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Measurements of cosmic-ray antiprotons with PAMELA

J. Wu on behalf of the PAMELA collaboration[1,*]

[1]KTH, Department of Physics, and the Oskar Klein Centre for Cosmoparticle Physics, AlbaNova University Centre, SE-10691 Stockholm, Sweden
[*]On leave from School of Mathematics and Physics, China University of Geosciences, CN-430074 Wuhan, China

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Abstract. The PAMELA experiment is a satellite-borne apparatus designed to study charged particles, and especially antiparticles, in the cosmic radiation. The apparatus is mounted on the Resurs DK1 satellite which was launched on 15 June 2006. PAMELA has been traveling around the earth along an elliptical and semi-polar orbit for almost five years. It mainly consists of a permanent magnetic spectrometer, a time of flight system and an electromagnetic imaging calorimeter, which allows antiprotons to be identified from a dominating cosmic-ray background. New measurements of the cosmic-ray antiproton flux and the antiproton-to-proton flux ratio between 60 MeV and 180 GeV are presented, employing data collected between June 2006 and December 2008. Compared to previous experiments, PAMELA extends the energy range of antiproton measurements and provides significantly higher statistics. The derived antiproton flux and antiproton-to-proton flux ratio indicates that the main source of cosmic-ray antiprotons is considered to be secondary production and no primary contribution has to be invoked.

1 Introduction

Antiprotons are a rare component in cosmic-rays and have attracted much attention over the last three decades. The standard picture of antiproton production is that they are generated as a result of collisions of cosmic-ray (CR) nuclei with the interstellar medium. Detailed CR antiproton measurements can provide important information concerning CR origin and propagation. Possible exotic antiproton sources including the annihilation of dark matter (Jungman et al., 1996; Bergström, 2000; Bertone et al., 2005) and the evaporation of primordial black holes (Hawking, 1974; Kiraly et al., 1981) have also attracted much attention. After PAMELA (a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) measured a positron fraction which showed a clear deviation from secondary production models (Adriani et al., 2009a, 2010a), both astrophysical models and dark matter sources have been proposed, some of which also predict an excess in the antiproton flux. Furthermore, the PAMELA antiproton results at low energy can be used to study solar modulation (Bieber et al., 1999; Langner and Potgieter, 2004).

Since cosmic-ray antiprotons were discovered in 1979 by Golden et al. (1979) and independently by Bogomolov et al. (1979), many measurements of CR antiprotons have been performed. More than 1000 antiprotons have been collected between $0.2-4$ GeV by BESS (Yamamoto et al., 2007) while at higher energies the statistics are more limited. Three experiments measured antiprotons above 4 GeV, namely MASS91 (Basini, 1999), HEAT (Beach et al., 2001) and CAPRICE98 (Boezio et al., 2001). However, only 2 antiprotons with an energy above 30 GeV were detected. Compared to all previous experiments, PAMELA significantly increases the statistics and extends the measured energy of antiprotons to ~ 180 GeV.

2 The PAMELA instrument

PAMELA comprises several subdetectors to achieve the capability to measure charged particles in the cosmic radiation with a particular focus on antiparticles (antiprotons and positrons). Figure 1 presents a schematic overview of the PAMELA instrument and shows the location of each subdetector. The core detector of PAMELA is a 0.43 T permanent magnet spectrometer (tracker) 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 spectrometer geometry and dimensions define the overall acceptance of the experiment which is 21.5 cm^2sr. The maximum detectable rigidity

Correspondence to: J. Wu
(wu@particle.kth.se)

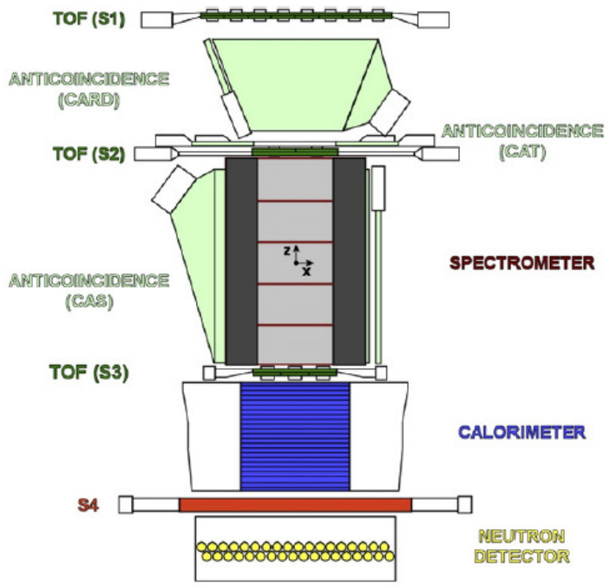

Fig. 1. A schematic overview of PAMELA instrument. The apparatus is ~ 1.3 m tall, with a mass of 470 kg (from Picozza et al., 2007).

