Measurement of the He nuclei flux at high energies with the PAMELA experiment

N. Mori[*], O. Adriani[†*], G. C. Barbarino[‡§], G. A. Bazilevskaya[¶], R. Bellotti[‖], M. Boezio[††], E. A. Bogomolov[‡‡], L. Bonechi[†*], M. Bongi[*], V. Bonvicini[††], S. Bottai[*], A. Bruno[‖**], F. Cafagna[‖], D. Campana[§], P. Carlson[xiii], M. Casolino[x], G. Castellini[xiv], M. P. De Pascale[xxii], G De Rosa[§], N. De Simone[xxii], V. Di Felice[xxii], A. M. Galper[xi], L. Grishantseva[xi], P. Hofverberg[xiii], S. V. Koldashov[xi], S. Y. Krutkov[‡‡], A. N. Kvashnin[¶], A. Leonov[xi], V. Malvezzi[x], L. Marcelli[x], W. Menn[xv], V. V. Mikhailov[xi], E. Mocchiutti[††], G. Osteria[§], P. Papini[*], M. Pearce[xiii], P. Picozza[xxii], M. Ricci[xvi], S. B. Ricciarini[*], M. Simon[xv], R. Sparvoli[xxii], P. Spillantini[†*], Y. I. Stozhkov[¶], A. Vacchi[††], E. Vannuccini[*], G. Vasilyev[‡‡], S. A. Voronov[xi], Y. T. Yurkin[xi], G. Zampa[††], N. Zampa[††], and V. G. Zverev [xi]**

[*] *INFN, Sezione di Florence Via Sansone 1, I-50019 Sesto Fiorentino, Florence, Italy*
[†] *University of Florence, Department of Physics, Via Sansone 1, I-50019 Sesto Fiorentino, Florence, Italy*
[‡] *University of Naples "Federico II", Department of Physics, Via Cintia, I-80126 Naples, Italy*
[§] *INFN, Sezione di Naples, Via Cintia, I-80126 Naples, Italy*
[¶] *Lebedev Physical Institute, Leninsky Prospekt 53, RU-119991 Moscow, Russia*
[‖] *University of Bari, Department of Physics, Via Amendola 173, I-70126 Bari, Italy*
[**] *INFN, Sezione di Bari, Via Amendola 173, I-70126 Bari, Italy*
[††] *INFN, Sezione di Trieste, Padriciano 99, I-34012 Trieste, Italy*
[‡‡] *Ioffe Physical Technical Institute, Polytekhnicheskaya 26, RU-194021 St. Petersburg, Russia*
[x] *INFN, Sezione di Roma "Tor Vergata", Via della Ricerca Scientifica 1, I-00133 Rome, Italy*
[xi] *Moscow Engineering and Physics Institute, Kashirskoe Shosse 31, RU-11540 Moscow, Russia*
[xii] *University of Rome "Tor Vergata", Department of Physics, Via della Ricerca Scientifica 1, I-00133 Rome, Italy*
[xiii] *KTH, Department of Physics, AlbaNova University Centre, SE-10691 Stockholm, Sweden*
[xiv] *IFAC, Via Madonna del Piano 10, I-50019 Sesto Fiorentino, Florence, Italy*
[xv] *Universität Siegen, D-57068 Siegen, Germany*
[xvi] *INFN, Laboratori Nazionali di Frascati, Via Enrico Fermi 40, I-00044 Frascati, Italy*

***Abstract*. The PAMELA experiment is a satellite-based apparatus launched in June 2006. Its core instrument is a magnetic spectrometer, whose high spatial resolution (~ 3 micron) provides the discriminative power to separate particles and antiparticles. It can measure the momentum and the energy-loss rate of an incident particles, thus allowing to identify higher charges (up to $Z \simeq 5$). The main goal for PAMELA is a precise measurement of the light antimatter component in cosmic rays (antiprotons, positrons), with unprecedented statistics and over a largely unexplored energy range. The instrument characteristics and the large statistics allow to precisely measure absolute fluxes for various cosmic-ray species up to high energy. Here the He flux analysis above some GeV is presented.**

***Keywords*: satellite detector, helium, absolute flux.**

I. INTRODUCTION

Launched in June 2006, the satellite-based PAMELA experiment (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) [1] is aimed at observing the various components of the cosmic ray spectra, with particular focus on antimatter particles (antiprotons and positrons). It is in continuous data-taking since the launch, so the high statistics combined with the absence of systematics due to the atmosphere can provide data with unmatched quality about a large and largely unexplored energy range.

