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**PAMELA Mission: In flight performances
and preliminary measurements of nuclear
abundances**

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Introduction

The present Ph.D. thesis work has been developed within the framework of the PAMELA experiment.

PAMELA (a "Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics") experiment is a satellite-borne apparatus designed to study charged particles in the cosmic radiation, with a particular focus on antiparticles (antiprotons and positrons), over the largest energy range ever achieved. In addition, it will measure the light nuclear component of cosmic rays and investigate phenomena connected with Solar and Earth physics. PAMELA is installed inside a pressurized container attached to a Russian Resurs DK1 earth-observation satellite that was launched into space by a Soyuz-U rocket on June 15th 2006 from the Baikonur cosmodrome in Kazakhstan.

The PAMELA apparatus comprises a magnetic spectrometer, a Time of Flight system, a silicon-tungsten electromagnetic calorimeter, an anticoincidence system, a shower tail catcher scintillator and a neutron detector. The combination of these devices allows antiparticles to be reliably identified from a large background of other charged particles. The semipolar orbit (70.0°) allows PAMELA to investigate a wide range of energies for antiprotons (80 MeV - 190 GeV) and positrons (50 MeV - 270 GeV). Three years of data taking will provide unprecedented statistics in this energy range and will set the upper limit for the ratio $\bar{H}e/He$ below 10^{-7} .

PAMELA is an international collaboration and in the framework of the Italian-Russian cooperation program RIM (Russian Italian Mission), generally aimed to the space environment study in the vicinity of the earth, with specific interest for the particle physics items. People participating in the PAMELA experiment belong to various Sections of the Italian National Institute of Nuclear Physics (INFN) and Physics Departments of Italian Universities (Trieste, Florence, Rome "Tor Vergata", Naples, Bari), to the INFN National Laboratories (Frascati) and the Institute of Applied Physics "Nello Carrara" (Florence). Besides, several foreign institutions are part of the PAMELA collaboration: the Physics Department of the Siegen University (Germany);

the Royal Technology Institute of Stockholm (Sweden); the Cosmic Rays Laboratory of the Moscow Engineering and Physics Institute; the Laboratory of Solar and Cosmic Ray Physics of the "Lebedev" Physics Institute of Moscow; the "Ioffe" Physico-Technical Institute of St Petersburg.

The Author's Contribution

During the three years of Ph.D. course (November 2004 - November 2007) I participated in the development of the PAMELA experiment with several contributions.

During my Physics Degree work (2003-2004) I had taken part in the integration and in the final qualification tests of the PAMELA Technological Model and in the first period of integration of the PAMELA flight apparatus. During the Ph.D. course I continued this work with the participation in the integration and in the final qualification tests of the PAMELA Flight Model at the Wizard laboratories of the Physics Department of Rome "Tor Vergata" University, where the various detectors, the associated electronics and several auxiliary systems have been assembled together.

When PAMELA was delivered to Samara for the integration in the Resurs satellite, I started to work for the development of Quick Look Software (for mission monitoring in real time) and for the Data Analysis Software. During this period I studied also the ground physics performance of the instrument, analyzing ground data to obtain the muon spectrum at sea level.

After the launch of PAMELA, I went three times in Moscow (in NTsOMZ ground segment) for shifts of monitoring and control, for an equivalent time of two months.

Another important part of my work was dedicated to the measurement of the the light attenuation lengths and trigger efficiencies of the TOF scintillator system. I determined the attenuation lengths of the scintillation light in the paddles, that are related not only to the characteristics of the scintillators but also to the optical properties of the lateral surfaces of the strips. After the optical characterization, I identified an algorithm to measure the trigger efficiencies of the single strips and of the 6 scintillator layers and to calculate the overall trigger efficiency of the TOF system in the "flight" configuration.

During the last period of my Ph.D course, I focused my attention to measurement of Boron to Carbon nuclear ratio in cosmic rays. This measurement is very important to put constraints to propagation parameters of cosmological models and, as a consequence, to make more easily visible a possible small contamination from primary sources in antiprotons and positrons spectra. A better determination of the cosmic ray propagation is fundamental for the search of exotic matter, like dark matter candidates or antimatter produced in exotic processes, since the signature of such processes can be recognized only by knowing with great precision the fluxes due to the con-

ventional production, acceleration and transport mechanisms.

Preliminary B/C ratio values in the energy range from 200 MeV/n up to 25 GeV/n have been derived using combined data from Calorimeter, Tracker and TOF systems.

Outline of the Thesis

Chapter 1 of the thesis introduces the physical theoretical background necessary to understand the scientific interest of the PAMELA mission. It provides an overview of cosmic rays, from production in space to detection on Earth. A description of their composition and propagation is given, with particular focus on the antimatter component and possible signatures arising from the annihilation of heavy supersymmetric particles in the antimatter spectra.

Chapter 2 illustrates the main characteristics of the PAMELA experiment and of the satellite mission, focusing on the description of the experimental capabilities of the apparatus, of all the detectors constituting PAMELA telescope and of the overall structure of the acquisition and trigger systems. Also some information about Resurs DK-1 satellite, data reception and NTsOMZ ground station are given.

Chapter 3 is dedicated to the description of PAMELA qualification tests before launch and to the study of physics ground performance of the instrument.

Chapter 4 deals with the PAMELA launch and the PAMELA status after the launch. In this chapter the task of people in shift in Moscow to monitor the mission in real time are described in detail.

Chapter 5 describes PAMELA Flight Software, starting from PAMELA Raw data to data ready to be used in physics analysis. Also the Quick Look Software is described, focusing attention on output files greatly important for on-line monitoring.

Chapter 6 is dedicated to the characterization of TOF detector in flight configuration. The method used for attenuation lengths and trigger efficiency measurements and related results are reported.

Chapter 7 deals with the analysis of high-Z nuclei (up to Oxygen) detected by the apparatus. The method used to estimate the ratio of secondary on primary components of cosmic radiation is described. PAMELA Boron to Carbon ratio measurements are shown together with all the experimental data existing in literature.

Finally, Chapter 8 contains conclusions and the outlook for future work.

Chapter 1

Cosmic Ray Physics

In this Chapter the physical processes of cosmic rays are outlined. Starting from an historical point of view I describe when and how cosmic rays were discovered. The basic aspects of primary radiation, its origin, acceleration and propagation mechanisms in the galaxy are discussed. Finally, something about antimatter in cosmic rays is described.

1.1 Discovering cosmic rays

The history of cosmic rays began approximately 100 years ago, when a ionizing power was found in the atmosphere thanks to a leaf electroscope. In that period it was the only detector which could measure the electric charge rate, far from radioactive sources providing an estimation of the ionization in the air. The discharge rate obtained on the ground was attributed to the radioactive elements in Earth's crust. Measurements were then taken on towers: in 1910, on the Eiffel tower, an ionization of the same order of magnitude as on the ground was observed, which did not correspond to the foreseen attenuation. Dedicated balloon missions were made by Hesse and Kolhoster in 1912-14, at an altitude varying between 12 and 14 km. They discovered that electroscope discharge rate was decreasing with altitude up to about 1.5 km, while it was increasing for upper heights: this was an evidence of a source of ionizing particles located outside the Earth. Scientist supposed they are high energy γ -rays. After the invention of the Geiger-Muller detector (1929), cosmic rays were recognized as charged particles by coincidence experiments.

In the following years, curved tracks in the cloud chambers, produced by cosmic rays, were observed. The first experimental antimatter signature came from cosmic rays too: particles identical to the electrons, but curved in the opposite direction, were discovered by Anderson [1]. In the following years cosmic rays have been employed as the available, low-cost source of

high energy particles; in this sense they have been early replaced by the accelerators. In the last years, starting from the 1970s, cosmic rays studies have been developing due to the growing interest on their origin and propagation, both related to the general knowledge of the Universe evolution.

1.2 Flux, composition and detection of cosmic rays

Charged particles, that enter the top of the atmosphere at a rate of about $1 \text{ cm}^2\text{s}^{-1}$, are known as cosmic rays. Two components can be distinguished, depending on their origin: primary and secondary cosmic rays. Primary cosmic rays arrive near the Earth directly from galactic or extra-galactic sources, while the secondary ones are produced by interaction of the primary particles with the interstellar medium. In addition, energetic particles emitted during solar flares have to be considered, but their emission is limited to short periods.

Cosmic rays are constituted mainly by electrons, protons and nuclei; the relative amounts of the most significant components, measured at 1 Astronomical Unit (1 AU) from the Sun are listed in table 1.1. Small fraction of antiparticles (namely positrons and antiprotons) are also present; in the current knowledge they can be compatible with a secondary production but the investigation of the antiparticles flux on a wider range of energy is necessary to understand if, on the contrary, primary sources can be present in the Universe (see section 1.5).

98% nuclei	87% p 12% He 1% $Z > 2$
2% electrons	
Antiparticles	0.01% $\bar{p}$ 0.1% e^+

Table 1.1: Cosmic ray composition: relative amounts of the main components at 1 Astronomical Unit (1 AU).

The differential energy spectrum of cosmic rays (shown in figure 1.1 for the main nuclear components) exhibits a maximum between 100 MeV/n and 1 GeV/n; above this value, it follows a power law behaviour for all the nuclear components:

$$\phi = E^{-\alpha} \quad (1.1)$$

where $\alpha \cong 2.7$ for energies lower than $\sim 3 \cdot 10^{15} \text{ eV}$. For this energy value (the so-called "knee") the spectrum steepens and becomes about 3; it flattens

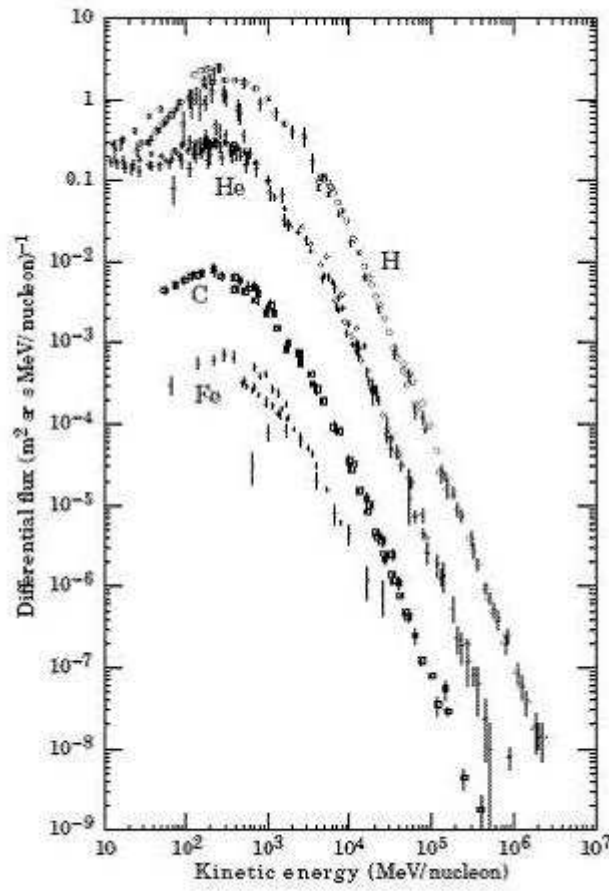


Figure 1.1: Differential flux of cosmic rays in the range $10^7 - 10^{13}$ eV/n. The most abundant nuclear species are reported in [2].

again for $E \sim 3 \cdot 10^{18}$ eV (known as "ankle"). These changes in the slope of the energy spectrum are not well understood, but they can be explained on the basis of the mechanisms of cosmic rays production. According to widespread theories, inside our Galaxy particles lying in hot plasma regions are accelerated by shock waves produced by explosion of supernovae. Cosmic rays energies reflect the nature of the cosmic source being characterized by a particular output spectrum. The knee is interpreted as due to the upper energy limit, reached by some galactic sources, which results in a decrease of the flux. The ankle, instead, is explained because of the presence of extragalactic cosmic sources, which produce highly energetic cosmic rays: the Larmor radius of a 10^{18} eV proton is of the order of 300 pc, comparable to the thickness of the galactic disk and so, for example, protons beyond this energy cannot be confined in the galactic disk otherwise it should be possible to distinguish the source point. Hence, at very high energies the particles are likely to be of extragalactic origin. Active Galactic Nuclei (AGN) stand out as the most likely sites for the acceleration of particles for those energies.

The maximum of the flux in the cosmic rays spectrum, observed at 0.1 - 1 GeV/n, is an effect due to the activity of the Sun and it is known as "Solar modulation". When cosmic particles enter in the solar system, they diffuse toward the Earth against the outflowing solar wind: it consists of low energy particles ($E \sim 500$ eV) emitted by the Sun. Modification on the interplanetary magnetic field, induced by the solar wind, determine the decrease of the flux observed below 1 GeV/n. Furthermore, since the intensity of the solar wind depends on the phase of solar activity, changes in the cosmic ray flux in this energy region are observed in different phases of the solar cycle. For $E \leq 60$ MeV/n an increase of the differential flux can be observed in the He spectrum (figure 1.1). This effect is explained on the basis of the anomalous He component: its origin is not clear but, according to some theories, neutral atoms are single ionized in the outer heliosphere, then accelerated and modulated by the solar activity like galactic particles.

For what concerns nuclei, the relative abundances of $Z = 1 - 28$ elements in cosmic rays, compared to the solar system's ones, are reported in figure 1.2. In both components odd- Z elements are less abundant than even- Z nuclei, due to the different binding energies of each group of nuclei. A disagreement between cosmic rays and solar system elements can be observed for nuclei with Z corresponding to Li, Be and B and for nuclei with atomic number between Carbon and Iron. These elements are supposed to be almost absent in the cosmic sources, whose chemical composition is similar to that of the Sun; while they are present to a larger extent in cosmic rays than what is found generally in the Universe. The observed abundances in cosmic rays are explained on the basis of "spallation" reactions with the interstellar medium, i.e. nuclear interactions in which a high- Z nucleus breaks in two or more products with lower atomic numbers: Li, Be and B are spallation products of C, N and O, while Sc, Ti, V, Cr and Mn derive from Fe.

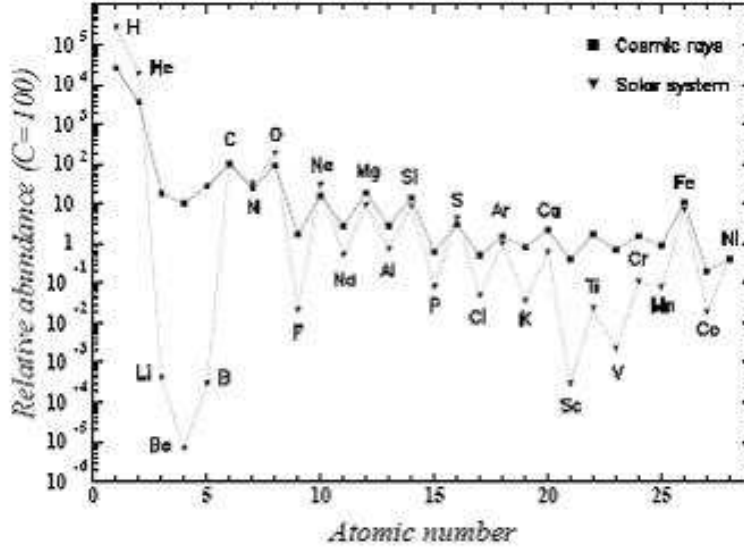


Figure 1.2: Relative abundances, measured at 1 AU, of $Z = 1 - 28$ elements in cosmic rays and in solar system. The vertical scale is normalized to the Carbon abundance (adapted from ref. [3]).

Since they are stable nuclei they provide information on the mean amount of matter traversed by the cosmic rays before escaping from the Galaxy. By knowing the secondary-to-primary ratio and the spallation cross sections, the amount of matter traversed by cosmic rays from sources to the Earth can be inferred [4]. It results $5\text{--}10 \text{ g/cm}^2$. This implies that they traversed the Galaxy several thousand of times during their lifetime since the amount of matter along a line of sight through the disk of the Galaxy is about 10^{-3} g/cm^2 : this disagreement is explained by the presence of the galactic magnetic field. Moreover the measured matter density traversed decreases for increasing energy, suggesting that higher energy cosmic rays spend less time in the Galaxy. It also suggests that cosmic rays are accelerated before most of the propagation occurs. On the contrary one should expect a constant ratio of secondary to primary cosmic rays as function of energy.

A very simplified scheme of the cosmic rays propagation through the galaxy is provided by the Leaky Box model (described in detail in section 1.4). According to this theory particles diffuse freely inside a confinement volume and are reflected at its boundaries, but a finite probability of escape limits the time spent in this region. Experimental results are compatible with a confinement time in our galaxy of about of 10^7 years. The confinement agrees with the observed complete isotropy of the cosmic ray flux, at least up to the knee energy.

For the cosmic ray detection, either direct or indirect techniques can be

employed, depending mainly on the expected fluxes. Particles that reach the Earth's surface are mostly products of the interactions of cosmic rays with the atmosphere: in order to gather the primary component, measurements are usually taken on balloons or spacecrafts.

For energies up to the knee, direct measurements outside the Earth are possible, but near and above the knee the very low flux becomes a limiting factor for such experiments: the required acceptances of the telescopes would exceed all the most optimistic constraints of a space mission. In the above-knee region the only existing experiments are based on the detection of atmospheric showers produced by highly ionizing particles. On-ground detector arrays, covering areas up to several kilometres, are employed in such kind of measurements.

This highest energy tail of the spectrum is of particular interest. The current theory for explaining the acceleration of cosmic rays is the so called Fermi acceleration model (see below 1.4.2) and it is not able to explain particles with energy greater than 10^{18} eV. Moreover a significant decrease in the flux of ultra high energy cosmic rays was predicted by Greisen, Zatsepin and Kuzmin [5]: protons with energies above $\sim 7 \cdot 10^{19}$ eV lost a significant fraction of their energy interacting with photons of the cosmic microwave background (CMB), the so-called GZK cut-off.

For extreme energy cosmic rays detection ($E \geq 10^{20}$ eV), some experiments are based on the observation of fluorescence light that is emitted in the very large showers, produced when such particles enter the atmosphere.

1.2.1 Isotopic abundance

In addition to the overall chemical abundance, there are several reasons why also the isotopic abundances are of particular interest (see section 1.4.3 about propagation models). A special group of isotopes is formed by the very lightest stable elements: ^1H , ^2H , ^3He and ^4He . ^2H and ^3He nuclei observed in galactic cosmic radiation are absent in their sources, in which they are unstable against thermonuclear reactions [6]. They are formed by high energy nuclear interactions between cosmic rays and interstellar matter [7].

Since ^3H decays into ^3He with a 12.2 year half-life, negligible with respect to the cosmic ray propagation time ($10^6 - 10^8$ years), it is possible to assimilate every ^3H production to an ^3He production (it is not true for secondary particles in atmosphere, when the time of life is less than ^3H half-life).

The cross sections for the production of ^2H , ^3H and ^3He are generally of the same order of magnitude in p-p, p- ^4He , ^4He - ^4He and p-($Z > 2$) interactions. Thus the most important reactions in this context are those in which the most abundant nuclei are involved (namely p-p and p- ^4He reactions).

The production of ^2H , ^3H and ^3He in p- ^4He collisions can occur in two ways:

1. Fragmentation of cosmic ray ${}^4\text{He}$ on interstellar hydrogen ${}^1\text{H}$;
2. Fragmentation of cosmic ray hydrogen ${}^1\text{H}$ on interstellar ${}^4\text{He}$.

In most cases the secondary ${}^2\text{H}$, ${}^3\text{H}$ or ${}^3\text{He}$ is emitted with a low energy in the frame of the ${}^4\text{He}$ nucleus. In a frame of reference fixed in space, it has an energy/nucleon close to that of the incident ${}^4\text{He}$ in first case, and gives rise to a low energy component in second case. Moreover, the ${}^2\text{H}$ and ${}^3\text{He}$ formed can themselves undergo fragmentation on interstellar matter. Here, p - ${}^2\text{H}$ and p - ${}^3\text{He}$ cross section are involved.

Finally protons, ${}^2\text{H}$, ${}^3\text{He}$ and ${}^4\text{He}$ nuclei may be slowed down to an appreciable extent (with respect to electronic collisions) by nuclear elastic scattering on interstellar matter. Therefore elastic cross sections are involved [8]. Table 1.2 reports the cosmic ray abundance of these elements at different energies compared with the local interstellar abundances [3].

Isotope ratio	60 MeV/ nucleon	80 MeV/ nucleon	200 MeV/ nucleon	local interstellar abundance
${}^2\text{H}/{}^1\text{H}$		$(4.4 \pm 0.5) \cdot 10^{-2}$	$(5.7 \pm 0.5) \cdot 10^{-2}$	$1.0 \cdot 10^{-5}$
${}^3\text{He}/{}^4\text{He}$		$(9.5 \pm 1.5) \cdot 10^{-2}$	$(11.8 \pm 0.7) \cdot 10^{-2}$	$3.0 \cdot 10^{-5}$
${}^2\text{H}/{}^4\text{He}$	(0.21 ± 0.09)		(0.31 ± 0.03)	$1.0 \cdot 10^{-4}$

Table 1.2: Isotope ratios of hydrogen and helium. Cosmic rays abundances are compared with the local interstellar abundances (last column).

Another important aspect of isotopic abundance is the fact that some of the species created in the spallation reactions are radioactive and so, if the production rates of the different isotopes of a certain element are known, the time taken by these samples to reach the Earth from their source can be estimated. The most famous of these "cosmic rays clocks" is the isotope ${}^{10}\text{Be}$ which has a radioactive half-life of $1.5 \cdot 10^6$ years and so it is very useful to determine the typical lifetime of the spallation products in the vicinity of the Earth (see also 1.4.3).

1.3 Life history of cosmic rays

It is known that some low energy cosmic rays are ejected by the Sun from time to time and since the Sun is a typical star it is reasonable to suppose that other stars emit cosmic rays. However, the rate of production of cosmic rays by stars similar to the Sun is too low to give the observed intensity and, as shown later, various theories have been proposed to account for the origin and acceleration of the particles. For the present it is sufficient simply

to distinguish between the radiation reaching the Earth from outside the heliosphere and those particles coming from the Sun.

From their origin to their arrival at some point of detection in the atmosphere, the primary cosmic rays are acted on by a variety of forces. These are best appreciated by reference to a diagram (see figure 1.3). The acceleration process for the general cosmic rays may occur in the source itself or perhaps take place over a separate region of the galaxy, so source and acceleration are bracketed together. The interaction of the particles with the galaxy can be divided into two main processes: the physical interaction with galactic matter (in the form of scattering, disintegration, collision with galactic atoms) and the interaction with magnetic field.

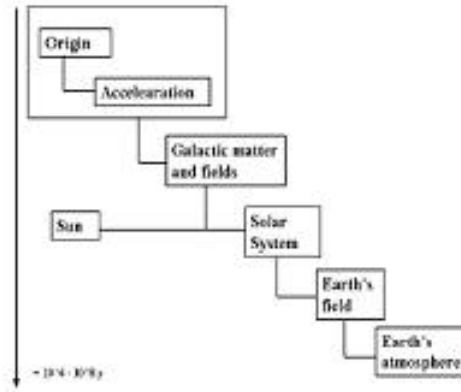


Figure 1.3: Life history of primary cosmic rays.

Similarly, in the solar system there are the physical interaction with solar system matter and the magnetic interaction. Sun is both a source of solar cosmic rays than a modulator of galactic cosmic rays. Finally, at the end of its travel to the Earth, a cosmic ray is affected by geomagnetic field and by Earth's atmosphere [9]. As expected, the cosmic ray data duplicate existing astrophysical and geophysical data in some places and extend them into others; in both cases they contribute to our knowledge of the properties of the universe.

1.4 From the sources to the Heliosphere

In this section the basic aspects of origin models, acceleration, confinement and propagation mechanisms of cosmic rays from the sources to the Heliosphere are outlined.

1.4.1 The origin of cosmic rays

One of the central questions of the astrophysics of cosmic rays is the problem of their origin, and below we shall be concerned with the origin of the main part of the cosmic rays observable on Earth. To answer this question means in the first place that we have to indicate at least roughly the position of the sources of the cosmic rays, for instance, to prove that they are in the galactic disc. Secondly, we have to identify the sources, for instance, relating them to supernova explosions. However, we have to emphasize that to know the nature of the sources is not of particular importance for clarifying a whole series of other questions. For instance, it is not particularly important for solving the third problem: to establish the trapping model of the cosmic rays in the Galaxy. Furthermore, there arise many other problems: how do cosmic rays propagate from the sources to the Earth, how does their chemical and isotopic composition change during this process, what role do plasma and magneto-hydrodynamic effects play in the propagation of cosmic rays and so on.

We assume that the intensity of cosmic rays depends only on the total energy $E(I_{Z.A} = I_{Z.A}(E))$ of the corresponding particles (of course, one can also use the kinetic energy E_k , or the energy for nucleon). This is a very good approximation in view of the high isotropy of the cosmic rays. It was already clear in the fifties, after radio-astronomical data on cosmic rays far from the Earth became available, that there was no basis for solar models [10]. As regards meta-galactic models the situation is more complicated. In such models the main sources of cosmic rays are assumed to be meta-galactic and, consequently, the cosmic rays observed on Earth first travel from a meta-galaxy to our Galaxy before reaching the solar system. There is no doubt that the electron component of the cosmic rays observed in the Earth has a galactic origin. For a number of reasons, which we shall not discuss here, it is also very probable that the proton-nuclear component of the cosmic rays has a galactic origin. Nevertheless, logically speaking not every conceivable model of a meta-galactic origin of the proton-nuclear component has been ruled out. Apparently, for this purpose only γ -ray astronomical methods are adequate.

In meta-galactic models, the cosmic rays outside the Galaxy should possess approximately the same characteristics as within the Galaxy. In particular, the energy densities should be equal:

$$W_{c.r;MG} \cong W_{c.r;G} \cong 10^{-12} \text{ erg/cm}^3 \quad (1.2)$$

The equation should be valid everywhere and, in particular, in the Magellanic Clouds. In such conditions we can predict fairly reliably the flux of γ -rays from π^0 decays, which should originate from each of the clouds. For instance, for the Small Magellanic Cloud the photon flux $F_\gamma(E_\gamma > 100 \text{ MeV})$ is equal to 107 photons/cm^2 if we take into account only the atomic hydro-

gen in the cloud. Obviously, if we take into account molecular hydrogen and the γ -rays from electronic bremsstrahlung emission, we get a larger flux. If the cosmic rays are formed in the clouds themselves, then in view of the relatively small size of these clouds they can rather quickly escape into interstellar space. Under such conditions the flux, for instance for the Small Magellanic Cloud, may turn out to be lower than the lower limit mentioned.

More precisely than the flux from each of the clouds one can predict the ratio of the γ -rays fluxes from the clouds. A clear discrepancy between the observations and these predictions will be a direct refutation of meta-galactic models. Namely, in meta-galactic models the value of the density of cosmic rays in the Galaxy, $W_{c.r;MG} \cong 10^{-12}$ erg/cm³, should be constant over the whole system, including the peripheral regions, and in particular it should not decrease away from the solar system in the direction of the galactic anti-centre. Meanwhile, some of the available observations of the γ -ray intensity $I_\gamma(E_\gamma > 100 \text{ MeV})$ in the direction of the anti-centre indicate a drop in the cosmic ray intensity (and, of course, their energy density $W_{c.r}$) away from the solar system [11].

The galactic models

In galactic models the sources of the cosmic rays are, of course, situated in the Galaxy. In which region and why the cosmic rays are concentrated is a different question. If we use the energy requirements and the non-thermal radiation in the various regions as a guideline, then the most probable candidates are supernovae, pulsars, and neutron stars in close binary system. In this section it will be described one of the most probable candidates in the cosmic rays galactic models: the supernova explosions [12]. From the energy point of view such a suggestion is completely acceptable. Supernovae explosions occur in our galaxy about each fifty years. As mentioned above, in the solar system, the average density of cosmic ray energy is 1 eV/cm³. Assuming that this is the typical value also for the rest of the galaxy, with a galactic disk volume of 10^{63} cm³, the total cosmic rays energy content is then about 10^{67} eV or $1.6 \cdot 10^{55}$ erg. The average cosmic rays lifetime is approximately $3 \cdot 10^{14}$ s (obtained by the ¹⁰Be isotope abundance). Thus the rate at which cosmic rays energy is lost amounts to $5 \cdot 10^{40}$ erg/sec, and this loss must be compensated by injection and acceleration of new cosmic rays.

If we assume supernova explosion each fifty years ($1.5 \cdot 10^9$ s), and the typical supernova yields of 10^{50} erg in fast particles, we obtained an average power of $6 \cdot 10^{40}$ erg/s. This simple calculation explains the reasons of supernova as most probable candidate for cosmic rays source.

The mechanisms responsible for cosmic rays acceleration are still not totally clear. In galactic models the sources are characterized by turbulent motion of the medium and the presence of high magnetic fields [13]. In addition, as it is well known, in variable magnetic fields, electric fields are

induced and accelerate charged particles. Unfortunately, however, we have to acknowledge that no model of cosmic ray acceleration has yet been developed that makes it possible to choose the main acceleration mechanisms among the many possible ones. The great variety of conditions and processes in the cosmos leads to the conclusion that there are numerous acceleration mechanisms of energetic particles. In particular, this is true for such well studied processes as the acceleration of particles in the radiation belts of the Earth [14] and of Jupiter [15], the appearance of fast particles during magnetospheric substorms [16], in the interplanetary space [17], and during solar flares [18]. All regions in which there are high voltages and strong magnetic fields could be considered as sites of mechanism acceleration processes. Supernovae represent only one source type in which rapid acceleration occurs in a relatively compact region.

In next section more complete descriptions of second and first order (in V/c) acceleration mechanisms are outlined.

1.4.2 Acceleration mechanisms

V/c second order acceleration mechanism

In 1949, Enrico Fermi evolved a theory in which the main process of acceleration is due to the interaction of cosmic particles with wandering magnetic fields which occupy the interstellar space [19]. In this theory charged particles are reflected from magnetic mirrors associated with irregularities in the galactic magnetic field. The mirrors are assumed to move with velocity V . The energy enhancement due to reflections is statistically described as:

$$\frac{dE}{dt} = \frac{2 \cdot V^2}{c\lambda} E = \alpha E \quad (1.3)$$

where $\lambda = \rho c \tau$ is the mean free path in g/cm^2 between magnetic clouds, which are site of mirroring (ρ being the mean matter density and τ the mean time interval). From 1.3 a power law energy spectrum of cosmic rays is obtained:

$$N(E) \propto E^{-\gamma} \quad \text{con} \quad \gamma = \left(1 - \frac{1}{\alpha \tau_\alpha}\right) \quad (1.4)$$

in which $dt \sim \tau_\alpha$ is the mean time spent by a particle in the acceleration regions. In a modern version of Fermi second order acceleration, the particles interact with various types of plasma waves and gain energy being scattered stochastically by these waves. In the interstellar space, the relativistic cosmic ray plasma streams along the large scale magnetic field lines. In this process they collectively excite a spectrum of hydromagnetic waves, called Alfvén waves. These kind of waves propagate in the ionized component of the interstellar gas along the streaming direction of the particles. Resonant interaction between cosmic rays and Alfvén waves occurs when cosmic ray

performs one gyration around the magnetic field lines while traversing one Alfvén wavelength.

V/c first order acceleration mechanism

This acceleration mechanism is the result of individual head-on collision leading to a more rapid increase of particle energy. The condition to obtain it is a strong shock wave propagating at a supersonic velocity V (higher than Alfvén velocity) in the direction of the magnetic field lines through stationary interstellar gas. We assume that the gas is flowing in at a velocity $u_s = V$ in the shock frame. After the shock, the velocity downstream becomes $u_d = V/\zeta$, if ζ is the compression factor of the shock. The presence of scattering centers is postulated, so that cosmic rays diffuse (with a diffusion coefficient function of position, particle momentum and time) on both sides of the shock. The scattering centers ensure that the particles will be reflected across the shock a large number of times. Every passage through the shock is equivalent to running head-on into the magnetic wall of velocity:

$$W = u_s - u_d = V(1 - \frac{1}{\zeta}). \quad (1.5)$$

Averaged over all incidence angles, there is a mean energy gain of:

$$\Delta E = \frac{4V}{3c}(1 - \frac{1}{\zeta})E \quad (1.6)$$

per traversal of the shock. Taking proper account of the probability of particles escaping the system leads to the time-independent spectrum:

$$N(E) \propto E^{-\gamma} \quad \text{con } \gamma = (\frac{2+\zeta}{\zeta-1}). \quad (1.7)$$

A typical value of ζ for strong adiabatic shocks is ~ 4 , and the consequential value of γ is ~ 2 . From 1.7 it is clear that weaker shocks generate steeper spectra. In the time independent limit the slope of the power law generated by the acceleration mechanism depends on the ζ value.

Energy spectra of cosmic rays near the Earth have been shaped by a combination of injection, acceleration and propagation processes. Energy losses and collisions contribute too, and they all depend on the particle energy. Observations show that different acceleration processes can all produce cosmic rays with energy spectra having the characteristic $E^{-\gamma}$ shape. Many other specific models and new interpretation have been proposed to describe acceleration process in different parts of Universe [20, 21, 22, 23].

1.4.3 Cosmic ray confinement and propagation

The transport mechanisms for cosmic rays in the galaxy are dominated by particle motion in the galactic magnetic fields. The cosmic rays, then, move

in spiral trajectories around the magnetic field with gyroradii appropriate to the particle energy. Even the field lying approximately in the galactic disk is somewhat disordered, and field "loops" extend out of the disk into a galactic halo. A cosmic ray particle gyrating around such a field will interact with these and smaller irregularities and can be scattered by them, so that the cosmic rays may become diffuse in the magnetic field. Therefore, diffusion theory is often employed to describe the large-scale propagation of the cosmic rays [10, 24]. Moreover the magnetic field configurations permit access of the cosmic rays to the galactic halo where the propagation conditions are different. Thus, a complete treatment of cosmic ray transport, in the diffusion approximation, must consider diffusion both in the galactic disk and also within the halo region [3].

A general transport equation proposed by Ginzburg and Syrovatskij [10] treats both the acceleration and the propagation of cosmic rays:

$$\frac{\partial N_i}{\partial t} = \nabla \cdot (D \nabla N_i) - \frac{\partial}{\partial E} [b_i N_i] - \nabla \cdot u N_i + Q_i - p_i N_i + \sum_{k \geq 1} N_k p_{k \rightarrow i} \quad (1.8)$$

where $N_i dE = N_i(E, \mathbf{x}, t) dE$ represents the density of particle of type i at position $\mathbf{x}$ with an energy between E and $E + dE$; the first term on the right describes the diffusion of particles and the diffusion coefficient D can be written as:

$$D = \frac{1}{3} \lambda_D \nu \quad (1.9)$$

where ν is the particle velocity and D the diffusion mean free path. The second term represents the gain of energy or loss (due for example to ionization), that is:

$$b_i \equiv \frac{dE}{dt} \quad (1.10)$$

the mean rate at which the particle i changes its energy. The convection term is the third one and represents convection with velocity u . Particles are produced by a source represented by $Q_i = Q_i(E, \mathbf{x}, t)$ particles per cubic centimeter at position $\mathbf{x}$ and time t per energy interval dE . The $p_i N_i$ term represents losses due to collisions and decay with:

$$p_i = n \beta c \sigma_i + \frac{1}{\gamma \tau_i} \quad (1.11)$$

where τ_i is the lifetime of nucleus i for radioactive decay, the interstellar gas is assumed to be hydrogen with density $n = n(x)$ and σ_i is the inelastic cross-section. As one can see a huge number of cross-sections are involved and not all are so well known [25]. The last term describes the production of nuclei of type i from the interactions of nuclei of different types and in

the sum only heavier nuclei are considered. Relation 1.11 can be used to express $p_{k \rightarrow i}$. The cross-section for the production of the nucleus i from the breakup of nucleus of type k is $\sigma_{k \rightarrow i}$ and $\tau_{k \rightarrow i}$ is the lifetime of the nucleus k with respect to the nuclear decay channel that leads to the production of a nucleus of type i . The production term can be written in the form of relation 1.11 because the kinetic energy per nucleon is to first approximation conserved in fragmentation reactions of relativistic nuclei, a process known as "spallation".

The different models of the Galaxy can be represented using equation 1.8 with specific boundary conditions and approximations. In succession I present two of the most referred models of cosmic rays propagation in the literature: the Leaky Box Model (LBM), with some its sub-models, and the Diffusion Halo Model (DHM). All models are able to explain the cosmic ray data surprisingly well although the physical framework of both models differs.

Leaky Box Model (LBM)

One of the more successful Galaxy models is the Leaky Box Model (LBM) [26] and its variants. In this model the cosmic rays move freely in a containment volume, with a constant probability per unit time of escape, $t_{esc}^{-1} \ll c/h$ where $2h \approx 200 - 300$ pc is the thickness of the Galaxy at the radius of the Earth. The diffusion term of equation 1.8 is then replaced by $-N/t_{esc}$. In this model collisions, other energy changing processes and convection are neglected. The solution for a delta function source $Q(E, t) = N_0(E)\delta(t)$ is:

$$N(E, t) = N_0(E) \exp\left[\frac{-t}{\tau_{esc}}\right] \quad (1.12)$$

where τ_{esc} can be interpreted as the mean time spent by the cosmic rays in the containment volume and $\lambda_{esc} = \rho\beta c\tau_{esc}$ as the mean amount of matter traversed by a particle of velocity c .

At equilibrium the time dependence of equation 1.8 vanishes. The equation assumes a simplified form and the secondary to primary ratios in the cosmic radiation can be explained under the assumption that all nuclei have the same propagation history, i.e. the same λ_{esc} . Within this model the energy dependence of the secondary to primary ratio is due to the energy dependence of λ_{esc} . In the case of a primary nucleus i for which the feed-down from fragmentation of heavier nuclei can be neglected, the solution of 1.8 has the form:

$$N_i(E) = Q_i(E) \frac{\tau_{esc}}{1 + \lambda_{esc}/\lambda_t} \quad (1.13)$$

The λ_{esc} energy dependence was obtained in [27] as:

$$\begin{aligned}\lambda_{esc} &= 10.8 (g/cm^2)\beta\left(\frac{4}{R}\right)^3 \quad \text{for } R > 4 \text{ GV} \\ \lambda_{esc} &= 10.8 (g/cm^2)\beta \quad \text{for } R < 4 \text{ GV}\end{aligned}\tag{1.14}$$

For protons the interaction length is $\lambda_p \cong 55 \text{ g/cm}^2$ [28] and $\lambda_{esc} \ll \lambda_p$ for all energies.

Hence if the observed spectrum of protons is $N \propto E^{-(\gamma+1)}$ at high energy with $\gamma \cong 1.7$ then equation 1.13 becomes:

$$Q(E) \propto E^{-\alpha}\tag{1.15}$$

with $\alpha = (\gamma + 1 - \delta) \cong 2.1$. The source spectrum of protons in the LBM can be represented by a power law function with a spectral index of about 2, in excellent agreement with the Fermi's first order acceleration model in supernovae [29].

In the case of iron the interaction length is much smaller than for protons and the energy losses are due more to interactions rather than to escape. Hence the spectrum should reflect the source spectrum directly. In conclusion the LBM suggests that the iron spectrum is flatter than the proton spectrum and this could explain the observation from the KASCADE experiment for which the chemical composition of cosmic rays becomes heavier with increasing energy [30].

Other major constraints to models of our Galaxy are given from ratios of unstable to stable isotopes of secondary nuclei. Unstable nuclei with lifetimes of the order of the escape time from the Galaxy can be used as "cosmic ray clocks". If the unstable nucleus lifetime is greater than the escape time from the Galaxy the unstable to stable isotopes ratio is expected to be the ratio at the production site, that is the ratio of the fragmentation cross-sections of the parent nuclei. If the measured ratio instead is much smaller than the expected one the implication is that the lifetime is smaller than the escape time from the Galaxy.

Unlike heavier secondary nuclei, such as Li, Be and B, lighter secondary nuclei like ^3He and deuterium have an interaction mean free path considerably larger than the escape mean free path from the Galaxy and they are ideal probes to study cosmic ray propagation in the whole containment volume. Moreover, the majority of cosmic rays are protons and helium nuclei; those with $Z > 3$ constitute only about 1% of the total. It is therefore very important to determine the propagation history of these lighter species. The rare isotopes ^2H and ^3He are believed to be produced by interactions of primary protons and helium nuclei with the interstellar matter. The measurement of the secondary to primary ratios ($^3\text{He}/^4\text{He}$, $^2\text{H}/^4\text{He}$ and $^2\text{H}/^1\text{H}$) along with

their absolute abundances is an excellent probe of the propagation of cosmic ray hydrogen and helium (see also section 1.2.1).

The Nested Leaky Box Model

A modified version of the LBM is the Nested Leaky Box Model (NLBM) [31, 32]. In this model the sources of cosmic rays are surrounded by a confinement high density region in which particles diffuse for a short and energy dependent time. The energy dependence of the secondary to primary nuclei ratios is due to the energy dependent leakage from the source region. The Galaxy is considered as an outer volume which nuclei traverse and in which they encounter a further small and constant amount of matter.

Supernovae inside dense clouds could be the physical scenario for this model. An observer inside a source region would measure a differential spectrum $E^{-\alpha}$ as in the case of the LBM. But the solar system is not inside a source region, so we would observe the source spectrum and hence this model needs cosmic accelerators that produce a differential spectrum with spectral index $\alpha = \gamma + 1 \cong 2.7$.

The Closed Galaxy Model

The Closed Galaxy Model (CGM) [33] can be considered a variant of the NLBM in which the source region is the local spiral arm of the Galaxy. Then Earth is inside the region from which the probability of escaping for a particle is energy dependent and this gives the observed decrease with energy of the ratio of secondary to primary nuclei. Particles are then fully contained in the larger volume. In this scenario the old component of cosmic rays consists of stable particles with a lifetime determined by the energy losses.

