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Imaging dark matter with the Pamela experiment

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Abstract

The search for dark matter is a fundamental issue for astroparticle physics. A satellite-borne experiment ('Pamela') is under construction and will study cosmic rays whilst executing a polar orbit at an altitude of 690 km. The experiment comprises a transition radiation detector; a magnetic spectrometer, incorporating silicon tracking and surrounded by an anti-coincidence shield; an electromagnetic imaging calorimeter and a time-of-flight trigger system. This combination of detectors is particularly apt for the study of the antiproton component of cosmic rays from 100 MeV up to a few 100 GeV and will provide important new information for dark matter searches. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

In recent years, observations of the rotational velocity of galaxies have indicated that approximately 90% of the mass of a typical galaxy is 'dark', i.e. it neither emits nor absorbs radiation [1]. There are several prominent candidates for dark matter. Known astronomical objects, such as low mass stars of standard baryonic composition, have been proposed and are studied using gravitational micro-lensing. It is generally accepted that only 25%–50% of required dark matter can be accounted for in this way. Standard Model neutrinos have long been a popular choice for a non-baryonic particle explanation of dark matter. The contribution from this source is likely to be small if reported claims for massive neutrinos are correct as masses less then 1 eV appear to be favoured [1]. Furthermore, it is problematic to reconcile large scale galactic structure with neutrino dominated dark matter. A prominent but as yet unobserved candidate for particle dark matter is the supersymmetric neutralino.

Neutralinos are Majorana particles and can thus annihilate in the galactic halo. Annihilations can result in the production of antiprotons through processes such as $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow$ q, g, gauge boson, MSSM (Minimal Supersymmetric Standard Model) Higgs Boson [2]. These antiprotons can then be detected as part of the cosmic radiation. The dominant production mechanism for cosmic ray antiprotons is secondary through the interaction of primary cosmic rays (protons or alpha particles) with the interstellar gas. This results in a well

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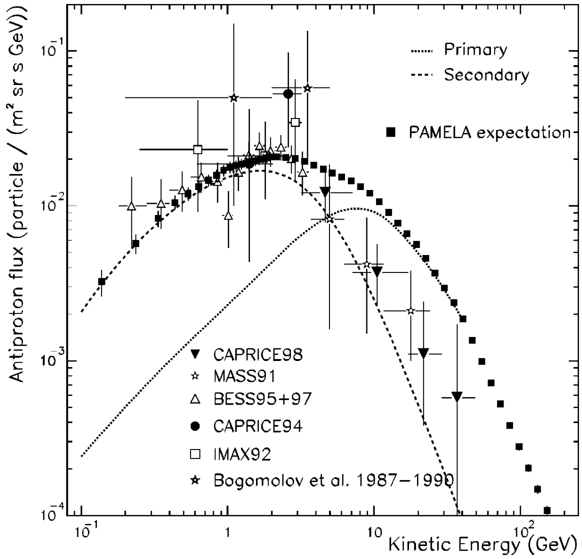

Fig. 1. Distortion to the spectrum of secondary antiprotons from neutralino annihilations. Adapted from [8] and [9]. The CAPRICE98 ratios [4] have been converted to fluxes using the CAPRICE94 proton fluxes [10] and the appropriate geomagnetic cut-off. The squares indicate the precision of Pamela measurements after a three year mission.

understood antiproton energy spectrum. An exotic source of antiprotons would cause a distortion to this spectrum, as shown in Fig. 1 for one possible model of neutralino annihilation based on the MSSM. This particular model predicts a high mass neutralino (~ 1 TeV). The annihilation signal greatly exceeds the background from secondary production above approximately 20 GeV. Since the first observation [3] of cosmic ray antiprotons, there have been several experiments measuring their energy spectrum ([4] and references therein). These observations are limited by statistics and energy range, so the antiproton spectrum has only been reliably determined below 4 GeV [5].

This paper focuses on the detection of high energy antiprotons from neutralino annihilations using a forthcoming astroparticle physics experiment called Pamela.

2. The Pamela experiment

Pamela will be launched onboard the Resurs-01 N5 satellite early in 2003. The satellite will execute a sun-synchronous polar orbit (98°) at an altitude of 690 km. With these orbital parameters, a total mission lifetime exceeding three years is expected. Once in orbit Pamela will always face directly away from the earth.

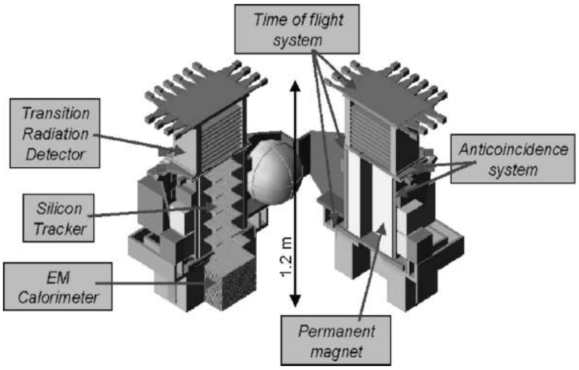

Fig. 2. An overview of the subsystems of the Pamela experiment.