Figure 1 provides a schematic representation of the PAMELA experiment. The core detector is a tracker (TRK) composed of six double-sided microstrip silicon layers, placed inside a magnetic cavity (which provides an average magnetic field $B \simeq 0.43\,T$; the combination of tracker + magnet is referred to as the magnetic spectrometer). The microstrips on one side of a layer are orthogonal to those on the other side, so each layer can provide both an X and a Y measure; the spatial resolution of the tracker is about $3\,\mu m$ in X and $12\ \mu m$ in Y. The spectrometer provides the particle-antiparticle discrimination power to the apparatus. To separate hadrons from leptons, a segmented, sampling electromagnetic calorimeter (CALO) is placed below the spectrometer. It consists of 22 modules composed by a central tungsten absorber between two sensitive silicon strip layers, whose implantation pitch is $\simeq 2.4\ mm$. This fine segmentation allows to precisely reconstruct the shower spatial development. Six layers of plastic scintillators arranged in three planes constitute the time-of-flight (TOF) system (layers belonging to i-th plane are referred to as Si1 and Si2, the latter on the bottom of the former). This detector provides the on-board trigger and a measure of the velocity of the incoming particle, thanks to an uncertainty in determining the instant of particle crossing on a plane of the order of 250 ps. The velocity measure is also used to reject *albedo* particles (ie., particles entering from below). An anti-coincidence (AC) system made also by plastic scintillators is used to reject those particles entering in the instrument from outside the acceptance. Other detectors are a shower-tail catcher scintillator (S4) and a neutron detector who can help the calorimeter in separating hadrons from leptons.

PAMELA is mainly focused on antimatter. The first scientific results published by the PAMELA Collaboration are the measurement of the antiproton-to-proton ratio [2] and of the positron fraction [3] in cosmic rays up to ~ 100 GeV. These raised great interest in the scientific community since they show a significant excess of the positron fraction at high energies respect to the expected value for a pure secondary production, while no antiproton excess is observed.

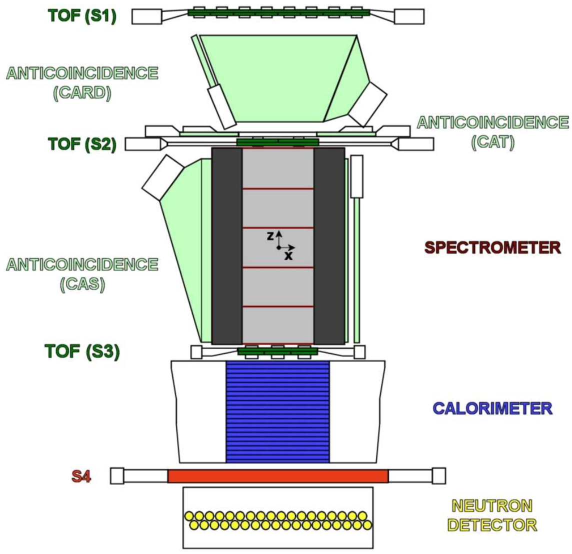

Fig. 1. the PAMELA experiment. From top to bottom, the first two TOF planes (S1 and S2) interleaved by the first module of the AC system (CARD), the magnetic spectrometer surrounded by the second AC device (CAS), the third TOF plane (S3), the imaging calorimeter, the bottom scintillator (S4) and the neutron detector. Total height is 1.3 m, weighting 470 kg. Average power consumption is 355 W.

II. Absolute fluxes with PAMELA

Thanks to the high number of events collected, PAMELA can also provide very accurate results for the absolute fluxes of the various cosmic rays components. To fully exploit the benefits of the high statistics it is necessary to carefully estimate the systematics introduced by the analysis. An accurate estimation of the efficiencies of the selection criteria is therefore mandatory.

In the present analysis, the chosen procedure is to use only those selection cuts whose efficiency can be measured using flight data. Simulations are used only when no other option is viable; no test beam data or ground calibration will be used (efficiencies from simulations will however be used to cross-check the proposed method). Doing so, the systematics due to the unavoidable limited accuracy of the simulation are greatly reduced, when not completely eliminated; furthermore, possible variations of the in-flight experimental setup with respect to the on-ground one can be taken into account. The possibility of relying only on flight data to estimate the efficiencies is thanks to the redundancy of the PAMELA detectors: independent detectors can be used to select a sample of events that can be clearly identified. This identification do not make use of the informations from the detector under study, so it can be used to measure the detector's efficiency in selecting that kind of events. Such a sample is referred to as a clean, unbiased efficiency sample. Likewise, the sample of selected events from which the flux will be estimated will be called the flux sample.

