Nuclear Instruments and Methods in Physics Research A 720 (2013) 45–48

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Dark matter search in space

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ARTICLE INFO

Available online 21 December 2012

Keywords:
Dark Matter
Cosmic Rays
Space experiments

ABSTRACT

The search of dark matter signals in space has considerably progressed in the recent years by the PAMELA space mission and the long duration flight balloon-borne BESS Polar experiments. Interesting and intriguing results have been obtained by PAMELA in the positron to electron fraction, theoretically interpreted as contributions from dark matter annihilation or nearby pulsars. More standard explanations are not excluded. The results on the antiproton flux and the antiproton-to-proton ratio obtained by PAMELA and BESS are in agreement with secondary production mechanisms. AMS-02 operating outside the ISS since May 2011 should clarify the positron fraction puzzle and open new windows in the cosmic-rays study.

1. Introduction

The most recent results in astrophysics and cosmology based on space observations strongly suggest that the energy budget of our Universe consists of only 4% of baryonic matter, while the 73% is made of an invisible and homogenous substance called "dark energy" and the 23% of "dark matter", particles not described by the Standard Model of subnuclear physics. The presence of dark matter has been inferred since the 30's of the last century from its gravitational effects on the motion of stars in the halo of the galaxies and in maintaining the stars to link together in the galaxies. However, only recent and precise astrophysical and cosmological measurements, interpreted in the context of the Big Bang theory, have definitively established the role of dark matter in the evolution of the Universe. The more promising candidates for dark matter are the WIMPs, weakly interacting massive particles with a mass in the range between tens of GeV and TeV. The most studied is the lightest neutralino χ, a linear combination of the super-symmetric partners of the neutral gauge bosons of the Standard Model. Another possible WIMP candidate is the lightest Kaluza–Klein particle in the Universal Extra Dimension framework.

A direct search for these particles is performed in underground laboratories to detect signals from weak interactions of the WIMPs with the nuclei of large mass detectors. The indirect searches, carried out in space or at the top of the atmosphere, is based on the principle that WIMPs can annihilate each other producing, through some primary annihilation channel, standard elementary particles as final state. Cosmic antimatter particles, as positrons and antiprotons, are the more studied signatures because they are produced only in small amount in the interaction of cosmic-rays with the interstellar matter, so it is easier to disentangle dark matter signals from astrophysics background. However, a complete knowledge of the standard production of antiprotons and positrons is required, as well of the mechanisms of their acceleration and transport in the Galaxy.

Several experiments, focused on antimatter detection, have been performed mainly by the WiZard, BESS and HEAT collaborations on board stratospheric balloons, and by AMS-01 on board the Space Shuttle. The core of these instruments was a magnetic spectrometer associated with some detectors for the identification of the hadronic and electromagnetic components. However, the short time in flight of these experiments limited the statistics and introduced important systematic uncertainties. New satellite and International Space Station experiments have been devised with the objective to measure at the same time and with the same instrument not only antiprotons and positrons, but also experimental parameters included in the background evaluation. PAMELA and AMS-02 are dramatically improving the indirect search of dark matter. Even BESS, an experiment on board a stratospheric balloon that flew for many days, has given interesting results.

2. PAMELA satellite experiment

2.1. The instrument

In June 2006 the PAMELA experiment was launched by a Soyuz-U rocket from the Bajkonur cosmodrome in Kazakhstan and placed in an elliptical orbit ranging between 350 and 610 km,

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http://dx.doi.org/10.1016/j.nima.2012.12.038

with an inclination of 70°. Since July 2006 PAMELA is daily delivering 16 GB of data to the Ground Segment in Moscow. PAMELA experiment is performed by an international collaboration involving Italy, Russia, Germany and Sweden. It has been mainly conceived for searching primordial antimatter, signals from dark matter annihilation, exotic matter as strangelets. PAMELA achieves also other important tasks as the study of the mechanisms of acceleration and propagation of cosmic-rays in the Galaxy, the monitoring of the cosmic-ray solar modulation and the detection of solar flares. Studies of the interaction of particles with the terrestrial magnetosphere complete the PAMELA research program.

The core of the apparatus is a magnetic spectrometer, made up of a permanent magnet and a silicon tracking system for a maximum detectable rigidity of 1.2 TV. Three double layers of segmented plastic scintillators provide timing and dE/dX measurements and define the primary PAMELA trigger. The separation between hadronic and leptonic components is made by an imaging silicon–tungsten detector and a neutron counter. The segmentation of the calorimeter allows the longitudinal and transverse shower profile to be reconstructed in a way to assure, in connection with the measurement of the momentum by the magnetic spectrometer, a rejection of protons, compared to positrons, at the order of 10^5. In addition the calorimeter permits measurements of the electron energy up to 300 GeV, with a resolution of few percent. The neutron detector, made of two layers of ^{3}He sensors, counts the number of neutrons contained in the shower produced by particles in the calorimeter and different for protons and electrons. A lateral anticoincidence system at the top of the instrument permits to reduce shower contaminations. More details on the PAMELA instrument are reported in Ref. [1].

