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Viewpoint

Debating the source of a rare particle

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Many cosmologists believe that antiprotons in cosmic rays come from the annihilation of dark matter. Data from the PAMELA experiment on board a Russian satellite provide an important test of this possibility.

Subject Areas: **Particles and Fields, Astrophysics, Cosmology**

A Viewpoint on:
New Measurement of the Antiproton-to-Proton Flux Ratio up to 100 GeV in the Cosmic Radiation
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At first sight, the observation of antiprotons in the cosmic radiation that bombards the earth from space seems a little surprising: “normal” matter dominates our galaxy, at least in a domain that appears to extend out to hundreds of millions of light years from earth. But the recent space instrument PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) (Fig. 1) flown on the Russian Resurs-DK1 satellite has detected more than a thousand of these rare particles with energies ranging up to 100 GeV[1]. This sample is ten times larger than previous measurements of antiprotons at high energies and can be used to identify the possible origins of this exotic material.

One favorite theory for explaining the presence of antiparticles in cosmic rays is that they are produced in the cascades that develop when heavy dark matter particles annihilate. This interesting possibility, which would provide indirect evidence for dark matter, is very difficult to prove because antiparticles are also readily created by collisions between particles of normal matter at sufficiently high energies. The PAMELA results are consistent with the levels of antiprotons expected from collisions between high-energy protons in cosmic rays and the nuclei of hydrogen and helium atoms in the interstellar medium. As such, they provide the strongest limits to date on a possible contribution from dark matter annihilations to antiprotons.

Before the PAMELA experiments, the ratio of antiprotons to protons in cosmic rays was investigated by high-altitude balloon experiments using magnet spectrometers. The crucial experimental problem was that the ratio of protons to antiprotons is more than 10,000 to 1 at a given particle energy. Consequently, the background level of these measurements had to be kept to extremely low levels. This was very difficult on a balloon flight where the small residual atmosphere above the instrument is comparable in thickness to the average amount of material crossed by a cosmic ray during its ∼30 million year winding trajectory through our galaxy. To compound this issue there are short-lived, relatively massive particles, such as negative kaons, pions, or muons, that can be locally produced in the atmosphere and survive long enough to be collected by the instrument. Also, electrons must be adequately rejected from the sample of negative particles.

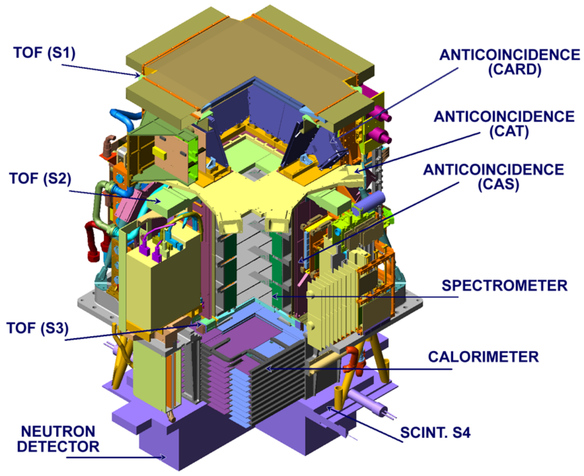

FIG. 1: The PAMELA instrument was designed to identify and measure the charged particles that are present in cosmic radiation. Combined measurements from the magnetic spectrometer, calorimeter, time of flight (TOF) system, and neutron detectors shown here distinguish the incident particles by their charge, momentum, and mass. More details can be found at http://pamela.roma2.infn.it. (Illustration: Courtesy of the PAMELA Collaboration)

What makes the interpretation of the results a little

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easier is that antiprotons have a large rest mass, so there is a kinematic threshold of ~ 1 GeV for their production by collision in the interstellar medium. This is why in the early history of the search for antiprotons of exotic origin in cosmic rays, measurements focused on low-energy antiprotons. Although several "signals" were claimed in this energy region, it is now believed that these probably resulted from different types of short-lived negative particles that are produced in the nearby atmosphere. By 1990 it was realized that the only way to successfully perform a conclusive measurement of antiprotons on balloon flights was to identify the particle mass and charge by looking at how the particle was deflected in a magnetic field. The most recent of these efforts, a Japanese–US collaboration called BESS (Balloon-borne Experiment with Superconducting Spectrometer) that performed a long duration Antarctic flight in 2004, provided the best sub-GeV antiproton balloon measurements to date and showed that the antiprotons in this energy range are consistent with production through collisions in our galaxy [2].