III. Selection of the events

A first event selection is done to reject corrupted data, ie., badly transmitted packets of events. Next, some criteria on the physical quality of the events are applied; first of all, no hit on the AC system is allowed, thus rejecting particles entering the instrument outside the acceptance. Only one physical track inside the tracker is allowed (thus rejecting multi-particle and fragmentation events). A χ^2 selection, designed to have an energy-independent efficiency, on the reconstructed track is then made; to reject albedo particles a positive value of β is required. The South Atlantic Anomaly is a high-radiation environment, which can create potential problems with the trigger efficiency (on-board trigger is based on TOF measurements): to eliminate it, only events observed in points of the orbit where the geomagnetic field was greater than 0.28 gauss are kept. These criteria will provide a very basic rejection of bad or unclear events; currently, studies are ongoing to define a complete set of cuts which will give a good efficiency and rejection power for flux sample selection, and also a set of cuts for selecting clean efficiency samples.

IV. Helium flux

After selecting events as described in the previous section, helium nuclei have to be separated from the other components of the cosmic-ray spectrum. Helium

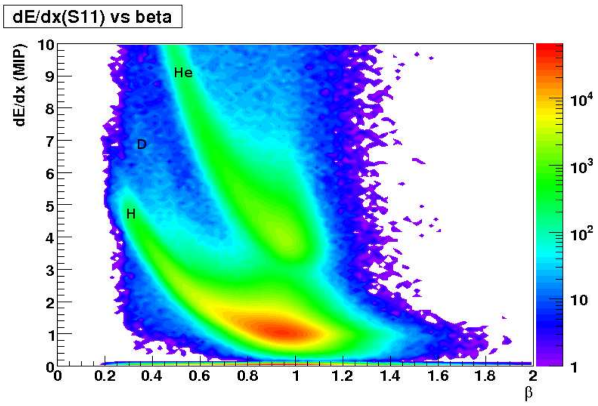

Fig. 2. plot of dE/dx (normalized to the energy release of a minimum ionizing proton) measured by the first layer of the ToF (S11) versus $\beta = v/c$. The data are relative to the period 1 Jan - 28 Feb 2007.

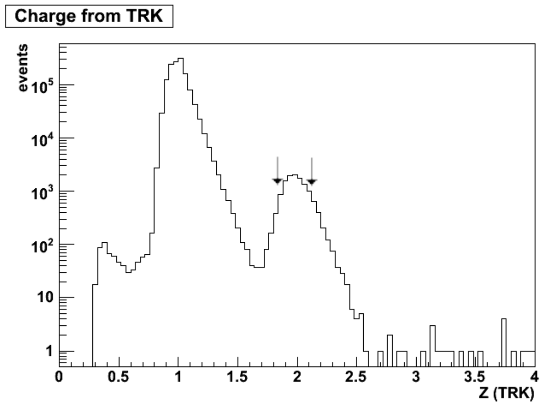

Fig. 3. the charge for a sample of events of all energies obtained from the informations provided by the tracking system, before any He selection. The arrows indicate the limits of the selected region around the peak.

is a fairly common particle in cosmic rays; it accounts for about 10% of the total flux. To identify it, a very straightforward way is to look for energy release: the mean energy loss of a charged particle traversing a thin layer of matter as a function of $\beta = v/c$ is described by the Bethe-Bloch equation, which gives a scaling with the particle's charge Z as Z^2. It gives also a mild mass dependence, allowing in some cases to separate isotopes at low energies. The ability of PAMELA to discriminate helium from protons is summarized in fig. 2.

There, dE/dx is the energy release per unit path length in traversed material. Protons and helium are clearly distinguishable; also the low-β tail of deuterium is visible. Note that for relativistic particles the energy release of He is about four times that of protons, in agreement with Bethe-Bloch formula. To reject protons and heavier nuclei from the He flux sample is therefore possible to cut on dE/dx Vs. β. To evalute the efficiency of such a selection cut is necessary to have a clean, unbiased efficiency sample of events made exclusively by He. This can be selected exclusively from flight data thanks to the other, independent detectors of PAMELA. Both the magnetic spectrometer and the imaging calorimeter are able to measure dE/dx; the spectrometer also provides a measure of the rigidity of the particle, defined as $R = p/(Zc)$, which can be used as a kinematical parameter to replace β in the selection criteria. So there are many possibilities: one can select He nuclei using ToF dE/dx Vs. ToF β and evaluate its efficiency with an efficiency sample selected using TRK dE/dx Vs. TRK R, or vice-versa. Another possibility is to select the flux sample with CALO dE/dx Vs. ToF β and the efficiency sample with TRK dE/dx Vs. TRK R, and so on. The independent, redundant information from every detector allows many combinations of flux - efficiency selection cuts. This analysis uses the TRK dE/dx Vs. TRK R to select the flux sample and ToF dE/dx Vs. ToF β to select a clean and independent He sample to measure the efficiency of the flux selection cuts.

A. *Flux sample*

The tracking system can provide the necessary information to identify helium nuclei.