The Diffusion Models

In 1980 Ginzburg, Khazan and Putskin [34] stated that the correct scenario for the cosmic ray propagation should be a diffusion model in which the diffusion equation is solved in a more realistic and physical sense. The diffusion operator can not be treated as a constant. Hence the main difference with a Leaky Box Model is that the distribution of cosmic rays in the steady state is not uniform in the containment volume. In the model with diffusion there are density gradients and consequently anisotropy.

The simplest diffusion model requires a Galaxy with a halo of scale height $H \gg h \cong 200$ pc which is the height of the galactic disk. Cosmic rays are assumed to escape freely at H where the cosmic ray density becomes zero.

For stable secondaries, the diffusion model and the LBM are equivalent in their treatment of the average path length for production of secondaries, even if the path-length distribution is different. Unstable secondaries with a lifetime smaller than the time needed to reach a height H ($\gamma\tau_s < \tau_h < H^2/D$)

are contained in a volume smaller than the full halo. Physically it means that they do not live long enough to reach a distance H from the galactic plane.

Figure 1.4 sketches the physical picture of the DHM. The shaded area illustrates the thin galactic disk of height h_g and the quantity H stands for the height of the halo. It is assumed that the cosmic ray sources are placed in the thin galactic disk, where most of the interstellar gas is located, but the cosmic rays themselves diffuse out and may spend considerable portions of their lifetime in the halo. A three dimensional diffusion equation would be the proper approach to the problem. It could cover physical details in our galaxy such as the spatial gas distribution of atomic and molecular hydrogen, could link the cosmic ray sources to the distribution of supernova remnants, and could also add aspects such as galactic winds and convection. This illustrates that the DHM accounts for much more physical details than the LBM.

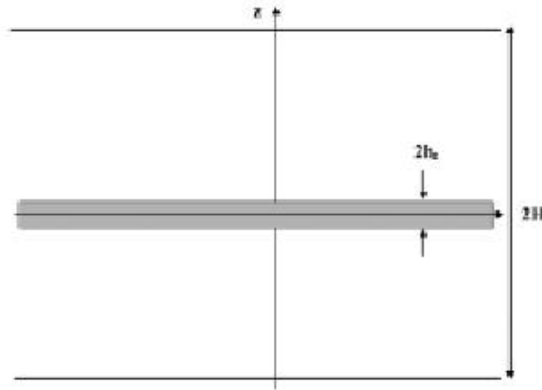


Figure 1.4: Schematic view of the physical concept of the DHM. The shaded area symbolizes the thin disk and H stands for the halo size. The sources of cosmic rays are in the disk and the escape into the halo and finally into the intergalactic space is controlled by diffusion.

For this discussion it is sufficient to make the picture somehow simpler. We will allow that the cosmic ray sources and the interstellar gas are homogeneously distributed throughout the thin galactic disk and will ignore convection and energy changing process. This provides symmetry and if one further ignores energy changing process, this scenario can be described with a one dimensional diffusion equation:

$$Q(E) \propto E^{-\alpha} \frac{\partial N_i(z, t)}{\partial t} = \frac{\partial}{\partial z} D(z) \frac{\partial}{\partial z} N_i(z, t) + \\ - N_i(z, t) \frac{1}{i\tau_{int}(E)} + iQ_{prim}(z) + \sum_{k>i} \frac{N_k(z, t)}{\tau_{int}^{k \rightarrow i}} \quad (1.16)$$

where $N_i(z, t)$ and $N_k(z, t)$ describe the density of i -type and k -type particles at position z at time t , with k heavier than i . The first term of the right side describes the diffusion and $D(z)$ means the diffusion coefficient at position z .

The second bracket on the right side of equation 1.16 accounts for the losses of i -type particles similar to those quantities described in the last section. In the last two terms one finds the sources for the i -type particles. One can have primary sources $iQ_{prim}(z)$ as well as secondary sources by spallation of k -type nuclei expressed by the last two term on the right side of equation 1.16.

I refer to [35] for the results obtained by solving 1.16 under different sets of parameters and boundary conditions, and simply point out that identical results from the LBM and DHM models are consequences of a mathematical relation between the diffusion equation and the equilibrium (or continuity) equation which describes DHM and LBM respectively.

1.5 Antimatter in Cosmic Rays

After the theoretical prediction of antimatter by Dirac and the experimental results that confirmed the existence of the positron, it was believed that the universe must consist of both matter and antimatter in equal amounts. This assumption was motivated by basic symmetry principles and on studies on Big Bang cosmology. In the late 1950s, the amount of antimatter in our galaxy was calculated to be less than one part in a hundred million. If there were an isolated system of antimatter in the universe, free from interaction with ordinary matter, no earth-bound observation could distinguish its true content. So, even if nothing was visible, the possibility of extragalactic antimatter was wide open. In the following years, motivated by basic symmetry principles, it was believed that the Universe must consist of both matter and antimatter in equal amounts but primary antinuclei have never been observed in space.

In case of matter and antimatter separated in domains, such regions must be apart at distances at least of the order of galaxy cluster; otherwise very intense γ -ray emissions, produced in the annihilation, would be observed. This hypothesis is still very speculative, since no strong sign of antimatter-matter annihilation (for instance 511 keV photons from $e^+ e^-$ annihilation) is visible in the γ -component of cosmic rays. Nasa's orbiting Compton Gamma

Ray Observatory (CGRO) spacecraft detected an unexpected cloud of antimatter in the Milky Way Galaxy. This is partially explained by ESA's space probe INTEGRAL, which resolved about 100 individual γ sources towards the centre of the galaxy [36].

Conclusive discoveries that could demonstrate the existence of antimatter sources would be represented by detection of antinuclei ($Z \geq 2$) because the production cross sections, starting from ordinary matter, are negligible in this case. Upper limits on the presence of antihelium, the most stable of any possibly existing antinuclei, have been imposed by experiments to be $\sim 10^{-6}$ ($\bar{H}e/He$ ratio). If any antihelium is discovered, it could have been produced either during primordial nucleosynthesis, together with all the other visible nuclei, or via nuclear fusion reactions between antinuclei. In order to demonstrate that somewhere in space there is an "antistar", anticarbon nuclei have to be discovered, since anticarbon could not have been produced in primordial nucleosynthesis.

The known antimatter component of cosmic rays consists of antiprotons and positron. The observed antiproton spectrum indicates that antiprotons are produced by collisions of cosmic ray nuclei with the interstellar gas. These antiprotons are called "interstellar secondary antiprotons". Positrons are instead produced through pair production ($\gamma \rightarrow e^+ e^-$) and through a multitude of reactions that involve the creation of pions ($\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$). However, antiproton and positron primary production can not be excluded at the moment.

The mystery surrounding the positron and antiprotons origins and abundances needs to be investigated further. To solve this mystery, a possibility is given by high energy measurements of antiprotons and positrons flux: above some tens of GeV, models of secondary production and theories describing primary sources give significantly different amounts of antiprotons and positrons, like described in detail for antiprotons in next subsection. In these measurements other theorized sources of primary antimatter could be detected and investigated, for instance exotic dark matter. In fact, signatures of relic particles, diluted during the inflationary era, may be observable in the cosmic ray spectra [37]. Among massive particles predicted by supersymmetric theories, neutralinos are Majorana particles ($\bar{\chi} = \chi$) predicted to leave a signature in the spectra of γ 's, ν , antiprotons and positrons (figure 1.5). Several experiments include in their scientific objectives the search for neutralino signature as distortions in the cosmic ray spectra components: γ 's (GLAST), antiprotons and positrons (PAMELA, Bess, HEAT, AMS, etc.) and ν (Amanda, Ice Cube).

These models are illustrated in figure 1.6 together with the available measurements of the abundance ratios $\bar{p}/p$ and $e^+/(e^+ + e^-)$. All of them have been obtained by balloon-borne missions in the last years. PAMELA will extend the measured values over greater energy intervals and with a significantly greater statistics (see section 2.1).

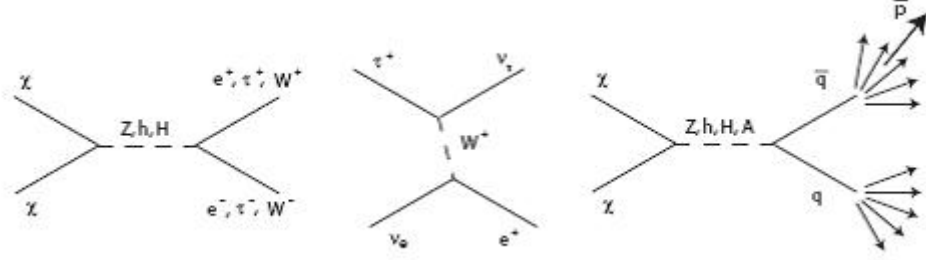


Figure 1.5: Secondary production of γ 's, antiprotons and positrons from neutralino interactions.

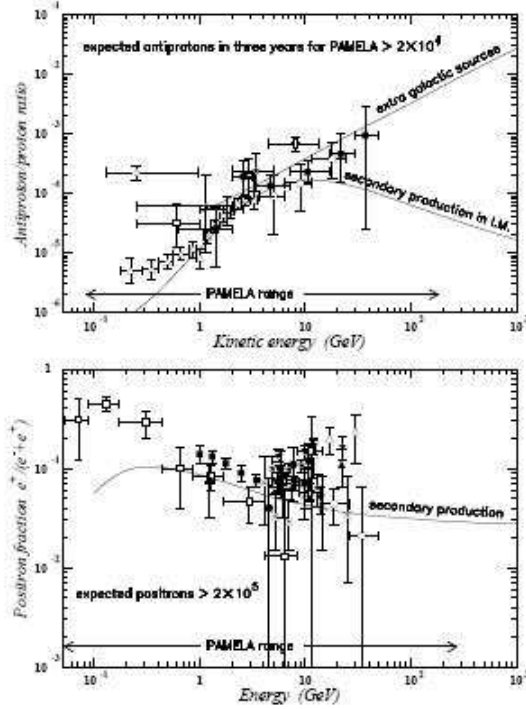


Figure 1.6: Current status of antiprotons and positrons acquisitions. All these measurements have been performed on ballon flights: for antiprotons and positrons data see respectively references [38, 39] and references therein. The PAMELA energy ranges and the expected counts for both antiparticles are reported. Curves refers to theoretical prediction of these ratios at higher energy according to a model of secondary production and to expected behaviour in case of extragalactic source.

1.5.1 Secondary and primary antiprotons

Secondary Antiprotons

Proton and helium cosmic rays interact with the interstellar hydrogen and helium nuclei, producing quarks and gluons that subsequently can hadronize into antiprotons. A calculation of this secondary antiproton flux has been done in [40], to which we refer for details. Figure 1.7 displays, along with experimental data, the computed antiproton flux with the contributions to the total flux coming from the various nuclear reactions: from top to bottom are represented the contribution of p-p, p-He, He-p and He-He.

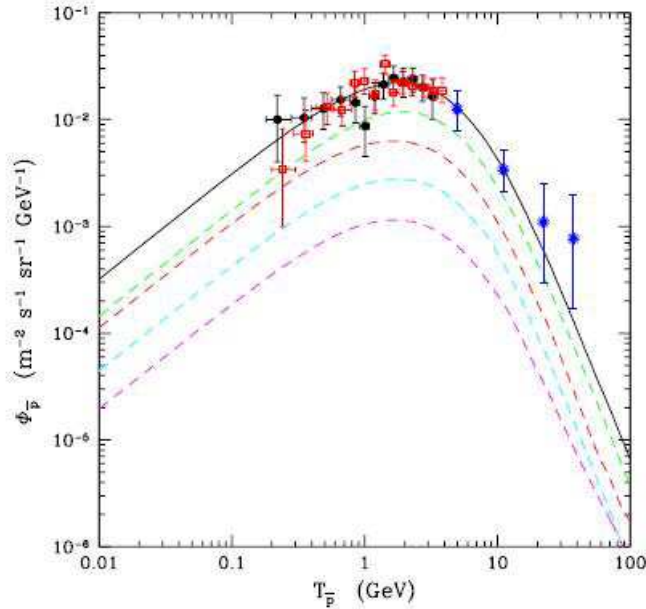


Figure 1.7: Solid line shows the total Top-Of-Atmosphere (TOA) secondary antiproton spectrum for the set of diffusion parameters giving the best χ^2 for B/C. Dashed lines are the contributions to this total flux from various nuclear reactions (from top to bottom: p-p, p-He, He-p and He-He). Data points are taken from BESS 95+97 (filled circles), BESS 98 (empty squares) and CAPRICE (starred).

First of all, we notice that the calculated spectrum agrees very well with the data points. This strong result gives confidence in a consistent treatment of nuclei and antiproton propagation in the galaxy. Second, even if the main production channel is the spallation of cosmic ray protons over interstellar hydrogen, it is possible to see that the contribution of protons over helium is very important, particularly at low energies (where a hypothetical primary signature would be expected). It emphasizes the necessity of having a good

parameterization of the p-He reaction. Figure 1.8 shows the uncertainties deriving from the propagation parameters and from the scarce knowledge of some nuclear cross sections, and have been calculated according to [40]. The resulting scatter is 9% from 100 MeV to 1 GeV, reaches a maximum of 24% at 10 GeV and decreases to 10% at 100 GeV. This estimate of the uncertainties related to diffusion may be considered as quite conservative. The uncertainties related to nuclear physics obtain a shift of the upper and the lower curve with respect to the central one of the order of 22-25% over the energy range 0.1-100 GeV. The major uncertainties come then from nuclear physics and are already comparable to experimental error bars. As antiproton spectrum measurements should better in the near future, antiproton studies could be limited by nuclear indeterminacies.

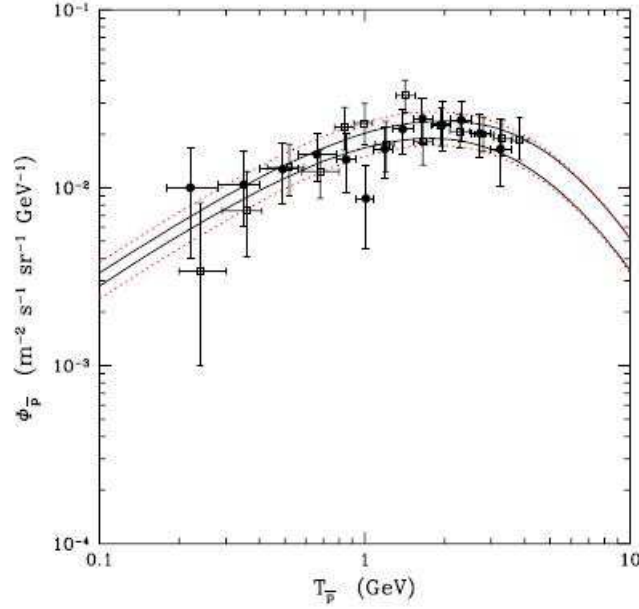


Figure 1.8: Uncertainty on the evaluation of the Top-Of-Atmosphere (TOA) secondary antiproton spectrum. Solid band: uncertainty on the propagation parameters, dotted band: uncertainty due to nuclear physics.

Antiprotons from Dark matter annihilation

If the dark matter is under the form of neutral, massive supersymmetric particles, we may expect that they annihilate in pair producing quarks and gluons. These elementary particles can then hadronize and give birth to antiproton nuclei. In principle, an excess of low-energy antiprotons is the signature of an unconventional production. Antiproton production from primary cosmic-ray spallations is the natural background to any unconventional

excess that would signal for instance the presence of the putative neutralinos. The calculation of this primary component has been performed in [41], to which we refer for further details. The solutions of the spatial diffusion equations are now very different than for the secondary counterpart, due to the fact that in the present case the antiproton sources (neutralinos) pervade the all diffusive volume. This characteristic breaks the degeneracy on the propagation parameters that can be observed for B/C and for secondary antiprotons, whose sources are located only in the thin disc.

The eMSSM (effective Minimal Supersymmetric Standard Model, see [41] and refs. therein) is a supersymmetric scheme directly developed at the electroweak scale, which is where the phenomenology of neutralino dark matter is actually studied. The large number of free parameters is reduced by a set of assumptions which are sufficient to shape the properties of the model at the electroweak scale. A calculation of the primary antiproton fluxes deriving from neutralino annihilations was applied, considering different possibilities for the propagation parameters. Reference configuration is the one which provides the best fit to B/C ratio [41, 42]. In figure 1.9 it is plotted the secondary flux (as from [40]) and the previous predictions for primary fluxes at different neutralino masses in the eMSSM: $m_\chi = 60, 100, 300, 500$.

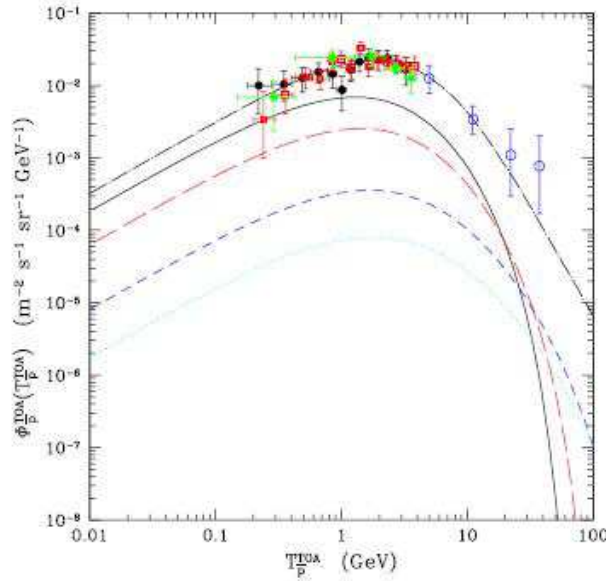


Figure 1.9: Top-Of-Atmosphere (TOA) antiproton fluxes for a few representative supersymmetric case: solid line refers to $m_\chi = 60$ GeV, long-dashed to $m_\chi = 100$ GeV, short-dashed to $m_\chi = 300$ GeV and dotted to $m_\chi = 500$ GeV. The upper dot-dashed curve corresponds to the antiproton secondary flux. Full circles: BESS 1995/97 data; open squares: BESS 1998; stars: AMS; empty circles: CAPRICE.

It can be noticed that the primary flux from neutralino annihilation is at most of the same order of magnitude as the secondary flux, and this occurs for neutralino masses close to their current lower bound in the eMSSM, which is around $m_\chi \approx 50$ GeV. The representative supersymmetric configurations refer to a large antiproton production for each mass. This indicates that the antiproton signal for neutralino dark matter will hardly produce an excess over the secondary flux, for the median (and best) choice of the astrophysical parameters which govern the diffusion and propagation of antiprotons in the Galaxy. However, the same primary antiproton fluxes calculated with propagation parameters providing a 4-sigma deviation from the best fit on B/C, differ by almost an order of magnitude - at least at low energy - from the reference (best fit) configuration. This means that the scarce knowledge of the astrophysical parameters induces an uncertainty of about 2 orders of magnitude on the calculation of primary antiproton fluxes. This is almost independent on the specific supersymmetric configuration. The large variation in the primary signal is due to the fact that the exotic signal is more sensitive to astrophysical parameters than the standard. Figure 1.10 shows the TOA antiproton fluxes for the $m_\chi = 100$ GeV reference configuration and for the maximal and minimal sets of astrophysical parameters. The figure shows that solar modulation has the effect of depleting the low-energy tail of the antiproton flux. It is evident how huge the astrophysical uncertainty band is.

As shown in [43], in Supersymmetric models without gaugino-mass unification at the grand unification scale, neutralinos can be lighter than the current lower bound of 50 GeV, which instead occurs in the case of gaugino-universal models. In [43] (see also refs. therein) the properties of these light neutralinos as relic particles are discussed and it is shown that an absolute lower limit of 7 GeV on the neutralino mass m_χ can be placed by applying the most recent determinations of the upper bound on the Cold Dark Matter (CDM) content in the Universe. Being the supersymmetric antiproton flux inversely dependent on the neutralino squared mass, it is easy to expect that for these light neutralinos the antiproton flux could provide interesting information. To show quantitatively how the experimental data could constrain the supersymmetric parameters, in figure 1.11 the antiproton flux evaluated at $T_{\bar{p}} = 0.23$ GeV is shown for a full scan of supersymmetric model described in [43].

As expected, the scatter plot is prominent at small masses. It is remarkable that for $m_\chi \approx 25$ GeV the scatter plot is funnel-shaped. The reason is explained in [43]. The set of propagation parameters is the one giving the best fit to the B/C ratio. The shaded region denotes the amount of primary antiprotons which can be accommodated at $T_{\bar{p}} = 0.23$ GeV without entering in conflict with the BESS experimental data and secondary antiproton calculations [43]. Due to the astrophysical uncertainties, the primary antiproton flux can be lowered by an order of magnitude. This does not permit of de-

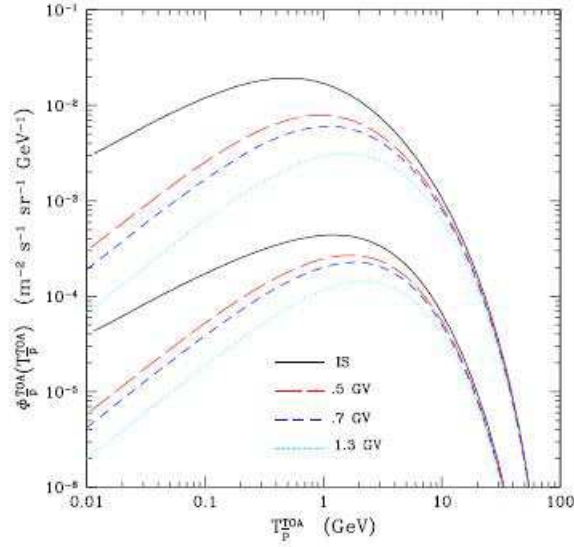


Figure 1.10: Top-Of-Atmosphere (TOA) antiproton fluxes as a function of the antiproton kinetic energy for the $m_\chi = 100$ GeV reference case. The upper (lower) set of curves refers to the maximal (minimal) set of of astrophysical parameters. Solid curves show the interstellar fluxes. Broken curves show the effect of solar modulation at different periods of solar activity: $\phi = 500$ MV (long dashed), $\phi = 700$ MV (short dashed), $\phi = 1300$ MV (dotted).

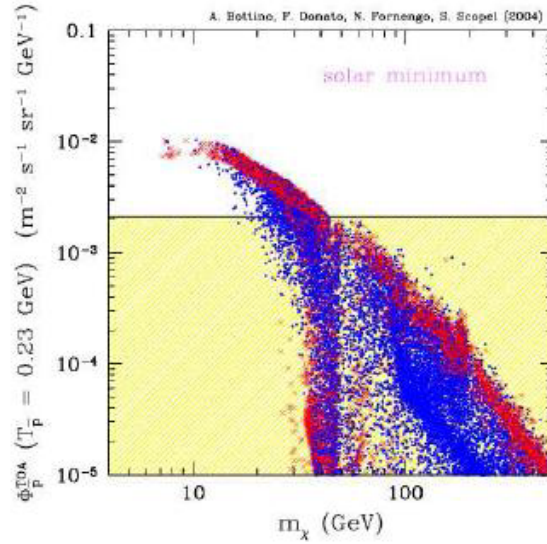


Figure 1.11: Antiproton flux at $T_{\bar{p}} = 0.23$ GeV as a function of the neutralino mass, calculated at solar minimum. See text for details.

giving any constraint on the supersymmetric parameters, if one assumes a very conservative attitude in the selection of the propagation parameters. It is important to stress that any further breakthrough in the knowledge of the astrophysical parameters would allow a significant exploration of small mass configurations, in case the conservative set of parameters is excluded. Should the effect of antiproton propagation turn out to be equivalent to the one obtained with the best fit set, the analysis of cosmic antiprotons would prove quite important for exploring very light neutralinos. This is particularly true for neutralino masses below 15 GeV, in view of the typical funnel shape displayed in the scatter plots.

Chapter 2

The PAMELA Experiment

The PAMELA experiment (a "Payload for Antimatter-Matter Exploration and Light-nuclei Astrophysics" [44, 45]) was conceived to study charged particles in the cosmic radiation outside the atmosphere by means of a satellite-borne apparatus, with a particular focus on the antiparticle component (antiprotons and positrons principally).

The PAMELA mission is also devoted to the investigation of dark matter, baryon asymmetry in the Universe, cosmic ray generation and propagation in our galaxy and in the solar system, and studies of solar modulation and interaction of cosmic rays with the Earth's magnetosphere.

PAMELA is installed inside a pressurized container attached to a Russian Resurs DK1 earth-observation satellite that was launched into space by a Soyuz-U rocket on June 15th 2006 from the Baikonur cosmodrome in Kazakhstan. The satellite orbit is elliptical and semipolar, with an altitude varying between 350 km and 600 km, at an inclination of 70.0° . The mission is foreseen to last for three years at least.

PAMELA is being built within the WiZard collaboration [45] and is a natural progression from the balloon flights performed during the past 15 years (MASS, TS93 and CAPRICE). It is part of the Russian Italian Mission (RIM) framework, which has generated the successful Sil-Eye I and II [46] and NINA [47] space experiments.

This chapter is organized as follows. Scientific goals are illustrated in section 2.1, subdetector components of the PAMELA instrument are discussed in section 2.2 along with results from performance studies with particle beams and cosmic rays. The data acquisition and trigger systems are described in section 2.3. The Resurs DK1 satellite which houses PAMELA and NTsOMZ ground segment are presented in section 2.4 and 2.5 respectively.

2.1 Scientific goals

The objective of this experiment is generically the study of the matter and, above all, antimatter components of the cosmic radiation with high statistic of acquired events. This is very important because, as explained better below, the study of the antimatter component permits to answer to many open questions regarding cosmological theories (like Matter/Antimatter asymmetry and Dark Matter models).

The semi-polar orbit (70.0° inclination) allows PAMELA to investigate a wide range of energies for antiprotons (80 MeV - 190 GeV) and positrons (50 MeV - 270 GeV). Three years of data taking will provide unprecedented statistics in this energy range and will set the upper limit for the ratio $\bar{H}e/He$ below 10^{-8} (figure 2.1). PAMELA will also perform a measurement of light nuclei ($H \rightarrow C$) in the energy range 100 MeV/n up to 700 GeV/n. The expected energy ranges for each particle type over which PAMELA will provide new results are listed in table 2.1.

Cosmic Ray particles	Energy Range	Statistics (3 years)
Antiprotons	80 MeV - 190 GeV	10^4
Positrons	50 MeV - 270 GeV	10^5
Electrons	50 MeV - 400 GeV	10^6
Protons	80 MeV - 700 GeV	10^8
Electrons/Positrons	Up to 2 TeV from calorimeter only	
Light Nuclei (up to Z=6)	Up to 200 GeV/n He/Be/C	$10^{7/4/5}$
Antinuclei	Sensitivity 95% C.L.	
Antihelium/helium ratio	of the order of 10^{-7}	

Table 2.1: Design goals for PAMELA performance.

The primary scientific goal of the experiment is the study of the antimatter component of the cosmic radiation in order to search for evidence of dark matter particle (e.g. non-hadronic particles outside the Standard Model) annihilations by precisely measuring the antiparticle (antiproton and positron) energy spectra.

Antiparticles could be produced from exotic sources such as primordial black holes [50] or the annihilation of supersymmetric [51] or Kaluza-Klein [52, 53] dark matter particles. Figures 2.2 and 2.3 show a summary of the current status of antiproton and positron flux measurements, respectively. Theoretical calculations for pure secondary production [54, 55, 56, 57] and

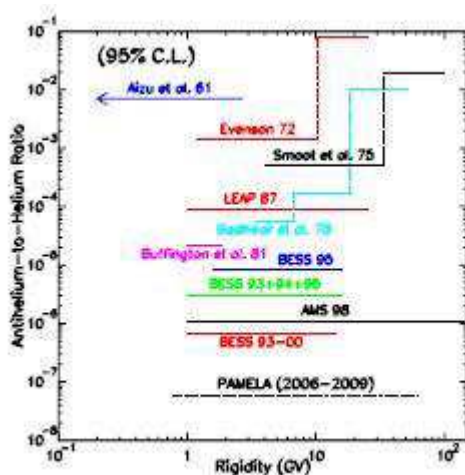


Figure 2.1: The ratio of anti-helium to helium in the cosmic radiation shown as a function of rigidity [48, 49]. No observation of antihelium has been made to date and so upper limits are shown. The expectation for PAMELA after a 3 year long mission is shown.

for pure primary production due to the annihilation of supersymmetric dark matter particles [58, 59] are also shown. In both figures the dotted lines (with a maximum around $E \sim 10$ GeV) show a possible distortion to the spectrum expected from neutralino annihilation (supersymmetric dark matter particle) or decay. The present limits are 50 GeV for antiprotons and 30 GeV for positrons. The majority of the data available comes from balloon-borne experiments, with the exception of AMS-01, that was flying on the Space Shuttle in 1998. The short data-taking time (~ 24 hours) at the presence of a residual overburden of atmosphere (~ 5 g/cm²) above the detecting apparatus limits the precision of such measurements for this kind of experiment.

The PAMELA experiment is primarily aimed at extending the known energy spectrum of both antiprotons and positrons and obtaining significantly smaller statistical uncertainties in the measured intensities with respect to those affecting the data collected by the experiments performed up to now. This goal has been achieved with the design of an apparatus characterized by a high sensitivity and efficiency in the identification of p and e^+ and in the measurement of their energies, coupled to the choice of operating it on board of a satellite, thus making it possible to collect a high number of primary antiparticle events in a very clean environment. PAMELA will be able to perform very precise measurements with high statistics ($\sim 10^4$ $\bar{p}$ and $\sim 10^5$ e^+ per year) and over a wider energy range than possible to date. The full boxes in figures 2.2 and 2.3 indicate the expected PAMELA performance in case of a pure secondary antiproton and positron components

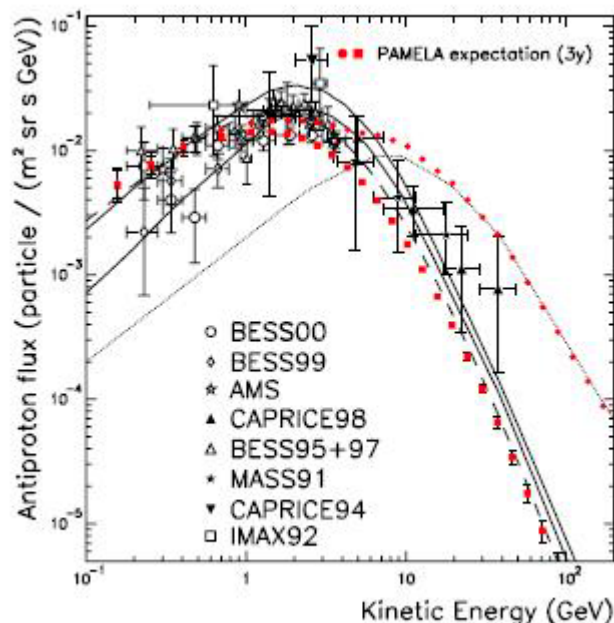


Figure 2.2: Recent experimental $\bar{p}$ spectra (BESS00 and BESS99 [61], AMS [62], CAPRICE98 [38], BESS95+97 [63], MASS91 [64, 65], CAPRICE94 [66], IMAX92 [67]) along with theoretical calculations for pure $\bar{p}$ secondary production (solid lines: [54], dashed line: [55]) and for pure $\bar{p}$ primary production (dotted line: [58], assuming the annihilation of neutralinos of mass $964 \text{ GeV}/c^2$). The expected PAMELA performance, in case of a pure secondary component (full boxes) and of an additional primary component (full circles), are indicated. Only statistical errors are included in the expected PAMELA data.

and the full circles show the expected performance in case of an additional primary component. The errors on the expected PAMELA data points only include statistical uncertainties. An average PAMELA orbit has been used to estimate the vertical geomagnetic cut-offs and, consequently, the expected number of antiproton and positron events at low energies [60].

A second prominent goal of PAMELA is to measure the antihelium to helium ratio with a sensitivity of the order of 10^{-8} . This would represent a factor of 50 improvement on contemporary limits, as shown in figure 2.1 as a function of rigidity (momentum /charge) [48, 78]. The contribution to the antihelium flux from cosmic ray interactions is expected to be less than 10^{-12} [78] and so an observation of antihelium would be a significant discovery as it could indicate the presence of antimatter domains in a baryon symmetric Universe (see section 1.5).

Another primary goal is to test cosmic-ray propagation models through

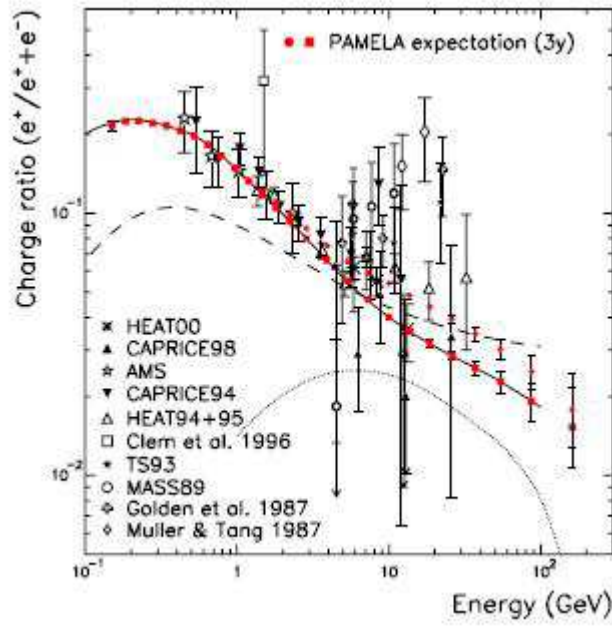


Figure 2.3: The positron fraction as a function of energy measured by several experiments ([68, 69, 70] and MASS89 [71], TS93 [72], HEAT94+95 [73], CAPRICE94 [74], AMS [75], CAPRICE98 [76], HEAT00 [77]). The dashed [56], and the solid [57] lines are calculations of the secondary positron fraction. The dotted line is a possible contribution from annihilation of neutralinos of mass $336 \text{ GeV}/c^2$ [59]. The expected PAMELA performance, in case of a pure secondary component (full boxes) and of an additional primary component (full circles), are indicated. Only statistical errors are included in the expected PAMELA data.

precise measurements of the antiparticle energy spectrum and precise studies of light nuclei and their isotopes. In fact, precise measurements of the properties of the cosmic rays, such as relative distribution of the various particle species, energy spectrum, direction of incidence and time dependence of the fluxes, can be compared with expectations from different theoretical models explaining their production mechanisms, the propagation in the interstellar medium and their interaction with the solar-system environment (see also section 1.4).

Beyond the primary objectives listed above, PAMELA can be used to address issues related to the solar-terrestrial environment (above 50 MeV) such as solar particle events (isotopic composition of H and He, e^- and, for the first time, e^+ spectrum) and composition and temporal dependence of the trapped and albedo particle component [79]. Besides there are additional objectives [45] involving Jovian protons [79] and electrons and the modulation of galactic cosmic rays in the heliosphere [45]. In particular way:

- The precise determination of the antiproton and positron energy spectra (and in general of light-nuclei and their isotopes) will provide important information concerning solar modulation. For example, indications of charge dependent solar modulation effects have been already seen in the antiproton to proton ratio data [61].
- The quasi-polar orbit and low geomagnetic cut-off experienced by the PAMELA apparatus combined with its intrinsic ability to measure low momenta will allow phenomena connected with solar (during the 24th solar minimum) and earth physics to be investigated [80].
- The ability to measure the combined electron and positron energy spectrum up to 2 TeV will allow the contribution of local sources to the cosmic radiation to be investigated [81].

2.2 The PAMELA apparatus

The PAMELA apparatus is composed of the following subdetectors, arranged as shown in figure 2.4:

- a Time of Flight system (ToF: S1, S2, S3);
- a magnetic spectrometer;
- an anticoincidence system (CARD, CAT, CAS);
- an electromagnetic imaging calorimeter;
- a shower tail catcher scintillator (S4);
- a neutron detector.

The apparatus is ~ 1.3 m high, has a mass of 470 kg and an average power consumption of 355 W. The masses are distributed according to table 2.2 and the power consumption according to table 2.3.

Subsystem	Mass (kg)
Spectrometer	127
Calorimeter	104
General Mechanism	85
Electronic Units	45
Neutron Detector	30
Thermal System	22
Time of Flight	18
Anticoincidence	16
Magnetic Screens	15
Bottom Scintillator	8
Total Mass	470

Table 2.2: The PAMELA mass budget.

Subsystem	Power (W)
Electronics	80
DC/DC converters	74
Spectrometer	63
Calorimeter	55
CPU	35
Power Supply System	35
Neutron Detector	10
Aticoincidence	1
Time of Flight	1
Bottom Scintillator	1
Total Power	355

Table 2.3: The PAMELA average power budget.

PAMELA is built around a 0.43 T permanent magnet spectrometer equipped with 6 planes of double-sided silicon detectors allowing the sign, absolute value of charge and momentum of traversing charged particles to be determined. The acceptance of the spectrometer (which also defines the overall acceptance of the PAMELA experiment) is $21.5 \text{ cm}^2\text{s}$ and the maximum detectable rigidity is $\sim 1 \text{ TV}$. Spillover effects limit the upper detectable antiparticle momentum to $\sim 190 \text{ GeV}/c$ ($\sim 270 \text{ GeV}/c$) for antiprotons (positrons).

The spectrometer is surrounded by a plastic scintillator veto shield. An electromagnetic calorimeter, mounted below the spectrometer, measures the energy of incident electrons and allows topological discrimination between electromagnetic and hadronic showers (or non-interacting particles). Planes of plastic scintillator mounted above and below the spectrometer form a Time of Flight system which also provides the primary experimental trigger. The timing resolution of the Time of Flight system allows albedo particles to be identified and proton-electron separation is also possible below ~ 1 GeV/c. Ionising energy loss measurements in the Time of Flight scintillator planes and the silicon planes of the magnetic spectrometer allow the absolute charge of traversing particles to be determined.

The volume between the upper two Time of Flight planes is bounded by an additional plastic scintillator anticoincidence system. A plastic scintillator system mounted beneath the calorimeter provides an additional stand-alone trigger for high energy electrons and is followed by a neutron detection system for the selection of very high energy electrons (up to 2 TeV) which shower in the calorimeter but do not necessarily pass through the spectrometer. The PAMELA subdetectors are read out and controlled by a data acquisition system based around Actel (54SX series) Field Programmable Gate Arrays (FPGA) [82] and Analog Devices (ADSP-2187L) Digital Signal Processors (DSP) [83]. Connections between different systems are realised with redundant data-strobe [84] Low Voltage Differential Signaling (LVDS) links. Each subdetector is also connected to a global trigger system and can issue alarm conditions (e.g. over-temperature, data corruption) to a house-keeping system. All the data acquisition boards (except for the calorimeter) are housed in a custom crate secured to the PAMELA superstructure, as shown in figure 2.4 (bottom). In order to promote reliability, common design rules have been followed for all electronics systems in PAMELA, e.g. over-current protection on all electronics boards, redundant data links, redundant power connections and the use of radiation qualified components.

Figure 2.5 also shows the PAMELA reference system, defined as the orthogonal right-handed frame with the origin in the center of the magnetic cavity and axes oriented as shown: the Z axis is directed along the longitudinal dimension of the apparatus, toward the incoming particles; the Y axis is directed opposite to the main direction of the magnetic field inside the spectrometer. All the positional information given in the present work is referred to this frame for clarity; $\hat{i}$, $\hat{j}$, $\hat{k}$ will indicate the unit vectors of X, Y, Z axes respectively.

2.2.1 The Time of Flight (ToF) system

The ToF system [85] comprises 6 layers of fast plastic scintillators (Bicron BC-404 [86]) arranged in three planes (S1, S2 and S3, figure 2.6) and read-out by photo-multiplier tubes (PMT) independently: S1, positioned on the

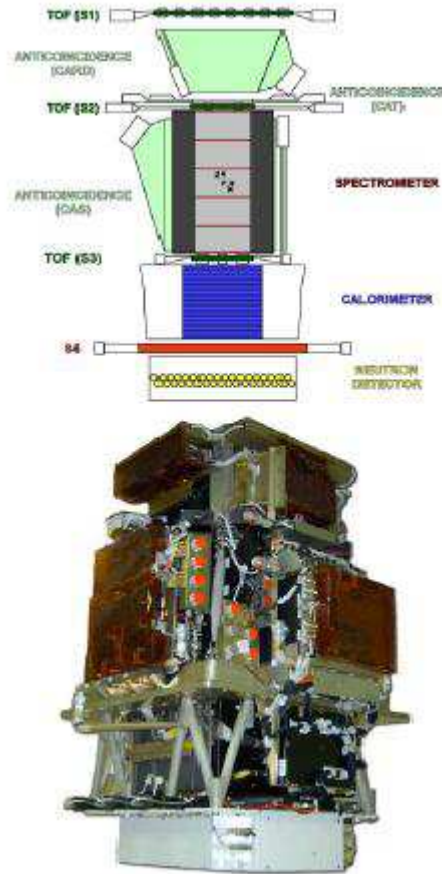


Figure 2.4: The PAMELA instrument. Top: a schematic overview of the apparatus. Bottom: a photograph taken just prior delivery to Russia for integration with the Resurs DK1 satellite. The detector is approximately 1.3 m tall. The magnetic field lines in the spectrometer are oriented along the y direction.

