data are also in excellent agreement with recent results from other experiments, as shown in figure 6.
Figure 4. The deflection reconstructed by the track fitting procedure for negatively and positively charged down-going particles that did not produce an electromagnetic shower in the calorimeter. The shaded histogram corresponds to the selected antiprotons.

Figure 5. The antiproton-to-proton flux ratio obtained by PAMELA [22] compared with theoretical calculations for a pure secondary production of antiprotons. The dashed lines show the upper and lower limits calculated by [24] for the Leaky Box model, while the dotted lines show the limits from [25] for a Diffusion model with reacceleration. The solid line shows the calculation by [26] for the case of a Plain Diffusion model.
5.3. Positron-to-all-electron ratio

Electrons and positrons can be reliably distinguished from the other CR species impinging on PAMELA (mostly protons) by combining information provided by the different detector components. The misidentification of electrons and, in particular, protons is the largest source of background when estimating the positron fraction. The electron spillover background was eliminated by imposing a set of strict selection criteria on the quality of the fitted tracks, as done for antiproteons. The spillover limit for positrons, estimated from flight data and simulation and verified by particle beam tests, is approximately 300 GeV.

The proton background is much larger than the positron signal. The proton-to-positron flux ratio increases from approximately $10^3$ at 1 GV to approximately $10^4$ at 100 GV. Robust positron identification is therefore required, and the residual proton background must be accurately estimated. The imaging calorimeter is 16.3 radiation lengths deep, so the maximum of the electromagnetic shower for electrons and positrons is well contained in the energy range of interest. In contrast, the majority of protons will either pass through the calorimeter as minimum ionizing particles or interact deep in the calorimeter.

In the first step of the data analysis, events with absolute charge value equal one and showering in the first tungsten layer of the calorimeter were selected; then a match between the momentum measured by the tracking system and the total energy detected in the calorimeter was required. In figure 7, the fraction of the energy deposited in the calorimeter within a cylinder having a diameter of about 0.6 Moliere radii, and with the axis defined by extrapolating the particle track reconstructed in the spectrometer, is shown as a function of deflection. The particle identification was tuned to reject 99.9% of the protons, while selecting 95% of the electrons or positrons. On the negative side, electrons are clearly visible having a value of the energy distributed mostly between 0.4 and 0.7. On the positive side, two bands can be seen: one similar

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**Figure 6.** PAMELA antiproton-to-proton flux ratio compared with previous measurements [27]–[33].
Figure 7. The fraction of calorimeter energy deposited inside a cylinder of diameter 0.6 Moliere radii, as a function of deflection. Colors indicate the amount of events in each bin from a few (blue) to a few tens (red).

to the electron one, naturally associated with positrons, and a broader one that can be associated with the residual proton contamination.

This characterization was also validated using the neutron detector information and the ionization (dE/dx) losses measured in the spectrometer. A higher number of neutrons is produced in hadronic interactions in the calorimeter, compared with electromagnetic showers, especially at energies greater than 10 GeV. In figure 8, the distribution of the energy fraction of the selected events is shown for the energy range 20–28 GeV for negatively (left, top) and positively (left, bottom) charged particles. Defining e\(^-\), e\(^+\) and p as shown in the figure, the corresponding neutron yields, shown in the right side (top and bottom panels) of the same figure, are obtained. The neutron distribution for positrons is similar to the electron one and different from the proton one. The small difference between the e\(^-\) and e\(^+\) distributions can be associated with a residual proton contamination, as expected. Similarly, competing density and logarithmic rise effects for dE/dx losses in the silicon detectors of the spectrometer yield different dE/dx distributions for the selected electrons and protons between 15 and 20 GeV. This can be seen in figure 9, that shows these distributions for positively and negatively charged particles (top panel) and for protons and positrons (bottom panel) selected similarly to figure 8 (left, bottom). This is a particularly important check, as the spectrometer information is independent from the calorimeter and can be used to rule out proton interactions resulting in, e.g. π\(^0\) production in the top-most calorimeter planes. The π\(^0\) will decay into two photons that can generate electromagnetic showers in the calorimeter. The event selection methodology was further validated using particle beam data collected prior to launch and data generated using the PAMELA Collaboration’s official simulation program.