Fig. 3 shows the charge obtained for a sample of events using TRK dE/dx Vs. TRK R. No helium selection cuts have been applied. Particles with unitary charge (protons, electrons, pions) dominate the spectrum, but a small fraction of helium is visible. A candidate flux sample is obtained by cutting the distribution at 1.5σ from the He peak. This sample still suffer from contamination, mainly due to protons with high energy release. The energy lost by a charged particle in a thin layer of matter follows a Landau distribution, whose peak is slightly below the Bethe-Bloch mean release. So a small fraction of protons in the tail of the Landau distribution can mimick the behaviour of a helium nuclei by releasing an inusually high amount of energy. Since protons are ~ 9 times the alpha particles, this can result in a significant contamination, which has to be estimated. A first extimate is given below. Heavier nuclei can similarly contaminate the helium sample, by means of smaller-than-normal releases. However, since the mean energy release scales as Z^2, the fraction of these events should be very small. Moreover, particles with $Z \geq 3$ in cosmic rays are much less than alpha particles. So this contamination is neglected in first approximation, and its extimation is postponed to future refinements of the analysis.

B. *Efficiency estimation*

To select a clean, independent, unbiased sample of He to estimate the efficiency of the selection cut based on tracker's information, the time-of-flight system can be used. Its six planes provide six independent measurements of the particle's dE/dx. By requiring that all the six planes give a charge consistent with that of an alpha particle one can greatly reduces the possibility that a proton could be mis-identified as an alpha. For this being, the proton should have a helium-like release

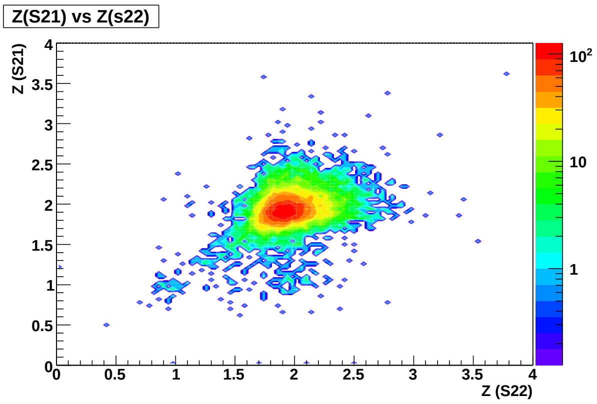

Fig. 4. the correlation of particle's charges measured in the two ToF layers S21 and S22 for the He flux sample.

in all the six layers; considering the six charges measured from ToF layers as independent from each other, the mis-identification probability is the sixth power of the probability of an unusually-high, He-like energy release in a single layer, which is already small. So the ToF charge selection can be considered as "clean", in first approximation. The efficiency of the tracker charge identification can then be measured using this "clean sample"; the measured efficiency is about 0.85. However, the charge identification routines still have to be calibrated and tweaked, so this value is likely to increase in future analysis. Also, simulations will be very useful in evaluating the residual contamination.

C. *Proton contamination*

As said above, the flux sample selected with the tracker suffers from proton contamination. This can be seen in fig. 4: the flux sample contains a clump of clearly identified alpha particles, but also some clearly identified protons, plus other uncertain events classified as protons by one layer and as helium by the other.

The ToF can be used to give a first extimation of the proton contamination in the flux sample. A more refined result can be obtained by complementing the ToF informations with simulations.

V. Conclusions

The PAMELA experiment so far has collected a high number of events, which can give very nice results for flux measurements of the various components of the cosmic ray spectrum. In doing so, it is necessary to carefully evaluate the efficiencies of the selection cuts and the remaining contaminations, to reduce the systematics as to exploit the full statistics.
The helium flux measurement can rely on the ability of the PAMELA detectors to provide independent measurement of the charge of a particle traversing the acceptance of the apparatus. This characteristics allows to measure the efficiency of the selection cuts directly from flight data, which is the chosen approach of this analysis. The time-of-flight system can give a high rejection factor against protons thanks to its six independent energy release measurements, so it is well suited to select clean efficiency samples for a flux selection cut based on the tracker's information. It can also serve to give a first extimation of the residual proton contamination in the flux sample. Further refinements can rely on the additional informations provided by the calorimeter, which can be of great help in separating protons from helium. Further investigations along this directions are ongoing, as well as measurements of the efficiencies for the other selection cuts. The results of these studies will be presented at the Conference.

References

[1] P. Picozza et al., *PAMELA: A Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics*, Astropart.Phys.27:296-315,2007 (arXiv:astro-ph/0608697)
[2] O. Adriani et al., *A new measurement of the antiproton-to-proton flux ratio up to 100 GeV in the cosmic radiation*, Phys.Rev.Lett.102:051101,2009 (arXiv:0810.4994 [astro-ph])
[3] O. Adriani et al., *An anomalous positron abundance in cosmic rays with energies 1.5.100 GeV*, Nature 458:607-609,2009 (arXiv:0810.4995 [astro-ph])