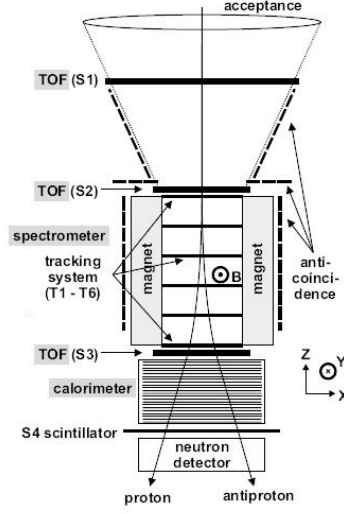


Figure 2.5: PAMELA apparatus with its reference system.

top of PAMELA apparatus, S2 and S3, immediately above and below the spectrometer respectively. The distance between S1 and S3 is 77.3 cm. Time of Flight information for charged particles passing between planes S1 and S3 is combined with track length information derived from the magnetic spectrometer (see section 2.2.3) to determine particle velocities and reject albedo (upward going) particles. Ionisation (dE/dx) measurements in the scintillator layers allow the particle charge to be determined at least up to $Z = 8$. Coincidental energy deposits in combinations of planes provide the main trigger to synchronize the data acquisition for the whole apparatus, as described in section 2.3.2. The segmentation of each plane allows redundant studies of the trigger efficiency.

The strips of the upper layer of each plane (S11, S21, S31) are orthogonal to the ones of the corresponding lower layer (S12, S22, S23 respectively), thus coupling to the timing information also a spatial information on the crossing point in the plane. The sensitive area of each of the two S1 layers is $33 \times 40.8 \text{ cm}^2$ with the first layer divided into 8 bars and the second layer divided into 6 bars. The total sensitive area of the S2 and S3 planes is $15 \times 18 \text{ cm}^2$ segmented into 2×2 and 3×3 orthogonal bars, respectively. The S1 and S3 layers are 7 mm thick while the S2 layers are 5 mm thick. There are 24 scintillator bars in total (see 6.1).

At each of the two ends of a strip a light guide conveys the scintillation light toward the input window of a PMT (Hamamatsu R5900U [87]), which transforms the light pulse into an electrical current signal, which is then processed by the front-end electronics; a total of 48 PMT are present for the read-out of the 24 scintillator strips.

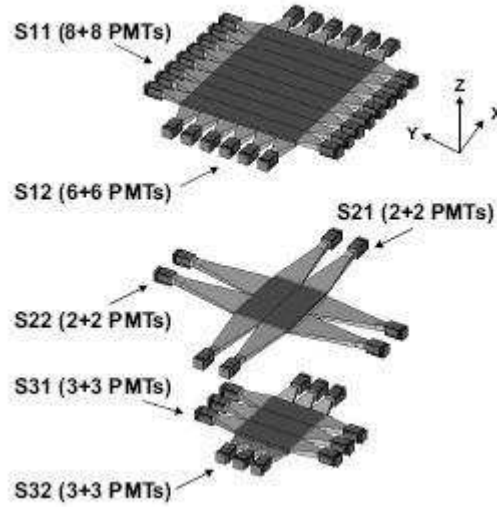


Figure 2.6: A schematic overview of the Time of Flight system. The distance between S1 and S3 planes is 77.3 cm.

The scintillators and light-guides are wrapped in 2 layers of $25\ \mu\text{m}$ thick Mylar foil. The S3 plane is mounted directly on the base plate of PAMELA, while the other two planes are enclosed in light-proof boxes suspended off the PAMELA structure. A high-voltage divider circuit is mounted directly behind each PMT. The high-voltage and discrimination threshold for each PMT is chosen to optimize the performance of a given ToF bar. The ToF electronics system converts the 48 PMT pulses into time and charge based measurements. In the timing section, a capacitor is linearly charged during a time interval defined by the passage of a particle through the ToF system. In the charge section, a capacitor is charged with the PMT pulse charge. In both cases, during read out the capacitor is linearly discharged into a time-to-digital converter. The ToF electronics system comprises a nine board electronics system based around the PAMELA-standard FPGAs and DSPs.

A separate trigger board processes signals [88] from the 48 PMTs as well as trigger signals from the calorimeter and bottom scintillator (see section 2.3). Rate counters, dead/live-time counters and the logic to generate calibration pulse sequences for different subsystems are also implemented. Control masks select trigger types (see section 2.3) and allow noisy or dead PMT channels to be vetoed and the PMT hit pattern to be recorded for each trigger.

Figure 2.7 shows the velocity of particles (in units of speed of light, c) measured by the ToF system as a function of their rigidity for data recorded at ground. Most of the events are relativistic muons. A small proton component is visible at low rigidity (the solid line indicates the theoretical for

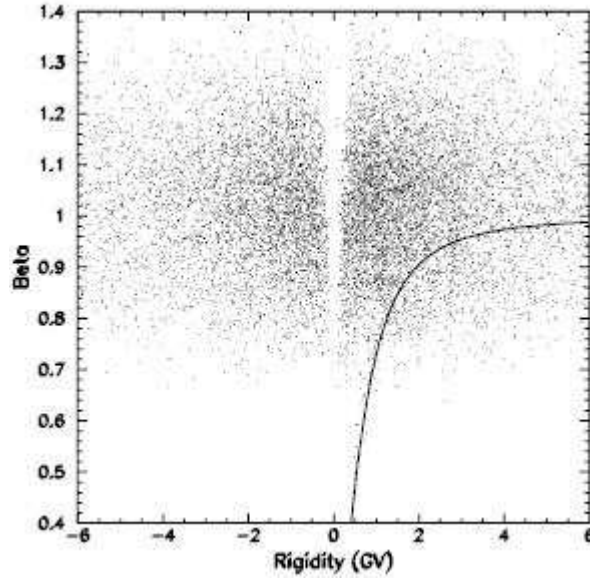


Figure 2.7: The particle velocity measured by the ToF system as a function of rigidity. The solid line is the theoretical β for protons. The figure comprises 46000 events acquired with the final ToF system at ground.

protons). The measured Time of Flight resolution of ~ 250 ps will allow electrons (positrons) to be separated from antiprotons (protons) up to ~ 1 GeV/c. Albedo particles can also be rejected with a significance of 60 standard deviations.

In addition, the measurement of ionization losses in the ToF scintillators will allow the determination of the absolute charge of the particles, as shown in figure 2.8. These data were collected during a beam test performed at the GSI facility in Darmstadt. Prototype versions of the S1, S2 and S3 ToF paddles were exposed to ^{12}C beams. Targets of aluminum and polyethylene were used to generate a variety of fragmentation products. During this test, the S1 and S2 layers were used to clean the data sample, and the particle charge was subsequently measured using the S3 layer. Data taken during this test also allowed the timing resolution for carbon to be determined as 70 ps. This improvement is reasonable (compared to the 250 ps quoted above), since the timing resolution improves with the inverse square root of the number of photons created in the scintillator.

2.2.2 Anticoincidence systems

The first level trigger in PAMELA is defined by the coincidental deposit of energy in the three Time of Flight (ToF) planes S1, S2 and S3. Most of these triggers (about 75%) will be "false triggers" (figure 2.9) [89], i.e.

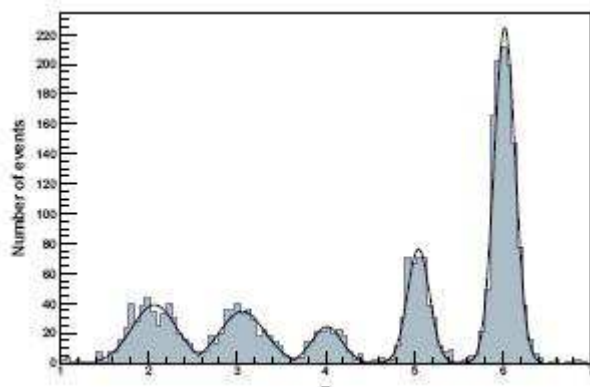


Figure 2.8: Results from the GSI beam test. Energy deposits in prototype S3 scintillators are converted by an ADC to identify the secondaries produced by fragmentation of the initial 1200 MeV/c ^{12}C beam.

events with particles not cleanly entering the acceptance of the experiment, but generating secondary particles through an interaction with the mechanical structure of the experiment or the satellite. These secondary particles eventually deposit coincidental energy in the ToF scintillators and are erroneously interpreted as "good triggers" by the first level trigger. The AC shields will help identify "false-trigger" events and reject them during off-line data analysis. Some of the "good-triggers", i.e. events characterized by one particle cleanly entering PAMELA's acceptance, may induce a signal into one or more of the AC scintillators due to backscattering. Studies to discriminate backscattering events from false triggers have been done with test-beam data. Information from the AC detectors is planned to be implemented in a second level trigger (see section 2.3.2), to reduce online the number of "false triggers", and may be activated by an uplink command from ground. The PAMELA experiment contains two anticoincidence (AC) systems [90].

The primary AC system [91] consists of 4 plastic scintillators (CAS) surrounding the sides of the magnet and one covering the top of the magnet with a hole in correspondance of the acceptance of the tracker (CAT), as shown in figure 2.10 and 2.11. A secondary AC system consists of 4 plastic scintillators (CARD) that surrounds the volume between the first two Time of Flight planes. The CARD detectors are a scaled-down versions of CAS. The AC systems use 8 mm thick plastic scintillators (Bicron BC-448M [86]) read out by Hamamatsu R5900U PMTs [87]. Each CAS and CARD detector is read out by two identical PMTs in order to decrease the possibility of single point failure. Also for this reason, and to cover the irregularly shaped area, the CAT detector is read out by 8 PMTs. A high-voltage divider is mounted directly behind each PMT and operated at a fixed voltage of -800

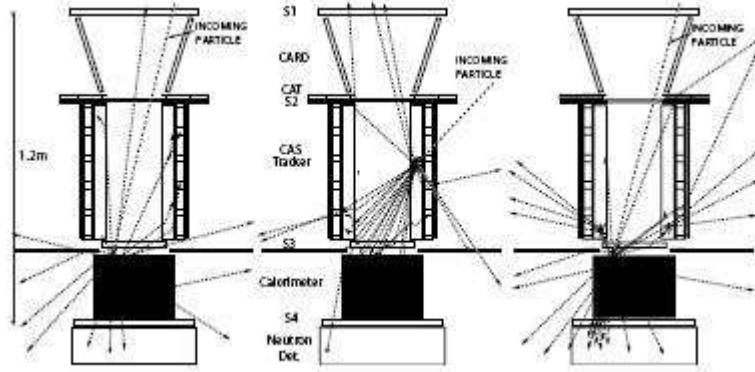


Figure 2.9: Schematic representations of simulated proton interactions in the PAMELA apparatus (non-bending view shown). Left: a good trigger event without anticoincidence (AC) activity, with the lateral AC system (CAS) represented by the outermost rectangles bracketing the tracker. Centre: a false trigger created by a particle entering the apparatus from the side generating a shower and AC activity. Right: Particles backscattered from the calorimeter can also give rise to AC activity for good trigger events.

V. The scintillators and PMTs are housed in aluminium containers which provide light-tightness, allow fixation to the PAMELA superstructure and ensure that a reliable scintillator-PMT coupling is maintained. The small fringe field from the magnetic spectrometer at the position of the PMTs means that additional magnetic shielding is not required.

The signals from the 24 PMTs are divided between two independent data acquisition boards with signals from PMTs for a given CAS or CARD detector or CAT quadrant routed to different boards. Only binary hit information is stored from each PMT indicating whether the deposited energy exceeds 0.5 mip (where 1 mip is the most probable energy deposited by a minimum ionising particle). On each board, an analogue front-end electronics system comprising an integration/amplification and discrimination stage processes the PMT signals before they are fed into a FPGA. The core of this digital system is a 16 bit shift register allowing hit information to be recorded in a time window of length $1.28 \mu\text{s}$ centered on the trigger time. Within this window the hit can be located with an accuracy of 80 ns. The FPGA also allows the PMT singles rates to be monitored and controls the data acquisition system. A DSP controls a monitoring system which is based around 640 nm miniature LEDs glued directly to the scintillator material. The efficiency of the large area CAS detectors has been studied using an external drift chamber to map the spatial distribution of incident cosmic ray muons. A detection efficiency for mips of $(99.91 \pm 0.04)\%$ was observed [92]. The AC system has also been tested by studying the backscattering of particles (see

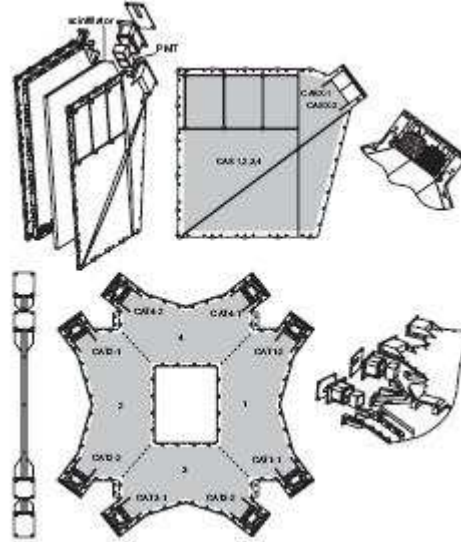


Figure 2.10: An overview of the AC system. Top: the CAS system. Bottom: the CAT system. The CARD system is not shown but the design closely follows that of CAS. The CAS scintillator is approximately 40 cm tall and 33 cm wide. The hole in the CAT scintillator measures approximately 22 cm by 18 cm.

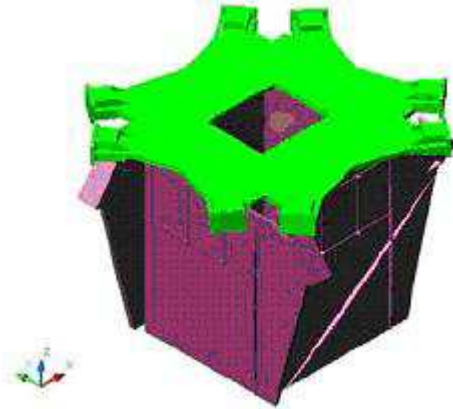


Figure 2.11: AC system: 3-D overview of CAS and CAT.

figure 2.9) from the calorimeter during tests with high energy particle beams [93]. The robustness of the AC system has been determined by studying the stability of the scintillator-PMT coupling to variations in temperature [92] and the vibration spectra expected during launch [94].

2.2.3 Magnetic spectrometer

The central part of the PAMELA apparatus is a magnetic spectrometer [95] consisting of a permanent magnet, with an internal rectangular cavity, and a tracking system with 6 planes of double-sided Si microstrip detectors, uniformly positioned along the cavity; each plane measures both the X and Y coordinates of the crossing point of an incident ionizing particle, for the reconstruction of the trajectory within the cavity. The magnetic spectrometer is used to determine the sign of charge and the rigidity of particles up to ~ 1 TV/c. Ionisation loss measurements are also made in the silicon planes, allowing absolute particle charge to be determined up to at least $Z=6$.

The magnet is composed of five superimposed identical modules forming a tower 44.5 cm high. Each module is obtained by gluing together several magnetized elements, shaped as right prisms with rectangular section made of a Nd-Fe-B alloy with a residual magnetisation of 1.3 T. The blocks are configured to provide an almost uniform magnetic field oriented along the y-direction inside a cavity of dimensions (13.1×16.1) cm². The dimensions of the permanent magnet define the geometrical factor of the PAMELA experiment to be 21.5 cm²sr. To allow precise rigidity measurements to be obtained from the reconstructed particle trajectory, the magnetic field has been precisely measured with a Hall probe through-out the cavity volume and the surrounding regions. Figure 2.12 shows the y-component of the magnetic field measured in the $z=0$ plane as a function of x and y and the y-component as measured along the z-axis. The mean magnetic field inside the cavity is 0.43 T with a value of 0.48 T measured at the centre. Any stray magnetic field outside of the cavity can potentially interfere with the satellite instruments and navigation systems. In order to attenuate the stray field, the magnet is enclosed by a ferromagnetic shielding.

Six equidistant 300 μ m thick silicon detector planes are inserted inside the magnetic cavity. The high-precision double-sided silicon sensors are positioned between the 5 magnetic modules and on the top and bottom of the magnetic tower, with equal spacing of 8.9 cm. The main characteristic of these detectors is the presence of a sensitive layer both on the upper and lower side (or view) of the Si plane, with the implanted strips of one side orthogonal to those of the other, so as to achieve the measurement of both the X and Y coordinates of the crossing point of an incident ionizing particle. Other distinctive features, illustrated in what follows, are the presence of an integrated capacitive coupling for read-out and of a double metallic layer on one of the views, to have the metallic readout strips parallel on both sides.

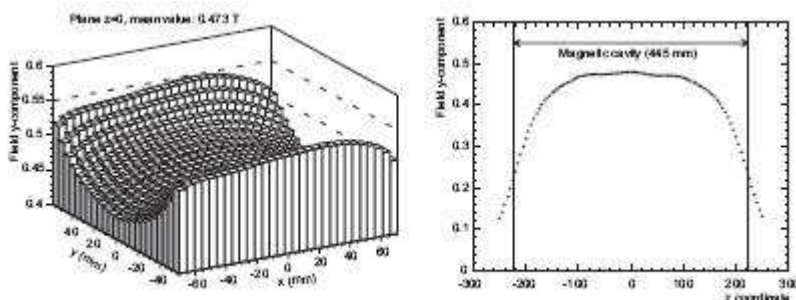


Figure 2.12: Left: the y-component of the spectrometer magnetic field (T) measured at $z=0$. Right: the variation of the y-component of the spectrometer magnetic field (T) evaluated along the z-axis (mm).

The use of double-sided detectors, instead of pairs of single-sided ones, offers several advantages, in particular the smaller thickness of material traversed by the incident particle¹ and a simplified support structure for the planes.

Each detector plane (see figure 2.13) is divided into three identical independent sections (known as ladders) along the X axis and housed in an aluminium support frame; each ladder is formed by two rectangular (5.3×7.0) cm^2 silicon sensors and a hybrid circuit, containing the first stage of the front-end electronics, realized partly with implantation and partly with standard printed-circuit board techniques (hence the name) on a Al_2O_3 insulating layer. The three components of a ladder are directly glued together; the 3 ladders constituting the plane are alternated and glued to 4 carbon-fibre rails, that stiffen the whole structure and guarantee the mechanical contact of the plane with the aluminium frame which connects to the magnet canister, through many glue points.

In order to limit multiple scattering in dead layers, no additional supporting structure is present above or below the planes.

Each high resistivity silicon sensor (manufactured by Hamamatsu [87]) is formed by a substrate of thickness $300 \mu\text{m}$, with residual n-type doping and high resistivity; on one side 2035 p^+ parallel strips are implanted to form $p^+ - n$ junctions with the substrate, separated each other by a $25.5 \mu\text{m}$ pitch. On the opposite side there are 1024 n^+ strips, with $67 \mu\text{m}$ pitch, alternated to p^+ blocking strips (see figures 2.14 and 2.15); the $n^+ - n$ contact is of ohmic type i.e. non-rectifying. The mip efficiency for a single plane (including dead regions) exceeds 90%.

¹This reduces the probability of multiple scattering of the particle inside the traversed material. The possible changes of direction caused by multiple scattering in the detector planes must be taken into account for the correct reconstruction of the trajectory in the magnetic cavity, contributing to the overall uncertainty in the measurement of the curvature.

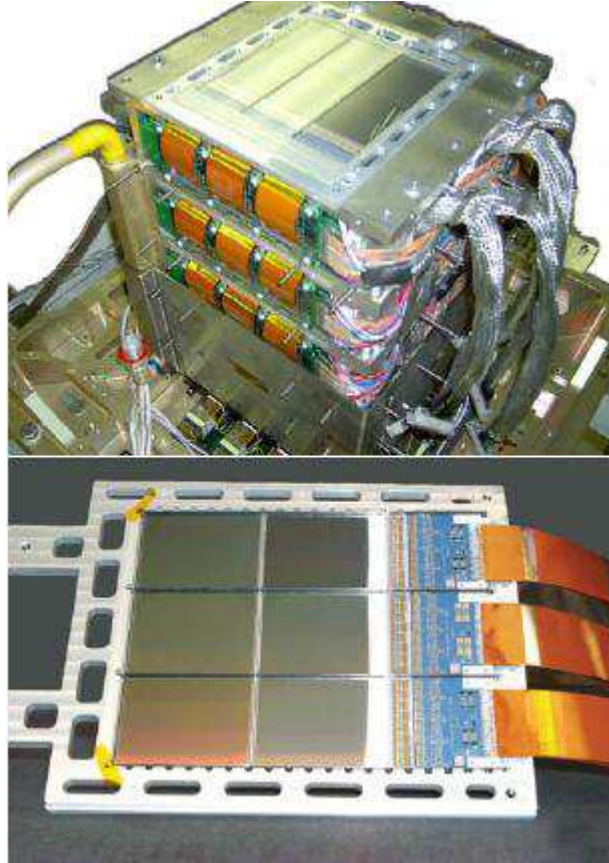


Figure 2.13: Top: an overview of the magnetic spectrometer showing the top silicon plane. The magnet cavity has dimensions $(13.1 \times 16.1) \text{ cm}^2$. A cooling loop enters from the left-hand side and the ADC boards mounted on the magnet canister are also visible. The lower part of the magnet canister is covered by a magnetic screen. Bottom: a silicon plane comprising three silicon strip detectors and front-end electronics.

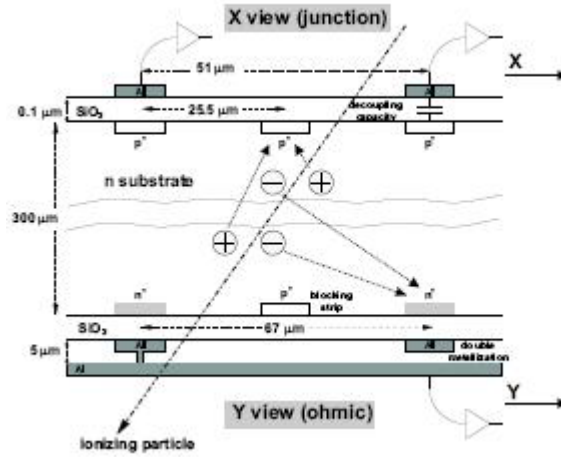


Figure 2.14: Section of a silicon sensor, with a draft of the charge collection mechanism. To better illustrate the structure, the Y side is represented rotated by 90° with respect to the X side.

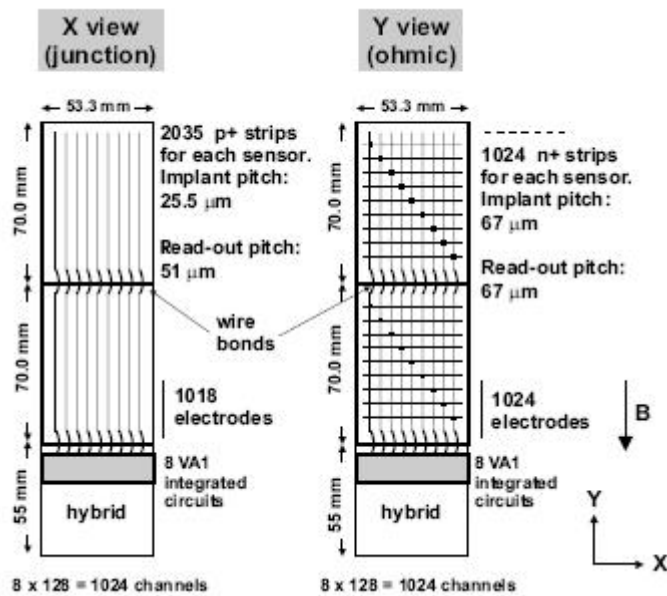


Figure 2.15: Scheme of the X and Y views of a ladder; note on the Y side the association of two n^+ strips, 7 cm apart from each other, to the same metallic electrode.

Since, as explained below, the junction view is characterized by a much better spatial resolution, it is used to measure the X coordinate of the impact point of the charged particle, which is by far the most important for the determination of the curvature of the trajectory, because the particle tends to bend in the XZ plane, normal to the main component of the magnetic field. For this reason the junction view is also indicated as X view or bending view; on the other hand, the ohmic side, measuring the Y coordinate, is indicated as Y side.

The front-end electronics system is based around VA1 Application Specific Integrated Circuits (ASICs) [96] which contain 128 charge sensitive preamplifiers connected to shapers and a sample and hold circuit. The signals from the VA1 chips are sent over 5 cm long kapton cables to be digitized by Analog-to-Digital (ADC) boards mounted on the magnet canisters. The digitised data are transferred by serial links to DSP-based read-out boards where they are compressed using a Zero Order Predictor (ZOP) algorithm. The compression factor is estimated at 95%.

The principle of operation of the magnetic spectrometer can be described as follows (see figure 2.5 for reference): a particle of charge $q = z \cdot e$ (z positive or negative, e electronic charge) with given initial downward going momentum $\vec{p} = -|\vec{p}|\hat{k}$ entering the cavity, characterized by the presence of a strong magnetic induction $\vec{B} = -|\vec{B}|\hat{j}$ (supposed uniform for clarity), moves along an arc of circumference in the XZ plane with curvature k given by²:

$$k \approx 0.3 \cdot |\vec{B}| \cdot \frac{Z}{|\vec{p}|} \quad (2.1)$$

where k is expressed in m^{-1} , $|\vec{B}|$ in Tesla, $|\vec{p}|$ in GeV/c [97]. From the knowledge of $|\vec{B}|$ and the measurement of k , operated through the reconstruction of the trajectory, it is possible to determine the ratio $\rho = |\vec{p}|/Z \cdot e$, known as the magnetic rigidity of the particle:

$$\rho \approx 0.3 \cdot \frac{|\vec{B}|}{k} \quad (2.2)$$

where ρ is expressed in GV/c, $|\vec{B}|$ in Tesla and k in m^{-1} . The sign of ρ is equal to the sign of z , which is fundamental in the discrimination between a particle and the corresponding antiparticle (proton from antiproton, electron from positron). From the measurement of the ionization energy loss ΔE in the silicon detectors, it is possible to determine the absolute value of z ($\Delta E \propto z^2$) and hence $|\vec{p}|^3$. In practice, in the actual reconstruction of the

²The absolute value of the curvature k is given by $1/R$, where R is the radius of the circumference; the sign of k is defined as positive when the particle moves clockwise along the circumference in the XZ plane, negative for counter-clockwise motion.

³Independent determinations of z through measurements of the ionization energy loss are also performed by the TOF system and by the calorimeter.

trajectory, we must take into account that the magnetic field is not exactly uniform and that the momentum of the incoming particle is not necessarily directed along the Z axis.

The performance of the spectrometer in the measurement of the rigidity depends critically on the precision with which the tracking system can determine the curvature of the trajectory, that is strongly affected by the intrinsic spatial resolution of the detectors. The resolution in the deflection (defined as ρ^{-1}) measurement depends on the geometrical configuration of the spectrometer, on the intensity of the magnetic field and on the spatial resolution of the position measuring system (the silicon sensors in this case). This spatial resolution depends on the particle incidence angle. For normally incident tracks, tests with particle beams show a spatial resolution of $(3.0 \pm 0.1) \mu\text{m}$ and $(11.5 \pm 0.6) \mu\text{m}$ in the bending and non-bending views, respectively. The spatial resolution in the bending view is shown in figure 2.16 (left). Figure 2.16 (right) shows the resulting deflection error as a function of rigidity obtained with proton beams. On the other hand, a stronger magnetic field

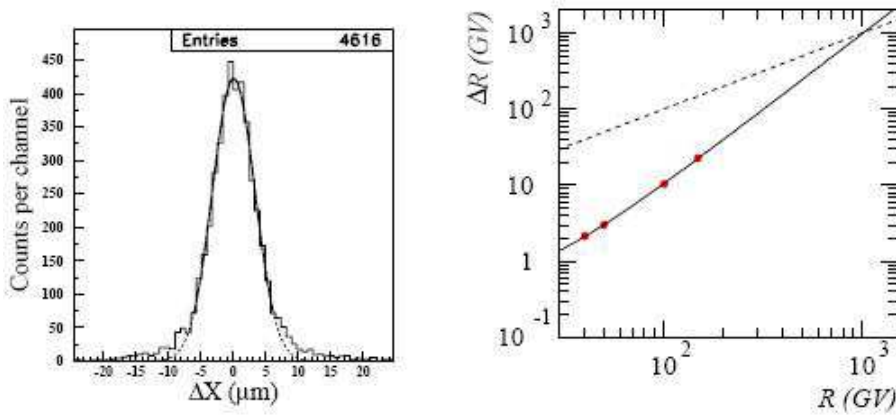


Figure 2.16: Left: The spatial resolution of the tracker in the bending view. The line indicates a Gaussian fit. Right: the deflection error $\Delta\rho$ measured by the magnetic spectrometer as a function of ρ obtained with proton beams. The dashed line is the bisector $\Delta\rho = \rho$. The functional form used to describe the experimental $\Delta\rho$ curve is obtained by assuming that two effects contribute to the deflection, $\eta = 1/\rho$ uncertainty, namely multiple scattering and spatial resolution. The former can be expressed (in the limit $\beta \sim 1$) as $\Delta\eta_{ms} \propto 1/\rho$. The latter is defined by $\Delta\eta_{res} = K$, where K is a constant. The intersection of the two curves gives the maximum detectable rigidity of the spectrometer.

in the cavity volume enhances the bending effect on the incoming particles and improves the overall performance of the spectrometer. Once fixed the

mass of the magnetic material surrounding the cavity⁴, the field intensity can be increased by reducing the cross-section of the cavity, with the drawback that in this way the geometric acceptance of the system is reduced and consequently also the number of particles that can be detected. Hence the dimensions of the magnetic cavity for the PAMELA spectrometer has been chosen for an optimum compromise between a sufficiently high number of particles entering the geometric acceptance of the system and the possibility of achieving a precise measurement of their rigidity.

The precision in the measurement of rigidity obtainable by a magnetic spectrometer becomes worse for higher values of $|\rho|$, since the trajectory of the particle is less affected by the magnetic field and tends toward a straight line. This in particular implies that it is more and more difficult to determine the sign of the rigidity, with a higher probability that a particle is wrongly identified as the corresponding antiparticle and viceversa. This effect is known as spillover and is particularly important in the case of the PAMELA experiment, which aims to explore the high-energy spectrum of $\bar{p}$ and e^+ , since the ratio between the flux of a particle species and the corresponding antiparticle is high ($\sim 10^4$ protons per $\bar{p}$, $\sim 10^2$ electrons per e^+). The resulting contamination of particles in the antiparticle sample must be properly estimated and subtracted for the measurement of the intensity of incident antiparticles.

The quality of the measurement operated by a spectrometer, in the limit of high absolute values of the rigidity, is usually expressed in terms of the maximum detectable rigidity (MDR), defined as the absolute value of ρ for which the relative error in the measurement is equal to 100% or, in other terms, for which $\Delta\rho = |\rho|$.

On the other hand, the discrimination of antiparticles from the corresponding particles can be performed up to a value $|\rho_{sp}|$ for which the spillover background and antiparticle signal are comparable; $|\rho_{sp}|$ depends not only on the intrinsic resolution of the spectrometer but also on the expected intensities of the various particle species and usually is much smaller than the MDR.

The PAMELA spectrometer has been designed to achieve an MDR of at least 740 GV/c for particles with both positive and negative charges and, basing on the predicted particle spectra, to identify the antiproton component up to $|\rho| \cong 190$ GV/c and the positron one up to $|\rho| \cong 270$ GV/c.

2.2.4 Electromagnetic Calorimeter

Protons and electrons dominate the positively and negatively charged components of the cosmic radiation, respectively. The main task of the calorimeter, besides the energy measurements of electrons and positrons, is to

⁴In the case of PAMELA the mass of the permanent magnet has been fixed to 120 kg on the basis of the limit imposed by the transport capabilities of the satellite.

select positrons and antiprotons from like-charged backgrounds which are significantly more abundant. Positrons must be identified from a background of protons that increases from about 10^3 times the positron component at 1 GeV/c to $\sim 5 \cdot 10^3$ at 10 GeV/c, and antiprotons from a background of electrons that decreases from $\sim 5 \cdot 10^3$ times the antiproton component at 1 GeV/c to less than 10^2 times above 10 GeV/c. This means that the PAMELA system must separate electrons from hadrons at a level of $10^5 - 10^6$. Much of this separation must be provided by the calorimeter, i.e. electrons must be selected with an acceptable efficiency and with as small a hadron contamination as possible.

The PAMELA imaging calorimeter is a sampling electromagnetic calorimeter made of 44 single-sided silicon sensor planes ($380 \mu\text{m}$ thick) interleaved with 22 plates of tungsten absorber [98]. Each tungsten layer has a thickness of 0.26 cm, which corresponds to $0.74 X_0$ (radiation lengths), giving a total depth of $16.3 X_0$, i.e. about 0.6 nuclear interaction lengths. Each tungsten plate is sandwiched between two printed circuit boards upon which the silicon detectors, front-end electronics and ADCs are mounted. The instrument is designed with high segmentation, both in the longitudinal (Z) and in the transversal (X and Y) directions. The $(8 \times 8) \text{ cm}^2$ silicon detectors are segmented into 32 read-out strips with a pitch of 2.4 mm. The silicon detectors are arranged in a 3×3 matrix and each of the 32 strips is bonded to the corresponding strip on the other two detectors in the same row (or column), thereby forming 24 cm long read-out strips. The total number of channels is 4416. The orientation of the strips of two consecutive layers is orthogonal and therefore provides two-dimensional spatial information. The granularity, along with the energy resolution of the silicon detectors, allows an accurate topological reconstruction of the shower development. Figure 2.17 shows the calorimeter prior to integration with the other PAMELA detectors. The calorimeter front-end electronics is based around the CR1.4P ASIC [99] which provides 16 channels containing a charge-sensitive preamplifier, a track-and-hold circuit and an output multiplexer. A charge injection calibration system is also implemented. Six CR1.4P chips are used per plane with the outputs multiplexed into a single 16-bit ADC. Data from all 44 ADCs are processed by 4 DSP-based read-out boards mounted within the calorimeter housing before being sent over serial links to the main PAMELA data acquisition system. The read-out is divided into 4 independent sections, corresponding to the X-even, Y-even, X-odd and Y-odd planes.

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. Electromagnetic and hadronic showers differ in their spatial development and energy distribution in a way that can be distinguished by the calorimeter. This is demonstrated in figure 2.18 which shows examples of an electromagnetic shower induced by an electron (left) and an interacting proton (right),

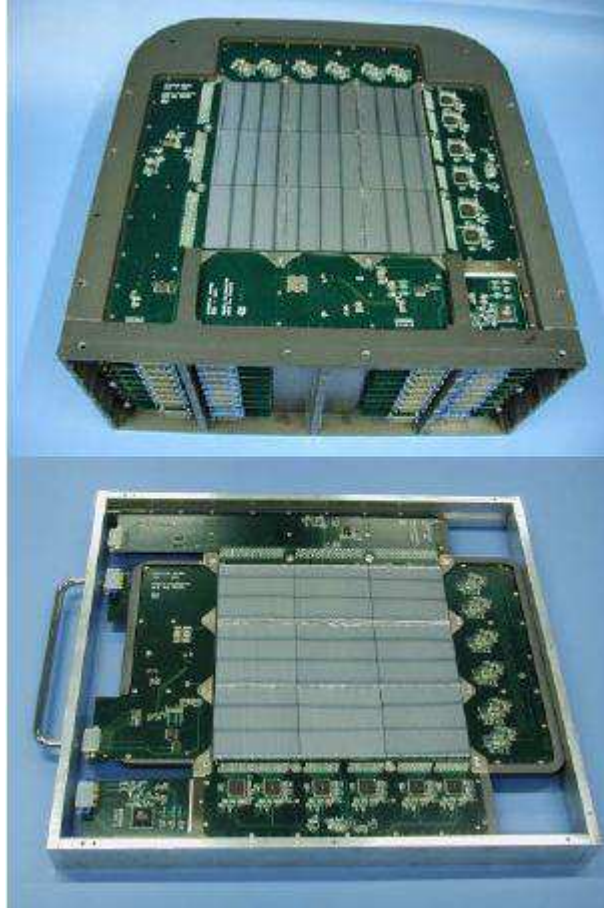


Figure 2.17: Top: The PAMELA electromagnetic calorimeter with the top-most silicon plane visible. The device is ~ 20 cm tall and the active silicon layer is $\sim 24 \times 24$ cm² in cross-section. Bottom: Detail of a single calorimeter module comprising a tungsten layer sandwiched between two silicon detector planes.

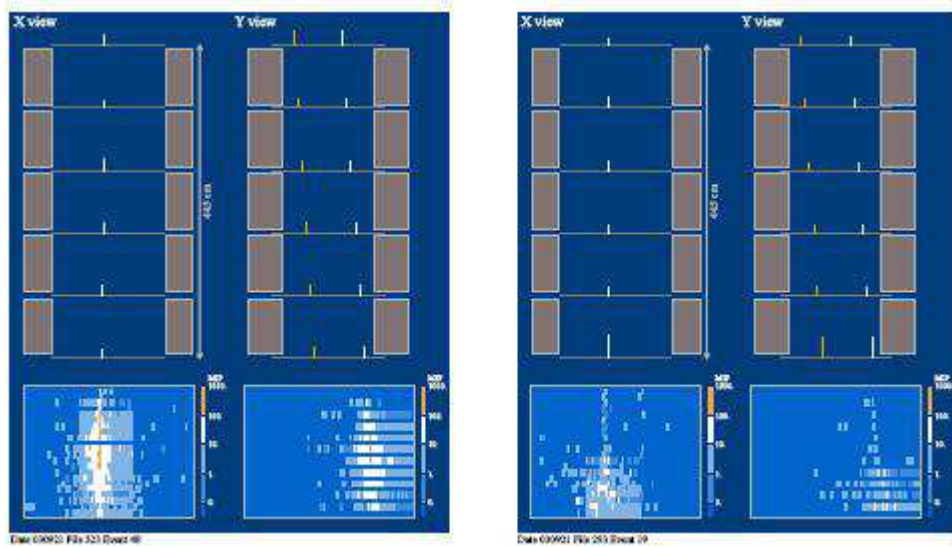


Figure 2.18: An event display of a 50 GeV/c electron (left) and proton (right) recorded at the CERN SpS facility. Hits in the tracking system are shown (including ambiguities for the Y-view) along with activity in the calorimeter. The signals from the odd planes of the Y-view of the calorimeter were not read-out during this test. One of the X-view planes was also not operational and was later replaced.

recorded during tests with particle beams at the CERN SpS facility. All incident particles have a momentum of 50 GeV/c. The electron-hadron separation performance of the calorimeter has been extensively studied in [100] where it was shown that the rare antiproton and positron components in the cosmic radiation can be identified with a background at the percent level and lower, especially at scientifically interesting momenta > 10 GeV/c. The calorimeter is found to have sufficient performance to reach the primary scientific objectives of PAMELA, providing a proton rejection factor of about 10^5 while keeping about 90% efficiency in selecting electrons and positrons. From simulations, an electron rejection factor of about 10^5 in antiproton measurements (about 90% antiproton identification efficiency) is demonstrated.

The calorimeter will also be used to reconstruct the energy of the electromagnetic showers. This will provide a measurement of the energy of the incident electrons independent from the magnetic spectrometer, thus allowing a cross-calibration of the two energy determinations. As shown in figure 2.19, the constant term for the calorimeter energy resolution has been measured as $\sim 5.5\%$ for electromagnetic showers generated by particles entering the calorimeter within the acceptance of the tracking system up to an energy of several hundred GeV.

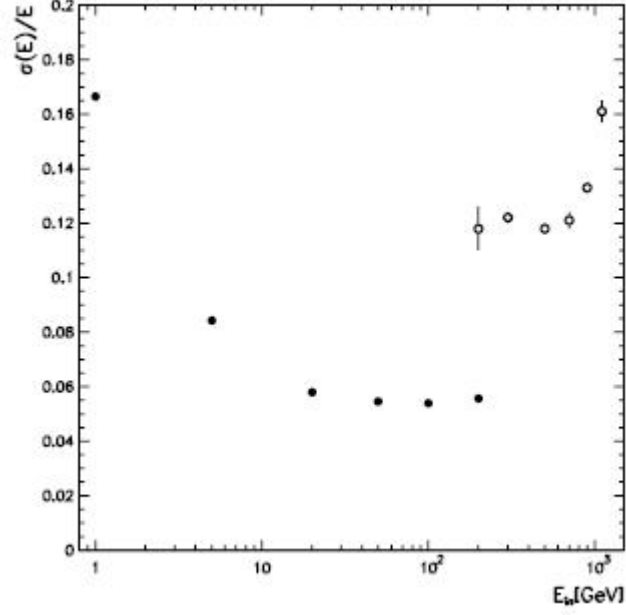


Figure 2.19: The energy dependence of the energy resolution of the electromagnetic calorimeter. The filled symbols are for normal operation (experimental data) and the open symbols are for the self-trigger mode (simulations), described in section 2.3.

The calorimeter also has a hardware-implemented self-trigger functionality, which allows it to record electrons from 300 GeV to more than 1 TeV with a geometrical factor of $\sim 600 \text{ cm}^2\text{sr}$ (to be compared to PAMELA acceptance: $20.5 \text{ cm}^2\text{sr}$). A self-triggered event is recorded if the particle enters one of the first 4 calorimeter planes and traverse at least 10 radiation lengths (X_0). Simulation studies have shown a self-triggering efficiency $> 99\%$ for electrons above 300 GeV (see also section 2.3.2).

2.2.5 Shower tail catcher scintillator

The shower tail catcher scintillator (S4) improves the PAMELA electron-hadron separation performance by measuring shower leakage from the calorimeter. It also provides a high-energy trigger for the neutron detector (described in section 2.3.2). This scintillator is placed just under calorimeter. It consists of a single square piece of 1 cm thick scintillator of dimensions $(48 \times 48) \text{ cm}^2$ which is read out by six PMTs, as shown in figure 2.20 (left).