2.2. Dark matter search

The antiproton-to-proton ratio and the antiproton energy spectrum measured by PAMELA in the interval between 60 MeV and 180 GeV are shown in Figs. 1 and 2, compared with the theoretical calculations in which pure secondary production of antiprotons by cosmic-rays in the Galaxy [2]. Data do not present features or structures expected from exotic sources, so they place strong limits to dark matter annihilation models. Moreover, they

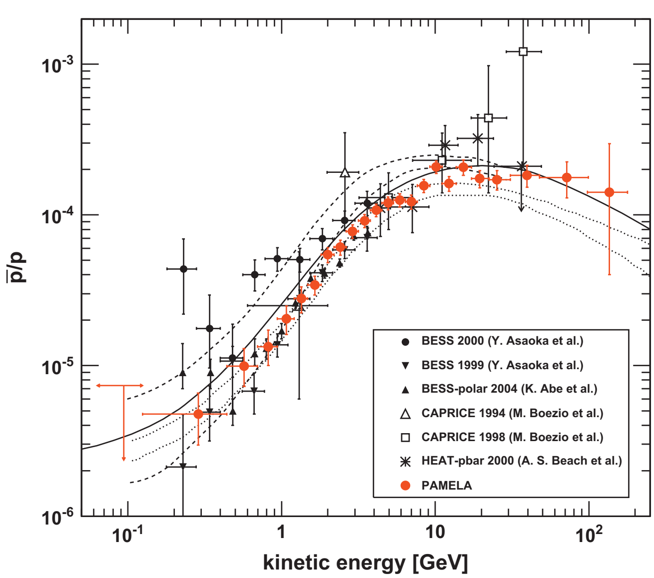

Fig. 1. The antiproton-to-proton flux ratio obtained by PAMELA compared with other measurements and theoretical calculations for a pure secondary production [2].

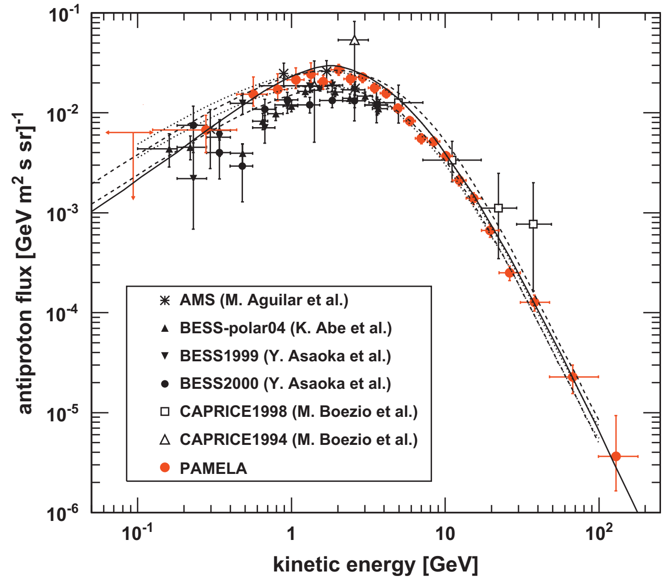

Fig. 2. The antiproton energy spectrum obtained by PAMELA compared with other measurements and theoretical calculations for a pure secondary production [2].

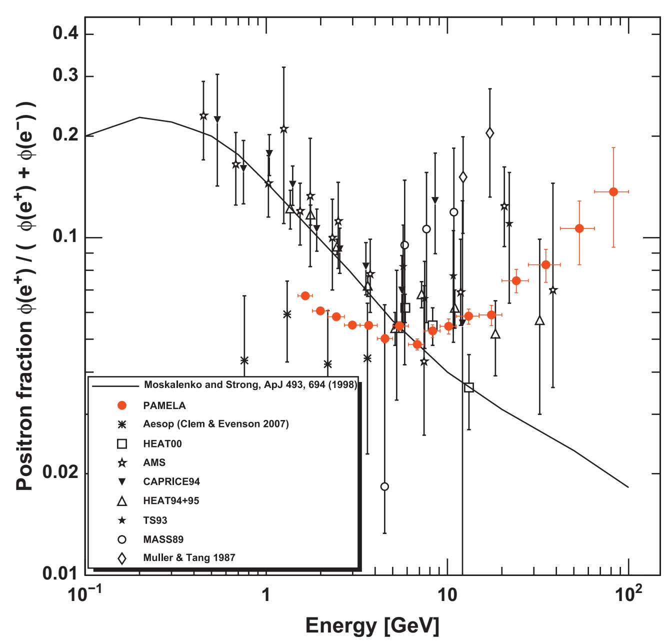

Fig. 3. The positron fraction measured by PAMELA compared with other recent experimental data [3].

set tight constraints on parameters relevant for secondary production calculations.

A great relevance was given to the results on the positron-to-all electron ratio measured by PAMELA [3], shown in Fig. 3. The data have been carefully analyzed, because the huge proton background can produce a large misidentification of protons as positrons. The matching between the momentum measured by the magnetic spectrometer, the total energy measured in the calorimeter, the starting point and the lateral and longitudinal profiles of the produced showers and the neutron detector response assured a very accurate separation between the hadronic and leptonic components.

The data, covering the energy range of 1.5–100 GeV, show two clear features. At low energies, below 5 GeV, the PAMELA results are systematically lower than the data collected in other experiments