It is worth pointing out that other criteria, related to features of the electromagnetic shower, could be used to further reduce the proton contamination. For example, figure 10 shows the suppression achieved by additional selections based on the longitudinal profile for events
Figure 8. Left side: top and bottom panels show the distribution, in the rigidity region 20–28 GeV, of the energy fraction for negatively and positively charged particles, respectively, selected as in figure 7. The blue arrows indicate the distribution regions dominated by electrons and positrons and the red that dominated by protons. Right side: top and bottom panels show the neutron yield for negatively and positively charged particles, produced in the showers induced in the calorimeter by the particles shown in the left side, and measured by the neutron detector. Blue histograms are for $e^-$ and $e^+$ and red histogram for protons.

selected between 20 and 28 GV for negatively (top panel) and positively (bottom panel) charged particles.

The amount of background contamination was obtained using the flight data, without any dependence on simulations, by the following approach. The total calorimeter depth of 22 tungsten detector planes was divided in two non-mutually exclusive parts: an upper part comprising planes 1–20, and a lower part comprising planes 3–22. A nearly pure sample of protons were obtained in the lower part of the calorimeter (planes 3–22) selecting particles that do not interact in the first 2 planes (only 2% of positrons with rigidities greater than 1.5 GV pass this condition). Then, the selection method illustrated before, with the exception of the longitudinal profile, was applied to electrons, proton sample and total $Z=1$ positive particles, by making use only of the upper part of the calorimeter (planes 1–20). The procedure was validated by simulations.

As an example, in figures 11 and 12 the energy fraction variable for the different configurations, in the rigidity range 6.1–7.4 GV and 28–42 GV, is shown. Panels (a)–(c) show the distributions for electrons, protons and positrons plus protons, respectively. The distributions in panels (a) and (b) are clearly different, while panel (c) shows a mixture of the two distributions, which strongly supports the positron interpretation for the electron-like fraction distribution in the sample of positively charged events. A parametric bootstrap analysis with maximum likelihood fitting was performed on the distributions for a number of rigidity intervals, and the numbers of detected electrons, positrons, and contaminating protons were obtained.
The measured positron fraction is shown in figure 13 ([23]) together with a pure secondary production curve (solid line) computed in [34]. In figure 14, the same data are compared with other recent measurements. Below 5 GeV PAMELA data are lower than most of the other data and are in agreement with the results from the AESOP balloon-borne experiment, which flew in June 2006 [35]. At higher energies the PAMELA positron fraction is compatible with other measurements, but the significantly higher statistics clearly shows that the positron fraction increases with energy.

6. Theoretical interpretations

The PAMELA positron and antiproton data generated a great deal of interest in the astroparticle community. These data, together with some reasonable assumptions, point two conclusions: the $\bar{p}/p$ ratio is in agreement with the expected secondary background, while the positron fraction needs some primary source to be fully explained. The results on the $\bar{p}/p$ ratio allow tight constraints to be placed on parameters relevant for secondary production calculations: e.g. the normalization and the index of the diffusion coefficient, the Alfvén speed, and contribution of
Figure 10. Distribution of the energy fraction obtained using the longitudinal profile in addition to the energy-momentum match and starting point of the shower for events selected between 20 and 28 GV. Top panel: negatively charged particles. Bottom panel: positively charged particles.

a hypothetical ‘fresh’ local CR component [44]. Actually, an important test for CR propagation models is their ability to reproduce both the antiproton-to-proton flux ratio and the secondary-to-primary nuclei ratio. On the other hand, the high-energy data (above 10 GeV) place limits on contributions from exotic sources, such as dark matter particle annihilations.

Concerning the positron fraction, the secondary production and propagation model considered in figure 13 is clearly not able to fully account for the experimental data. In particular the rise above 10 GeV is very difficult to reproduce with a pure secondary component without using an unrealistic soft electron spectrum [45], suggesting the existence of other primary sources [46].

In order to explain the positron excess, many explanations invoking more-or-less exotic sources have been proposed, ranging from purely astrophysical ones, like pulsars or few nearby supernova remnants (SNR), to the more speculative ones, such as the annihilation or decay of dark matter particles and even cosmic strings. All these models share a spectral index change around an energy of a few GeV, with respect to the secondary propagation models; an extensive list of references can be found in [47].

The explanations in terms of dark matter annihilations or decays is extremely suggestive, since the PAMELA data would constitute clear evidence for the existence of dark matter. A rise in the positron fraction at high energy was postulated for the annihilation of dark matter particles
Figure 11. Panel (a) shows the distribution of the energy fraction for negatively charged particles with rigidity between 6.1 and 7.4 GV, selected as electrons in the upper part of the calorimeter. Panel (b) shows the same distribution for positively charged particles selected as protons in the bottom part of the calorimeter. Panel (c) shows positively charged particles, selected in the upper part of the calorimeter, i.e. protons and positrons.

in the galactic halo about 20 years ago (e.g. see [48]). The first measurements performed with high-quality particle identification by the TS93 [41] and HEAT [40] balloon-borne experiments (both apparatus included an electromagnetic calorimeter and a transition radiation detector) obtained a positron fraction larger than expected from purely secondary production above a few GeV, which prompted new interpretation studies based on dark matter (e.g. see [49]).