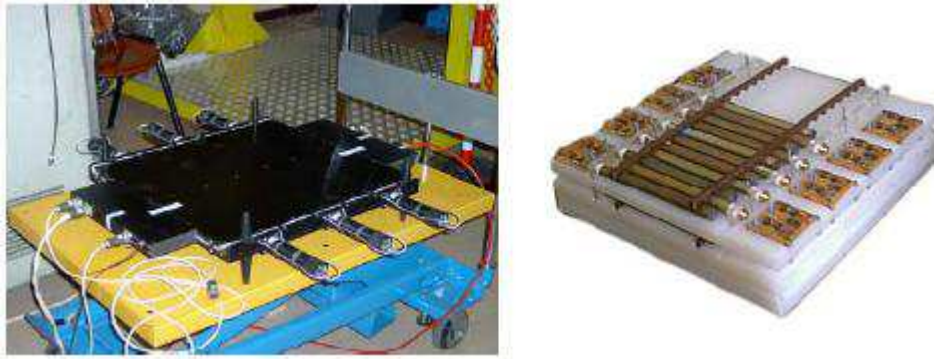


Figure 2.20: Left: the shower tail catcher scintillator, S4, showing the 6 PMTs used for read-out. The scintillator has dimensions $(48 \times 48) \text{ cm}^2$. Right: The neutron detector partially equipped with ^3He proportional counters. The neutron detector covers an area of $(60 \times 55) \text{ cm}^2$.

2.2.6 Neutron detector

The neutron detector complements the electron-proton discrimination capabilities of the calorimeter. The evaporated neutron yield in a hadronic shower is 10-20 times larger than expected from an electromagnetic shower. The neutron detector is sensitive to evaporated neutrons which are thermalised in the calorimeter. The detection efficiency (including thermalisation) is $\sim 10\%$. Joint analysis of the calorimeter and neutron detector information will allow primary electron energies to be determined up to several TeV.

The neutron detector [101] is located below the S4 scintillator and has been added to the PAMELA instrument to expand the energy range of the recorded primary protons and electrons up to $10^{11} - 10^{13} \text{ eV}$. It consists of 36 proportional counters, filled with ^3He and surrounded by a polyethylene moderator enveloped in a thin cadmium layer to prevent thermal neutrons entering the detector from the sides and from below. The counters are stacked in two planes of 18 counters, oriented along the y-axis of the instrument. The size of the neutron detector is $(60 \times 55 \times 15) \text{ cm}^3$ and is shown in figure 2.20 (right).

2.3 PAMELA data acquisition and trigger system

2.3.1 Data acquisition system

A schematic overview of the PAMELA data acquisition (DAQ) system is shown in figure 2.21. The PSCU (PAMELA Storage and Control Unit) handles all slow controls, communication with the satellite, data acquisition, storage and downlink tasks. The PSCU contains 4 subsystems:

- A processor module built around a CPU based on a ERC-32 architecture (SPARC v7 implementation) running the RTEMS real time operating system at 24 MHz. The CPU is custom built by Laben and is fully space qualified. Communication with the Resurs satellite is realised via a standard 1553B data-bus;
- Two redundant 2 GByte mass memory modules. The modules include latchup detection, allowing operation to be transparently switched to the safe module when a latch-up is detected;
- A PIF (PAMELA interface board) that performs three main tasks: communication with the IDAQ (Intermediate DAQ) system through a DMA (Dynamic Memory Access) controller, handling the interface with the mass memory, and providing the interface with the VRL (Very high-speed Radio Link) module of the satellite;
- A TMTC (Telemetry and Control) board that handles the housekeeping operations of PAMELA, such as alarm, temperature and voltage monitoring (once per second). Such monitoring is performed both directly (ADC inputs and contact closure telemetries) and through a dedicated housekeeping board that communicates through serial data links with the subdetector read-out boards, with the IDAQ board and with the power supply control boards.

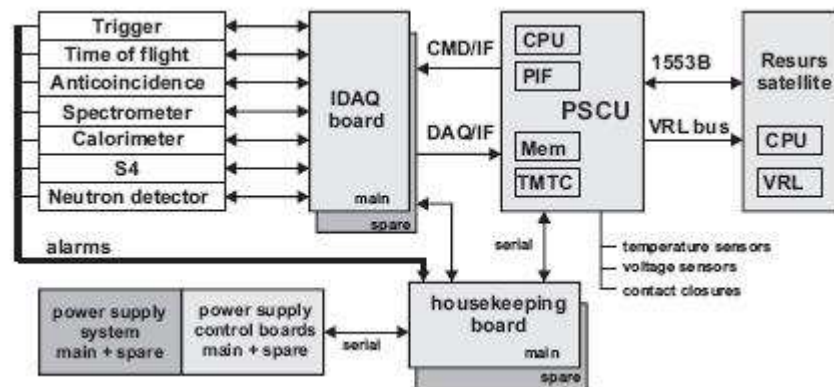


Figure 2.21: Scheme of the PAMELA data acquisition system. The interfaces (IF) between the IDAQ and the PSCU handle the data acquisition and transfer the commands to the IDAQ. The communication between PAMELA and the spacecraft is handled by the 1553B bus and by the link to the VRL module (Very high-speed Radio Link) for data download to the Resurs memory. Adapted from [102].

Data acquisition from the subdetectors is managed by the IDAQ system at a rate of 2 MByte/s. Upon receipt of a trigger, the PSCU initiates the

IDAQ procedure to read out data from the subdetectors in sequence. The resulting data are stored in the PSCU mass memory. Several times a day, the data are transferred to the satellite on-board memory via the 12 MByte/s VRL bus where it is stored prior to downlinking to earth. Approximately 15 GBytes are transferred to ground per day during 2-3 downlink sessions. In Appendix B data format is explained.

The PSCU automatically handles the flow of PAMELA physics tasks and continuously checks for proper operation of the apparatus. At boot, the PSCU manages the operation of the power supply system to power up all subsystems, initializes all detectors and starts the data acquisition cycle. In parallel, once per second the PSCU checks the TMTC information on voltages and alarms. In case of abnormal conditions the PSCU can perform a hardware reset of the whole system or, if insufficient to solve the problem (e.g. in case of electronics latch-up), powers down and then up PAMELA. The PSCU also checks the temperature environment by reading dedicated temperature sensors distributed in various locations around the instrument. If the readings exceed predefined values (set with dedicated commands from ground) the PSCU powers down PAMELA until acceptable working conditions are reached. The PSCU also handles communication with the Resurs satellite CPU and VRL system. Data is downloaded to the VRL upon receipt of a dedicated command from the Resurs CPU. The scheduling of data downloads from the PAMELA mass memory to the VRL hard disk system is defined from ground on a daily basis.

The PSCU organizes the data acquisition cycle in "runs". A "run" is defined as a continuous period of data taking in which the trigger and detector configurations are constant. These configurations are defined by the PSCU according to information stored in on-board memory or received from ground. The duration of a "run" is determined by the PSCU according to the orbital position (e.g. inside radiation belts or South Atlantic Anomaly SAA or outside these areas). The orbital position also dictates the trigger configuration, as described in section 2.3.2. The orbital position is derived from the "ascending node" notification issued by the Resurs CPU when the satellite crosses the equator from the southern hemisphere to the northern hemisphere. From this position information, the CPU extrapolates the entry time into high radiation environments. This can be performed in three ways, chosen from ground:

- when the counting rate of the S1 scintillator exceeds a given threshold (changeable from ground with dedicated command);
- according to fixed time periods conservatively chosen and modifiable from ground;
- according to a table with crossing times in absolute Moscow time⁵

⁵On a regular basis the Resurs CPU sends a time synchronization command with the

provided on a bi-weekly basis from ground with a dedicated command.

Additionally, the PSCU can interrupt and close a run if anomalous conditions that require action upon the subsystems (e.g. hardware resets, etc.) are detected.

Periodically the PSCU calibrates the detectors, namely the anticounter system, the tracker, the calorimeter and the S4 scintillator. By default, the calibration is performed at the point of lowest cosmic-ray trigger rate, i.e. the equator, upon receiving an "ascending node" notification from the Resurs CPU. The frequency of calibrations can be modified from ground.

2.3.2 Trigger system

The PAMELA trigger condition is defined by coincident energy deposits in the scintillator ToF layers. Various configurations can be selected. The default ones (the subscripts 1 and 2 refer to the upper and lower layers in each ToF plane) used outside and inside radiation environments are:

- (S11 or S12) and (S21 or S22) and (S31 or S32): outside radiation belts and SAA;
- (S21 and S22) and (S31 and S32): inside radiation belts and SAA; since, according to simulation, the radiation environment will saturate the S1 counting rate but will not affect significantly the S2 and S3 scintillators since they are more shielded.

These trigger configurations can be changed from ground with dedicated commands to the PSCU. A total of 31 configurations have been implemented on the trigger board. Various combination of AND and OR of the scintillators layers with or without the calorimeter self-trigger and S4 trigger (described below) are implemented (see Appendix A). The PMTs can be masked on the trigger board by the PSCU. The calorimeter is equipped with a self-trigger capability (see also 2.2.4). A trigger signal is generated in calorimeter when a specific energy distribution is detected in predetermined planes within the lower half of the calorimeter. The sets of planes used in this configuration can be changed with a dedicated command from ground. This allows PAMELA to measure very high-energy (~ 300 GeV to > 1 TeV) electrons in the cosmic radiation. At present, very few measurements have covered this energy range [103]. Since these events are rare, it is important to have a large geometrical factor. By requiring that triggering particles enter through one of the first four planes and cross at least 10 radiation lengths, the geometrical factor is $\approx 600 \text{ cm}^2\text{sr}$, i.e. about a factor of 30 larger than the default PAMELA acceptance defined by the magnetic spectrometer. The behavior

Moscow time to the PSCU. The precision of this information is ~ 1 s.

of the calorimeter in self-trigger mode has been studied by means of simulations [98]. The simulated energy resolution of the calorimeter in self-trigger mode is approximately constant ($\sim 12\%$) up to about 800 GeV, as shown in figure 2.19. At higher energies the resolution decreases because of increasing longitudinal leakage and saturation of the signal from the strips (about 1000 MIP). The choice of energy loss and activated planes implemented in the calorimeter electronics to generate a trigger signal has been taken to have the highest proton rejection while keeping a trigger efficiency of better than 90% for electrons of energies higher than 300 GeV [98]. Combined with the neutron detector information, the apparatus will be able to cleanly identify very high-energy electrons. The neutron detector can also be triggered when an energy deposit exceeding 10 MIP is detected in the S4 scintillator.

The trigger rate observed during a typical orbit is shown in figure 2.22. The maxima at ~ 2000 events per minute (~ 30 Hz) correspond to passages over the polar regions (North Pole, NP and South Pole, SP) while the minima (~ 15 Hz) correspond to equatorial regions (E). The contribution from the South Atlantic Anomaly (SAA) is clearly visible (~ 70 Hz). Note that data is taken in the SAA using the second default trigger configuration. The missing acquisition time after the peaks of the SAA corresponds to the detector calibrations upon crossing the equator (about 1 minute in duration). If the

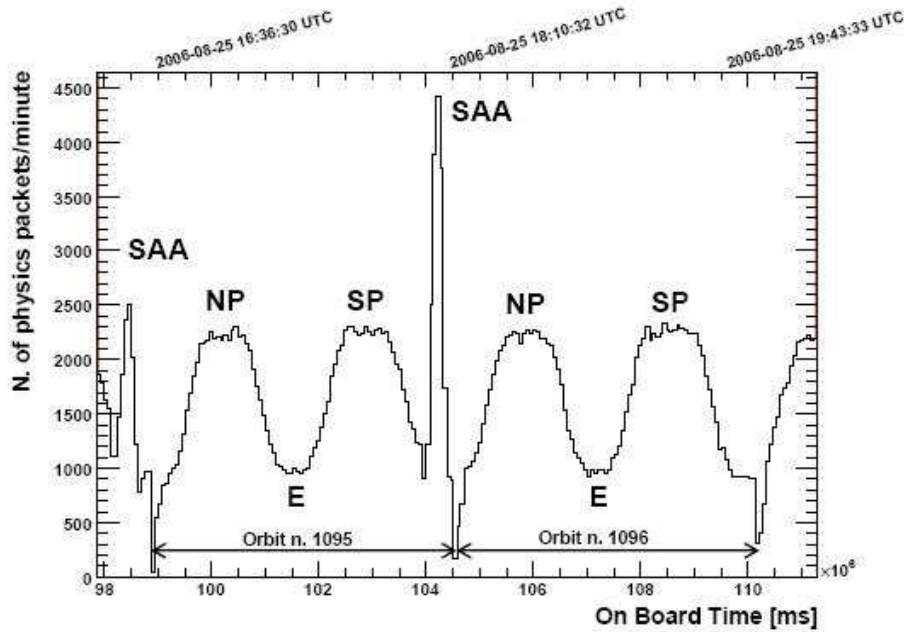


Figure 2.22: The PAMELA trigger rate shown in events per minute evaluated during two consecutive orbits (period ~ 94 minutes). The trigger rate is strongly dependent on the orbital position: NP, North Pole; SP, South Pole; E, Equator; SAA, South Atlantic Anomaly.

amount of event data exceeds the storage dedicated to PAMELA on board the Resurs satellite or the daily downlink limit, an on-line event selection is provided by a second level trigger. The second level trigger is not normally activated and must be activated via an uplinked command from ground. Information from the CAS anticoincidence system is used to reject "false triggers" (see section 2.2.2) and information from the calorimeter are used to reduce the impact of particles backscattered from the calorimeter. The second level trigger is described in detail elsewhere [93].

2.4 The Resurs DK1 satellite and data reception

The Resurs DK1 satellite is manufactured by the Russian space company TsSKB Progress to perform multi-spectral remote sensing of the Earth's surface and acquire high-quality images in near real-time: it is designed to transmit prompt data on sea surface status, ice coverage, meteorological conditions in Earth polar regions and information for Earth natural resources study. The satellite will take high resolution images of the Earth surface. For this reason, a large amount of hard disk space (> 100 GB) will be available on the satellite. Data delivery to ground is realised via a high-speed radio link.

The satellite is presented in figure 2.23, it has a mass of ~ 6.7 Tonnes and a height of 7.4 m. Solar panels and batteries will supply the required electrical power. The solar array span is ~ 14 m. The satellite is three-axis stabilized with an axis orientation accuracy of 0.2 arcmin and an angular velocity stabilization accuracy of $0.005^\circ/\text{s}$. The orbital altitude varies between 350 km and 600 km at an inclination of 70.0° . The design lifetime is three years. PAMELA is mounted in a dedicated Pressurized and temperature controlled Container (PC) attached to the Resurs DK1 satellite. During launch and orbital manoeuvres, the PC is secured against the body of the satellite. During data-taking it is swung up to give PAMELA a clear view into space. The container is cylindrical in shape and has an inside diameter of about 105 cm, a semi-spherical bottom and a conical top. It is made of an aluminium alloy, with a thickness of 2 mm in the acceptance of PAMELA. Figure 2.24 shows tests of the PC tilting mechanism performed in May 2002 at the TsSKB Progress facility in Samara. The movement of the PC from the parked to the data-taking position was tested in simulated weightless conditions.

2.5 NTs OMZ ground segment

The ground segment of the Resurs DK1 system is located at the Research Center for Earth Operative Monitoring (NTsOMZ) in Moscow, Russia [104]. This forms part of the Russian Space Agency (Roskosmos) ground segment



Figure 2.23: A sketch of the Resurs DK1 satellite which hosts the PAMELA experiment in a Pressurized Container. The satellite has a height of 7.4 m. The camera that will take high resolution images of the Earth is shown at the bottom of the figure. The shaded area on the right is the pressurised PAMELA container in data acquisition configuration. During launch and orbital manoeuvres, the container will be placed in the downward configuration.

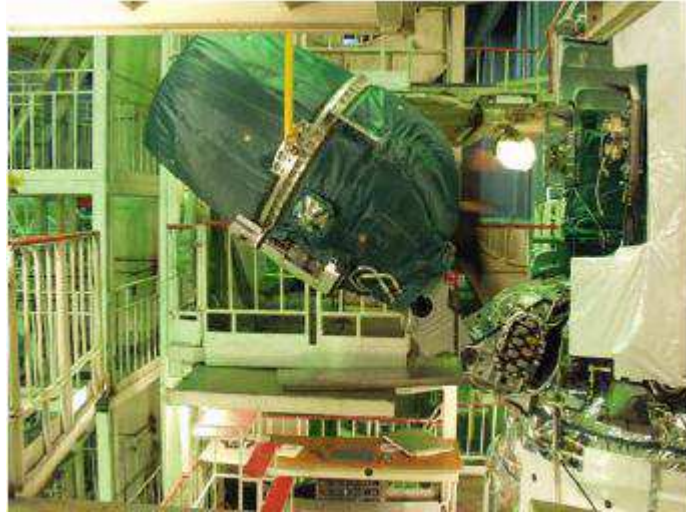


Figure 2.24: Tests of the PAMELA Pressurized Container during orbital operations (May 2002). The body of the Resurs DK1 satellite can be seen to the right of the picture.

designed for acquiring, recording, processing and distributing data from remote sensing systems in space.

The reception antenna at NTsOMZ is a parabolic reflector of 7 m diameter, equipped with an azimuth-elevation rotation mechanism, and has two frequency multiplexed radio channels. The Resurs DK1 radio link towards NTsOMZ is active 2-3 times a day. The average volume of data transmitted during a single downlink is currently ~ 6 GBytes, giving a total of 16 GBytes/day. Data received from PAMELA are collected by a data-set archive server. The server calculates the downlink session quality (the error probability per bit) and faulty downlink sessions can be assigned for retransmission up to several days after the initial downlink.

The downlinked data are transmitted to a server dedicated to data processing for instrument monitoring and control, and is also written to magnetic tape for long-term storage. All such operations are automatized to minimize the time delay between the data reception and the extraction of monitoring information (see chapter 5 for reference). After this first level of data analysis, both raw and preliminary processed data are moved through a normal internet line to the main storage centre in Eastern Europe, which is located at MePHI (Moscow, Russia). From here, GRID infrastructure is used to move raw and first level processed data to the main storage and analysis centre of the PAMELA Collaboration, located at CNAF (Bologna, Italy), a specialized computing centre of INFN. Here data are accessible to all various institutions within the PAMELA collaboration.

Chapter 3

PAMELA Qualification Tests and Ground Physics Performance

3.1 Qualification tests

Space-borne apparatus must maintain a high level of performance and stability throughout the mission duration in the harsh environment of space. The mechanical design must be such that the payload and satellite withstand the significant shocks and vibrations of the launch. The extremes of temperature that may be encountered in space requires that the thermal and mechanical designs be such that the sensitive components maintain excellent stability over a broad range of temperatures. The radiation environment in space is major consideration in the design of electronic circuitry. All chosen components must be tested for radiation tolerance prior to use. ElectroMagnetic Interference (EMI) from electronic devices must be minimized by the use of different types of filters and shielded cables.

In this section the steps taken to qualify PAMELA for operation in space are reviewed [105]. During the period of my thesis, I participated to these tests actively. In particular I followed electrical tests performed initially on PAMELA Technological Model (TM) and then on PAMELA Flight Model (FM), as explained in section 3.1.3. I studied the first real physics performance of the apparatus also, analyzing first events acquired on ground during the same electrical tests. From this analysis (in section 3.2.2), a first muon charge ratio was obtained.

3.1.1 Radiation tolerance

In orbit all on-board electronic devices will be subject to the passage of ionizing particles, which can degrade their performance and eventually lead to their permanent damage or loss of functionality. Since malfunctioning com-

ponents cannot be replaced once the instrument is in orbit, all critical devices must either be already space qualified, or tested for radiation tolerance before use. For economic, performance and power consumption reasons, most of the PAMELA electronic components are "off-the-shelf" commercial products. Radiation tolerance tests therefore had to be carried out before their integration into electronic boards. A selection of electronic components was been tested under gamma and heavy ion beams during the construction phase of the PAMELA subsystems.

As an example, the DSP and FPGA chips used through-out the PAMELA data acquisition system were extensively tested in the period 2000-2002, using heavy-ion beams. The tests were performed at GSI in Darmstadt (Germany), and JINR in Dubna (Russia). At GSI the devices were exposed to beams of ^{131}Xe and ^{238}U , in the energy range 100-800 MeV/n. Different incidence angles allowed different doses to be achieved. At JINR slow beams of ^{24}Mg at 150 MeV/n were used, in order to maximize the energy transfer to the components under test. Test results have been published elsewhere [106].

3.1.2 Mechanical and Thermal Qualification

The mechanical and thermal space qualification tests of the PAMELA instrument were performed in the years 2002-2003. In order to perform such tests, a mock-up of the entire instrument, Mass-Dimensional and Thermal Model (MDTM), was manufactured. The MDTM reproduces the geometrical characteristics of PAMELA (e.g. dimensions, total mass, center of gravity, inertial moments) and the basic thermal behaviour. All particle detectors in the MDTM were simulated by dummy aluminum boxes. The electronics systems were non-functional and only reproduced the power consumption of each subsystem.

Mechanical Qualification

In order to ensure that no damage occurs to PAMELA or the spacecraft during any of the different operational phases of the mission (transport, launch, orbital operations, unlocking of the Pressurized Container, flight), the MDTM was exposed to vibration spectra at mechanical loads exceeding those expected during the mission. The MDTM vibration tests were performed at IABG Laboratories (Munich, Germany) in August 2002, as shown in figure 3.1. During the test it was verified that structural integrity was maintained and that there was no change in the dynamic behavior of MDTM (using resonance searches).

The MDTM structure was subjected to the required vibration loads along three orthogonal axes. Additional transport, vibration and shock tests of the MDTM whilst integrated into the Pressurized Container were performed at



Figure 3.1: The PAMELA MDTM on the shaker system in IABG (August 2002).

the TsSKB-Progress Testing Center in May 2003. Additional information about PAMELA mechanical space qualification can be found in [107].

Thermal Qualification

The PAMELA thermal cooling system consists of a 8.6 m long pipe that joins 4 radiators and 8 flanges connected throughout the PAMELA detector system.

The task of this system is to dissipate the heat produced by the PAMELA subsystems and transfer it into the spacecraft, where a custom designed thermal control system is located. This transfer is performed by means of a heat transfer fluid pumped by Resurs satellite through the PAMELA pipelines. The total heat release of PAMELA cannot exceed 360 W. Thermal and vacuum tests of the PAMELA MDTM were performed in the laboratories of TsSKB-Progress in April 2003. Six thermal modes of operation were implemented, where the three relevant parameters which regulate the instrument thermal behaviour (PAMELA power consumption, external heat flows and heat-transfer fluid temperature and flow rate) were varied between the design extrema to simulate in-flight operations. Each mode persisted until a steady state condition was reached. As an example, a test simulating an interruption in the flow of the heat-transfer fluid due to a malfunctioning was interrupted after 3 hours when the PAMELA MDTM reached a temperature of $\sim 60^\circ \text{C}$.

The qualification test of the PAMELA thermal system showed that all parameters of the system stayed within the design limits (5°C - 40°C). During the Resurs DK1 orbit, the operating temperature range of PAMELA

will vary between 7°C for the coldest systems and 38°C for the warmest ones, as shown in figure 3.2.

Additional information about PAMELA thermal space qualification can be found in [107].

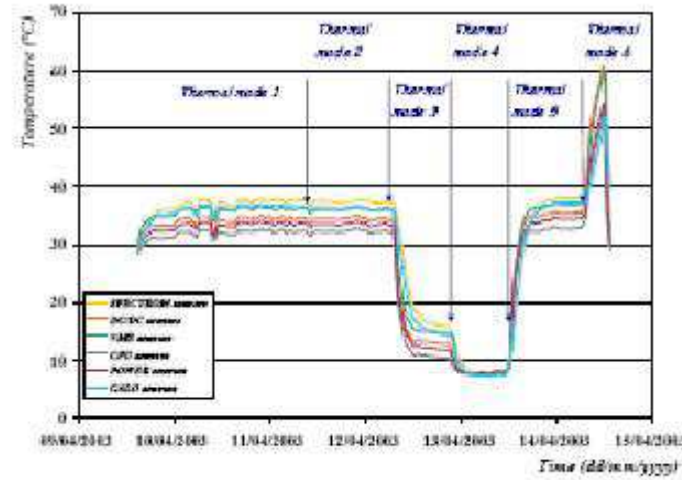


Figure 3.2: Results of the PAMELA thermal qualification tests. Temperatures in different subsystems are shown during the execution of the 6 different thermal modes. The temperature remained always between acceptable limits (5°C - 40°C) except for thermal mode number 6 where a stop in the heat transfer fluid was simulated.

3.1.3 Electrical tests

To perform tests of the electrical interface between PAMELA and the spacecraft, a second mock-up of the PAMELA instrument was assembled. This Technological Model (TM) was an exact copy of the Flight Model from the point of view of electrical connections to the satellite and for the readout electronics boards, with the particle detectors substituted by dummies. The Technological Model was shipped to TsSKB-Progress in April 2004 (see figure 3.3). The task of the Technological Model was to thoroughly test the electrical interface to the Resurs DK1 satellite. In addition, it was used to check that the residual magnetic field from the PAMELA spectrometer did not interfere with the Resurs instrumentation. These complex tests proceeded in phases. A first test was performed in Rome in December 2003, with the satellite emulated by a Ground Support Equipment (EGSE) system. A second test started in May 2004 at TsSKB-Progress and verified the powering procedures. In October 2004 the PAMELA Technological Model was fully integrated into the Resurs DK1 to complete all remaining tests.

The apparatus was switched-on and put in acquisition for some consecutive months during which every electrical device was tested: data acquisition board (IDAQ board), telemetry and control board (housekeeping board), trigger board, VRL for download sessions, power supply board (see figure 2.21).



Figure 3.3: The PAMELA Technological Model during transportation from Rome to the TsSKB-Progress plant (April 2004).

From the end of the year 2004, during and after the complete integration of the apparatus, similar tests were performed on PAMELA Flight Model, simulating real acquisition runs and acquiring first cosmic ray events. In this way each detector was tested and monitored for some months of continuing data-taking. Then in 2005, in April, PAMELA were shipped to Samara, for final qualification tests and then to Baikonur to be integrated on the Resurs DK-1 satellite.

I participated to these tests monitoring personally the apparatus during Rome and Samara tests.

To analyze first acquired data, software to unpack raw data was developed to obtain Level1 and Level2 Data. I took care of developing Telemetry, S4 and ND unpacking Software, as described in Chapter 5.

During these final tests was also important the development of Quick Look Software to monitor in real time what happened through tests activity. I personally attended in particular to Telemetry and Temperature QL, Packet QL and, for what concern detectors, to S4 and ND (described in detail in chapter 5). The same QL Software, tested and improved, is still used during the flight to monitoring the mission.

3.2 Physics Performance

3.2.1 Beam tests

Between July 2000 and September 2003, the PAMELA subsystems were periodically exposed to particle beams at the CERN PS and SPS facilities. Electron and proton beams were used with energies in the 10's - 100's GeV range. Results from these tests for the study of calorimeter performances are described in section 2.2.4 and in [100].

3.2.2 Ground data analysis

Prior to the delivery to Samara (Russia), where the spacecraft is built, the PAMELA apparatus was assembled at the laboratories of the University of Rome "Tor Vergata", Italy. Here the system was tested with cosmic rays (obviously atmospheric muons above all) over a period of several months, in order to calibrate the sub-detectors and check the overall performance of the instrument. As a whole, a total of about 480 hours of ground cosmic rays have been collected. Once PAMELA reached Samara, it was extensively tested again before being integrated inside the spacecraft. As a result, about 140 hours of cosmic ray acquisition have been recorded in Samara. During all these period, QL Software was very useful to monitor PAMELA behaviour.

Figures 3.4 and 3.5 show two cosmic ray events recorded in Rome. The first one is a 1.5 GeV/c negatively charged particle, with high probability of being a μ^- considering the clean non-interacting pattern in the calorimeter. Selecting this kind of events from the total statistic acquired during ground test in Rome, the muon charge ratio has been obtained as described below. The second one is a 67 GeV/c particle with an hadronic interaction in the calorimeter, consistent with a proton. All PAMELA detectors are shown in the figures along with the signals produced by the particles in the detectors and derived information. Highly detailed information is provided for each cosmic-ray event. The solid lines indicate the tracks reconstructed by the fitting procedure [108] of the magnetic spectrometer. The figures show also the "ghost" hits due to the common readout of the 2 silicon sensors of the same ladder in the non-bending projection. This ambiguity is solved with the help of track fitting procedure and with a consistency check with the other Pamela subdetectors.

Muon charge ratio

Analyzing data acquired in Rome (50 m above sea level) during ground tests, we obtained muon charge ratio and flux. The results are shown in figures 3.6 and 3.7. Muons were selected as non interacting particles in the calorimeter and having unit charge in the ToF scintillators (as shown in figure 3.4). Additionally, low-energy protons were rejected based on the ionization losses

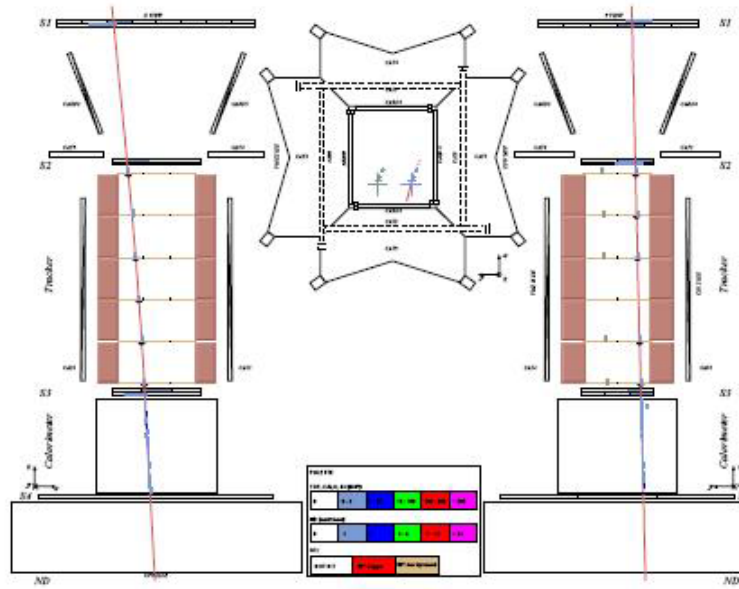


Figure 3.4: The event display of a $1.5 \text{ GeV}/c \mu^-$ from ground data. On the left (right) the x, bending view (y, non-bending view) of PAMELA are indicated. A plan view of PAMELA is shown in the centre. The signals as detected by PAMELA detectors are shown along with the particle direction (solid lines) reconstructed by the fitting procedure of the tracking system.

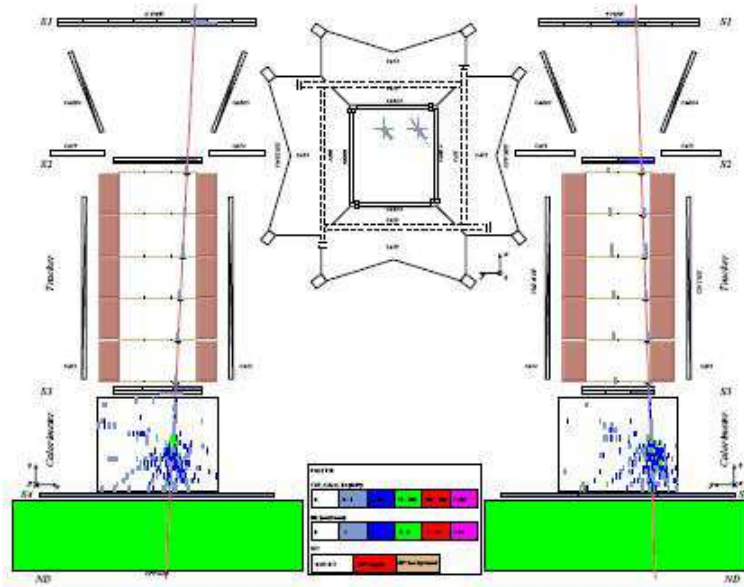


Figure 3.5: The event display of a 67 GeV/c hadron from ground data. On the left (right) the x, bending (y, non-bending view) of PAMELA are indicated. A plan view of PAMELA is shown in the centre. The signals as detected by PAMELA detectors are shown along with the particle direction (solid lines) reconstructed by the fitting procedure of the tracking system.

in the calorimeter. Momenta were determined by the magnetic spectrometer. It is possible to see that PAMELA data agree well with other published results [109, 110, 111].

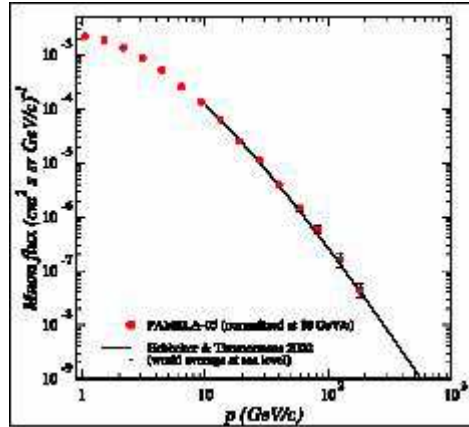


Figure 3.6: Muon flux.

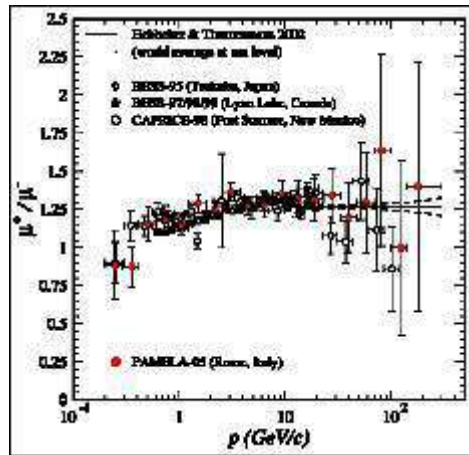


Figure 3.7: Muon charge ratio as measured by PAMELA during ground data acquisition (preliminary results) compared with the 2002 global fit of experimental data by Hebbeker and Timmermans [109], and more recent experimental results [110, 111]. The dashed lines indicate a one standard deviation of the fit.

Chapter 4

PAMELA: In-orbit performance

PAMELA was successfully launched on June 15th 2006 from Baikonur Cosmodrome in Kazakhstan by a rocket Soyuz (see figure 4.1) and it was first switched on on the 20th of June. In figure 4.2 the first PAMELA life signal from the space is shown: the rise up of the CPU and IPM temperature during the first minutes after the first switch on of the apparatus (see 5.3.1 for a more detailed explanation of the figure).

4.1 PAMELA status

The commissioning phase, during which several trigger and hardware configurations were tested, ended in mid September 2006. However, PAMELA has been in a nearly continuous science data taking mode since July 11th 2006. Until September 2007, the total acquisition time has been ~ 380 days, for a total of ~ 800 million triggers and 6.4 TByte of down-linked raw data. About 16 GB of PAMELA 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 (see 2.5 for details). After receiving the data, a dedicated computer facility unpacks and transfers them to various institutions for further data processing and analysis.

All in-flight operations are handled by the PSCU (PAMELA Storage and Control Unit). The PSCU manages the data acquisition and other physics tasks and continuously checks for proper operation of the apparatus. The average trigger rate of the experiment is ~ 25 Hz, varying from ~ 20 Hz at the equatorial region to ~ 30 Hz at the poles. The average fractional live time of the experiment is $\sim 73\%$. During this time some error conditions (approximately three per week) have occurred, mainly attributable to anomalous conditions in the detector electronics. Every time the PSCU has

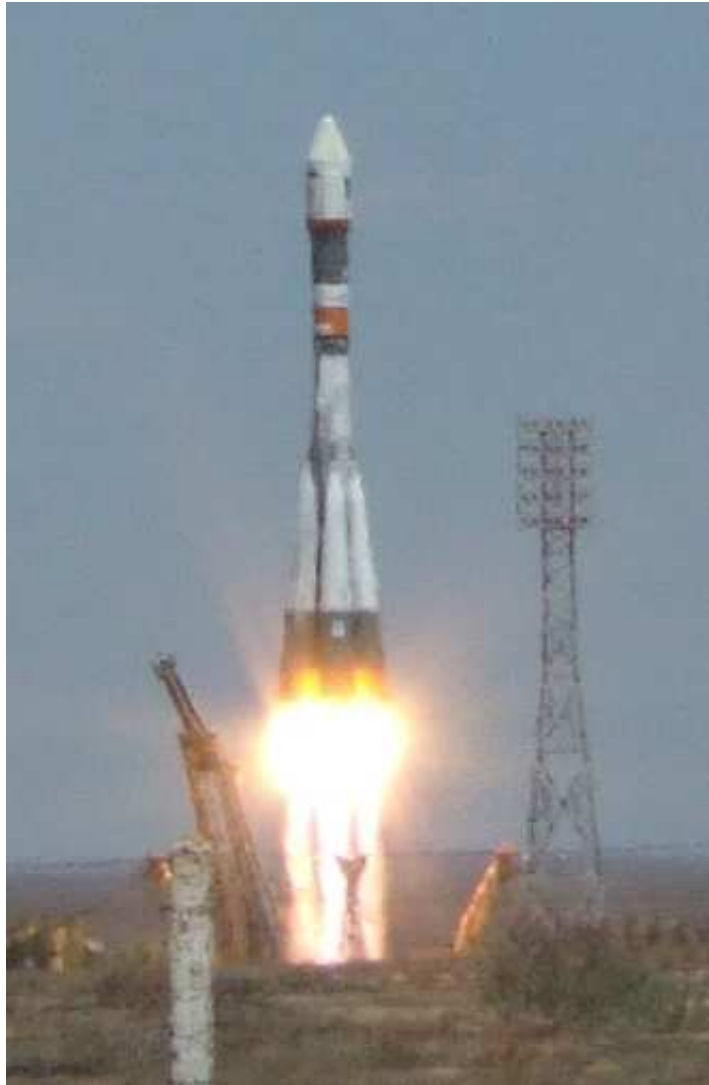


Figure 4.1: PAMELA launch from Baikonur Cosmodrome.

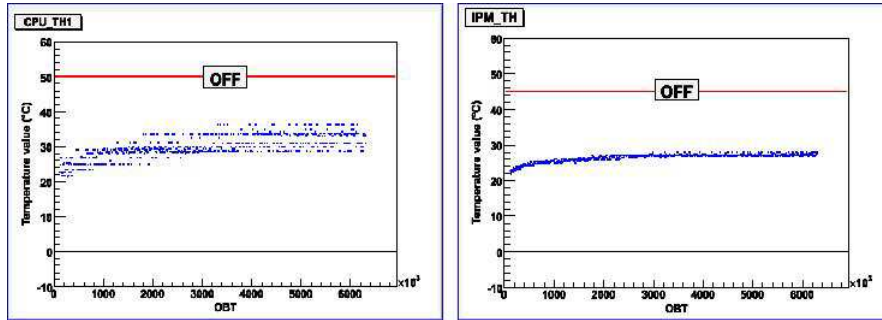


Figure 4.2: PAMELA: first life signal. CPU and IPM temperatures rise up after the first switch on of the apparatus.

been able to recover the system functionality and continue the acquisition.

First data downlinked to ground showed that the entire instrument was working as expected. Figure 4.3 shows a ~ 3 GV non-interacting proton recorded in-orbit while figure 4.4 shows a ~ 13 GV helium nucleus interacting in the calorimeter.

In this way, several tens of thousand events have been identified as positrons and about a thousand of events as antiprotons. As an example, figure 4.5 shows a ~ 84 GV negatively-charged particle with an hadronic interaction in the calorimeter identified as an antiproton and figure 4.6 shows a ~ 92 GV positively-charged particle with a typical electromagnetic shower in the calorimeter identified as a positron. In these figures a different signature in the neutron detector can be clearly noticed. Additional hadron-rejection power is provided by the neutron detector and this increases as the energy increases.

Besides selection of charge one particles, PAMELA is able to identify light nuclei particles, up to Oxygen at least, using the ionization losses in the calorimeter, ToF and tracker systems.

4.2 Moscow shifts

During last year I went to Moscow, in NTsOMZ ground segment, three time for monitoring shift, for an equivalent time of two months.

Daily the shifter has to perform different tasks, explained in detail below. He has to:

- monitor data flow;
- monitor mission status;
- update software for processing and analysing data.

For what concern data flux, it has to be checked daily to monitor if:

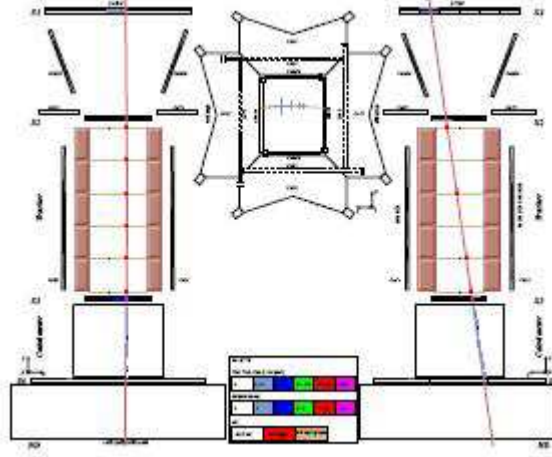


Figure 4.3: The event display of a ~ 3 GV non-interacting proton from flight data. On the left (right) the x, bending view (y, non-bending view) of PAMELA are indicated. A plan view of PAMELA is shown in the centre.

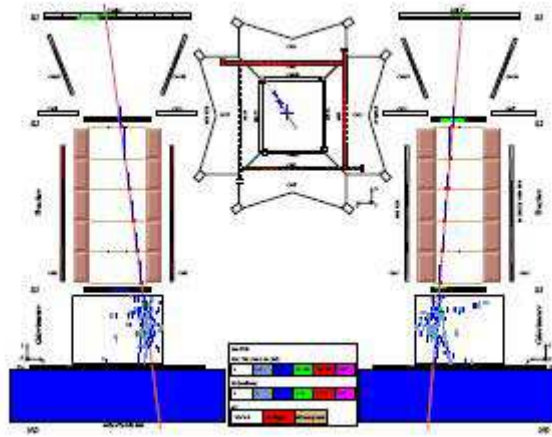


Figure 4.4: The event display of a ~ 13 GV interacting helium nucleus from flight data. On the left (right) the x, bending (y, non-bending view) of PAMELA are indicated. A plan view of PAMELA is shown in the centre. Note the increased energy deposit in the silicon tracker planes (denoted by the vertical bars) compared to figure 4.3. The activity in the anticounter system is probably due to secondary particles backscattered from the calorimeter.