A significant advantage of searching for cosmic-ray antiprotons on a space platform like PAMELA is that the amount of locally produced particle background is much lower than in balloon flights. The only remaining sources of short-lived secondaries are collisions in the spacecraft or in the housing of the instrument itself. In PAMELA these levels are at only a few percent of the expected cosmic-ray antiproton flux from galactic collisions, which means measuring the particle mass is no longer necessary to determine its source. On the other hand, space instruments can't handle the large instrument mass that high-altitude balloons can, so to collect a sufficient sample of particles the space experiments must operate for several years rather than the several weeks typical of long duration balloon flights. The collecting area of PAMELA is a few hundred cm^2, which is sufficient to collect antiprotons up to energies of ~ 100 GeV in the 20-month period reported so far.

Our understanding of cosmic radiation provides a useful context for the results that are now emerging from PAMELA. The overall picture of cosmic-ray origin is that an event, presumably a supernova, accelerates particles (mainly protons and nuclei) in the galaxy to high energies. We know the population of energetic charged particles follows a more or less uniform power-law distribution up to energies near 10^{20} eV. This power law has the form $dN/dE \propto E^{-\alpha}$, where dN/dE is the intensity of particles, E is the particle energy, and the power-law index α has a value near 2.8–3.0. The details of this distribution below a few hundred MeV are unclear because the outflow of the solar wind suppresses the entry of lower energy particles into the solar system. The detailed nuclear *isotopic* composition of cosmic rays, at least in the $\sim$ GeV energy range, is similar to that of our local solar system. Interestingly the *elemental* composition is quite different, which is likely because the atomic energy levels of the particles are influential in some way during the initial stages of their acceleration.

High-energy electrons are also present in cosmic rays, but at a given energy they are 100 to 1000 times less abundant than protons. This difference is generally ascribed to radiative losses during the acceleration process. We can estimate the average amount of material (the "path length") cosmic rays pass through on their way to earth by considering the ratio of a largely "primary" element, such as carbon, to a much less abundant element, such as boron, that is similar in atomic number. (Boron is largely produced in cosmic rays through spallation reactions of carbon on the interstellar medium.) It turns out that cosmic rays at high energy have shorter path lengths than those at low energies. This is generally interpreted to imply that high-energy cosmic rays escape more easily from the galaxy than low-energy cosmic rays. A direct result of this observation is that the observed energy spectrum of cosmic rays on earth is not the source spectrum of these particles, which is expected to be significantly flatter, nearer to $dN/dE \propto E^{-2.2}$. This is an important parameterization needed to fully understand particle acceleration in supernova remnants.

In recent years the subject of cosmic-ray propagation in our galaxy has been the object of a significant numerical modeling effort [3], which aims to reconcile not just these secondary measurements in cosmic rays but also the intensity of gamma rays produced by the collisions that are observed in the galaxy. The recently published results of PAMELA offer an important advance in our understanding of cosmic rays. Since they provide measurements of antiprotons above 10 GeV they are not affected by the solar wind and are a good sample of the general cosmic-ray population in the interstellar medium. Using calculations based on the expected interstellar path lengths derived from observations of heavy nuclei, the amount of antiprotons at high energy is consistent with the values expected from secondary production by collision. There is even a hint in these data that the level of secondary production decreases at high energy—exactly what is observed for heavy nuclei. This confirms that the propagation of protons in cosmic rays is similar to heavy nuclei at high energy. While this has been suspected for many years to be the case, this is the first measurement with good enough statistics to be convincing. This agreement seems to significantly exclude exotic origins such as dark matter for these particles, since any significant contribution of antiprotons from dark matter would be expected to result in a larger amount of antiprotons than observed by PAMELA. An obvious way to further explore the propagation of cosmic rays and develop a coherent picture of this process will be to incorporate these new measurements with gamma-ray images of the galaxy from the recently launched Fermi gamma-ray satellite into numerical simulations [3]. To take the next step in the antiproton field we need measurements with better statistics at higher energy to demonstrate that the energy dependence in the escape of protons from the galaxy is similar to heavy nuclei. This can directly

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lead to the establishment of the actual source spectrum of protons—by far the most abundant cosmic-ray particles—from measurements of particles at earth.

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About the Author

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Simon Swordy has been involved in experimental research in cosmic rays and high-energy gamma rays for many years. He is currently working with the VERITAS high-energy gamma-ray telescope in Arizona. In the 1990s he was part of the HEAT balloon collaboration that made an important investigation of positron and antiproton abundances in cosmic rays at energies above 10 GeV. He received his Ph.D. from the University of Bristol in 1979 and is at present the Director of the Enrico Fermi Institute at the University of Chicago.

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