An overview of the Pamela experiment is shown in Fig. 2. Pamela comprises of five main subsystems [6]. The first layer of Pamela is formed by a Transition Radiation Detector (TRD) which allows electron–hadron separation. The TRD consists of nine planes of Xe/CO_2 filled straw tubes (4 mm diameter) which are interleaved with carbon fibre radiators. This structure also allows for basic track reconstruction. The next layer is a magnetic spectrometer which allows measurements of rigidity[1] and is made up from 5 Nd–B–Fe permanent magnet segments which give a bore field of 0.4 T. Six planes of 300 μm thick double-sided silicon detectors are located in the magnetic cavity. A resolution of at least 4 μm in the bending view dictates the maximum detectable rigidity of 740 GV. The spectrometer is surrounded by a plastic scintillator based anticoincidence system with binary read-out. This allows the acceptance of the tracker to be clearly defined. A silicon–tungsten imaging electromagnetic calorimeter makes up the base of Pamela. The calorimeter has a Si-X/W/Si-Y structure, where the single-sided Si-X(Y) silicon detectors have 2.5 mm read-out strips running in orthogonal directions. There are 22 Si and 21 W layers which represent 16

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[1] Rigidity is defined as momentum divided by charge.

radiation lengths and 0.9 interaction lengths. The segmentation of the calorimeter allows the longitudinal and transverse shower profile to be reconstructed. Simulations have shown that the energy resolution for electromagnetic showers in the calorimeter is $(12 \pm 4)\%/\sqrt{E} + (0.1 \pm 0.5)\%$, where energy E is expressed in units of GeV. A time-of-flight system consisting of three layers of segmented plastic scintillator provides timing and $\mathrm{d}E/\mathrm{d}x$ measurements and defines the primary Pamela trigger. In addition, a plastic scintillator counter mounted under the calorimeter allows high energy (10^{12}–10^{13} eV) electrons to be triggered on.

Although this paper concentrates on the detection of high energy antiprotons, Pamela is also capable of a wide variety of measurements for electrons, positrons, protons and light nuclei. Also, since there is negligible geomagnetic cut-off around the polar regions, low energy particles can be studied which is important for understanding the cosmic ray solar modulation and particles from solar flares.

3. Detecting antiprotons

The Pamela apparatus is well suited for the identification of cosmic ray antiprotons and the reconstruction of their energy spectrum. The combined capabilities of the TRD, the magnetic spectrometer and the calorimeter along with the time-of-flight information permits safe identification of antiprotons against a background of electrons. Furthermore, the capability to distinguish different particles independently with different detectors allows a reliable determination of the rigidity dependent efficiency and rejection power of each detector. This is essential for a precise determination of absolute fluxes.

Down-going particles can be selected using the time-of-flight system. From this sample, charge one particles will be identified using the measured energy loss in the time-of-flight scintillators. A time-of-flight resolution of better than 180 ps, compared with a time-of-flight of about 4 ns, assures that there will be no contamination from albedo (up-going) particles. Negatively charged particles can be selected by requiring a well defined track when deriving rigidity with the tracking system. Antiprotons can then be extracted from the remaining event sample by combining information from the TRD and calorimeter. Across the whole energy range of interest, antiprotons will produce no transition radiation signal in the TRD while electrons will. An electron detection efficiency of 90% with a hadron contamination of 5% is expected for the TRD.

The final selection will be performed by the calorimeter. This type of Si-W imaging calorimeter

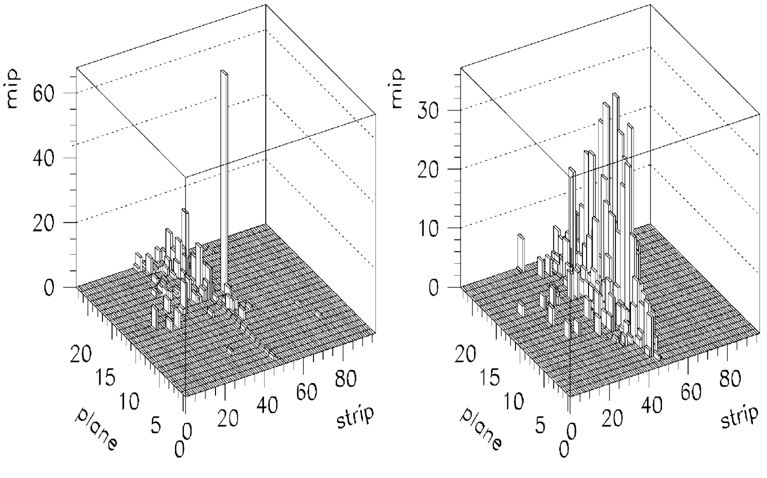

Fig. 3. Simulated longitudinal and transverse profile of the energy loss distributions in the strips of the calorimeter for a 10 GeV antiproton (left) and a 10 GeV electron (right).

has already proven able to reliably select antiprotons from a vast background of electrons in balloon-borne experiments [4,7]. The Pamela calorimeter is an expanded version of this calorimeter. Its longitudinal and transverse segmentation combined with the measurement of the energy lost by the particle in each silicon strip will allow antiprotons to be identified with an efficiency of more than 95% and a rejection factor for electrons of 10^3–10^4. The performance of the Pamela calorimeter has been studied using GEANT Monte Carlo codes which were developed from simulations of the calorimeter used in the balloon-experiments and trimmed with experimental data (e.g. [7]). Fig. 3 (left) shows a simulated 10 GeV interacting antiproton (about 70% of the antiprotons will interact in the calorimeter). The distinguishing features of the hadronic shower are evident in comparison to the electromagnetic shower induced by a 10 GeV electron which is also shown in Fig. 3 (right). It is worth mentioning that at momenta below 1 GeV antiprotons can also be identified from time-of-flight measurements.

4. Conclusions

It has been shown how the Pamela experiment will measure with an unprecedented precision the primary cosmic ray antiproton spectrum. This will allow theoretical models which predict neutralino dark matter to be thoroughly tested.

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