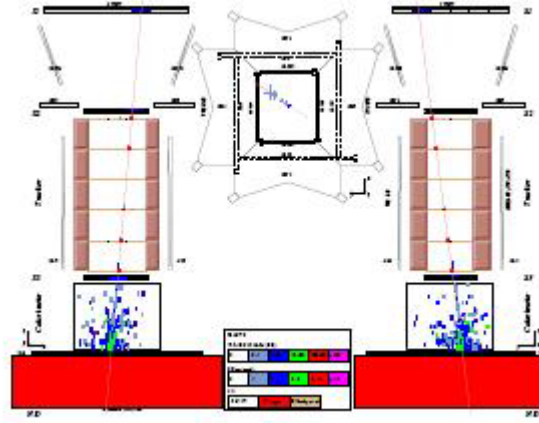


Figure 4.5: The event display an ~ 84 GV antiproton interacting in the calorimeter. The bending (x) and non-bending (y) views are shown on the left and on the right, respectively. A plan view of PAMELA is shown in the center. The signal as detected by PAMELA detectors are shown (plane 19 of the calorimeter x-view was malfunctioning) along with the particle trajectory (solid line) reconstructed by the fitting procedure of the tracking system.

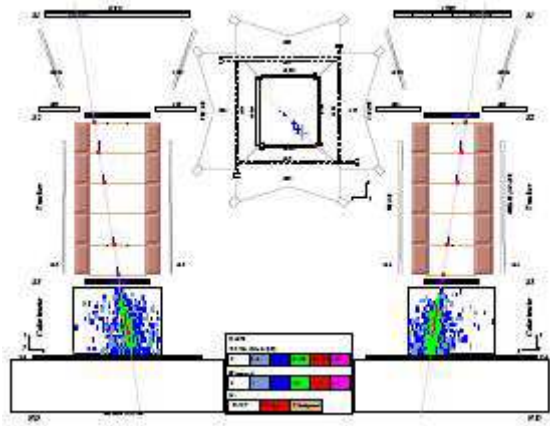


Figure 4.6: The event display a ~ 92 GV positron. The bending (x) and non bending (y) views are shown on the left and on the right, respectively. A plan view of PAMELA is shown in the center. The signal as detected by PAMELA detectors are shown (plane 19 of the calorimeter x-view was malfunctioning) along with the particle trajectory (solid line) reconstructed by the fitting procedure of the tracking system.

- every packets have been downlinked from Resurs satellite Mass Memory to ground as scheduled; if not the shifter has to request a new donwlink session;
- downlinked data have been transmitted correctly; if notthe shifter has to request a new retransmission;
- downlinked data have benn processed correctly till to obtain good QL outputs and good Level2 files, as explained in chapter 5; if not the shifter has to solve this problem that can depend on different trouble.
- processed data are correctly transferred to Mephi farm to be copied from all the other Western-European PAMELA collaborations as explained in section 2.5; if not the shifter has to retransmit data.

As said before, monitoring daily the status of the mission is another task of the shifter. To do this all necessary information are contained in the output of Quick-Look software, as for example main information relative to thermistor temperatures and alarms status (relating Quick-Look outputs are described in detail in section 5.3). If some alarm is present, the shifter has to understan what happenedand, if necessary, to request the uplink of some macroccomands (MCMDs) to solve alarm condition.

To fill a database with primary information relative mission status is another task of the shifter. For each downlinked file some information are stored in the database as for axample: file name, date and hour of relative donwlink, trigger acquisition mode and alarm status.

At least, software update for processing and Quick-Look analysis (PAMELA software chain is described in detail next chapter) is a shifter responsibility.

Chapter 5

Flight Software Development: Processing and Monitoring

In this chapter PAMELA Flight Software is explained in detail: starting from PAMELA RAW data to arrive, step by step, to data ready for scientific analysis.

As said in section 2.5, about 2-3 downlink per day are performed for a total amount of ~ 16 GB of data per day.

5.1 PAMELA offline software chain

A complicated Software chain was written to produce data for the analysis (Level2 Data) starting from Data transmitted to Earth by satellite (RAW Data). All the Software is written in C++ language. In figure 5.1 a simplified scheme of this Software chain is shown.

As said, Raw Data are data such as downlinked to Earth by the apparatus. They are written in a hexadecimal code and their format is described in Appendix B.

RawReader software was developed to extract PAMELA data from RAW files. A RAW file represent the input for RawReader and the output is an identical file but containing PAMELA information only. This kind of file is named post-RawReader file (for post-RawReader file format see Appendix B). This post-RawReader file, written in hexadecimal code as the RAW file, is processed by YODA Software to obtain Level0 file which contains the same information of post-RawReader file but written in a more comfortable way: Level0 file is a .ROOT file with its characteristic and easily handable structure of TFile and TTree. In figure 5.2 a typical structure of a Level0 file is shown. For each kind of packet in the RAW file (i.e for each packet id) there is a TTree in the Level0 file. All the events of the same kind are stored in a specific TTree: all physic events are stored in the "Physics" TTree and

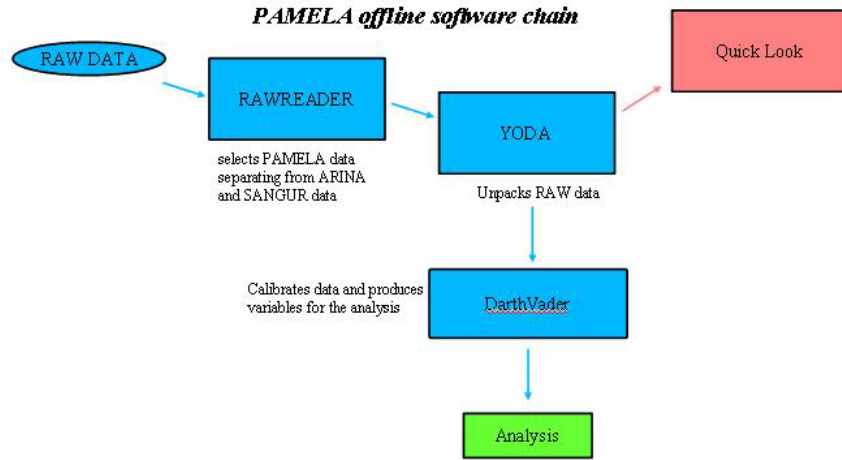


Figure 5.1: PAMELA offline Software chain.

the number of events correspond to the entries of the correspondent Tree, all infos about Telemetry are stored in "Tmtc" TTree. Each TTree has an internal structure of TLeaf corresponding to the format of the specific relative RAW packet.

Level0 file represents the input file for DarthVader Software. DarthVader produces the final product of the offline software chain: a .ROOT file with calibrated Data ready for the analysis, named Level2 file. During the calibration analysis, the Level1 file is produced but it is not stored because it is not useful for the analysis. In figure 5.3 the typical structure of a Level2 file is shown.

As shown in figure, a Level2 file contains a total of nine TTree: one TTree for each detector for physics events and two others TTree filled with Orbital and Run information relative to that events.

5.2 S4 and ND Level2 Software Development

During the first period of my PhD, I developed the code relative to the production of Level2 (in DarhVader Software) file for what concerns S4 and ND. For S4, the Level2 Software produces a TTree with calibrated Data; the necessary information for the calibrated production is taken from "CalibS4" TTree in Level0 files.

```

TFile**      ne3000_30gev.root
TFile*
KEY: TTree   PhysEndRun;1      TechmodelEventReader
KEY: TTree   CalibCalPulse1;1   TechmodelEventReader
KEY: TTree   CalibCalPulse2;1   TechmodelEventReader
KEY: TTree   Physics;1          TechmodelEventReader
KEY: TTree   CalibTrkBoth;1     TechmodelEventReader
KEY: TTree   CalibTrk1;1        TechmodelEventReader
KEY: TTree   CalibTrk2;1        TechmodelEventReader
KEY: TTree   CalibTof;1         TechmodelEventReader
KEY: TTree   CalibS4;1          TechmodelEventReader
KEY: TTree   CalibCalPed;1      TechmodelEventReader
KEY: TTree   Calib1_Ac1;1       TechmodelEventReader
KEY: TTree   Calib1_Ac2;1       TechmodelEventReader
KEY: TTree   Calib2_Ac1;1       TechmodelEventReader
KEY: TTree   Calib2_Ac2;1       TechmodelEventReader
KEY: TTree   RunHeader;1        TechmodelEventReader
KEY: TTree   RunTrailer;1       TechmodelEventReader
KEY: TTree   CalibHeader;1      TechmodelEventReader
KEY: TTree   CalibTrailer;1     TechmodelEventReader
KEY: TTree   InitHeader;1       TechmodelEventReader
KEY: TTree   InitTrailer;1      TechmodelEventReader
KEY: TTree   EventTrk;1         TechmodelEventReader
KEY: TTree   Log;1              TechmodelEventReader
KEY: TTree   VarDump;1          TechmodelEventReader
KEY: TTree   ArrDump;1          TechmodelEventReader
KEY: TTree   TabDump;1          TechmodelEventReader
KEY: TTree   Tmtc;1             TechmodelEventReader
KEY: TTree   Mcmd;1             TechmodelEventReader
KEY: TTree   ForcedFECmd;1      TechmodelEventReader
KEY: TTree   Ac1Init;1          TechmodelEventReader
KEY: TTree   CalInit;1          TechmodelEventReader
KEY: TTree   TrkInit;1          TechmodelEventReader
KEY: TTree   TofInit;1          TechmodelEventReader
KEY: TTree   TrgInit;1          TechmodelEventReader
KEY: TTree   NdInit;1           TechmodelEventReader
KEY: TTree   S4Init;1           TechmodelEventReader
KEY: TTree   Ac2Init;1          TechmodelEventReader
KEY: TTree   CalAlarm;1         TechmodelEventReader
KEY: TTree   Ac1Alarm;1         TechmodelEventReader
KEY: TTree   TrkAlarm;1         TechmodelEventReader
KEY: TTree   TrgAlarm;1         TechmodelEventReader
KEY: TTree   TofAlarm;1         TechmodelEventReader
KEY: TTree   S4Alarm;1          TechmodelEventReader
KEY: TTree   Ac2Alarm;1         TechmodelEventReader
KEY: TTree   Isbi;1             TechmodelEventReader
KEY: TTree   TshR;1             TechmodelEventReader
KEY: TTree   SoftInfo;1         YODA software info

```

Figure 5.2: Level0 file structure: output of Yoda Software

```

TFile**      L2PAM070430.root
TFile*
KEY: TTree   Tracker;1          PAMELA tracker level2 data
KEY: TTree   TOF;1              PAMELA Level2 TOF data
KEY: TTree   Trigger;1          PAMELA Level2 Trigger data
KEY: TTree   Anticounter;1      PAMELA Level2 Anticounter data
KEY: TTree   S4;1               PAMELA Level2 S4 data
KEY: TTree   NeutronD;1         PAMELA Level2 NeutronD data
KEY: TTree   OrbitalInfo;1      PAMELA OrbitalInfo data
KEY: TTree   Run;1              PAMELA Level2 data from the GL_RUN table
KEY: TTree   Calorimeter;1      PAMELA Level2 calorimeter data

```

Figure 5.3: Level2 file structure: output of DarthVader Software.

5.3 Quick Look Software Development

This section is dedicated to the explanation of the Quick Look Software that I personally developed during ground test of Roma and Samara and during the first period of PAMELA data-taking.

In particular, as shown in detail below, I worked to keep under control housekeeping and temperature informations during the acquisition and to monitor Packet and Event Rates with time. Moreover I developed the QL Software for S4 and Neutron Detector, the two detectors placed justly under the calorimeter. Quick Look Software takes the necessary information from the Level0 files, as shown in figure 5.1, and it is daily used to monitor PAMELA status.

5.3.1 Check of Temperatures

For monitoring PAMELA temperatures, the script takes informations from Tmtc Packet of Level0 data. In figure 5.4 the output is shown. This graph shows the values of 16 temperatures in degrees centigrade, read out by Be-tatherm sensors located in different PAMELA subsystems, as a function of the On Board Time (OBT) in ms. The temperature values are drawn in blue color. The red line shows the maximum temperature value allowed for each sensor (usually equal to 45° C, except only for sensors placed on CPU for which it is equal to 50° C); if one of the sensors overcomes this value (in the average of 30 consecutive reading), the CPU software switches off PAMELA automatically. Only when this exceeding temperature drops below 40° C, the CPU switches on PAMELA again. In nominal/standard configuration all temperatures, including fluctuation, must be several degrees below 40° C.

5.3.2 Check of Housekeeping (CC and voltages)

As the previous one, also this script takes informations from Tmtc Packet of Level0 data. For each Level0 data file it creates two output graphs, shown below in figure 5.5 and 5.6.

The first graph (in figure 5.5) shows, as a function of the On-Board-Time (OBT) in ms, the status (1 or 0) of the bilevel monitor signals of PAMELA CPU for the following systems:

- status line of the input power to the Intermediate Power Modules (hot and cold) IPM 1 and 2 input;
- status line of the input power to the Intermediate Power Modules (hot and cold) IPM 3 and 4 input;
- status line of the input power to the Intermediate Power Modules (hot and cold) IPM 5 and 6 input;

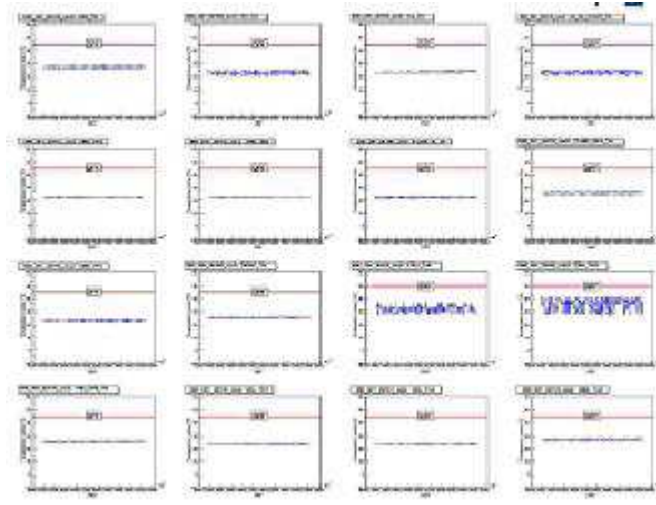


Figure 5.4: QL for Temperatures check. The values of 16 temperatures in degrees centigrade, read out by Betatherm sensors located in different PAMELA subsystems, as a function of the On Board Time (OBT) in ms.

- status line of Intermediate Housekeeping board (hot and cold):
KHB_HOT and KHB_COLD;
- status line of Intermediate Acquisition board (hot and cold):
IDAQ_HOT and IDAQ_COLD;
- status line of TOF High Voltage control board (hot and cold):
TOFHV_HOT and TOFHV_COLD;
- status line of Power Supply board (hot and cold):
PSB (a unique line, ON when one at least of the two boards is on);
- status line of VRL adapter (hot and cold):
VRL_HOT and VRL_COLD.

In figure a typical output graph is reported; in the default post-launch configuration the hot devices can be turned on (0, ON, highlighted in green) while the cold ones are normally kept off (1, OFF, highlighted in gray); for the TOFHV boards the color convention is different, since both on and off status mean that the bilevel line is 1 (ON-OFF-LATCHUP, highlighted in cyan). However the correct configuration at a specific OBT depends on the operations performed by the CPU which controls the state of each device (except for TOFHV and PSB lines whose status should always be the same as the first IPM pair: for example if IPM 1 is ON and IPM 2 is OFF, then TOFHV_HOT is ON, TOFHV_COLD is OFF and PSB is ON). It can

happen for example that all devices go in the OFF status when the CPU turns off the PAMELA apparatus.

The most significant alarm conditions are automatically highlighted in red (ALARM): for example, when both a hot device and its cold counterpart are simultaneously on. Other alarm conditions can be determined only by checking the actual configuration, shown by these bilevel monitors, with the nominal configuration, looking at the CPU parameter `POWER_MODE` in the VarDump Packet informations; for example, the CPU could be programmed by Macro Commands to turn on the cold IDAQ board, while keeping off the hot one. In the nominal/standard configuration, one and only one IPM INPUT or board for each hot/cold pair must be ON, except for VRL that are off for most, even all, of time. No ALARM conditions (red lines) have to be seen.

The second graph (in figure 5.6) shows the value of the voltage (in Volts) measured at the output of the IPMs, after having been attenuated by "voltage dividers". The voltage value is shown in blue color. The two upper red lines define the interval corresponding to the on status of the IPM. The third, lower red line sets the threshold for the off status of the IPM. In nominal/standard configuration, for each pair (1/2, 3/4 and 5/6) one and only one voltage MUST be ON and the other one OFF. In figure a typical output graph is reported. To check the correct functioning of PAMELA IPMs, one has to compare this plot with the status lines of the input power of the 6 IPMs in figure 5.5. A non-standard configuration appears if both IPM OUTPUT of a hot/cold pair are either ON or OFF, or their voltage is not within the intervals defining the ON and OFF status.

5.3.3 Check of Packet Type

The check of Packet Type acquired by the apparatus happens using a script that scans all packets present in the downlinked file, catches the header and extracts the Packet ID. To control informations from this QL script it is important for monitoring the life of the instrument: if all detectors were calibrated, if there are alarms and from which detector, if the acquisition runs begin and end correctly and many others things as it is possible to see from the three output graphs in figures 5.7, 5.8 and 5.9.

Graph in figure 5.7 shows the packet ID variable as a function of OBT (in ms), for acquired packets with packet ID from 0 to 40. In this range we find the set of calibrations (reverse triangles) at the beginning of the acquisition session; the beginning and end of each single run (blue squares); the physics event packet (red line composed by a sequence of single red squares) with also the Physics End Run packet (red square with low value=7); the header and trailer initialization (normal gray triangles).

Figure 5.8 shows the packet ID variable as a function of OBT (in ms),

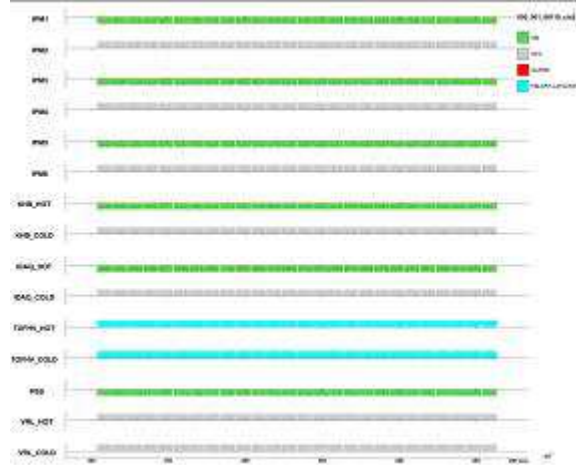


Figure 5.5: QL for Contact Closure check. The status (1 or 0) of the bilevel monitor signals of PAMELA CPU as a function of the On-Board-Time (OBT) in ms.

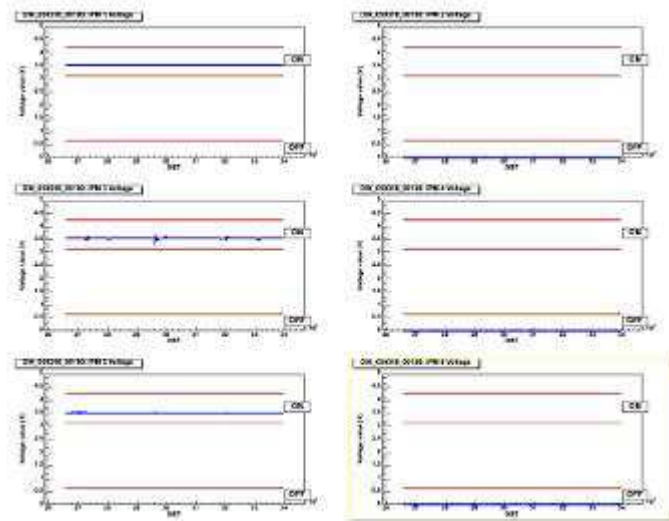


Figure 5.6: QL for votages check. The value of the voltage (in Volts) measured at the output of the IPMs, after having been attenuated by "voltage dividers", as a function of the On-Board-Time (OBT) in ms.

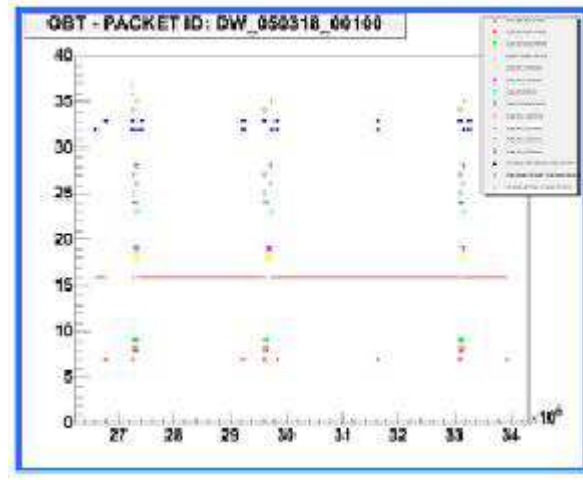


Figure 5.7: QL for Packet Type check. The packet ID variable as a function of OBT (in ms), for acquired packets with packet ID from 0 to 40.

for acquired packets with packet ID from 40 to 90 instead. In this range we find the block of macrocommand and tmtc records, log packets (containing log infos from PAMELA PSCU), vardump, arrdump and tabdump packets (containing infos about values of variables, arrays and tables relative to on-board PAMELA Software); they are highlighted as stars of various colors, filled or not filled.

At last the graph in figure 5.9 shows the packet ID variable as a function of OBT (in ms), for acquired packets with packet ID from 110 to 140. In this range we find the block of alarms (squares of various colors for different detectors, filled or not), and the detectors initialization packets (triangles).

5.3.4 Check of Physics Packet and Event Rate

The monitoring of the rate of Physics Packet and in general of the events collected by the apparatus along its orbit gives a quick look to what is happening. The typical expected behaviour for the rate along the orbit is shown in the following figures.

Physics packet rate per minute, collected by the apparatus during the orbits 1095 and 1096, as a function of the OBT is shown in figure 5.10. Passages at the North and South Pole are evident, like also the crossing of the South Atlantic Anomaly (SAA). At the end of each orbit, when the rate is lower, PAMELA is calibrated and this is the reason because the rate goes near zero in that orbital points.

Similar behaviour is shown in figure 5.11 for the total countings (over one minute) collected by S1 (green line), S2 (blue line) and S3 (red line) TOF plane scintillators. The typical orbital behaviour is more evident for S1

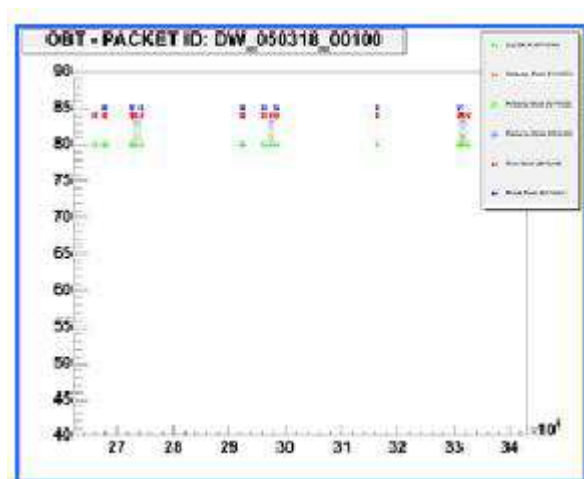


Figure 5.8: QL for Packet Type check. The packet ID variable as a function of OBT (in ms), for acquired packets with packet ID from 40 to 90.

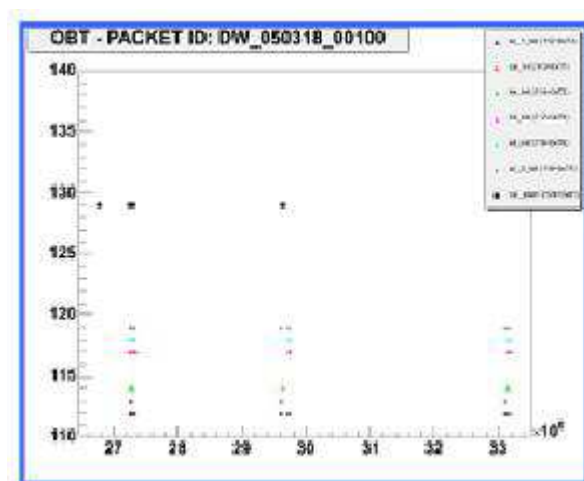


Figure 5.9: QL for Packet Type check. The packet ID variable as a function of OBT (in ms), for acquired packets with packet ID from 110 to 140.

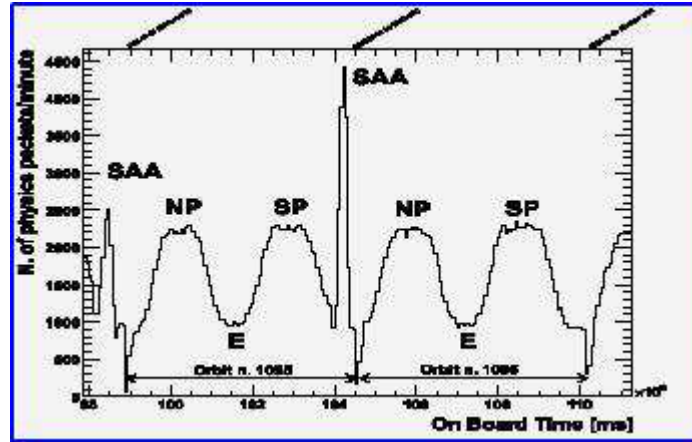


Figure 5.10: QL for orbital check. The evolution of the trigger rate (countings/minute) for two consecutive PAMELA orbits. Each orbit has a period of ~ 94 minutes. A sinusoidal structure is evident as PAMELA completes one orbit. The narrow spikes correspond to passages through the South Atlantic Anomaly. The trigger rate drops to zero as PAMELA crosses the equator on an ascending node due to the execution of a calibration procedure.

because it is placed above the other detectors. It is possible to see, besides the crossing of SAA, also the crossing of the outer radiation belt (the pick at 447 ms). The outer radiation belt is visible only after the passage at the South Pole, and not at North Pole, because of the different height of the PAMELA orbit in such points due to elliptical orbit. It is evident in figure 5.12 also where the event rate collected by a PMT (in this case S111A) of the TOF system is shown as a function of the position of the satellite (latitude versus longitude): red regions correspond to high rate regions (SAA and outer radiation belt), green region to low rate region (at the equator).

5.3.5 Check of S4 Behaviour

S4 Detector QL Software permits to monitor S4 behaviour with time. It produces three different output graphs to check ADC values collected and the event rate.

Figure 5.13 shows the histograms of ADC collected value for all triggered events (first pad) and for S4 triggered events only (second pad). S4_threshold and trigger configurations used in the relative acquisition run are shown. It is possible to notice that used trigger configurations are the standard default ones.

Time evolution of S4 ADC collected values for all triggered events (first pad) and for S4 only triggered events (second pad) is shown in figure 5.14. In these graphs each point represents the mean of ADC values collected during

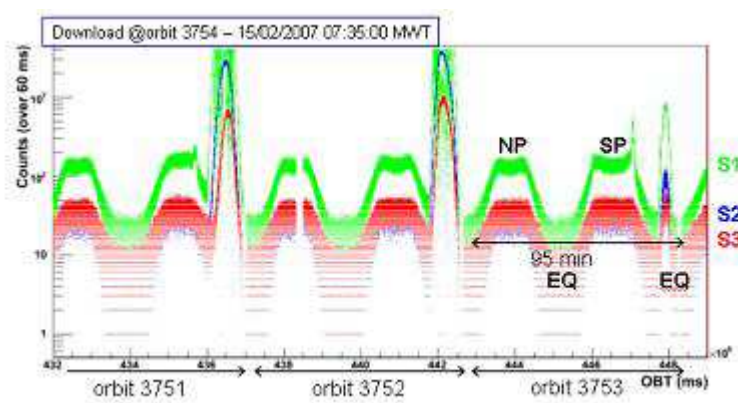


Figure 5.11: QL for orbital check. The evolution of the total countings collected by S1 (green line), S2 (blue line) and S3 (red line) TOF plane scintillators for two consecutive PAMELA orbits. The narrow spikes correspond to passages through the South Atlantic Anomaly. Inner and outer radiation belts are visible.

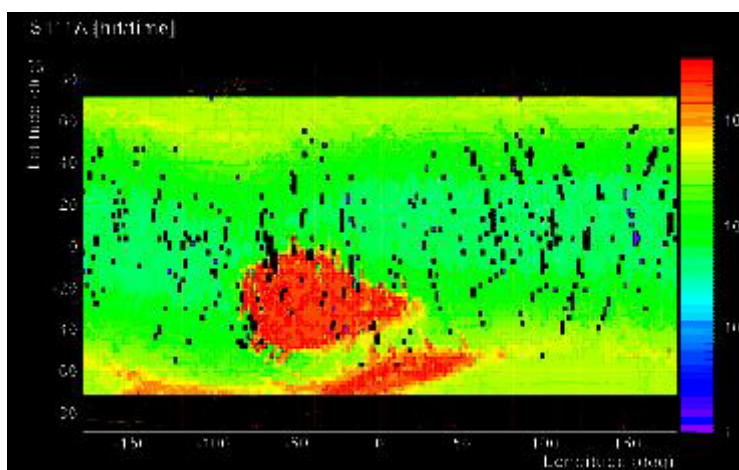


Figure 5.12: QL for orbital check. Event rate collected by a PMT (in this case S111A) of the TOF system as a function of the position of the satellite (latitude versus longitude): red regions correspond to high rate regions (SAA and outer radiation belt), green region to low rate region (at the equator). Inner and outer radiation belts are good visible.

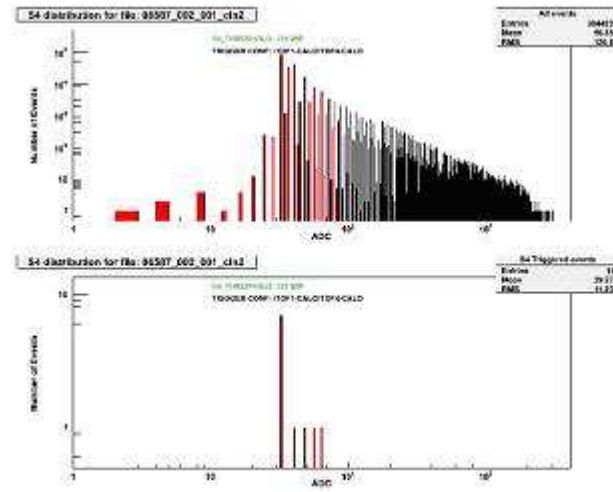


Figure 5.13: QL for S4 check. Histograms of ADC collected value for all triggered events (first pad) and for S4 triggered events only (second pad). S4_threshold and trigger configurations used in the relative acquisition run are shown.

the previous 1 minute temporal interval (default value). This duration is settable by the user. In the figure is evident a typical orbital behaviour, but it is different from the relative one to the rate: in this case the picks correspond to the equator crossing (where particles of higher energy are detected).

Figure 5.15 shows S4 rate (in Hz) versus OBT (On Board Time, in ms). This information is taken from Trigger Packet. The bottom graph shows a smoothed behaviour of S4 rate where each point represents simply the mean value over 100 Trigger events. Orbital behaviour is evident.

5.3.6 Check of ND Behaviour

As for S4, ND Detectors QL Software permits a continuous monitoring of S4 behaviour. It produces same different graphs to take under control ND countings for what concern triggered neutrons and background neutrons, i.e. the neutrons collected during the time interval between two following trigger events.

Figure 5.16 shows the histograms of distributions of neutrons number as recorded by the Bottom (upper pad) and the Top (lower pad) Background channels, respectively. The time interval for collection of the Background channels recording for these histograms is set to the default value of 1000 ms (but the user can change it setting the input parameter). It means that each event of the histograms corresponds to the total number of neutrons collected during this temporal interval.

Graphs in figure 5.17 show time evolution (as a function of OBT) of the

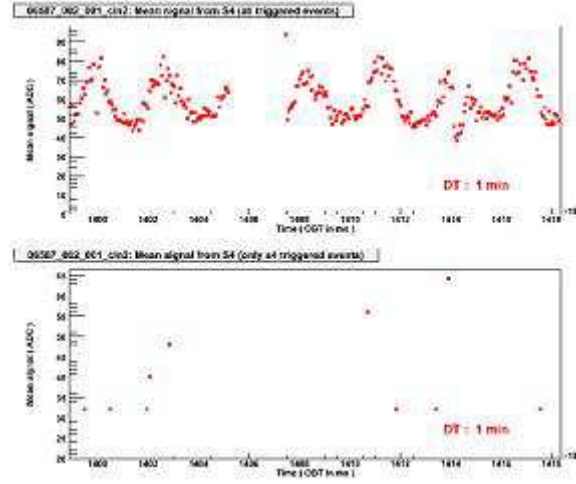


Figure 5.14: QL for S4 check. Time evolution of S4 ADC collected values for all triggered events (first pad) and for S4 only triggered events (second pad). In these graphs each point represents the mean of ADC values collected during the previous temporal interval of duration 1 minute (default value).

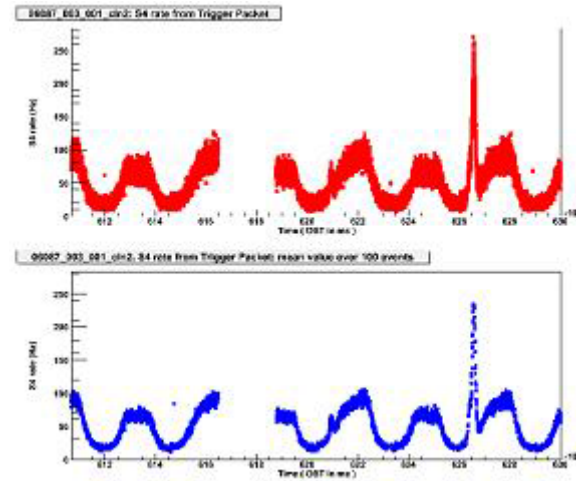


Figure 5.15: QL for S4 check. S4 rate (in Hz) versus OBT (On Board Time, in ms). This information is taken from Trigger Packet. The bottom graph shows a smoothed behaviour of S4 rate where each point represents simply the mean value over 100 Trigger events. Orbital behaviour is evident.

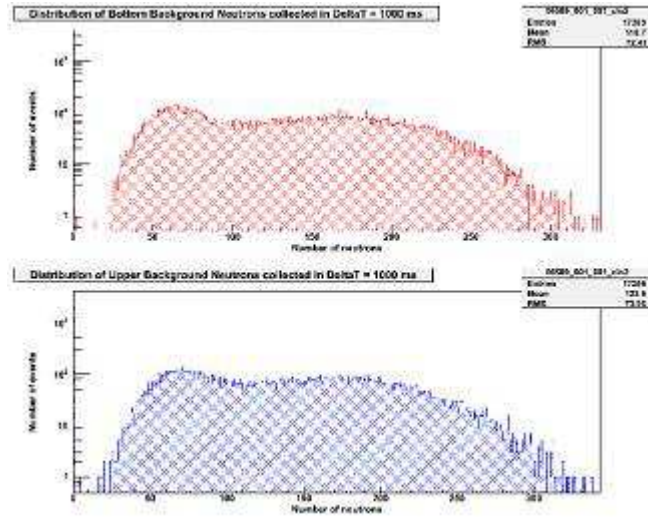


Figure 5.16: QL for ND check. Histograms of distributions of neutrons number as recorded by the Bottom (upper pad) and the Top (lower pad) Background channels, respectively.

counting rates collected during a time interval DT for the Top (green points) and the Bottom (red points) Background channels (upper pad) and for the ratio of Top/Bottom Background channels (lower pad). Points in the pads are placed at the end of each temporal interval. The duration of a temporal interval DT is set to the default value of 1 minute (but the user can change its value setting an input parameter of the script). The corridor defined by horizontal lines in the lower pad corresponds to the expected value of the Top/Bottom channels ratio; this value is expected to be near to one in nominal condition obviously (situation is not normal if the count rates in the Top and Bottom Background channels are strongly different so that their ratio value is beyond the corridor).

The behaviour for the background neutrons rate shown in figure 5.17 is the typical one expected in nominal conditions along the orbits, as shown in figure 5.18 also. In figure 5.18 the rate of background neutrons is put in correspondence with the PAMELA position along the orbit. The SAA crossing is evident.

In figure 5.19, it is shown time evolution (as a function of OBT) for trigger events: each point represents the counting rate of triggered neutrons collected during a temporal interval DT (the point is placed at the end of such interval). As for background neutrons, the duration of a temporal interval is set to the default value of 1 minute (but the user can change its value setting an input parameter of the script).

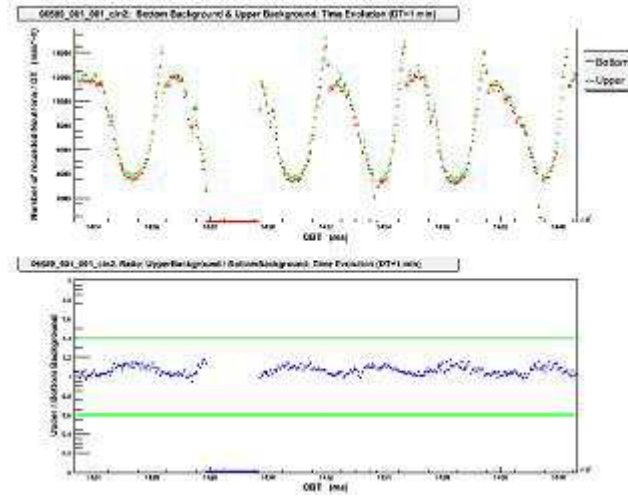


Figure 5.17: QL for ND check. Time evolution (as a function of OBT) of the counting rates collected during a time interval DT for the Top (green points) and the Bottom (red points) Background channels (upper pad) and for the ratio of Top/Bottom Background channels (lower pad). The corridor defined by horizontal lines in the lower pad corresponds to the expected values of the Top/Bottom channels ratio; this value is expected to be near to one in nominal condition obviously.

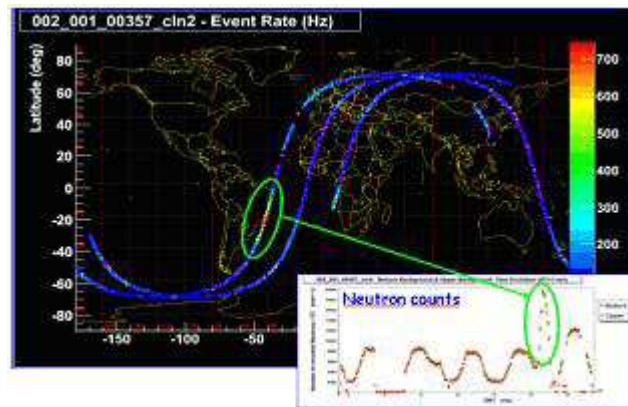


Figure 5.18: QL for ND check. The behaviour for the background neutrons rate shown in figure 5.17 is the typical one expected in nominal conditions along the orbits, as shown here. In this figure the rate of background neutrons is put in correspondence with the PAMELA position along the orbit. The SAA crossing is evident.

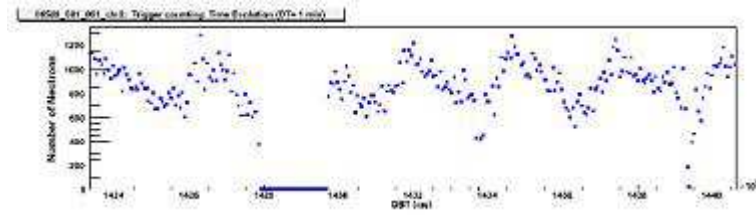


Figure 5.19: QL for ND check. Time evolution (as a function of OBT) for trigger events: each point represents the counting rate of triggered neutrons collected during a temporal interval DT (default value 1 minute).

Chapter 6

Characterization of TOF detector in Flight configuration: Attenuation Length and Trigger Efficiency

The present chapter contains the description of a study that I have done on the characteristics of the signals produced by the 6 scintillator layers of the TOF system of PAMELA, in particular for the determination of the attenuation length of the scintillation light and of the trigger efficiencies for the various strips of each layer and for the different layers.

This analysis is based on cosmic rays collected by the apparatus during its first seven months of flight data taking. I considered helium to estimate attenuation lengths for each strip of scintillator and proton and helium separately to estimate trigger efficiency for each plane and for the complete trigger configuration.

The first three sections of the present chapter are dedicated to the measurement of the characteristic attenuation lengths of scintillation light for the various strips of the TOF system. In section 6.1 the propagation mechanisms of the scintillation light along a strip, from the point of production by an ionizing particle to the collection at the interface with the light guide, are briefly discussed; section 6.2 contains the description of the method that I have developed for the analysis of the data collected by the PAMELA apparatus, and in particular for the determination of the coordinate of incidence of the ionizing particle along the strip, using the information provided by the tracking system; in section 6.3 the results of the analysis are presented.

The rest of the chapter describes the measurement of the trigger efficiency for the various strips and layers of the TOF system. Section 6.4 contains a general discussion on the adopted method; in section 6.5 the measured trigger efficiencies are reported and commented. Finally the overall efficiency of the TOF system is calculated in section 6.6.

6.1 Attenuation lengths of TOF scintillators

The structure and basic operation of the 3 double planes of scintillators strips, constituting the TOF system of PAMELA, has been introduced in section 2.2.1. Here the mechanisms of light propagation along a scintillator strip and of collection on the light guides positioned at both ends of the strip are discussed in further detail.