The most problematic theoretical challenge posed by the PAMELA results is the asymmetry between leptonic (positron fraction) and hadronic (antiproton–proton ratio) data. This is difficult to explain in a framework where the neutralino is the dominant dark matter component. A suitable explanation requires a very high mass (>10 TeV) neutralino [50], which, however, is not in a favored part of the supersymmetric phase space. Better descriptions are obtained for supersymmetric models with purely leptonic annihilation channels for a wide range of the WIMP mass [50]. This, however, would exclude the neutralino, since, as a Majorana particle, it cannot annihilate directly into light fermions with large rates, due to helicity suppression. To overcome this problem various mechanisms have been proposed, such as radiative corrections [51], that may significantly enhance the dark matter induced positron yield and result in a pronounced spectral signature (figure 15), while the impact on the expected antiproton spectrum would be negligible. Alternatively, new light (mass < 1 GeV)
Figure 12. The same as figure 11, but for the rigidity interval between 28 and 42 GeV.

Figure 13. PAMELA positron fraction with a theoretical model. The solid line shows a theoretical calculation [34] for pure secondary positron production during the propagation of CR in the galaxy.
bosons may mediate the annihilation (figure 16), hence suppressing kinematically the antiproton production [52].

Moreover, by using the simplest models of thermally produced dark matter and the WMAP data [53], an average annihilation rate \( \langle \sigma v \rangle \) of the order of \( \sim 3 \times 10^{-26} \) cm\(^3\) s\(^{-1}\) is obtained, compared to a \( \langle \sigma v \rangle \sim 10^{-23} \) cm\(^3\) s\(^{-1}\) as inferred by the PAMELA data. All explanations in terms of dark matter annihilation subsequently require the annihilation rate to be boosted by a factor ranging between \( 10^2 \) and \( 10^4 \). Moderate boost factors, of the order of ten, can be provided by clumpiness in the dark matter distribution to support leptonic annihilation channels (usually \( e^+e^- \)) and small WIMP masses, while models that require high boost factors (of order \( 10^4 \)) seem to be completely ruled out. This conclusion can be weakened if other scenarios are considered, in which the boost factor is provided by a mechanism which is able to enhance in some way the cross section, such as non-thermal production of dark matter in the early universe, i.e. the present annihilation cross section is not related to that at the production [54], some non-perturbative effects like the so-called Sommerfeld enhancement [55] and near resonance effects [56].

Among the models proposed to explain the PAMELA data one of the most interesting involves KK dark matter [57]. This explanation is intriguing, due to the fact that in this scenario the lightest stable particle is a boson with a direct annihilation channel into \( e^+e^- \) pairs with no helicity suppression factor. For a lightest KK particle (LKP) mass of order \( M_{\text{LKP}} \sim 800 \) GeV [20, 58], the boost factor needed to fit the PAMELA data is of the order of \( 10^3 \) (figure 17).

Although this paper is focused on the dark matter interpretation, a variety of astrophysical models have been put forward to explain the rise in the positron fraction. The production of...
**Figure 15.** The solid line is the expected flux ratio $e^+/\left(e^++e^-ight)$ as calculated following [34]. The data points are the combined HEAT [40] and PAMELA data. The expected flux ratio is shown without (dotted lines) and after taking into account radiative corrections [51] (dashed lines).

**Figure 16.** The positron fraction as a function of energy for the annihilation mode: $\chi\chi \rightarrow \phi\phi$, followed by $\phi \rightarrow e^+e^-$, where $\phi$ is the light boson that only interacts in the dark sector [52].
Figure 17. The positron fraction as a function of energy including contributions from KK dark matter annihilations, compared to the measurements of the PAMELA experiment. Results are shown for dark matter masses of 600 and 800 GeV, and for two propagation models. The dashed line denotes the positron fraction with no contribution from dark matter (secondary positron production only) [57].