(MDR) due to the finite spectrometer position resolution is found to be ~ 1 TV from test beams. Spillover effects limit the upper detectable antiparticle momentum to ~ 190 GeV/c (~ 270 GeV/c) for antiprotons (positrons). The spectrometer is surrounded by a plastic scintillator veto shield which can be used to reject particles not cleanly entering the acceptance. 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 (ToF) system. It provides the primary experimental trigger, identifies albedo particles, measures the absolute charge of traversing particles and also allows proton-electron separation below ~ 1 GeV/c. The volume between the upper two time-of-flight planes is surrounded by an additional plastic scintillator anticoincidence (AC) system. A plastic scintillator system mounted beneath the calorimeter aids in the identification of 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. Technical details about the entire instrument can be found in Picozza et al. (2007).

3 Antiproton identification

Results presented in this paper concern data acquired between July 2006 and December 2008 (~ 850 days). More than 10^9 triggers have been collected. A reliable clean antiproton sample was selected by a set of criteria. Since the rigidity determination is fundamental for particle identification, only events with good track quality were selected to minimize the uncertainty on the tracking fit and therefore on the rigidity measurement. The reconstructed rigidity was required to exceed the vertical geomagnetic cutoff (estimated using the satellite orbital information) by a factor of 1.3 to ensure a robust selection of galactic particles. Singly charged particles were selected using ionization losses (dE/dx) in the silicon tracker layers and in the ToF scintillator. Moreover, requiring no spurious signals in the ToF system and AC scintillators above the tracker system rejected multi-particle events inside the acceptance. Pion contamination was also significantly reduced since they are created in interactions of primary particles with the payload and thus were often accompanied by additional particles. Downward-going particles were selected by requiring positive velocity in the ToF system. A cut on the velocity of particles was used at low energy to discard particles with mass incompatible with that of proton (antiproton). The calorimeter was used to separate antiprotons from an electron background which is significantly more abundant (about 10^3 times the antiproton component). The longitudinal and transverse segmentation of the calorimeter, combined with a dE/dx measurement in each silicon strip, allowed a rejection factor of about 10^5 for electromagnetic showers (Boezio et al., 2006). The remaining electron contamination was estimated to be negligible while the contamination from pions created locally in PAMELA payload by cosmic-ray interactions was estimated to be less than 10% between 1 GV/c and 3 GV/c and negligible at other rigidities (Hofverberg, 2008; Bruno, 2008; Adriani et al., 2009b).

Surviving negatively charged particles were selected as antiprotons, while strict selections on the quality of the fitted tracks were applied to remove the oppositely charged contamination in the antiproton sample due to the spillover effect. The finite spectrometer spatial resolution makes it difficult to properly determine the sign of curvature and this causes a non-negligible background when measuring antiparticles at high energy. In addition, protons that scatter in the material of the tracking system may mimic the trajectory of negatively-charged particles. Since the number of antiprotons is about 10^{-4} times of the number of protons, the tracking quality cuts are crucial. To reduce "spillover" protons, events with bad tracking position measurements were discarded (e.g. tracks accompanied by delta-ray emission) and the MDR estimated for each event was required to be 6 times larger than the measured rigidity. This allowed the detectable energy of antiprotons to be extended to 180 GV/c with an acceptable spillover contamination. At high energy the deflection distribution before applying the MDR selection was applied to simulated data and reproduced the distribution observed in real flight data within 20%. This difference was considered as a systematic uncertainty on the spillover contamination which was estimated to be $\sim 30\%$ for the rigidity bin $100 - 180$ GV/c.

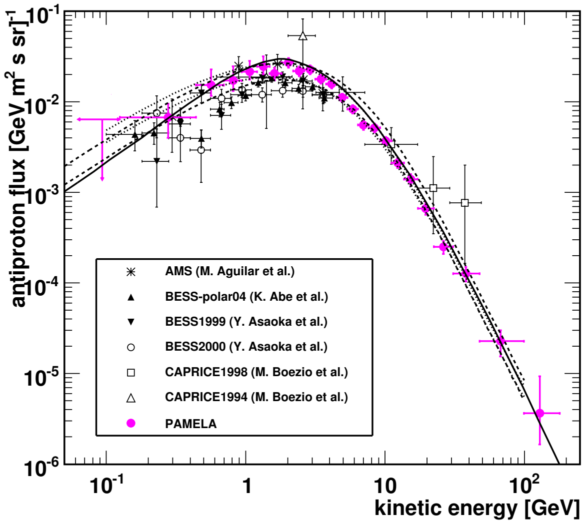

Fig. 2. The antiproton flux at the top of the payload measured by PAMELA compared with contemporary measurements (Boezio et al., 1997, 2001; Asaoka et al., 2002; Abe et al., 2008; Aguilar et al., 2002). The lines show theoretical expectation of secondary production of antiprotons. The dotted and dashed lines indicate the upper and lower limits calculated by Donato et al. (2001) for different diffusion models, including uncertainties on propagation parameters and antiproton production cross sections, respectively. The solid line represent the GALPROP prediction by Ptuskin et al. (2006) for the case of a plain diffusion model.