When an ionizing particle crosses one of the 24 strips of the TOF system, the fluorescence light generated in the interaction with the molecules of the material (BC-404 [86]) is guided toward the two read-out PMTs, positioned at the opposite ends, mainly by means of total reflections on the lateral walls of the strip and of the plexiglas light guide connecting it to the input window of the PMT; the PMT converts the light incident on the photo-cathode into an electric current pulse at its anode. This pulse, on one hand, enters the fast discriminator of the time section of the Front-End (FE) electronics, starting the timing measurement and producing the event signal for the generation of the trigger; on the other hand, it reaches the charge section where it is integrated by a charge preamplifier and finally converted into a 12-bit digital value: the digital charge value, for each of the 48 electronic channels (PMT) of the TOF system, depends linearly on the intensity of light collected on the photo-cathode of the corresponding PMT.

During the propagation of the light along the strip a fraction of the initial intensity is inevitably lost mainly because of partial loss at the walls of the strip and because of self-absorption in the bulk of the scintillator; this in general introduces a dependence of the height of the anode pulse on the coordinate of production of the light by the ionizing particle along the strip.

A simplified two-dimensional model of the mechanism of light propagation is illustrated in figure 6.1 and explained in what follows.

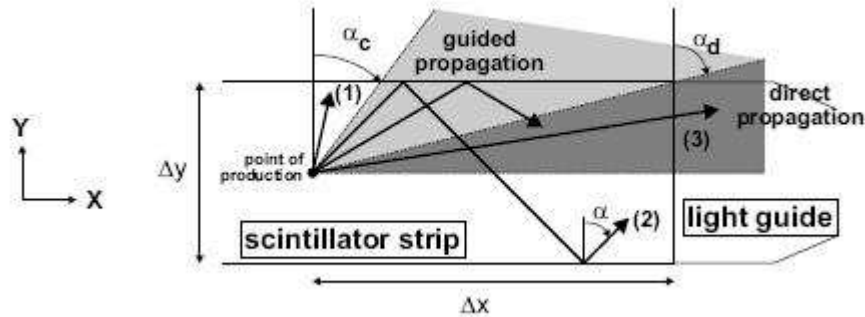


Figure 6.1: Two-dimensional drawing illustrating the mechanisms of light collection on the light guide positioned at one end of a strip of the TOF system.

Consider a strip of the TOF detectors (of thickness 7 or 5 mm, depending on the TOF plane), directed along the X axis in the PAMELA reference system (defined in section 2.2), which is crossed by a charged particle, moving along the Z axis, at its centre and at a distance Δx from the strip end.

The particle releases part of its energy within the scintillators with the production of isotropically distributed fluorescence light. Consider for simplicity the light emitted in the XY plane, with angle of emission α (between 0 and 90°) respect to the Y axis, in the hypothesis of perfectly polished lateral walls and absence of diffusion within the bulk of the scintillator material.

If the angle of emission α is small (case (1) in figure 6.1), the light, propagating along a straight line, reaches the lateral wall of the strip where it is partly reflected back and partly transmitted across the boundary of the scintillating material; the fraction of light that is reflected back in the scintillator then continues propagating in straight line inside the strip and maintaining the same angle of incidence with respect to the lateral wall, until another partial reflection happens at the opposite wall and so on. As mentioned in section 2.2.1, each scintillator strip has been enveloped in a thin aluminized mylar foil; with this system a fraction of the light escaping from the walls of the strip is reflected back by the Al film. Anyway it is expected that after several reflections most of this light will be lost out of the scintillator and will not contribute significantly to the intensity entering the light guide at the end of the strip.

For angles of emission α greater than α_c , critical angle¹ characteristic of the external boundary of the scintillator (case (2) in figure), the light incident on the wall is subjected to total internal reflection and hence propagates along the strip with practically no loss of intensity; this fraction of the light is usually indicated as guided light. Finally for $\alpha > \alpha_d$, with α_d given by

$$\tan \alpha_d = \frac{\Delta y}{2 \cdot \Delta x} \quad (6.1)$$

(case (3) in figure), the light can directly enter the guide, without reaching the lateral wall of the strip. This part of the light is indicated as direct light.

The guided light component constitutes the main contribution to the overall intensity collected on the guide for points of incidence of the ionizing particle along most of the strip length; in fact the direct light contribution is practically important only when the light is produced in the vicinity of the strip end. In fact, given the isotropic angular distribution of the scintillation light, the fraction of direct light is proportional to the solid angle under

¹The critical angle α_c for total internal reflection of light propagating in a material characterized by a refraction index n_1 and reaching the interface with another material of index $n_2 < n_1$ is given by $\sin \alpha_c = n_2/n_1$. In the present case the two materials are respectively the scintillator BC-404 ($n_{BC-404} = 1.58$) and the thin layer of N2 (or air during the tests on earth) which is expected to be present between the scintillator and its envelope of mylar: $\alpha_c = \arcsin(n_{air}/n_{BC-404}) \approx 39^\circ$.

which the end wall is seen from the point of production, and hence decreases as the square of the distance Δx .

The guided light travelling from the point of production toward the end of the strip is attenuated because of the self-absorption inside the scintillator volume (bulk attenuation) and, in practical applications, also because of a non-negligible partial loss at the lateral walls (surface attenuation). This surface attenuation is due to the fact that in a real strip the walls are not perfectly polished², but instead microscopic defects and impurities are in general present; as a consequence the critical angle can locally be greater than α_c thus causing a partial reflection even in the case that $\alpha > \alpha_c$.

The derivation of the effective dependence of the light intensity collected at the end of the strip, I_f , on the intensity I_i of the initially produced light at a distance Δx , taking into account the combined effect of the bulk and surface attenuations, the spatial geometry of the strip and the optical properties of the scintillator walls and of the external Al reflecting layer, is quite complicated and can be done with the help of purposely written computer programs. Anyway for practical applications a good phenomenological approximation of this dependence is given by the exponential law:

$$I_f = I_i \cdot \exp\left(\frac{-\Delta x}{\lambda_{att}}\right) \quad (6.2)$$

where λ_{att} is the effective attenuation length of scintillation light in the strip. The study described in the next sections uses this simple phenomenological model for the measurement of the effective attenuation length λ_{att} for the various strips of the TOF system, comparing it to the known bulk attenuation length characteristic of the BC-404 (140 cm [112]).

6.2 Method for attenuation lengths measurement

The method described here, for the measurement of the effective attenuation length λ_{att} of the TOF scintillator strips, uses the cosmic-ray events acquired during the first months of flight of the apparatus; it is based on the combined analysis of the charge signals collected by the TOF electronics for each channel (PMT) of the system and of the spatial information given by the tracking system on the position along the scintillator strip where the incident particle has initially produced the scintillation light.

The data produced by the TOF and tracking system can be processed by custom designed event reconstruction software programs, developed within the PAMELA collaboration for the automatic extraction of the significant physical information from the bulk of data produced by the apparatus at

²The surfaces of the scintillator are "optically polished" when the dimensions of the irregularities left by the machining process are much smaller than the wavelength of the incident light (in the present case ≈ 400 nm).

each event; in particular for the tracking system this means the automatic determination of the trajectory of the incident particle on the basis of the pattern of signals on the microstrips of the 6 detector planes.

The method employed to determine λ_{att} considers helium particles at MIP energy within the sample of collected cosmic-ray events during the first seven months of data-taking. These helium particles can be considered MIP for rigidities greater than 4 GV/c, as can be derived from the dependence of the linear energy transfer (LET) of an ionizing particle on its velocity, given by the Bethe-Bloch formula³.

A MIP traversing a strip of the TOF system is characterized by a distribution of the LET that is well represented by a Landau function, which describes the energy lost by relativistic particles across thin layers of material [97]. On the other hand, the intensity of the scintillation light produced by an ionizing particle in a thin layer of plastic scintillator is given by the semi-empirical Birks law [97], stating that for small LET the light intensity is proportional to the linear energy transfer.

As a conclusion, applying a selection cut to the collected sample of cosmic rays to select helium particles, the distribution of the intensity of scintillation light is expected to be described by a Landau function. By dividing each strip, along the longitudinal axis, into suitably small sections (pads), such that it is possible to neglect the effect of the light attenuation over the pad length, the distribution of the charge signal for a TOF channel (PMT), for MIP particles crossing the strip in correspondence of a specific pad, is expected not to significantly differ from the Landau distribution, characterized by a most probable (peak) value of the charge signal Q_{mp} . Finally λ_{att} can be determined by fitting an exponential function to the observed dependence of Q_{mp} on the central coordinate of the pad. Further details of the method will be given in the next section.

In the selection of the data sample to analyze we must also take into account that the proportionality factor between the intensity of light, entering the input window of the PMT, and the 12-bit digital output of the corresponding charge section, can be varied by adjusting the gain of the PMT⁴. Clearly this makes it necessary to separately consider, for each PMT, data samples collected with different gain settings, because the associated digi-

³The ionizing power of a particle species in a thin layer of material is commonly represented by the linear energy transfer (LET), defined as the ratio between the energy released by ionization and the length of the path inside the traversed material. Usually this quantity is normalized to the density of the material and typically measured in MeV · cm²/mg. The LET of a charged particle decreases for higher velocities until it reaches a minimum ionization plateau [97].

⁴The PAMELA apparatus is equipped with the electronics for the adjustment of the gain for the 48 PMT of the TOF system; this is achieved by changing the high voltage applied between the anode and photo-cathode of the PMT, and exploiting the exponential increase of the gain with the high voltage. For the specific characteristics of the R5900 PMT employed in the TOF system see [87].

tally converted Landau distributions for a given pad would be significantly shifted from each other.

The separate adjustment of the PMT gains is of fundamental importance because, together with the variation of the discrimination thresholds for the time sections of the TOF front-end electronics, it allows to set the system in an optimized configuration taking into account the unavoidable differences, among the various electronics channels in the proportionality factor between the intensity of light, entering the PMT photo-cathode after surviving the attenuation in the scintillator, and the charge producing the corresponding anode signal. This proportionality is affected by many parameters, such as the effective attenuation length of the scintillator strip, the transmission efficiencies of the optical couplings strip/light guide and guide/photo-cathode, and the characteristics of the PMT, in particular the quantum efficiency and the (adjustable) gain of the electron multiplier structure. These parameters generally show important differences from channel to channel and also variations with time.

The present analysis is focused on the statistically most significant sample, collected with the "flight" high-voltage configuration.

6.2.1 Determination of the position on the TOF layers

In the present method the determination of the coordinates of the crossing points of a particle in the 6 TOF layers, necessary for the identification of the traversed strips and the association of the corresponding charge signal to a specific pad, is done on the basis of the informations given by Level2 data.

Level2 data provide informations on the trajectory and on the rigidity of the particle in the Pamela reference system. From this information the crossing points of the particle for the 6 layers of the TOF system have been reconstructed.

A complication in the use of the information given by the tracking program comes from the fact that the crossing point of the particle in a silicon plane of the tracking system is not uniquely identified along the Y axis, since each read-out channel of the Y view of a detector is associated with two microstrips separated by 7 cm (see section 2.2.3), thus yielding two possible Y coordinates per plane for the same event. The tracking program, only on the basis of the pattern of microstrips that have reported a significant signal for each of the 6 Si detector planes, is able to identify the physical trajectory if this ambiguity can be clearly solved, like in the example at left in figure 6.2; otherwise the program cannot do better than identifying two possible and mutually excluding trajectories, separated by 7 cm, like in the example at right side in figure 6.2.

An efficient method to solve this ambiguity is to use the spatial information given by the TOF system itself, with the pattern of scintillator strips

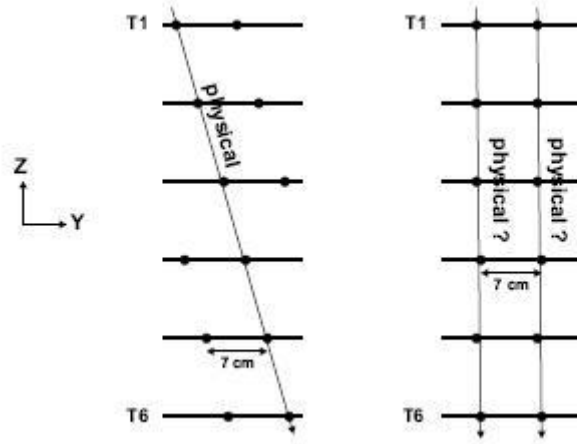


Figure 6.2: At left: the identification of the physical trajectory with only the information from the tracking system is relatively simple for inclined incidence; at right: the identification is much more difficult for vertical incidence.

that have provided an event signal for the 3 layers (S12, S21 and S32) which are segmented along the Y axis (with strips directed along the X axis, see figure 6.3 and table 6.1) and calorimeter information also. The employment of this method in the data analysis is described in the next section.

plane	layer	number of strip	Z (cm)	thickness (mm)	strip dim. X (cm)	strip dim. Y (cm)	strip cross-section (cm ²)
S1	S11	8	+53.74	7	5.1	33.0	3.57
	S12	6	+53.04	7	40.8	5.5	3.85
S2	S21	2	+23.94	5	18.0	7.5	3.75
	S22	2	+23.44	5	9.0	15.0	4.50
S3	S31	3	-23.49	7	6.0	15.0	4.20
	S32	3	-24.34	7	18.0	5.0	3.50

Table 6.1: Table resuming the main geometrical characteristics of the TOF scintillator system; X, Y, Z axes are those of the PAMELA reference system.

6.3 Data analysis for attenuation lengths

The initial sample used in this analysis consists of helium events, collected with the apparatus during its first months of flight (July 2006 - January 2007), for which the tracking program has reported either a unique physical trajectory or two mutually excluding trajectories (for the unsolved ambiguity

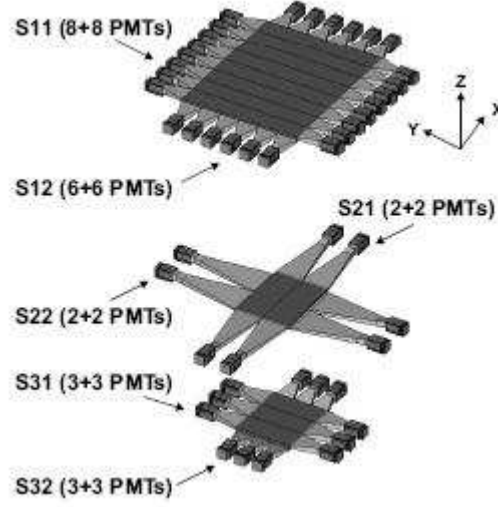


Figure 6.3: Layout of the TOF scintillator system.

in Y coordinate). The trigger pattern analyzed is the standard used outside the radiation belts (S11 OR S12) AND (S21 OR S22) AND (S31 OR S32). The applied cuts for data selection have been minimized in order to keep the fraction of rejected events low enough to be able to populate a sufficient number of pads for each scintillator strip. The number of longitudinal pads for each strip is fixed to 40 but only the pads with a "good" Landau fit participate to the determination of the attenuation length value. The choice of the pad length has been done by taking into account the request of a sufficiently high number of events per pad to correctly reconstruct the expected Landau distribution, at the same time avoiding the distortion of this distribution because of the light attenuation, in particular for the strips characterized by the shortest λ_{att} .

As said, during the events selection, one important cut has been applied in order to take into analysis only helium events with a single reconstructed track from tracker or with two mutually excluding trajectories. To do this I used some methods of the Level2 software developed by the PAMELA collaboration.

A further cut on the rigidity of the incident particle measured by the tracking system assures that the considered particles are MIP, as discussed in the previous section. With these cuts about 10% of the events are rejected. For each of the surviving events and for each TOF layer, the strip crossed by the incident particle has been determined on the basis of the tracking information and the corresponding charge signals for the two PMT has been associated with a specific pad of that strip.

The distribution, over the considered event sample, of the 12-bit charge

signals Q for a given PMT and pad has been fitted with the Landau function:

$$f(Q) = \frac{A}{\sqrt{2\pi\xi}} \exp^{-\frac{1}{2}\lambda + \exp^{-\lambda}} \quad \text{with} \quad \lambda = \frac{Q - Q_{mp}}{\xi} \quad (6.3)$$

where Q_{mp} represents the most probable value of Q (peak value).

Examples of two typical distributions of charge signals Q (expressed in least significant bits, LSB, of the 12-bit value) for a fixed strip and PMT (layer S21, strip 1, PMT 2) and two different pads (pad 3 and 6, about 7 cm apart) are shown in figure 6.4 and 6.5. It can be seen that the number of events contributing to the distribution is about 800 and the $\chi^2/\text{d.o.f.}$ of the fit is 1.5 - 1.7 meaning that the Landau function describes sufficiently well the actual distribution of Q . The difference between the values of Q_{mp} (81 and 94 LSB respectively) means that the intensity of light collected in the considered PMT is smaller for the farther pad (pad 3).

To finally determine the attenuation length, the distribution of the most probable values Q_{mp} along the pads, for a given strip and PMT, has been fitted with an exponential function. Further selections have been necessary on the set of considered pads for each strip and PMT.

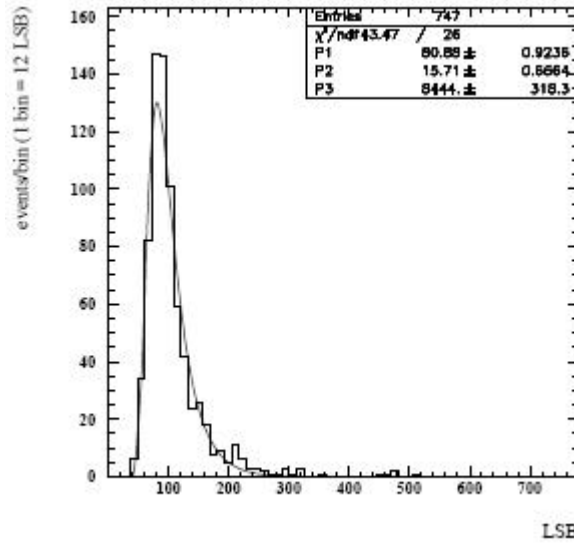


Figure 6.4: Distribution of the charge signal (in LSB) for pad 3 of strip 1 of TOF layer S21, PMT 2; superimposed is the Landau fit. P1, P2 and P3 respectively represent the parameters Q_{mp} , ξ and A of the formula 6.3.

Since this study aims at measuring the attenuation length given by the combined effect of bulk and surface attenuation on the guided light component, the nearest pad to each PMT has been excluded from the fit; in fact for this pad the contribution of direct light, entering the guide without any

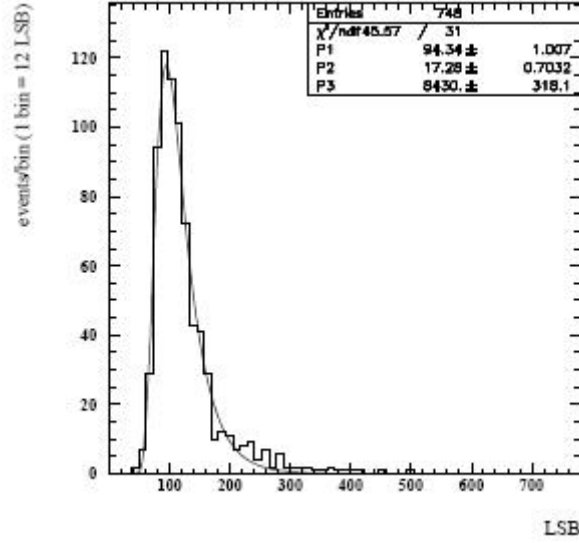


Figure 6.5: Distribution of the charge signal (in LSB) for pad 6 of strip 1 of TOF layer S21, PMT 2; superimposed is the Landau fit. P1, P2 and P3 respectively represent the parameters Q_{mp} , ξ and A of the formula 6.3.

reflection on the lateral walls of the strip, is expected to be of the same order of the intensity of guided light. For the other pads the intensity of direct light is expected to be much smaller, given its dependence on the inverse square of the distance between the point of production and the end wall of the strip.

The number of events per pad tends to decrease along the strip going from the center toward both ends; this clearly is an effect of the shape of the acceptance window of PAMELA, that excludes a greater domain of directions of incidence near its boundaries.

For this reason the pads have been considered in the fit only if the accumulated statistics was significant and the Landau distribution sufficiently well fitted: pads with the sigma of the fitted Landau greater than 200 have been rejected, thus excluding the most external pads on both ends of each strip. For the same reason the most external strips of layer S11 (strip 1 and 8) have been considered in this analysis but the result for these strips is not realistic really, since only a fraction of their area is within the acceptance window of the apparatus⁵. The results of the exponential fit for some representative strips are shown in figures 6.6, 6.7 and 6.8. Each figure refers to one strip and to one of its PMT; it reports the dependence of the measured Q_{mp} on the pad centre coordinate (above) for the pads considered accor-

⁵The plane S1 has been designed to cover a greater area than the one matching the purely geometric acceptance of the spectrometer, to be able to study also particles of lower energies that significantly bend within the volume of the magnetic cavity of PAMELA.

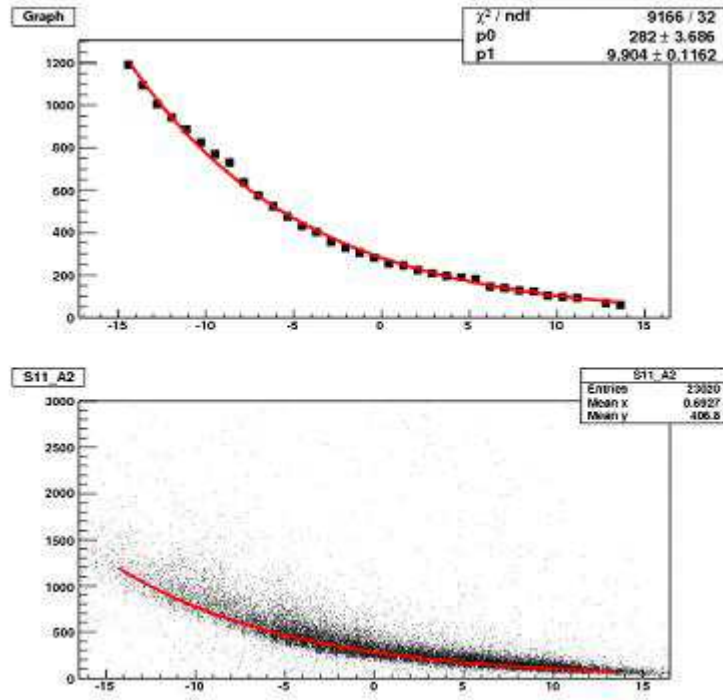


Figure 6.6: Most probable charge signal Q_{mp} for the PMT A of strip 2 of layer S11 (i.e. S11_A2), as a function of the longitudinal coordinate for the selected pad; the corresponding exponential fit is superimposed at real data. The attenuation length is given by $\lambda_{att} = |p_1|$ (cm). The behaviour of its correspondent PMT in the same TOF paddle (i.e. S11_B2) is shown in figure 6.7.

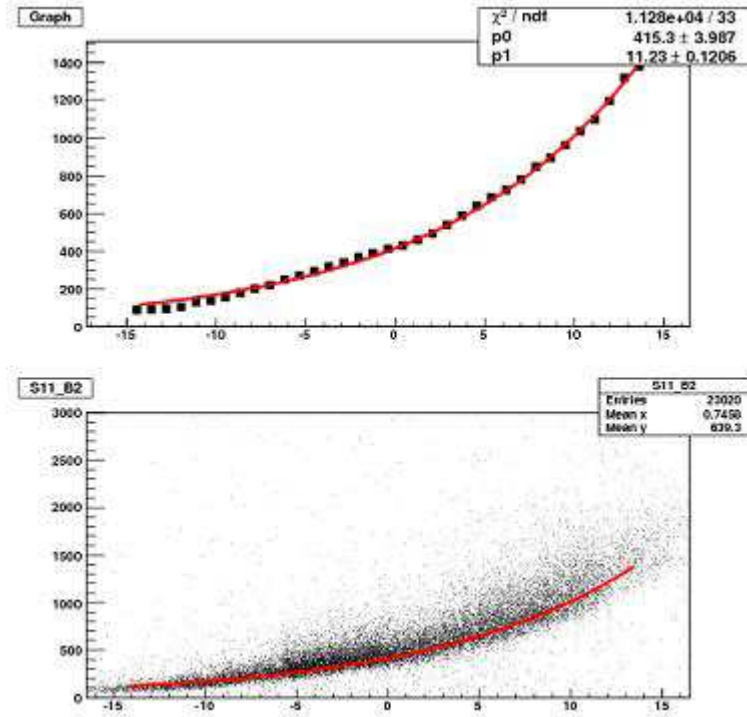


Figure 6.7: Most probable charge signal Q_{mp} for the PMT B of strip 2 of layer S11 (i.e. S11_B2), as a function of the longitudinal coordinate for the selected pad; the corresponding exponential fit is superimposed at real data. The attenuation length is given by $\lambda_{att} = |p_1|$ (cm). The behaviour of its correspondent PMT in the same TOF paddle (i.e. S11_A2) is shown in figure 6.6.

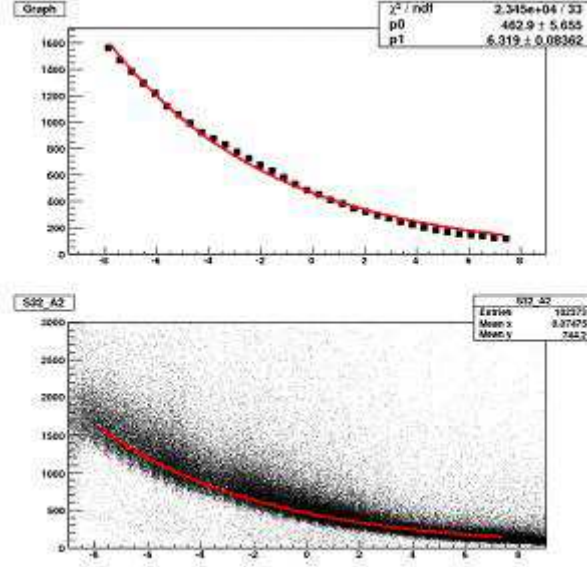


Figure 6.8: Most probable charge signal Q_{mp} for the PMT A of strip 2 of layer S22 (i.e. S22_A2), as a function of the longitudinal coordinate for the selected pad; the corresponding exponential fit is superimposed at real data. The attenuation length is given by $\lambda_{att} = |p_1|$ (cm).

ding to the selection cuts mentioned above. The figure also reports the two exponential functions fitted on the experimental points (below):

$$Q_{mp}(l) = P_1 \cdot \exp\left(\frac{l}{P_2}\right) \quad (6.4)$$

relating Q_{mp} (in LSB) to the longitudinal coordinate l along the strip (x or y in the reference of PAMELA, depending on the orientation of the strip) expressed in cm. The parameters of the fit, characteristic of the channel considered, are p_0 (LSB) and p_1 (cm), whose absolute value is the effective attenuation length ($\lambda_{att} = |p_1|$); note that p_1 is negative for the PMT positioned at the end of the strip corresponding to lower values of the longitudinal coordinate (PMT A), positive for the PMT at the opposite end of the strip (PMT B). Note also the variation in the absolute response of the two PMT of a given strip, due to the intrinsic differences in the characteristics of the optical couplings and signal amplification chain, as already mentioned. Tables 6.2 (S11), 6.3 (S12), 6.4 (S2) and 6.5 (S3) report the behaviour of the values of attenuation lengths for all PMTs during the first seven months of data-taking. The estimation of the values of λ_{att} for each strips of the TOF system are reported in table 6.6. Some comments are necessary at this point.

As expected, the values of λ_{att} obtained with the independent fits for

PMT	λ (cm) (06/07)	λ (cm) (06/08)	λ (cm) (06/09)	λ (cm) (06/10)	λ (cm) (06/11)	λ (cm) (06/12)	λ (cm) (07/01)	λ (cm) mean
S11_A1	12.05 $\pm$ 0.35	11.96 $\pm$ 0.16	11.97 $\pm$ 0.15	11.77 $\pm$ 0.18	12.15 $\pm$ 0.18	11.84 $\pm$ 0.12	11.57 $\pm$ 0.15	11.90 $\pm$ 0.35
S11_B1	9.77 $\pm$ 0.15	9.82 $\pm$ 0.15	9.84 $\pm$ 0.15	9.66 $\pm$ 0.14	9.94 $\pm$ 0.16	9.67 $\pm$ 0.15	9.90 $\pm$ 0.14	9.80 $\pm$ 0.16
S11_A2	10.02 $\pm$ 0.13	10.08 $\pm$ 0.13	9.93 $\pm$ 0.12	9.90 $\pm$ 0.12	10.14 $\pm$ 0.16	9.87 $\pm$ 0.14	9.99 $\pm$ 0.13	9.98 $\pm$ 0.16
S11_B2	11.13 $\pm$ 0.11	11.26 $\pm$ 0.11	11.10 $\pm$ 0.11	11.23 $\pm$ 0.12	11.27 $\pm$ 0.12	10.93 $\pm$ 0.11	10.95 $\pm$ 0.11	11.12 $\pm$ 0.19
S11_A3	14.49 $\pm$ 0.34	14.64 $\pm$ 0.32	14.54 $\pm$ 0.31	14.62 $\pm$ 0.31	14.73 $\pm$ 0.29	14.56 $\pm$ 0.32	14.66 $\pm$ 0.29	14.61 $\pm$ 0.34
S11_B3	11.96 $\pm$ 0.27	12.24 $\pm$ 0.27	12.06 $\pm$ 0.26	12.10 $\pm$ 0.25	12.14 $\pm$ 0.25	11.96 $\pm$ 0.25	11.83 $\pm$ 0.25	12.04 $\pm$ 0.27
S11_A4	10.38 $\pm$ 0.17	10.38 $\pm$ 0.16	10.14 $\pm$ 0.16	10.08 $\pm$ 0.16	10.11 $\pm$ 0.18	9.94 $\pm$ 0.16	9.86 $\pm$ 0.16	10.14 $\pm$ 0.28
S11_B4	10.01 $\pm$ 0.15	10.03 $\pm$ 0.16	9.64 $\pm$ 0.13	9.56 $\pm$ 0.15	9.59 $\pm$ 0.16	9.38 $\pm$ 0.15	9.47 $\pm$ 0.15	9.68 $\pm$ 0.35
S11_A5	11.26 $\pm$ 0.14	11.21 $\pm$ 0.13	11.16 $\pm$ 0.14	11.30 $\pm$ 0.15	11.26 $\pm$ 0.15	11.06 $\pm$ 0.15	11.23 $\pm$ 0.18	11.21 $\pm$ 0.18
S11_B5	12.93 $\pm$ 0.18	12.85 $\pm$ 0.25	12.77 $\pm$ 0.18	12.55 $\pm$ 0.16	13.02 $\pm$ 0.17	12.98 $\pm$ 0.17	12.61 $\pm$ 0.18	12.82 $\pm$ 0.27
S11_A6	11.34 $\pm$ 0.09	11.53 $\pm$ 0.10	11.50 $\pm$ 0.10	11.54 $\pm$ 0.10	11.54 $\pm$ 0.10	11.47 $\pm$ 0.10	11.31 $\pm$ 0.10	11.46 $\pm$ 0.15
S11_B6	8.58 $\pm$ 0.12	8.63 $\pm$ 0.11	8.55 $\pm$ 0.11	8.63 $\pm$ 0.10	8.56 $\pm$ 0.10	8.47 $\pm$ 0.11	8.47 $\pm$ 0.10	8.55 $\pm$ 0.12
S11_A7	10.25 $\pm$ 0.17	10.22 $\pm$ 0.16	10.16 $\pm$ 0.16	10.23 $\pm$ 0.16	10.19 $\pm$ 0.16	9.98 $\pm$ 0.14	10.01 $\pm$ 0.15	10.15 $\pm$ 0.17
S11_B7	9.17 $\pm$ 0.12	9.10 $\pm$ 0.55	9.14 $\pm$ 0.11	9.02 $\pm$ 0.13	9.18 $\pm$ 0.11	9.07 $\pm$ 0.10	8.92 $\pm$ 0.11	9.09 $\pm$ 0.17
S11_A8	7.38 $\pm$ 0.18	7.53 $\pm$ 0.16	7.53 $\pm$ 0.16	7.37 $\pm$ 0.14	7.52 $\pm$ 0.15	7.38 $\pm$ 0.16	7.24 $\pm$ 0.16	7.44 $\pm$ 0.22
S11_B8	5.90 $\pm$ 0.30	5.98 $\pm$ 0.19	6.25 $\pm$ 0.25	6.20 $\pm$ 0.25	6.13 $\pm$ 0.16	5.87 $\pm$ 0.21	5.78 $\pm$ 0.40	6.01 $\pm$ 0.40

Table 6.2: S11: Attenuation Lenght Values.

PMT	λ (cm) (06/07)	λ (cm) (06/08)	λ (cm) (06/09)	λ (cm) (06/10)	λ (cm) (06/11)	λ (cm) (06/12)	λ (cm) (07/01)	λ (cm) mean
S12_A1	7.33 $\pm$ 0.14	7.49 $\pm$ 0.12	7.49 $\pm$ 0.12	7.45 $\pm$ 0.14	7.51 $\pm$ 0.12	7.36 $\pm$ 0.13	7.67 $\pm$ 0.18	7.47 $\pm$ 0.20
S12_B1	9.46 $\pm$ 0.21	9.34 $\pm$ 0.17	9.45 $\pm$ 0.19	9.25 $\pm$ 0.15	9.76 $\pm$ 0.23	9.64 $\pm$ 0.16	9.24 $\pm$ 0.22	9.45 $\pm$ 0.31
S12_A2	10.84 $\pm$ 0.23	10.99 $\pm$ 0.19	10.78 $\pm$ 0.19	10.92 $\pm$ 0.15	10.62 $\pm$ 0.16	10.61 $\pm$ 0.17	10.62 $\pm$ 0.20	10.77 $\pm$ 0.23
S12_B2	10.21 $\pm$ 0.20	9.31 $\pm$ 0.35	9.55 $\pm$ 0.24	9.80 $\pm$ 0.20	9.55 $\pm$ 0.33	9.52 $\pm$ 0.16	10.01 $\pm$ 0.24	9.70 $\pm$ 0.51
S12_A3	16.48 $\pm$ 0.21	16.37 $\pm$ 0.21	16.45 $\pm$ 0.20	16.27 $\pm$ 0.20	16.25 $\pm$ 0.21	16.16 $\pm$ 0.21	16.09 $\pm$ 0.21	16.30 $\pm$ 0.21
S12_B3	14.58 $\pm$ 0.34	14.33 $\pm$ 0.60	14.61 $\pm$ 0.34	14.64 $\pm$ 0.34	14.86 $\pm$ 0.32	14.67 $\pm$ 0.32	14.72 $\pm$ 0.31	14.63 $\pm$ 0.30
S12_A4	9.36 $\pm$ 0.22	9.13 $\pm$ 0.20	9.06 $\pm$ 0.20	9.01 $\pm$ 0.19	9.01 $\pm$ 0.20	9.24 $\pm$ 0.27	8.85 $\pm$ 0.19	9.09 $\pm$ 0.27
S12_B4	15.80 $\pm$ 0.40	15.60 $\pm$ 0.33	15.60 $\pm$ 0.35	15.29 $\pm$ 0.29	15.34 $\pm$ 0.32	15.28 $\pm$ 0.30	15.38 $\pm$ 0.28	15.47 $\pm$ 0.35
S12_A5	12.66 $\pm$ 0.30	12.55 $\pm$ 0.28	12.58 $\pm$ 0.29	12.81 $\pm$ 0.30	12.75 $\pm$ 0.30	12.72 $\pm$ 0.30	12.61 $\pm$ 0.30	12.67 $\pm$ 0.30
S12_B5	10.22 $\pm$ 0.22	10.36 $\pm$ 0.22	10.18 $\pm$ 0.22	10.39 $\pm$ 0.22	10.26 $\pm$ 0.21	10.16 $\pm$ 0.20	10.12 $\pm$ 0.19	10.24 $\pm$ 0.22
S12_A6	10.47 $\pm$ 0.28	10.61 $\pm$ 0.29	10.41 $\pm$ 0.33	10.60 $\pm$ 0.33	10.72 $\pm$ 0.26	10.45 $\pm$ 0.30	10.38 $\pm$ 0.25	10.52 $\pm$ 0.33
S12_B6	13.58 $\pm$ 0.21	13.74 $\pm$ 0.30	13.84 $\pm$ 0.28	13.47 $\pm$ 0.30	13.86 $\pm$ 0.27	13.74 $\pm$ 0.29	13.95 $\pm$ 0.29	13.74 $\pm$ 0.30

Table 6.3: S12: Attenuation Lenght Values.

PMT	λ (cm) (06/07)	λ (cm) (06/08)	λ (cm) (06/09)	λ (cm) (06/10)	λ (cm) (06/11)	λ (cm) (06/12)	λ (cm) (07/01)	λ (cm) mean
S21_A1	40.72 $\pm$ 0.80	40.50 $\pm$ 1.12	39.79 $\pm$ 0.97	40.45 $\pm$ 0.95	41.02 $\pm$ 1.03	40.69 $\pm$ 1.21	40.27 $\pm$ 1.19	40.49 $\pm$ 1.21
S21_B1	44.63 $\pm$ 0.98	45.82 $\pm$ 0.96	44.12 $\pm$ 1.18	45.43 $\pm$ 0.85	45.49 $\pm$ 0.92	44.18 $\pm$ 1.21	43.64 $\pm$ 1.13	44.76 $\pm$ 1.21
S21_A2	36.54 $\pm$ 1.21	36.67 $\pm$ 1.49	35.89 $\pm$ 1.24	36.4 $\pm$ 1.35	36.17 $\pm$ 1.36	36.05 $\pm$ 1.40	35.73 $\pm$ 1.46	36.21 $\pm$ 1.49
S21_B2	39.08 $\pm$ 1.08	40.19 $\pm$ 1.21	39.51 $\pm$ 0.75	39.72 $\pm$ 0.83	40.23 $\pm$ 1.03	39.21 $\pm$ 0.98	40.48 $\pm$ 1.13	39.77 $\pm$ 1.21
S22_A1	11.55 $\pm$ 0.18	11.51 $\pm$ 0.17	10.94 $\pm$ 0.15	10.67 $\pm$ 0.13	10.29 $\pm$ 0.12	11.00 $\pm$ 0.11	10.93 $\pm$ 0.11	10.98 $\pm$ 0.69
S22_B1	11.19 $\pm$ 0.08	11.09 $\pm$ 0.08	11.14 $\pm$ 0.58	10.75 $\pm$ 0.06	10.48 $\pm$ 0.04	10.50 $\pm$ 0.05	10.89 $\pm$ 0.04	10.85 $\pm$ 0.39
S22_A2	37.03 $\pm$ 1.36	37.05 $\pm$ 1.21	36.28 $\pm$ 1.11	37.04 $\pm$ 1.22	36.26 $\pm$ 1.18	36.90 $\pm$ 1.29	36.19 $\pm$ 1.15	36.68 $\pm$ 1.36
S22_B2	35.48 $\pm$ 0.71	35.27 $\pm$ 0.87	34.86 $\pm$ 0.72	34.06 $\pm$ 0.69	35.27 $\pm$ 0.65	35.49 $\pm$ 0.66	35.78 $\pm$ 0.63	35.17 $\pm$ 1.40

Table 6.4: S2: Attenuation Lenght Values.

PMT	λ (cm) (06/07)	λ (cm) (06/08)	λ (cm) (06/09)	λ (cm) (06/10)	λ (cm) (06/11)	λ (cm) (06/12)	λ (cm) (07/01)	λ (cm) mean
S31_A1	7.25 $\pm$ 0.15	7.00 $\pm$ 0.16	6.96 $\pm$ 0.15	6.92 $\pm$ 0.15	6.86 $\pm$ 0.15	6.82 $\pm$ 0.15	6.74 $\pm$ 0.15	6.93 $\pm$ 0.32
S31_B1	8.12 $\pm$ 0.22	7.95 $\pm$ 0.22	7.84 $\pm$ 0.22	7.73 $\pm$ 0.22	7.71 $\pm$ 0.22	7.71 $\pm$ 0.23	7.70 $\pm$ 0.23	7.82 $\pm$ 0.30
S31_A2	6.21 $\pm$ 0.11	6.08 $\pm$ 0.13	5.99 $\pm$ 0.12	5.94 $\pm$ 0.11	5.89 $\pm$ 0.11	5.86 $\pm$ 0.11	5.83 $\pm$ 0.11	5.97 $\pm$ 0.24
S31_B2	5.99 $\pm$ 0.11	5.83 $\pm$ 0.11	5.83 $\pm$ 0.11	5.83 $\pm$ 0.11	5.79 $\pm$ 0.11	5.78 $\pm$ 0.10	5.78 $\pm$ 0.11	5.85 $\pm$ 0.14
S31_A3	6.34 $\pm$ 0.13	6.17 $\pm$ 0.12	6.10 $\pm$ 0.11	6.02 $\pm$ 0.11	6.00 $\pm$ 0.11	5.99 $\pm$ 0.11	5.92 $\pm$ 0.10	6.08 $\pm$ 0.26
S31_B3	7.37 $\pm$ 0.16	7.22 $\pm$ 0.15	7.10 $\pm$ 0.15	7.05 $\pm$ 0.15	7.01 $\pm$ 0.14	6.98 $\pm$ 0.14	6.95 $\pm$ 0.14	7.10 $\pm$ 0.27
S32_A1	10.17 $\pm$ 0.30	9.93 $\pm$ 0.29	9.61 $\pm$ 0.27	9.53 $\pm$ 0.27	9.47 $\pm$ 0.28	9.44 $\pm$ 0.28	9.36 $\pm$ 0.27	9.65 $\pm$ 0.52
S32_B1	6.56 $\pm$ 0.06	6.44 $\pm$ 0.05	6.37 $\pm$ 0.05	6.24 $\pm$ 0.06	6.17 $\pm$ 0.05	6.15 $\pm$ 0.05	6.11 $\pm$ 0.05	6.27 $\pm$ 0.29
S32_A2	6.76 $\pm$ 0.10	6.57 $\pm$ 0.09	6.44 $\pm$ 0.09	6.37 $\pm$ 0.09	6.32 $\pm$ 0.08	6.27 $\pm$ 0.08	6.23 $\pm$ 0.09	6.42 $\pm$ 0.34
S32_B2	7.58 $\pm$ 0.17	7.44 $\pm$ 0.17	7.25 $\pm$ 0.16	7.22 $\pm$ 0.16	7.16 $\pm$ 0.17	7.13 $\pm$ 0.16	7.06 $\pm$ 0.16	7.26 $\pm$ 0.32
S32_A3	8.75 $\pm$ 0.23	8.62 $\pm$ 0.23	8.49 $\pm$ 0.23	8.46 $\pm$ 0.22	8.44 $\pm$ 0.24	8.36 $\pm$ 0.22	8.37 $\pm$ 0.23	8.50 $\pm$ 0.25
S32_B3	7.32 $\pm$ 0.11	7.17 $\pm$ 0.11	6.97 $\pm$ 0.10	6.87 $\pm$ 0.10	6.86 $\pm$ 0.10	6.81 $\pm$ 0.10	6.78 $\pm$ 0.10	6.97 $\pm$ 0.35

Table 6.5: S3: Attenuation Length Values.