Positrons through pair production processes in the magnetosphere of pulsars, a well known cosmic particle accelerator, would also yield a similar positron signature (for example see [59]). The details of the acceleration processes are as yet unclear, but primary electrons are expected to be accelerated in the magnetosphere of pulsars at the polar cap and in the outer gap along the magnetic field lines, emitting gamma rays by synchrotron radiation. In the presence of an extremely high pulsar magnetic field, such gammas can produce pairs of positrons and electrons. Pairs are further accelerated and confined in the pulsar nebula for about $10^5$ years before escaping into the interstellar medium, contributing to the CR electron and positron components. Since the energy spectrum of these particles is expected to be harder than that of the secondary positrons, such pulsar-originated positrons may dominate the high energy end of the CR positron spectrum. However, due to the energy losses of electrons and positrons during
Figure 18. Contributions of $e^-$ and $e^+$ from Geminga assuming different distance, age and energetic of the pulsar. For a detailed description see [60].

their propagation—mainly inverse Compton scattering and synchrotron radiation—only pulsars less than 1 kpc away can contribute significantly to the positron energy spectrum (see [60, 61]). Examples of this interpretation are given in figures 18 and 19.

The positron fraction measured by PAMELA taken alone is likely insufficient to distinguish between the dark matter and pulsar hypotheses, but an additional measurement may help to solve this issue. The signal from nearby pulsars is expected to generate a small but significant dipole anisotropy in the CR electron spectrum, potentially providing a method by which the Fermi space telescope would be capable of confirming a pulsar origin of the observed high-energy positrons [61].

The main uncertainties in these calculations are connected to incomplete knowledge of the primary CR nuclei and primary electron spectra and modeling of interaction cross-sections and CR propagation in the galaxy. Despite all these approximations, explaining the increasing ratio with contributions from standard secondary production would require large modifications of the experimentally established spectra of electrons, protons and helium nuclei [46], although some papers report an explanation of the observed excess in terms of nearby SNR [62] or of secondary production taking place in the same region where CR are being accelerated [63]. However, to distinguish among the different hypothesis a better knowledge of the standard production of electrons and positrons is required as well as of the mechanisms of their acceleration and transport in the galaxy. PAMELA is performing accurate measurements of the absolute fluxes of electrons, positrons, protons and light nuclei. These new data will constrain tightly the secondary production models.

Concerning the lower energy part of the spectrum, a disagreement between PAMELA data and almost all previous measurements is evident. This difference is interpreted as a consequence of time and charge-dependent solar modulation effects. The solar modulation has a significant effect mostly on CR with rigidities less than about 10 GV. This modulation has an 11 year cycle varying from a period of maximum activity and maximum effect on CR to a minimum. At each maximum the polarity of the solar magnetic field reverses. First indications that solar modulation effects depend on the CR sign-of-charge arose when comparing the helium flux versus the electron flux and the electron flux alone as a function of time for alternate solar
Figure 19. Contributions of $e^-$ and $e^+$ from Geminga, B0656 + 14 and mature pulsars at distance $\gtrsim 500$ pc. For a detailed description see [61].

Cycles [64, 65]. Charge-sign-dependent solar modulation has also been clearly seen in the antiproton-to-proton flux ratio measured before and after the most recent (2000) reversal of the solar magnetic field by a series of flights of the BESS balloon-borne experiment [32].

PAMELA data have been collected in phase A$^-$, where the magnetic dipole projection on the solar rotational axis and the rotational axis itself are anti-parallel. In the A$^+$ phase, the situation is inverted. In addition, data were collected in a solar quiet phase, where drift processes are most relevant [66]. The charge sign-dependent effect of the solar modulation is different between the two phases, due to a systematic deviation from reflection symmetry of the interplanetary magnetic field [35]. The Parker field has opposite magnetic polarity above and below the equator, but the spiral field lines themselves are mirror images of each other. This antisymmetry produces drift velocity fields that for positive particles converge on the heliospheric equator in the A$^+$ state or diverge from it in A$^-$ state. Negatively charged particles behave in the opposite manner and the drift patterns interchange when the solar polarity is inverted.
In figure 20, phenomenological calculations [67, 68] for the positron–electron and antiproton–proton ratios are shown for several solar phases and compared with data at 1.25 GV momentum for different experiments, including PAMELA. The positrons are modulated more than electrons in the $A^-$ phase and less in $A^+$ phase. For a different approach to the problem see [69].

7. Conclusions

Results from the analysis of the data collected and transmitted to ground from the PAMELA instrument in the first 1.5 years of operation show very interesting features in the positron to all electron fraction. Above 10 GeV, an increase in the ratio, compared as expected from the standard secondary production, is generally interpreted in terms of primary sources of positrons. Two different scenarios have been proposed as an explanation of the positron excess: one involving standard astrophysics, either nearby young pulsars or nearby SNR or non-standard processes in the secondary production of positrons, and the other involving more exotic explanations, like DM annihilations. The antiproton-to-proton flux ratio appears in agreement with the standard secondary production models. This result puts strong constraints on DM models since they usually do not predict an asymmetry between leptonic and hadronic production.

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