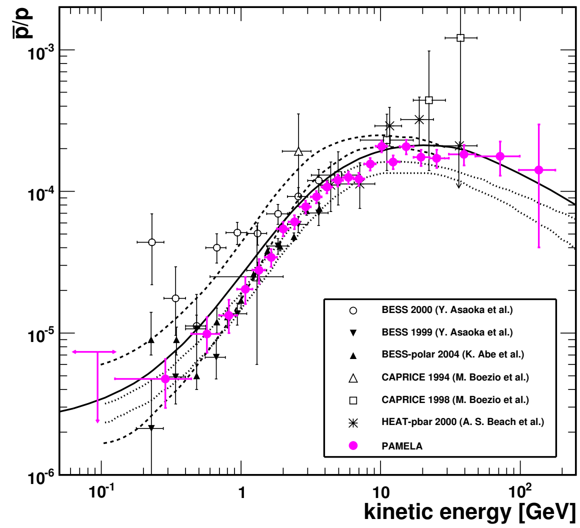

Fig. 3. The $\bar{p}/p$ ratio measured by PAMELA compared with contemporary measurements (Boezio et al., 1997, 2001; Asaoka et al., 2002; Abe et al., 2008; Beach et al., 2001). The lines show theoretical expectation of secondary production of antiprotons. The dashed lines show the upper and lower limits calculated by Simon et al. (1998) for the leaky box model, while the dotted lines show the limits from Donato et al. (2009) for a diffusion reacceleration with convection model. The solid line represents the GALPROP prediction by Ptuskin et al. (2006) for the case of a plain diffusion model.

In order to determine the antiproton flux, the selection efficiencies were estimated accurately using both flight data and simulated data (Hofverberg, 2008; Bruno, 2008; Wu, 2010). The global efficiency was measured to be about 30% and was dominated by the tracker selection. The loss of particles rejected by the selection criteria due to inelastic collisions was evaluated by simulation, varying from $\sim 10\%$ below 1 GeV to $\sim 6\%$ above 50 GeV. Energy loss was compensated for using an unfolding method based on Bayes' theorem (D'Agostini, 1995). Galactic particles discarded by the requirement on the geomagnetic cutoff were compensated for by multiplying the measured flux with the inverse of the transmission function, defined as the fraction of an orbit accessible to a cosmic ray of given rigidity. The geometric factor and the total live time were also calculated. Taking into account all these corrections, the antiproton flux was reconstructed. Comtamination from pions and spillover protons has been subtracted from the raw numbers of selected events. Systematic uncertainties refer to the acceptance, contamination, efficiencies, energy losses, hadronic interactions and spectrum resolution were taken into account and quadratically summed to derive the total systematic uncertainty.

Figure 2 shows the antiproton flux and Fig. 3 shows the antiproton-to-proton ratio measured by PAMELA together with other recent experiment data. The error-bars in the these figures are the quadratic sum of the statistical and systematic errors. The values of calculated flux can be found in Adriani et al. (2010b), as well as the antiproton-to-proton ratio. PAMELA antiproton results are consistent with other measurements but with significantly better statistics and extending to the highest energy ever achieved. The antiproton-to-proton ratio is consistent with a previously published ratio derived from ~ 500 days data collecting (Adriani et al., 2009b). The theoretical models describing pure secondary production of antiprotons are also superimposed in Figs. 2 and 3. The curves were calculated for solar minimum which is suitable for the PAMELA data taking period. Overall, the PAMELA results agree well with pure secondary models, which indicates that the antiprotons measured by PAMELA in the considered energy range originate mainly from secondary production and no exotic contribution has to be invoked. The experimental uncertainties are smaller than the spread in the different theoretical curves and can provide important constrains on parameters relevant for secondary production calculations. A primary component still cannot be ruled out considering current uncertainties on propagation parameters. For example a reasonable choice of GALPROP (Moskalenko et al., 2002) propagation parameters allows an inclusion of the 180 GeV wino-annihilation signal (Kane et al., 2009) which can both reproduce the antiproton-to-proton ratio and the positron excess measured by PAMELA. Another model which suggests that antiprotons are created as secondary products of hadronic interactions in aged SNRs (Blasi and Serpico, 2009) is also compatible with the PAMELA results. Higher energy antiproton measurements and other secondary cosmic-ray nuclei data are needed to further probe the models.

4 Conclusions

The antiproton flux and the antiproton-to-proton flux ratio over the widest energy range ever achieved have been measured by PAMELA with highly improved statistics compared to previous measurements. While PAMELA observed a dramatic rise in the positron fraction above 10 GeV, the measured antiproton results show no significant deviations from secondary production expectations. The results are sufficiently precise to place tight constraints on the propagation parameters, and can be used to study solar modulation.

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