Layer	strip	PMT A (λ_{att})	PMT B (λ_{att})	λ_{att} value
S11	1	11.90 $\pm$ 0.35	9.80 $\pm$ 0.16	10.85 $\pm$ 1.05
	2	9.98 $\pm$ 0.16	11.12 $\pm$ 0.19	10.55 $\pm$ 0.57
	3	14.61 $\pm$ 0.34	12.04 $\pm$ 0.27	13.33 $\pm$ 1.29
	4	10.14 $\pm$ 0.28	9.68 $\pm$ 0.35	9.91 $\pm$ 0.35
	5	11.21 $\pm$ 0.18	12.82 $\pm$ 0.27	12.02 $\pm$ 0.81
	6	11.46 $\pm$ 0.15	8.55 $\pm$ 0.12	10.01 $\pm$ 1.46
	7	10.15 $\pm$ 0.17	9.09 $\pm$ 0.17	9.62 $\pm$ 0.53
	8	7.44 $\pm$ 0.22	6.01 $\pm$ 0.40	6.73 $\pm$ 0.72
S12	1	7.47 $\pm$ 0.20	9.45 $\pm$ 0.31	8.46 $\pm$ 0.99
	2	10.77 $\pm$ 0.23	9.70 $\pm$ 0.51	10.24 $\pm$ 0.54
	3	16.30 $\pm$ 0.21	14.63 $\pm$ 0.30	15.47 $\pm$ 0.84
	4	9.09 $\pm$ 0.27	15.47 $\pm$ 0.35	12.28 $\pm$ 3.19
	5	12.67 $\pm$ 0.30	10.24 $\pm$ 0.22	11.46 $\pm$ 1.22
	6	10.52 $\pm$ 0.33	13.74 $\pm$ 0.30	12.13 $\pm$ 1.61
S21	1	40.49 $\pm$ 1.21	44.76 $\pm$ 1.21	42.63 $\pm$ 2.14
	2	36.21 $\pm$ 1.49	39.77 $\pm$ 1.21	37.99 $\pm$ 1.78
S22	1	10.98 $\pm$ 0.69	10.85 $\pm$ 1.36	10.92 $\pm$ 1.36
	2	36.68 $\pm$ 1.36	35.17 $\pm$ 1.40	35.93 $\pm$ 1.40
S31	1	6.93 $\pm$ 0.32	7.82 $\pm$ 0.30	7.38 $\pm$ 0.45
	2	5.97 $\pm$ 0.24	5.85 $\pm$ 0.14	5.91 $\pm$ 0.24
	3	6.08 $\pm$ 0.26	7.10 $\pm$ 0.27	6.59 $\pm$ 0.51
S32	1	9.65 $\pm$ 0.52	6.27 $\pm$ 0.29	7.96 $\pm$ 1.69
	2	6.42 $\pm$ 0.34	7.26 $\pm$ 0.32	6.84 $\pm$ 0.42
	3	8.50 $\pm$ 0.25	6.97 $\pm$ 0.35	7.74 $\pm$ 0.77

Table 6.6: Attenuation Length Values for each strip of TOF System.

the two PMT of a given strip show differences of the order of 10% that are generally larger than the statistical uncertainties estimated from the fit; this can be explained with the fact that the hypothesis of exponential dependence of the intensity of guided light on the travelled distance is a good but not exact approximation of the true dependence. It can also be observed that for the same reason the values of $\chi^2/\text{d.o.f.}$ show quite significant variations.

Hence the simple average of the all measurements for each PMT during seven months has been assumed as a more realistic estimate of λ_{att} (indicated as "mean" in the tables) for the PMT under analysis with a systematic error, related to the exponential approximation, equal to the absolute difference between this average and each of the values for that PMT given by the fit during the seven months taken in consideration. In the few cases for which this absolute difference is smaller than the statistical errors from the fit, the higher of the statistical uncertainties has been conservatively taken as error in the λ_{att} measurement. Than a simple average between the two values of the two PMTs of each strip is calculated to estimate the characteristic λ_{att} of the strip under analysis with a systematic error, related to the exponential approximation, calculated as explained before.

Comparing the measured λ_{att} for the various strips, it can be seen that strips of the same layer show quite similar values, while large differences are observed between different layers. In particular the central layers (S21 and S22) have the best values of attenuation length (sometime also greater than 30 cm), at least a factor 3 higher than for the S11 and S12 layers (about 10 cm) and for S31 and S32 (of the same order of S11 and S12). On the other hand all these values are much smaller than the bulk attenuation length of the scintillator BC-404 (140 cm). It can be concluded that the surface attenuation is the major contribution to λ_{att} for the TOF strips of PAMELA, and that the optical properties of the strips differ significantly for the 3 double planes; in particular for the layers of S1 and S3 they are much worse than what would be expected on the basis of the standard processes that are usually employed in the fabrication of scintillator strips.

The reason for this unexpected worsening, that was pointed out by the present analysis, has been investigated by the PAMELA collaboration. The most probable explanation takes into account that an additional machining process was performed on the strips of S1 and S3 to reduce their thickness from the 10 mm standard to the desired 7 mm one; on the other hand, for the S2 strips the 5 mm thickness was already made available by the manufacturer (Bicron): the hypothesis is that during the additional processing a deterioration of the scintillator surfaces happened. Only with this dedicated analysis, during the final qualification tests, the effect was discovered; a subsequent study of the available "Engineering model" spare strips, used for the first prototyping phase of the TOF system, has reported the presence of micro-cracks (figure 6.9) on the strip surface, that are known to worsen the reflectivity properties; since these strips have been machined with the same

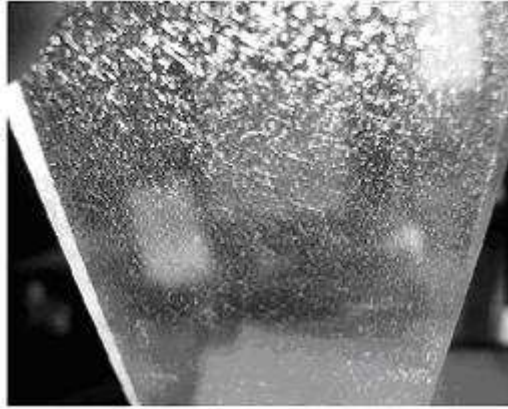


Figure 6.9: A detail of an "Engineering model" strip of the TOF system with micro-cracks; the width of the strip (horizontal dimension in figure) is about 5 cm.

procedure used for the "Flight model" ones, it is reasonable to assume the presence of micro-cracks also on the "Flight model" strips.

Anyway after having reported these not satisfying results on the attenuation lengths, a detailed analysis of all the data collected during the final qualification tests has been done, to verify if the characteristics of the TOF system, from the point of view of the trigger efficiency and of the time resolution, were still compatible with the requirements of the design. In particular the analysis of the trigger efficiencies for all the strips of the TOF system is described in the following sections.

6.4 Trigger efficiency

For the determination of the trigger efficiency of the strips and layers of the TOF system in flight, I have done an analysis similar to the one described in the previous sections, using cosmic ray events collected by the PAMELA apparatus during its first seven months of data taking in space and exploiting the spatial information given by the tracking system of PAMELA.

The efficiency ϵ of a strip is defined as the probability that an incident particle, crossing the strip within the acceptance and live time of the PAMELA apparatus, is accompanied by the generation of an event signal toward the trigger board by one at least of the two PMT read-out channels associated with that strip. An analogous definition holds for each of the 6 layers of the TOF system, considering the generation of an event signal from one at least of the corresponding PMT channels.

The overall efficiency of the TOF system for a specific trigger configuration can then be derived from the efficiencies of the single scintillator layers,

given that each layer and the corresponding electronics independently reacts to the passage of an ionizing particle.

During this analysis I calculated the efficiencies of the various strips and layers of the apparatus with the analysis of the data collected by PAMELA in the two following trigger configurations:

- the standard trigger configuration used usually outside the radiation belts (named TOF1):

$$(S11 \text{ OR } S12) \text{ AND } (S21 \text{ OR } S22) \text{ AND } (S31 \text{ OR } S32) \quad (6.5)$$

where the generation of a trigger happens in presence of an event signal in correspondence of one at least of the layers of each pair;

- the standard trigger configuration used inside the radiation belts usually (named TOF4):

$$(S21 \text{ AND } S22) \text{ AND } (S31 \text{ AND } S32) \quad (6.6)$$

where the generation of a trigger happens in presence of an event signal in correspondence of all planes constituting S2 and S3.

In fact, with the redundant double-plane structure, characteristic of the TOF system, and with this specific trigger pattern, it is possible to detect and characterize also particles for which a given layer has not generated an event signal (because its trigger efficiency is less than 1); at the same time it is possible to use the information from these events and from those for which the same layer has produced an event signal, to measure the efficiency of the layer.

The trigger efficiency depends in particular on the distribution of the intensity of scintillation light produced by an ionizing particle crossing the TOF layers, varying in general with the particle species and rigidity, according to the Bethe-Bloch formula as mentioned in section 6.2; the smallest value of efficiency is reached for minimum ionizing particles (MIP), which on the other hand constitute the events of primary interest for the PAMELA mission (antiprotons with $|\rho|$ up to ≈ 190 GV/c, positrons with $|\rho|$ up to ≈ 270 GV/c).

In order to understand the real in flight performances of the trigger system, the efficiencies have been measured by using the cosmic-ray events acquired in flight during the first seven months of data-taking and applying a cut on the rigidity, similar to that discussed in section 6.2, to selected protons and helium events. For heavier nuclei, the trigger efficiency is expected to be equal or greater to that one of helium nuclei.

In general the measured efficiency of a scintillator strip or layer depends on the spatial and angular distribution of the incident particles used in the

analysis (usually indicated as conditions of illumination), because of the not completely uniform sensitivity of the detector. It must also be noted that the trigger efficiency of a specific TOF PMT channel depends on the various parameters that affect the height of the anode pulse at the PMT output and on the low and high thresholds of the discriminator generating the corresponding event signal. In particular the height of the anode pulse depends on the characteristic attenuation length of the strip read-out by the PMT; this effect introduces a dependence of the efficiency of the PMT on the longitudinal coordinate of incidence along the strip.

When considering the combined efficiency of the two PMT of a strip, this dependence is greatly reduced, on one hand because of the complementary paths travelled by the scintillation light from the point of production to the two PMT at the opposite ends of the strip, on the other hand because the adjustable parameters for each PMT signal channel have been set to take into account the effect of the light attenuation. The adjustable parameters are the high voltage for the PMT, affecting the gain of the electron multiplier structure and the low and high thresholds for the discrimination of the anode output of the PMT.

The analysis has been focused on the most significant data samples, acquired with the standard high voltage configuration and trigger patterns (6.5 and 6.6). The "flight" threshold configuration was set to obtain the best compromise between a high efficiency and a small number of spurious event signals due to noise: 23 mV and 70 mV for the low and high thresholds of most PMT except for a group of 4 particularly noisy PMT, with thresholds set at 33 mV and 100 mV respectively.

6.5 Data analysis for trigger efficiency

By operating with a method similar to the one discussed in section 6.3 for the study of the attenuation lengths, a set of general selection cuts has been applied to the initial samples of acquired events for which the tracking program has reconstructed either a unique physical trajectory or two mutually excluding trajectories, because of the Y coordinate ambiguity.

The analysis of the data has been repeated for each of the 6 TOF layers, to separately determine the trigger efficiencies for the single strips of the layer and for the whole layer.

Once the layer under test has been fixed, the following cuts have been applied to determine the physical trajectory:

- cut 1: for each of the TOF layers, different from the layer under test, one and only one strip has generated an event signal for the trigger board on one or both the corresponding channels (PMT);
- cut 2: one and only one of the two reconstructed tracks is in agree-

ment with the signals released in TOF planes: it has a distance less than 5 centimeter from the track reconstructed from TOF taking into consideration the six interacting point on the six TOF planes).

For the selection of protons and helium events the following cut has been applied to some quantities measured by tracker:

- protons: $1 < \text{Rigidity} \times dE/dx < 7$
- helium: $(1/\text{Rigidity})^2 < 0.8 \quad \&\& \quad dE/dx > 4$

It is important to underline that the cut 1 involves also the following condition: given the layer under test (e.g. S11), an event signal has been generated by the other layer of the same double plane (e.g. S12). This condition exploits the fact that, with the standard trigger configuration 6.5, the presence of an event signal for the other layer of the same double plane (e.g. S12) implies that the trigger has been generated independently from the behaviour of the layer under test (e.g. S11). If this cut were not applied, the sample would contain a certain number of events that have been acquired because the layer under test has produced an event signal (necessary to have the trigger in absence of event signal for the other layer of the same double plane), thus causing an overestimation of the true trigger efficiency.

The procedure for the measurement of the trigger efficiency for each single strip of the layer under test is described below; the determination of the efficiency of the whole layer is analogous, with some differences that will be pointed out when discussing the results of the analysis. For each strip under test two values are recorded in the analysis: the number N of events with a reconstructed physical trajectory crossing the strip and the fraction N_{ok} of the N events for which the strip has given an event signal. The best estimate of the corresponding trigger efficiency is then given by the ratio N_{ok}/N ; the statistical uncertainty associated with this measurement will be separately discussed in Appendix C.

The measurement of efficiency for a TOF strip is potentially affected by greater systematic uncertainties, with respect to the ones present in the determination of the corresponding attenuation length. In fact, the identification of the strip that has been crossed by the incident cosmic ray is based on the trajectory reconstructed by the tracking program in the PAMELA reference system, which is operatively defined in a consistent way within the reconstruction procedure itself; the obtained trajectory is then compared with the nominal positions of the TOF strips in this reference system. These nominal positions are known with an accuracy of the order of the millimeter, which takes into account the combined contributions of the mechanical tolerances of the various elements connecting each strip to the magnetic tower of the spectrometer. If the discrepancy between the true position of the strip and the nominal one is such that for a specific event (see figure 6.10)

the reconstructed trajectory is not associated with the strip actually crossed (strip 2), but with an adjacent strip (strip 1) which correctly has not given any event signal, this implies an underestimation of the efficiency measured for strip 1. The resulting relative systematic uncertainty on the efficiency of strip 1 is of the order of the fraction of events with trajectories external to the strip and within a distance from the strip border, where δ (≈ 1 mm) is the spatial displacement of the strip from its nominal position. This fraction of events, on the other hand, is of the order of the ratio between δ and the transverse width of a strip (between 5 and 9 cm, depending on the layer), thus being 1 – 2%, comparable with the statistical uncertainties obtained with the present measurement, as discussed below.

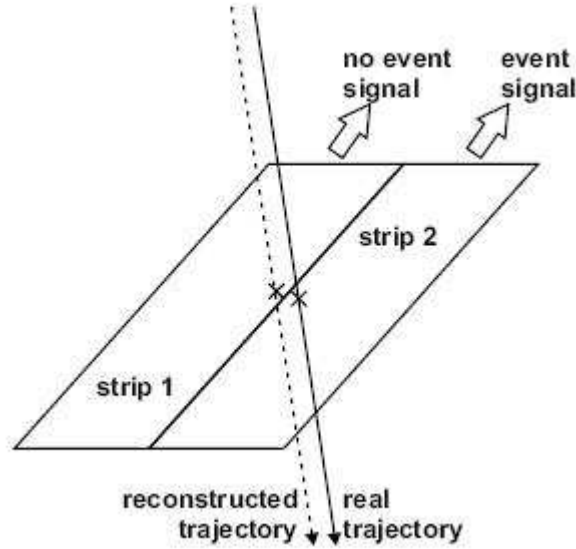


Figure 6.10: Systematic error in the measurement of the efficiency of a TOF strip, caused by the discrepancy between the nominal and true position of the strip in the PAMELA reference system. The particle has crossed strip 2 which has produced an event signal on one at least of its two PMT channels, but the reconstructed trajectory is wrongly associated to the adjacent strip (strip 1) which has not generated any event signal; this causes an underestimation of the true efficiency for strip 1.

To avoid introducing this systematic error in the measurements, a fiducial cut has been applied on the nominal area of each considered strip, excluding events for which the trajectory reconstructed by the tracking program crosses the strip in the vicinity of its lateral walls (within a distance δ_{cut}). By studying the variation of the measured efficiencies with δ_{cut} it can be concluded that a value $\delta_{cut} = 1.5$ mm is sufficient to remove this systematic contribution for all the strips; this applied cut is consistent with the previously

estimated order of magnitude for the displacement.

An acceptable drawback of the application of this further selection cut is a reduction of the order of some percent of the available statistical sample. It must also be considered that the excluded external area of the strip is expected to be characterized by a smaller trigger efficiency with respect to the rest of the area, because particles with inclined trajectories that cross the strip near its external border can escape from the lateral wall before reaching the lower face of the strip, thus releasing a significantly smaller amount of energy within the strip volume.

A more refined analysis, avoiding the application of this fiducial cut on the area, will be done after the accumulation of a large statistical sample of events, which will make it possible to align the strip with respect to the PAMELA reference system, with the precise determination of its true position.

The efficiencies ϵ measured with the present method for the single strips of the 6 layers are summarized in table 6.7 and 6.8 for protons and helium respectively. It can be generally observed that the efficiencies, taking into account the statistical uncertainties, are compatible with values greater than 98% for almost all the strips, and for most strips are above 99%. Besides, strips with different attenuation lengths λ_{att} do not show a corresponding variation of ϵ , as expected on the basis on the considerations made in the previous section (compare for example ϵ for the strips of S2 and S3, characterized by att of more than 30 cm and less than 7 cm respectively). Note also that the statistical uncertainties are much greater for layers S11 and S12; this is clearly a consequence of the fact that these layers are divided into a larger number of strips (8 and 6 respectively) with respect to the other ones, and therefore the number of events collected on a single strip is correspondingly smaller.

As mentioned before, a similar analysis has been done also for the 6 TOF layers, each one considered as a whole. The same event selection cuts described before have been applied, with the only difference that in the definition of the fiducial area, only the external part of the layer has been excluded and not the region between adjacent strips within the layer; in fact this is sufficient to take into account the possible systematic error caused by the use of the nominal position of the layer in the PAMELA reference.

For a fixed layer under test the trigger efficiency has been estimated as the ratio N_{ok}/N , where N is the number of events with a reconstructed trajectory crossing the layer and N_{ok} is the fraction of these events for which any strip of the layer has given an event signal. The ϵ measured with this method, for the 6 layers, are summarized in table 6.9 for proton and 6.10 for helium. In these tables the time behaviour during the seven months is shown also.

Note that the number of events N , accumulated for each layer, is greater than the sum of the events used for the measurement of ϵ for the single

layer	strip	N_{ok}	N	ϵ	$\Delta\epsilon$
S11	1	1130	1148	0.9843	0.0037
	2	4745	4836	0.9812	0.0020
	3	8423	8532	0.9872	0.0012
	4	8523	8589	0.99232	0.00094
	5	12150	16745	0.99022	0.00076
	6	6815	6917	0.9853	0.0014
	7	3679	3743	0.9829	0.0021
	8	474	484	0.9793	0.0064
S12	1	4098	4174	0.9818	0.0021
	2	10487	10654	0.9843	0.0012
	3	7057	7154	0.9864	0.0014
	4	8561	9618	0.99339	0.00087
	5	11267	11321	0.99523	0.00065
	6	4372	4419	0.9894	0.0015
S21	1	19708	19715	0.99965	0.00013
	2	17938	17958	0.99889	0.00025
S22	1	22179	22187	0.99964	0.00013
	2	19720	19740	0.99899	0.00023
S31	1	11123	11133	0.99910	0.00028
	2	14900	14915	0.99899	0.00026
	3	14075	14082	0.99950	0.00019
S32	1	14368	14399	0.99785	0.00039
	2	13136	13162	0.99803	0.00039
	3	11936	11962	0.99783	0.00043

Table 6.7: Measured efficiencies for the various TOF strips for proton particles.

layer	strip	N_{ok}	N	ϵ	$\Delta\epsilon$
S11	1	360	362	0.9945	0.0039
	2	1218	1227	0.9927	0.0024
	3	1828	1834	0.9967	0.0013
	4	1901	1908	0.9963	0.0013
	5	2205	2374	0.9288	0.0012
	6	1577	1582	0.9963	0.0014
	7	1040	1044	0.9962	0.0019
	8	195	197	0.98985	0.00071
S12	1	1211	1213	0.9984	0.0012
	2	2226	2233	0.9969	0.0012
	3	1421	1426	0.9965	0.0016
	4	1645	1650	0.9970	0.0014
	5	2427	2431	0.99836	0.00082
	6	1182	1188	0.9950	0.0020
S21	1	5000	5003	0.99940	0.00035
	2	4496	4499	0.99933	0.00038
S22	1	5316	5318	0.99962	0.00027
	2	4907	4908	0.99980	0.00020
S31	1	2695	2698	0.99889	0.00064
	2	3667	3673	0.99837	0.00067
	3	3698	3702	0.99892	0.00054
S32	1	3576	3580	0.99888	0.00056
	2	3011	3016	0.99834	0.00074
	3	3140	3147	0.99778	0.00084

Table 6.8: Measured efficiencies for the various TOF strips for helium particles.

PROTON	S11	S12	S21	S22	S31	S32
2006-07	0.990510	0.989829	0.995183	0.998110	0.997402	0.979723
2006-08	0.993875	0.990292	0.997071	0.997864	0.998170	0.983855
2006-09	0.993397	0.991381	0.996333	0.997931	0.998458	0.982216
2006-10	0.996951	0.994567	0.997979	0.998357	0.998537	0.985171
2006-11	0.993096	0.989624	0.996728	0.997945	0.997979	0.982856
2006-12	0.988488	0.984135	0.996479	0.996042	0.997588	0.971934
2007-01	0.973684	0.968667	0.992925	0.995365	0.999404	0.979278
All Data	0.992595	0.989588	0.996685	0.997701	0.998176	0.981735

Table 6.9: Trigger Efficiency behaviour for proton particles for all planes of TOF System.

HELIUM	S11	S12	S21	S22	S31	S32
2006-01	0.999050	0.998949	0.999202	0.999112	0.999272	0.998685
2006-08	0.999075	0.998875	0.999285	0.999114	0.999297	0.998679
2006-09	0.998872	0.998852	0.999252	0.998994	0.999195	0.998840
2006-10	0.998889	0.998892	0.999244	0.999039	0.999253	0.998835
2006-11	0.998844	0.998926	0.999304	0.999116	0.999331	0.998834
2006-12	0.998345	0.998891	0.999275	0.999201	0.999319	0.998907
2007-01	0.998925	0.999203	0.999654	0.999539	0.999465	0.999415
All Data	0.998896	0.998901	0.999278	0.999098	0.999279	0.998807

Table 6.10: Trigger Efficiency behaviour for helium particles for all planes of TOF System.

strips; this was expected since the fiducial area of the layer, considered in this analysis, is larger than the sum of the fiducial areas of the single strips forming the layer. Note also that the values of N are comparable for the various layers, since the initial sample is composed of events with a particle crossing all the three double planes (standard trigger configuration TOF1).

We can observe that the absence, in this case, of a fiducial cut on the area along the boundary between adjacent strips, allows the inclusion in the selected sample also of events characterized by a particle passing in the vicinity of this boundary, and, if sufficiently inclined, sharing its path on both strips, with a smaller energy release for each; the inclusion of these events gives a more correct evaluation of the actual performance of the layer in the generation of the event signal. On the other hand, it must be considered that the adopted definition of efficiency for the layer under test implies that also events with a signal, typically due to noise, associated to a strip that has not been crossed by the particle, contribute to the calculated N_{ok} ; also in this case the definition takes into account the actual behaviour of the system, since the presence of a spurious event signal on a layer, with a reconstructed physical trajectory and with event signals on two other TOF double planes at least (in the standard trigger configuration TOF1) is not sufficient to conclude that the event must be considered as spurious.

The measured efficiency ϵ for a given layer is thus different from the value ϵ' expected considering the ratio between the sum of the N_{ok} values for the single strips of that layer and the sum of the corresponding selected events N :

$$\epsilon' = \frac{\sum_{strip} N_{ok}^{strip}}{\sum_{strip} N^{strip}} \quad (6.7)$$

In fact the two effects (different fiducial cut and inclusion of "noisy" events) tends respectively to decrease and increase ϵ respect to ϵ' . As a general conclusion of this analysis it can be stated that the high efficiencies measured for the 6 TOF layers are quite satisfying and do not justify the replacement

of the detectors, in spite of their bad performances in terms of attenuation lengths; similar conclusions have been drawn from an independent analysis on the time resolution of the system [113].

6.6 Trigger efficiency of TOF system in "flight" configuration

After having directly measured, with the method described above, the efficiencies of the single layers of the TOF system, it is possible to calculate the trigger efficiency of the single double planes (ϵ_{s1} , ϵ_{s2} , ϵ_{s3}) and the overall efficiency of the TOF system (ϵ_{trig}). As said, I focused my attention on "flight" trigger configurations TOF1 (see 6.5) and TOF4 (see 6.6), but it is possible to apply a similar analysis to obtain trigger efficiency value for each-one of the other PAMELA trigger configurations (see Appendix A).

Note that a direct measurement of the trigger efficiency of the single double planes is only possible by acquiring events with an active trigger configuration that excludes the double plane under test, while a direct measurement of ϵ_{trig} in the "flight" configuration is clearly impossible and its calculation, starting from the ϵ of the single TOF detectors, is unavoidable.

The dependence of ϵ_{s1} , ϵ_{s2} , ϵ_{s3} and ϵ_{trig} on the measured ϵ for the single layers can be derived as follows. Given the efficiencies of the two layers of a double plane, generically indicated here as $\epsilon_A = P(A)$ and $\epsilon_B = P(B)$, the combined efficiency of the double plane is defined as $\epsilon_{OR} = P(A \text{ OR } B)$; taking into account the independence of the two probabilities ϵ_A and ϵ_B , the following formula can be derived:

$$\epsilon_{OR} = 1 - (1 - \epsilon_A) \cdot (1 - \epsilon_B) = \epsilon_A + \epsilon_B - \epsilon_A \cdot \epsilon_B \quad (6.8)$$

For plane S1, composed of layers S11 and S12, we can write:

$$\epsilon_{S1} = \epsilon_{S11} + \epsilon_{S12} - \epsilon_{S11} \cdot \epsilon_{S12} \quad (6.9)$$

Similar relations hold for the other two planes S2 and S3.

Finally the total trigger efficiency of the TOF system in the standard trigger configuration is obtained, given the independence of the probabilities ϵ_{S1} , ϵ_{S2} and ϵ_{S3} as:

$$\epsilon_{trig} = P(S1ANDS2ANDS3) = \epsilon_{S1} \cdot \epsilon_{S2} \cdot \epsilon_{S3} \quad (6.10)$$

and substituting ϵ_{S1} with 6.9 etc..

With this calculation and applying the method for the estimation of the uncertainties used also for the single layers and described in Appendix C, the values shown in tables 6.11 and 6.12 are obtained for protons and helium respectively, in TOF1 and TOF4 configurations.

6.6 Trigger efficiency of TOF system in "flight" configuration 123

PROTON		
Trigger Configuration	Efficiency Value	Statistical Error
TOF1	0.9999	0.0012
TOF4	0.97445	0.00073

Table 6.11: Trigger Efficiency for proton particles in TOF1 and TOF4 configurations.

HELIUM		
Trigger Configuration	Efficiency Value	Statistical Error
TOF1	0.99999	0.00087
TOF4	0.996467	0.000050

Table 6.12: Trigger Efficiency for helium particles in TOF1 and TOF4 configurations.

Chapter 7

Nuclei Analysis: Boron to Carbon ratio

In this first period of in flight running of the PAMELA experiment, the effort of the analysis group has been concentrated essentially to the optimization of the algorithms for antiproton and positron track reconstruction in the magnet spectrometer, to the study of the Calorimeter performance for lepton to hadron discrimination. In the last months more attention has been focused towards nuclei analysis.

In this chapter we report the first preliminary analysis I performed on the Boron to Carbon ratio using the tools I developed up to now.

7.1 Theoretical importance of Boron to Carbon ratio

Most of the available information about matter in our Universe, and in our Galaxy in particular, comes indirectly from the collection of the electromagnetic radiation (from meter waves to γ rays) that was emitted or absorbed by this matter. A completely different information is provided by the cosmic ray nuclei, which constitute a genuine sample of galactic matter. Many different nuclei species are observed, in a wide range of energy, and with different origins.

The sources of CR are believed to be supernovae (SNe) and supernova remnants (SNRs), pulsars, compact objects in close binary systems, and stellar winds. Observations of X-ray and γ -ray emission from these objects reveal the presence of energetic particles thus testifying the efficient acceleration processes in their neighborhood [114, 115]. Particles accelerated near the sources propagate tens of millions years in the ISM before escaping into the intergalactic space. In the course of CR propagation, secondary par-

articles and γ -rays are produced, and the initial spectra of CR species and composition change. The destruction of primary nuclei via spallation gives rise to secondary nuclei and isotopes which are rare in nature, antiprotons, and pions ($\pi^\pm$, π^0) that decay producing secondary $e^\pm$'s and γ -rays. The CR source composition and CR propagation history are imprinted in their abundances.

The relative abundances of the constituents of Galactic cosmic rays provide information about cosmic-ray transport within the Galaxy. In particular, cosmic rays of primary origin such as Carbon, Nitrogen and Oxygen may interact with the interstellar medium to produce secondary fragments such as Lithium, Beryllium and Boron. The measured ratio of secondary to primary cosmic rays can be used to compute the mean amount of interstellar matter that cosmic rays have encountered before reaching the Earth, which ultimately provides important constraints on the composition and homogeneity of the ISM in which they propagate.

One of the most sensitive quantity is B/C, as B is purely secondary and its main progenitors C and O are primaries. The shape of this ratio is seriously modified by changes in the propagation coefficients. Moreover, it is also the quantity measured with the best accuracy, so that it is ideal to test models. Indeed, as a ratio of two nuclei with similar Z, it is less sensitive to systematic errors and to Solar modulation than single fluxes or other ratios of nuclei with more distant charges. For the same reasons, the sub-Fe/Fe may also be useful. Unfortunately, since existing data are still affected by sizeable experimental errors, we can only use them to cross-check the validity of B/C but not to further constrain the parameters under scrutiny.

A better determination of the cosmic ray propagation is fundamental for the search of exotic matter, like dark matter candidates or antimatter produced in exotic processes, since the signature of such processes can be recognized only by knowing with great precision the fluxes due to the conventional production, acceleration and transport models [116].

7.2 PAMELA nuclear events

In its first fourteen months of data taking (from June 2006 to August 2007), PAMELA recorded about 7×10^8 events.

In order to separate nuclei events from the other and more numerous events (electrons, positrons, protons, pions, muons etc. etc.) a first selection on the complete set of PAMELA data has been done.

Within the total number of events (7×10^8 about), I selected about 120000 nuclei obtained applying the following simple set of cuts:

- single reconstructed track from Tracker: events without track or with more than one track are discarded;

- an energy release greater than 6 MIP in each one of the six layers of the PAMELA TOF System to select particles with $Z > 2$ (according to Bethe-Block formula) and traversing the apparatus from the top to the bottom;
- beta value greater than zero to avoid albedo events;

No other cut (like for example the request of the existence of a good track reconstructed for the event) is imposed, not to reduce the statistical sample before analysis.

All the selected nuclei events are stored in a .ROOT file and used for the work described in the following sections.

7.3 Z reconstruction for low energy events

According to Bethe-Block formula, at low energy the particle energy release in a material is greater than at high energy. As a consequence, a low energy particle produces a great number of delta rays in the silicon planes of Tracker instrument and makes the rigidity reconstruction for that event difficult and inaccurate. New algorithms that take into account this process are under development.

As a consequence a low precision in rigidity reconstruction is seen at low energy on real events and on Monte Carlo simulations (figure 7.1 for Boron nuclei and 7.2 for Carbon nuclei). Then, it has been decided to consider for the selected sample (section 7.2) only Calorimeter and TOF information to reconstruct the B/C ratio for nuclei events in the energy interval between 200 MeV/n and 3 GeV/n. The particle kinetic energy was obtained by using the "beta" TOF values and not the Tracker rigidity.

To extract a Boron and a Carbon sample, Z value for each event has been reconstructed.

In figure 7.3 a 2-D histogram of the energy released in the first layer of the Calorimeter is shown versus "beta" value for each event of the sample selected. Different families are identifiable up to Oxygen, with the exception of Nitrogen due to its low statistic.

Starting from this result, it is possible to indentify a region for each nuclear family delimited by two exponential curves as shown in figure 7.4 and, in each region, to make an exponential fit (figure 7.5).

Using as reference the fitted curves, a simple interpolation method allows Z recostruction for all events as in figure 7.6. This result could be improved to obtain a better resolution using more Calorimeter planes for the estimation of the energy released for each event, but to the detriment of the precision of the ratio, due to the different interaction cross sections with tungsten for Boron and Carbon nuclei.

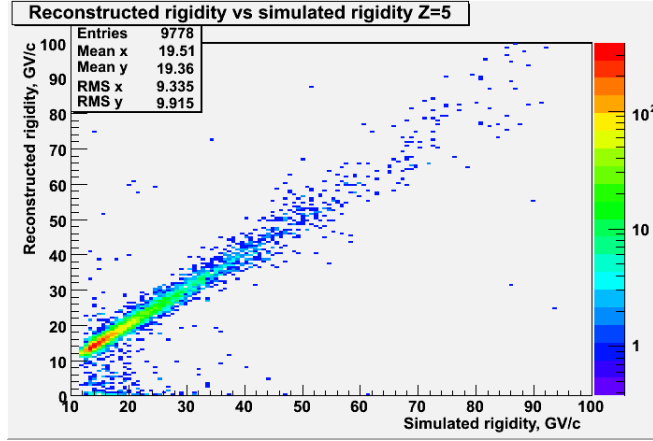


Figure 7.1: Monte Carlo simulation: Reconstructed rigidity versus simulated rigidity for Boron nuclei. At low energy the agreement between the two values is not as good as at high energy.

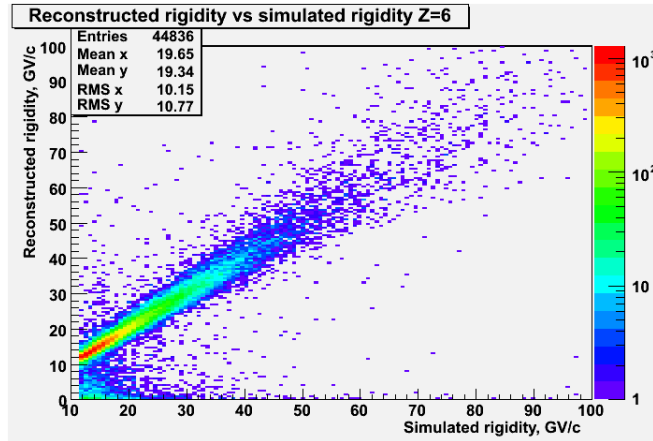


Figure 7.2: Monte Carlo simulation: Reconstructed rigidity versus simulated rigidity for Carbon nuclei. At low energy the agreement between the two values is not as good as at high energy.

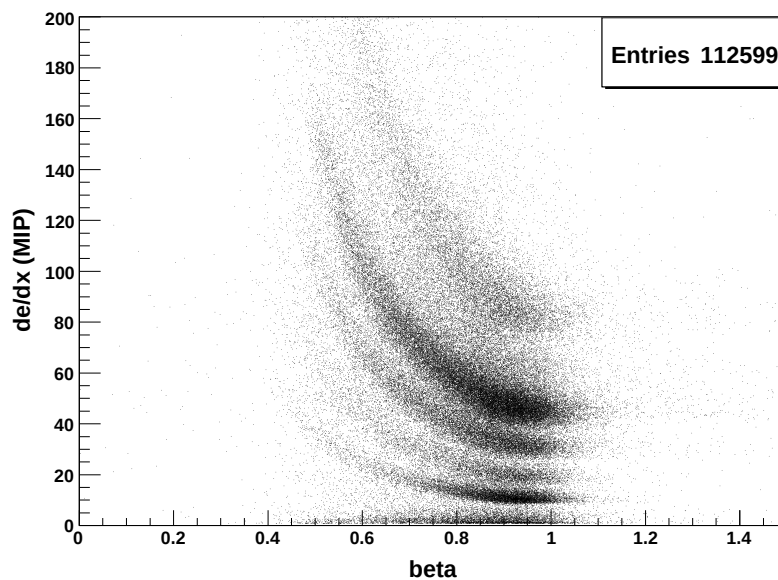


Figure 7.3: Nuclear families: energy released in Calorimeter first plane versus beta value. Particles fall into distinct charge bands.

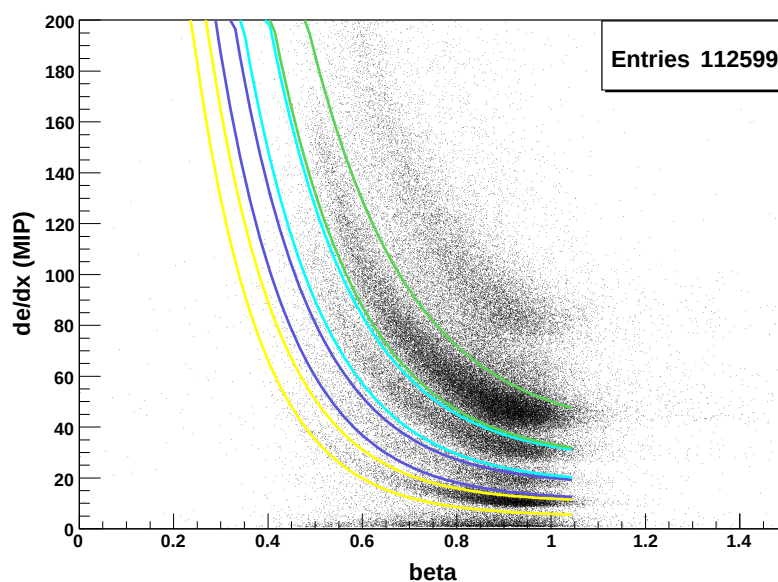


Figure 7.4: Nuclear families: energy released in Calorimeter first plane versus beta value. Particles fall into distinct charge bands. Regions identifying nuclear families can be recognized.

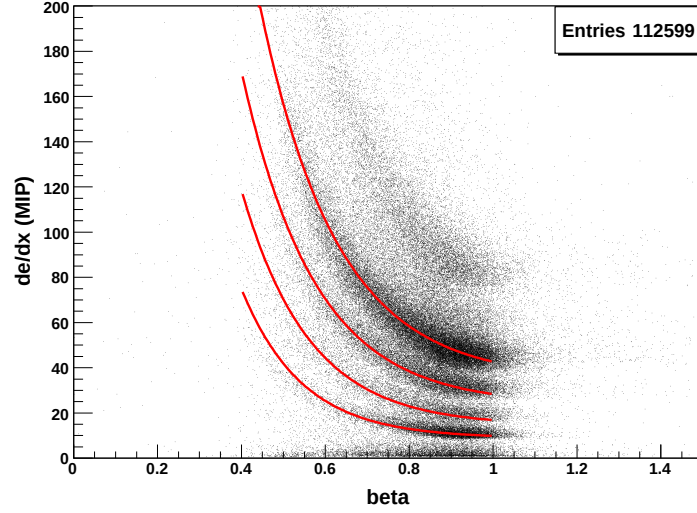


Figure 7.5: Nuclear families: energy released in Calorimeter first plane versus beta value. Particles fall into distinct charge bands. Fit is superimposed for each family.

Histogram in figure 7.6 refers to the entire selected sample and contains events in the full PAMELA energetic range. To obtain a better discrimination between different families, the energy range between 200 MeV/n and 3 GeV/n has been divided into six energetic bins. Z reconstructions for all energetic bins are shown in figure 7.7.

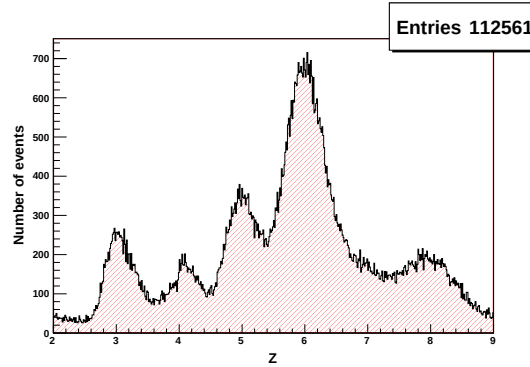


Figure 7.6: Z reconstruction histogram for all events. It is obtained starting from the energy release in the first calorimeter plane.

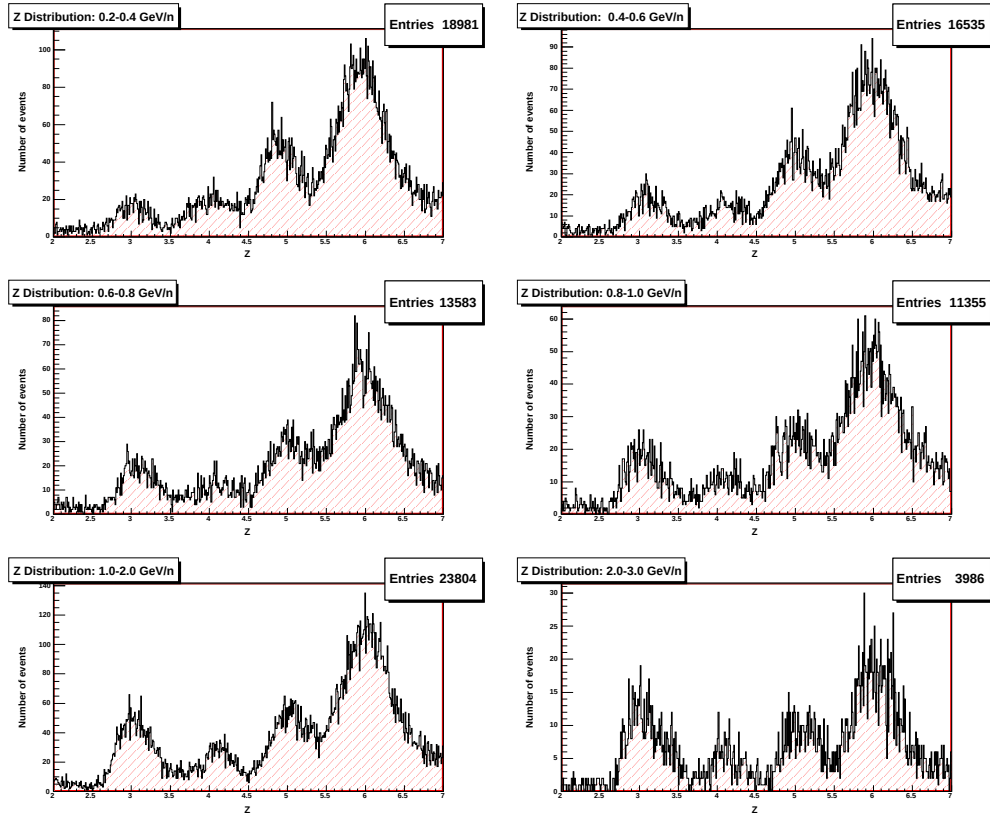


Figure 7.7: Z reconstruction for different energy bins at low energy.

7.4 Boron to Carbon ratio at low energy

Starting from Z reconstruction histograms relative to different energy bins, it is quite simple to obtain Boron to Carbon ratio value. We made a triple gaussian fit correlating in this way Berillium, Boron and Carbon behaviours (as example the triple gaussian fit relative to the energy interval 0.2-0.4 GeV/n is shown in the upper part of figure 7.8) and then we used the parameters obtained by this triple fit to do single fits on Boron and Carbon peaks. B/C values have been achieved as the ratio between the two subtended relating areas, as shown in the bottom part of figure 7.8. Results for Boron to Carbon ratio at low energy, from 200 MeV/n up to 2 GeV/n are summarized in table 7.1.

It is important to underline that these values have to be corrected for the different Tracker efficiency in reconstructing Boron and Carbon nuclei tracks and for the different Calorimeter efficiency in the detection of the same particles. These efficiencies are estimated in section 7.7 and 7.8 respectively. Corrected B/C ratio values are reported in section 7.9.

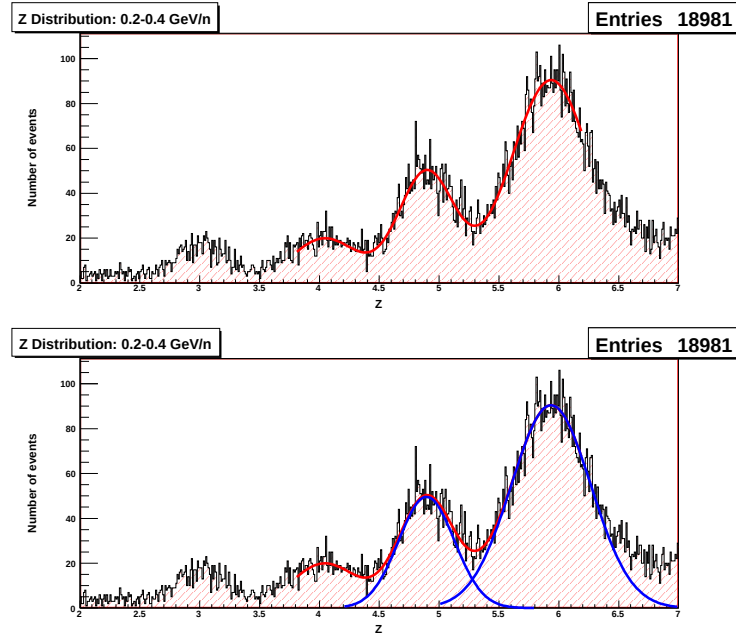


Figure 7.8: Z reconstruction for events with energy in the interval 200 MeV/n - 400 MeV/n. Upper: Triple gaussian fit to correlate Berillium, Boron and Carbon families is superimposed. Bottom: Single gaussian fits for Boron and Carbon peaks are superimposed.

Energy Interval GeV/n	B/C ratio	$\Delta(B/C)$
0.2 - 0.4	0.3449	0.0073
0.4 - 0.6	0.3730	0.0085
0.6 - 0.8	0.3825	0.0096
0.8 - 1.0	0.390	0.011
1.0 - 2.0	0.3770	0.0073
2.0 - 3.0	0.345	0.017

Table 7.1: Boron to Carbon ratio at low energy before efficiency corrections.

7.5 Z reconstruction for high energy events

Unlike low energy events, at high energy (over 2 GeV/n) we can use rigidity Tracker information to select nuclear families. As already shown in figures 7.1 and 7.2, the reconstructed rigidity values are in better agreement with simulated rigidity. For this energy region "beta" values are not usable because of the limited resolution of the PAMELA Time of Flight System. The particle kinetic energy has been reconstructed by Tracker rigidity.

Then we applied to the data new cuts to request a "good" track in Tracker:

- more than five X views hitted with a "good" energy release;
- more than four Y views hitted with a "good" energy release;
- "Lever Arm" equal or greater than five; "Lever Arm" is a number between zero and six and corresponds to the number of planes between the first and the last hitted plane, including the first and the last one also.

Figure 7.9 shows the energy released in first calorimeter layer versus deflection for this new data sample. Also here, it is possible to distinguish inside the graph a region for each nuclear family and to make a fit for each one of these. Results are shown in figure 7.10 and 7.11.

With the same procedure discribed in the previous section and considering only events with deflection value lower than 0.3 (corrisponding to energy greater than 1 GeV/n about), we obtain Z reconstruction for high energy events (fig 7.12). Also in this case, using more than one Calorimeter plane for the calculation of the energy released, the discrimination among different nuclear families would improve sensitively, but to the detriment of the Boron to Carbon ratio as explained for low energy.

The energy range from 1 GeV/n to 25 GeV/n has been divided in six energy bins; the Z reconstructed histograms are shown in figure 7.13.

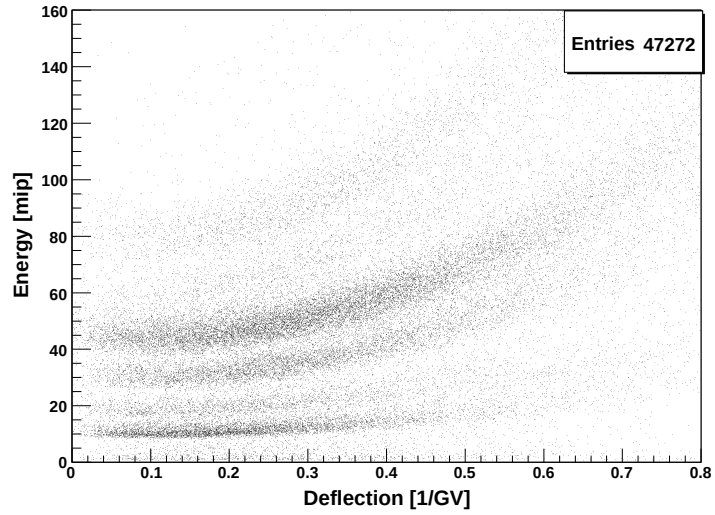


Figure 7.9: Nuclear families: Energy released in first calorimeter plane versus deflection. Particles fall into distinct charge bands.

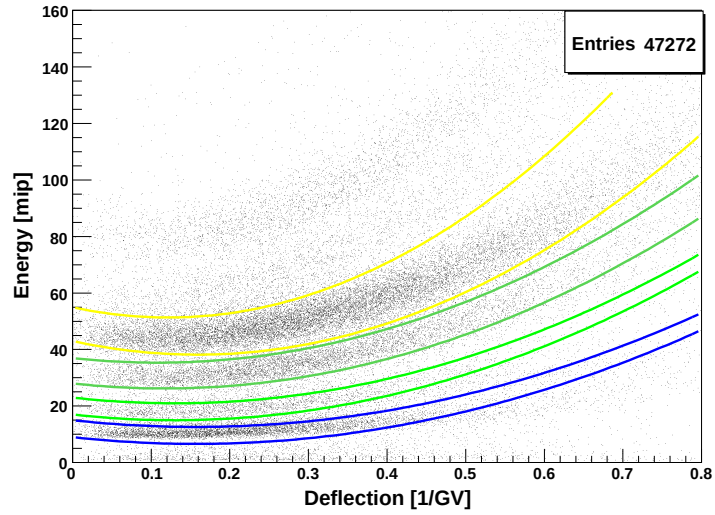


Figure 7.10: Nuclear families: Energy released in first calorimeter plane versus deflection. Particles fall into distinct charge bands. Regions identifying nuclear families can be recognized.

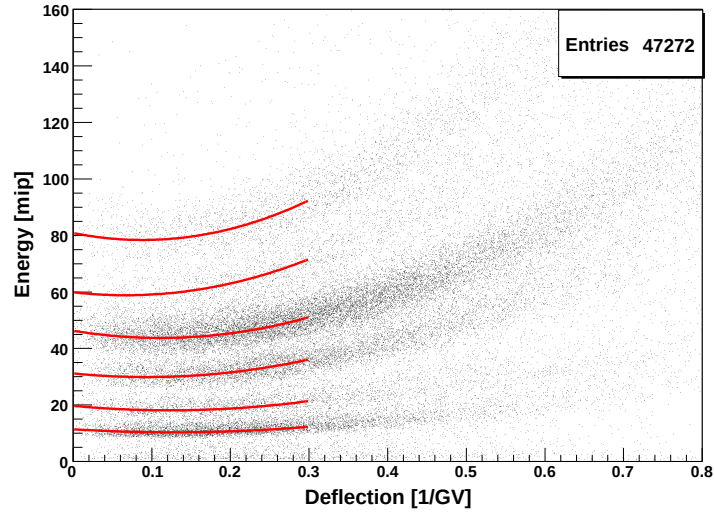


Figure 7.11: Nuclear families: Energy released in first calorimeter plane versus deflection. Particles fall into distinct charge bands. Fit is superimposed for each family.

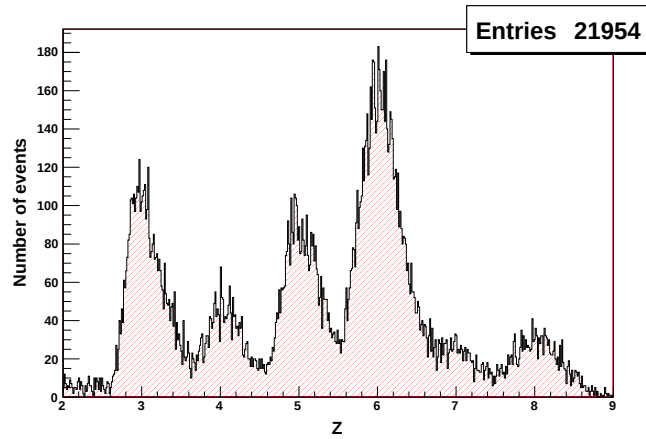


Figure 7.12: Z reconstruction histogram calculated for all the events starting from Tracker selection.

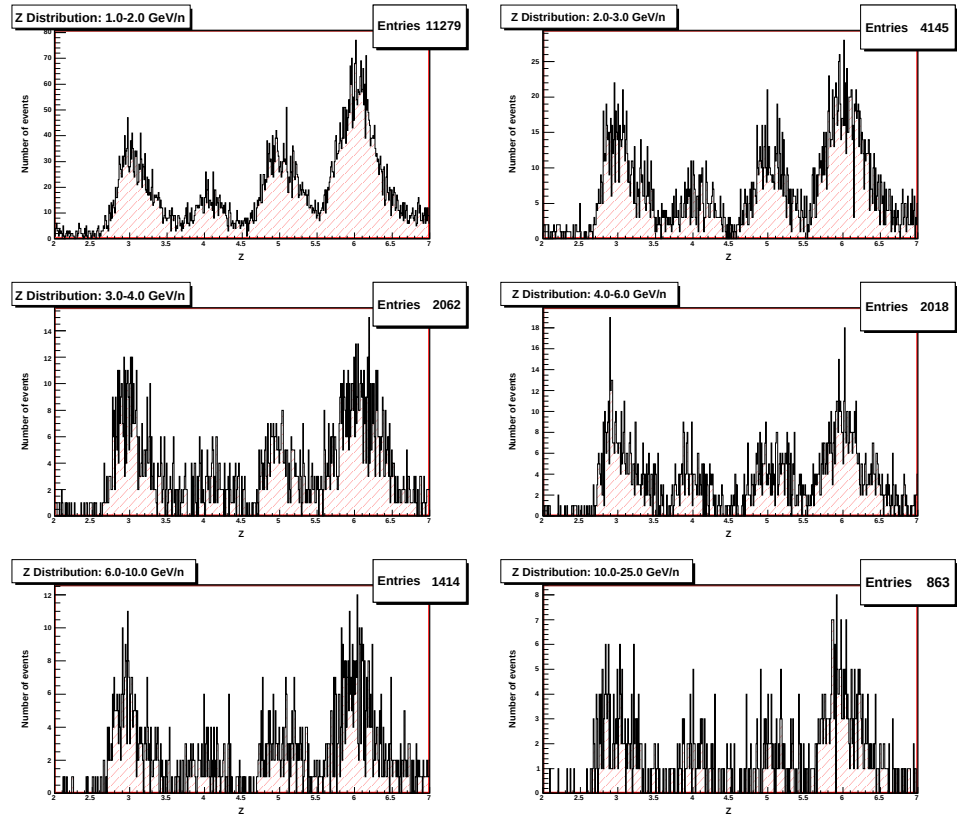


Figure 7.13: Z reconstruction for different energy bins at high energy.

7.6 Boron to Carbon ratio at high energy

Starting from histograms in figure 7.13, the same procedure explained in section 7.4 for low energy analysis has been used to analyze this high energy data. Results are summarized in table 7.2. Also these results have to be corrected to take into account Tracker and Calorimeter efficiencies discussed in section 7.7 and 7.8 respectively. Corrected results are estimated in section 7.9.

Energy Interval GeV/n	B/C ratio	$\Delta(B/C)$
1.0 - 2.0	0.448	0.013
2.0 - 3.0	0.413	0.021
3.0 - 4.0	0.365	0.027
4.0 - 6.0	0.355	0.029
6.0 - 10.0	0.355	0.029
10.0 - 25.0	0.295	0.032

Table 7.2: Boron to Carbon ratio at high energy before efficiency corrections.

7.7 Tracking Reconstruction Efficiency

As already reported, at this phase of the analysis the PAMELA tracking reconstruction software routine is optimized for tracking $Z=1$ particles; it is not complete for the nuclei events.

To estimate tracking reconstruction efficiency that we obtain using this algorithm, a Boron and a Carbon confident sample from Calorimeter and TOF has been selected. Then track efficiency has been obtained at low energy imposing only single track existence, while at the higher energy the cuts on the track described in section 7.5 have been applied.

In table 7.3 and 7.4 are reported respectively and for each bin the number of selected Boron and Carbon nuclei, the number of them passing the track requests, the consequent efficiency and errors.

Boron	N_B	N_{B_track}	Efficiency	Error
low energy track request				
0.2 - 0.4	3655	2435	0.666	0.017
0.4 - 0.6	3227	2252	0.698	0.019
0.6 - 0.8	2600	1791	0.689	0.021
0.8 - 1.0	2065	1448	0.701	0.024
1.0 - 2.0	4578	3180	0.695	0.016
2.0 - 3.0	1161	825	0.711	0.032
high energy track request				
1.0 - 2.0	4578	1525	0.3331	0.0098
2.0 - 3.0	1161	363	0.313	0.019
3.0 - 4.0	406	122	0.300	0.031
4.0 - 6.0	274	83	0.303	0.038
6.0 - 10.0	141	50	0.355	0.058
10.0 - 25.0	70	25	0.357	0.083

Table 7.3: Track Efficiency for Boron nuclei.

Carbon	N_C	N_{C_track}	Efficiency	Error
low energy track request				
0.2 - 0.4	7579	4270	0.563	0.011
0.4 - 0.6	7492	4288	0.572	0.011
0.6 - 0.8	6330	3686	0.582	0.012
0.8 - 1.0	5117	3085	0.603	0.014
1.0 - 2.0	12268	7332	0.5977	0.0088
2.0 - 3.0	3219	1917	0.596	0.017
high energy track request				
1.0 - 2.0	12268	3088	0.2517	0.0051
2.0 - 3.0	3219	784	0.2436	0.0097
3.0 - 4.0	1207	291	0.241	0.016
4.0 - 6.0	852	200	0.235	0.018
6.0 - 10.0	475	117	0.246	0.025
10.0 - 25.0	232	61	0.263	0.039

Table 7.4: Track Efficiency for Carbon nuclei.

7.8 Calorimeter Efficiency

Percentage of Boron and Carbon events triggered by PAMELA apparatus but not detected by Calorimeter as a function of the particle energy is not the same. For this reason is important to calculate Calorimeter efficiency for a correct B/C ratio estimation.

A confident sample of Boron and Carbon nuclei has been obtained using TOF System and selecting only events contained in one sigma around Boron and Carbon peaks in the Z reconstruction, respectively. Then, the number of nuclei that release energy along the reconstructed track in the first layer of the calorimeter is considered. The efficiency, calculated for the same energy bins used for B/C ratio calculation, is given by the ratio between this number and the primary sample.

Results are summarized in table 7.5 for Boron and in table 7.6 for Carbon. N_B (N_C) is the number of Boron (Carbon) nuclei of the initial sample, N_{B_calo} (N_{C_calo}) is the fraction of N_B (N_C) detected by first Calorimeter plane.

Boron	N_B	N_{B_calo}	Efficiency	Error
0.2 - 0.4	3833	3693	0.963	0.022
0.4 - 0.6	3631	3504	0.965	0.023
0.6 - 0.8	2944	2866	0.974	0.026
0.8 - 1.0	2297	2245	0.977	0.029
1.0 - 2.0	5304	5170	0.975	0.019
2.0 - 3.0	1440	1416	0.983	0.037
3.0 - 4.0	534	521	0.976	0.060
4.0 - 6.0	402	395	0.983	0.070
6.0 - 10.0	192	188	0.98	0.10
10.0 - 25.0	105	104	0.99	0.14

Table 7.5: First plane Calorimeter Efficiency for Boron nuclei.

Carbon	N_C	N_{C_calo}	Efficiency	Error
0.2 - 0.4	3799	3695	0.973	0.022
0.4 - 0.6	3812	3724	0.977	0.023
0.6 - 0.8	3344	3249	0.972	0.024
0.8 - 1.0	2688	2633	0.980	0.027
1.0 - 2.0	6822	6712	0.984	0.017
2.0 - 3.0	1843	1816	0.985	0.033
3.0 - 4.0	755	743	0.984	0.051
4.0 - 6.0	522	515	0.987	0.061
6.0 - 10.0	282	279	0.989	0.084
10.0 - 25.0	164	162	0.99	0.11

Table 7.6: First plane Calorimeter Efficiency for Carbon nuclei.

7.9 Boron to Carbon ratio results

B/C ratio values for each energy bin have been calculated taking into account the Tracker and Calorimeter efficiencies. Results are reported in table 7.7 and drawn in figure 7.14. In figure 7.15 the same data are shown together with the main experimental data existing in literature.

Energy Interval	B/C ratio to correct	$\Delta(B/C)$	B/C ratio (corrected for track)	$\Delta(B/C)$	FINAL B/C ratio (corrected for calo)	$\Delta(B/C)$
low energy						
0.2 - 0.4	0.3449	0.0073	0.292	0.012	0.294	0.015
0.4 - 0.6	0.3730	0.0085	0.306	0.013	0.310	0.017
0.6 - 0.8	0.3825	0.0096	0.323	0.015	0.323	0.019
0.8 - 1.0	0.390	0.011	0.335	0.018	0.336	0.022
1.0 - 2.0	0.3770	0.0073	0.324	0.011	0.327	0.014
2.0 - 3.0	0.345	0.017	0.289	0.022	0.290	0.027
high energy						
1.0 - 2.0	0.448	0.013	0.338	0.015	0.341	0.018
2.0 - 3.0	0.413	0.021	0.322	0.028	0.322	0.033
3.0 - 4.0	0.365	0.027	0.293	0.042	0.296	0.049
4.0 - 6.0	0.367	0.026	0.284	0.047	0.285	0.054
6.0 - 10.0	0.355	0.029	0.247	0.052	0.249	0.062
10.0 - 25.0	0.295	0.032	0.217	0.064	0.217	0.074

Table 7.7: Boron to Carbon ratio results.

In the low energy region PAMELA data seem to be in good agreement with other experimental data, while some disagreement appears at high energy. Though PAMELA data are consistent with other data inside the statistical error, the high energy measurements are systematically higher. This problem seems to be related to the not completely correct tracker information about deflection. For the intermediate bins, between 1 GeV/n and 3 GeV/n, for which both the beta and the tracker deflection methods have been used, data obtained with the first procedure are in better agreement with the other experimental data than the one calculated using Tracker deflection.

In conclusion, this is only a first analysis of the nuclear components of cosmic rays detected by the PAMELA instruments. As already mentioned at the beginning of this chapter, the development of an algorithm for the tracker optimized for nuclei is mandatory. This work is in progress. In addition the loss of Boron and Carbon nuclei in the interaction with the top of the pressurized container and the different detectors and the contribution to the Boron and Carbon fluxes coming respectively from Carbon and Oxygen breakup have to be precisely calculated using Monte Carlo simulations. Nevertheless the data obtained in the first analysis seem to be promizing.

Furthermore, the statistic will be greatly improved with the efficiencies that will be obtained using the new algorithms optimezed for nuclei track

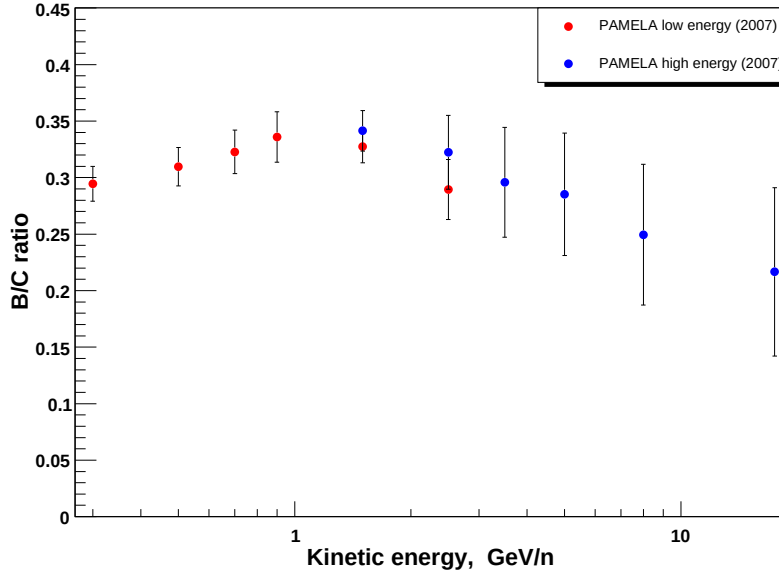


Figure 7.14: PAMELA experimental Boron to Carbon ratio values. Red markers refer to PAMELA low energy data, blue ones to high energy data.

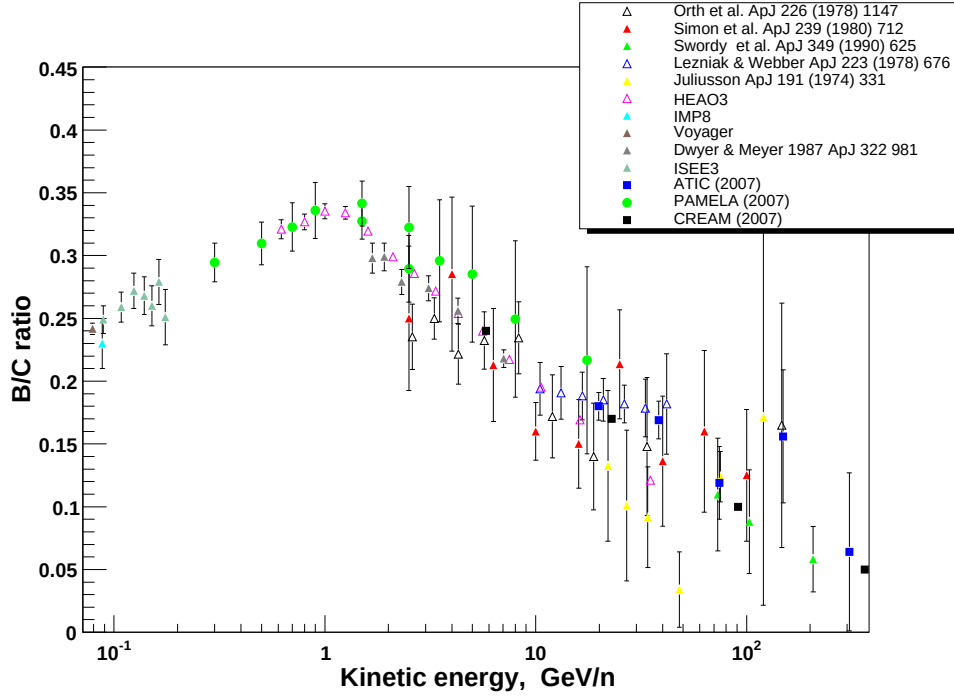


Figure 7.15: PAMELA experimental Boron to Carbon ratio values. Results from other experiments are also shown.

reconstruction and for the impact point recognition on the first layer of the the calorimeter.

Conclusions

PAMELA is a satellite-borne experiment designed for precision studies of the charged cosmic radiation. The primary scientific goal is the study of the antimatter component of the cosmic radiation (antiprotons, 80 MeV - 190 GeV; and positrons, 50 MeV - 270 GeV) in order to search for evidence of dark matter particle annihilations. PAMELA will also search for primordial antinuclei (in particular, anti-helium), and test cosmic-ray propagation models through precise measurements of the antiparticle energy spectrum and studies of light nuclei and their isotopes. Concomitant goals include a study of solar physics and solar modulation during the 24th solar minimum by investigating low energy particles in the cosmic radiation; and a reconstruction of the cosmic ray electron energy spectrum up to several TeV thereby allowing a possible contribution from local sources to be studied.

PAMELA is housed on-board the Russian Resurs-DK1 satellite, which was launched on June 15th 2006 in an elliptical (350 - 600 km of altitude) orbit with an inclination of 70.0 degrees. PAMELA consists of a permanent magnet spectrometer, to provide rigidity and charge sign information; a Time of Flight and trigger system, for velocity and charge determination; a silicon-tungsten calorimeter, for lepton/hadron discrimination; and a neutron detector. An anticoincidence system is used offline to reject false triggers. Detectors did not suffer any damage due to the launch and the experiment has been continuously taking data since then. Individual detectors are performing nominally allowing for precise measurement of cosmic-ray spectra over a wide energy range. Up to now, PAMELA has recorded the largest antiparticle statistic ever and results will be published soon.

The work presented in this thesis can be divided in two main periods: before and after launch.

About the period before the launch, I have described in this thesis the work I did in the last phases of integration and test of the apparatus, the software development, for what concern Quick Look and Data Unpacking

Software, and also the first on-ground results with the estimation of muon spectra.

After launch, the work concerned the analysis of the data collected by the PAMELA experiment during its first months of data taking. The procedures to estimate attenuation length for each single paddle for calibration of the Tof System and to evaluate trigger efficiency of the apparatus are described. Finally, I did a first analysis on B/C ratio in the energy range from 200 MeV/n up to 25 GeV/n. This item has a physical importance for the understanding of propagation phenomena: it could put constraints to propagation parameters of cosmological models and, as a consequence, to make more easily visible a possible small contamination from primary sources in antiprotons and positrons spectra.

This work will be improved in the next future.

Appendix A

PAMELA Trigger Configurations

The active PAMELA acquisition mode is defined in the on-board acquisition software running on PAMELA PSCU with a specific variable.

There are two acquisition modes: A and B. One, B, for the acquisition inside high radiation environments such as belts and South Atlantic Anomaly and one, A, outside. The acquisition modes defines the trigger configuration and their values can be changed from ground with dedicated commands to the PSCU.

There are 31 trigger configurations from which to choose:

TRIGGER_CONF_01 $\Rightarrow$ TOF_1
TRIGGER_CONF_02 $\Rightarrow$ TOF_2
TRIGGER_CONF_03 $\Rightarrow$ TOF_3
TRIGGER_CONF_04 $\Rightarrow$ TOF_4
TRIGGER_CONF_05 $\Rightarrow$ TOF_5
TRIGGER_CONF_06 $\Rightarrow$ TOF_6
TRIGGER_CONF_07 $\Rightarrow$ TOF_7
TRIGGER_CONF_08 $\Rightarrow$ S4
TRIGGER_CONF_09 $\Rightarrow$ CALO
TRIGGER_CONF_10 $\Rightarrow$ CALO OR S4
TRIGGER_CONF_11 $\Rightarrow$ TOF_1 OR S4
TRIGGER_CONF_12 $\Rightarrow$ TOF_2 OR S4
TRIGGER_CONF_13 $\Rightarrow$ TOF_3 OR S4
TRIGGER_CONF_14 $\Rightarrow$ TOF_4 OR S4
TRIGGER_CONF_15 $\Rightarrow$ TOF_5 OR S4
TRIGGER_CONF_16 $\Rightarrow$ TOF_6 OR S4
TRIGGER_CONF_17 $\Rightarrow$ TOF_7 OR S4
TRIGGER_CONF_18 $\Rightarrow$ TOF_1 OR CALO
TRIGGER_CONF_19 $\Rightarrow$ TOF_2 OR CALO
TRIGGER_CONF_20 $\Rightarrow$ TOF_3 OR CALO
TRIGGER_CONF_21 $\Rightarrow$ TOF_4 OR CALO

TRIGGER_CONF_22 $\Rightarrow$ TOF_5 OR CALO
TRIGGER_CONF_23 $\Rightarrow$ TOF_6 OR CALO
TRIGGER_CONF_24 $\Rightarrow$ TOF_7 OR CALO
TRIGGER_CONF_25 $\Rightarrow$ TOF_1 OR CALO OR S4
TRIGGER_CONF_26 $\Rightarrow$ TOF_2 OR CALO OR S4
TRIGGER_CONF_27 $\Rightarrow$ TOF_3 OR CALO OR S4
TRIGGER_CONF_28 $\Rightarrow$ TOF_4 OR CALO OR S4
TRIGGER_CONF_29 $\Rightarrow$ TOF_5 OR CALO OR S4
TRIGGER_CONF_30 $\Rightarrow$ TOF_6 OR CALO OR S4
TRIGGER_CONF_31 $\Rightarrow$ TOF_7 OR CALO OR S4

Appendix B

PAMELA Data Structure and Reduction

Data produced from PAMELA apparatus are written by the PAMELA Storage and Control Unit (PSCU) in its mass memory (MM), then they are downloaded toward the Resurs satellite VRL device (through the VRL adapter integrated within the PAMELA apparatus) and finally they are downlinked to the NTsOMZ ground station. Data are then processed by the RawReader (RR) software and the RR output files are subsequently used by the PAMELA Yoda manager.

B.1 Structure of data downloaded from PAMELA to VRL

For each block of 1015 bytes downloaded from PAMELA to VRL, the VRL adds an 8- byte "VRL header" and a 1-byte trailer, with the CRC code of the data block. The resulting 1024-byte structure is called "cadre" or "VRL packet" and shown in figure B.1.

A PAMELA download is formed by a number of VRL packets; for a given download, the first cadre has always its cadre number equal to 0. The number of packets forming the download, or in other words the size of the downloaded MM area for that download, can be scheduled by using a download request form. Several PAMELA downloads can be present in the VRL memory at the same time; in general one or more of these downloads are packed by the VRL within one single downlink to ground.

Note that a single downlink can also contain downloads (with formats that are different from the PAMELA ones) coming from the other detectors operating on board of the Resurs satellite (Arina and Sangur). At the NTsOMZ ground station one or more PAMELA downloads in the downlink

FF	46	D5	Route number (see sect. 3)	Cadre number (3 bytes)	CRC of data block of previous cadre (1 byte)
1015 bytes (data block from PSCU)					
					CRC of data block of this cadre (1 byte)

Figure B.1: "VRL packet" format.

are grouped together and saved as a "PAMELA download-group file" (.pam) which is then processed by RR.

B.2 How RawReader (RR) processes the PAMELA download-group files

The PAMELA download-group file is the input of RR program, which recognizes each new download in the group from the presence of a cadre number equal to 0, followed by increasing cadre numbers for the subsequent VRL packets.

The RR fills each output file with the PSCU data blocks of all the VRL packets of that download, excluding the VRL headers and CRC bytes. Only in one case a VRL packet is completely excluded from the output file, that is when the number of bytes forming that packet is different from 1024 bytes; the following VRL packet is recognized by means of its VRL header.

B.3 Structure of PAMELA mass memory (MM)

The PSCU, immediately after boot or immediately after a download, and before writing any data on its mass memory (MM), writes a route number in the MM, with the following 64 bytes structure ("route header"): 3 not significant bytes, followed by 61 bytes each reproducing the route number. The route number is automatically increased by one each time it is written; the route number ranges cyclically from 0 to 255.

The PAMELA MM (2 GB) is structured as a circular buffer, where data are sequentially written by the PSCU; when the last MM location is reached, writing starts again from the first location. The same considerations are true for the download (reading) of MM to the VRL. After boot of PSCU, when a

given location has been written, it is not possible for the PSCU to overwrite its content again (after a complete loop over the MM circular buffer) until this is downloaded to the VRL.

In principle each download from the MM to the VRL should begin in correspondence of a 64-byte "route header" (first thing to be written after boot or after download) and end in correspondence of the last written location; the next download then starts from the MM location immediately following the last downloaded one (with the beginning of the new "route header").

Statistical uncertainty in trigger efficiency measurement

The present appendix contains a discussion of the method adopted in chapter 6 for the determination of the statistical uncertainty in the measurement of the trigger efficiencies for the TOF system of PAMELA.

Considering for example a scintillator strip of the TOF system and a sample of N events, characterized by the presence of a charged particle crossing the strip, the fraction N_{ok} , for which the strip has produced an event signal, is expected to follow a binomial distribution:

$$B(N_{ok}, \epsilon) = \frac{N!}{N_{ok}! \cdot (N - N_{ok})!} \cdot \epsilon^{N_{ok}} \cdot (1 - \epsilon)^{(N - N_{ok})} \quad (C.1)$$

where the efficiency ϵ ($0 < \epsilon < 1$) is defined as the probability that the strip, crossed by an ionizing particle, generates an event signal. The binomial distribution is discrete, limited ($0 \leq N_{ok} \leq N$) and asymmetric with respect to the most probable value of N_{ok} , equal to the integer part of $\epsilon \cdot (N + 1)$ ¹.

For a measured value N_{ok}^{meas} , the best estimate of the efficiency is given by $\epsilon_{meas} = N_{ok}^{meas}/N$, for which N_{ok}^{meas} is the most probable value of the corresponding distribution $B(N_{ok}, \epsilon_{meas})$.

The statistical uncertainty associated with the efficiency measurement is represented as a confidence interval at a specified confidence level (for example at the 68%), according to a general procedure first introduced by Neyman [121, 113]. The confidence interval includes all the physically allowed values ϵ , on both sides of the best estimate ϵ_{meas} , that satisfy the following condition:

- given the distribution of probability for N_{ok} with parameter ϵ , $B(N_{ok}, \epsilon)$, the measured N_{ok}^{meas} is contained in the interval of values contributing

¹For $\epsilon = 1$, a degenerate distribution $B(N_{ok}, 1)$ is expected, which is 0 for $0 \leq N_{ok} \leq N$ and 1 for $N_{ok} = N$. The most probable value for N_{ok} is N in this degenerate case.

to 68% of the total probability; this interval of values of N_{ok} is known as the acceptance interval for the considered ϵ .

Note that according to this definition the acceptance interval is not unique; a coverage condition must also be specified for its construction.

A usual practice for the determination of the confidence interval is to approximate the binomial distribution with a Poisson distribution (discrete and asymmetric, but with no upper limit) or more commonly with a Gaussian one (continuous, symmetric and unlimited):

$$G(N_{ok}, \epsilon) = \frac{1}{\sqrt{2\pi}\sigma} \cdot \exp \left[-\frac{(N_{ok} - N_{ok}^{mp}(\epsilon))^2}{2 \cdot \sigma^2} \right] \quad (C.2)$$

where the parameters of the Gaussian distribution are given by [122]:

$$N_{ok}^{mp}(\epsilon) = \epsilon \cdot N \quad \sigma(\epsilon) = \sqrt{N \cdot \epsilon \cdot (1 - \epsilon)} \quad (C.3)$$

where the parameter N_{ok}^{mp} is real. With this approximation and with a symmetric coverage condition for the construction of the acceptance interval around $N_{ok}^{mp}(\epsilon)$, the obtained confidence interval (at the 68% level) is centered on ϵ_{meas} with length given by twice the quantity² (see also figure C.1):

$$\Delta\epsilon = \frac{\sigma(\epsilon_{meas})}{N} = \sqrt{\frac{1}{N} \cdot \frac{N_{ok}^{meas}}{N} \cdot \left(1 - \frac{N_{ok}^{meas}}{N}\right)} \quad (C.4)$$

The advantage of the Gaussian approximation is the possibility of using this analytical relation to determine the confidence interval, avoiding a numerical calculation. On the other hand this simplified approach is physically consistent only when the set of values of N_{ok} characterized by a non-negligible probability, according to the Gaussian distribution $G(N_{ok}, \epsilon_{meas})$, is contained in the allowed interval $0 \leq N_{ok} \leq N$ (in a typical efficiency measurement the critical condition to be satisfied is $N_{ok} \leq N$, since $\epsilon_{meas} \cong 1$). This can be obtained by requiring, for example, that only 2.3% or less of the Gaussian-distributed values of N_{ok} are greater than N , or equivalently, for the properties of the Gaussian function, that $N_{ok}^{meas} + 2 \cdot \sigma(\epsilon_{meas}) \leq N$, which for $\epsilon_{meas} < 1$ implies:

$$N > 4 \cdot \frac{\epsilon_{meas}}{1 - \epsilon_{meas}} \quad (C.5)$$

while for $\epsilon_{meas} = 1$ the condition can never be satisfied.

In the analysis of trigger efficiencies discussed in chapter 6, there condition C.5 is always verified thanks to the high statistic collected by the apparatus.

²It is implicitly assumed that it is possible to neglect the variation of (with ϵ within the confidence interval; this is correct in practical cases, for which $\Delta\epsilon$ is much smaller than ϵ_{meas}).

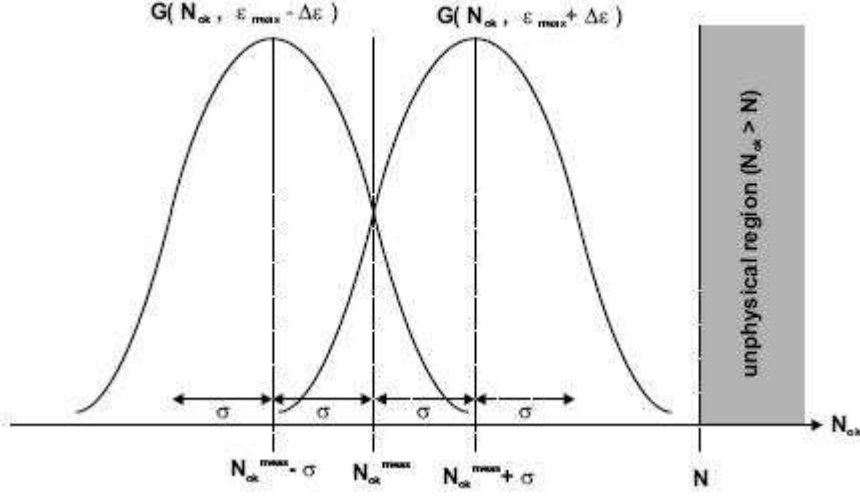


Figure C.1: Determination of the 68% confidence interval for the Gaussian probability distribution C.2. The distribution $G(N_{ok}, \epsilon_{meas} + \Delta\epsilon)$ (at right), with the corresponding acceptance interval (at the 68% level) centered in $N_{ok}^{meas} + \sigma$ and of amplitude twice the value of σ , characterizes the upper limit of the confidence interval, $\epsilon_{meas} + \Delta\epsilon$; a similar consideration holds for the lower limit $\epsilon_{meas} - \Delta\epsilon$.

From the above observations it can be concluded that in this situation, with high measure efficiencies but also with high statistical samples, the approximation with an unlimited (Poisson or Gaussian) distribution guarantees a correct evaluation of the confidence interval and that a numerical calculation, starting from the binomial distribution, is not necessary.

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