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Space-station experiment measures arriving positrons with unprecedented precision

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Space-station experiment measures arriving positrons with unprecedented precision

The excess positrons above those produced by cosmic-ray collisions may result from dark-matter annihilation or from extreme astrophysical environments.

Positrons are copiously produced in interstellar space as a result of collisions between energetic cosmic-ray nuclei and ambient gas. But recent observations show far more positrons than expected at high energies. Within the past few years, the PAMELA particle detector and the Large Area Telescope aboard the *Fermi Gamma-Ray Space Telescope* established that excess for energies above 10 GeV. Moreover, they showed that the positron fraction—the ratio of positrons to positrons plus electrons—rises with increasing energy; by the time the energy is 100 GeV, the positron fraction is many times that attributable to the well-understood cosmic-ray collisions. (For more on *Fermi*, see the article by David Thompson, Seth Digel, and Judith Racusin, PHYSICS TODAY, November 2012, page 39.)

In an experimental tour de force, the excess has now been confirmed with an order-of-magnitude improvement in precision by the Alpha Magnetic Spectrometer (AMS),[1] which has been aboard the International Space Station (see figure 1) since May 2011. Moreover, the AMS experiment, led by MIT's Samuel Ting, has extended by more than 100 GeV, to 350 GeV, the energy range over which the positron fraction is measured and has observed a flattening of the spectrum at the highest energies.

As the AMS group continues its observations over the next decade or two, it will gather enough data to further extend the energy range over which it can make precise measurements. If the slope of the spectrum becomes negative, the details of the turnover should be particularly valuable in helping scientists determine if dark-matter annihilation is the source of the positron excess or if astrophysical sources such as pulsars are the culprits. Already, the team has reported a feature of its positron measurements that may be difficult to reconcile with isolated astrophysical sources: The observed spectrum shows no evidence of anisotropy.

Off the straight and narrow

The heart of the AMS detector is a 0.14-T magnet that deflects incoming electrons and positrons in opposite directions. That differential bending allows the two oppositely charged particles to be distinguished; the bend's radius of curvature determines the particle's momentum. Of course, determining the curvature is easier said than done. At the very high energies with which positrons and electrons traverse the AMS, their paths are virtually straight lines. To determine the trajectories' tiny bend, the AMS uses silicon-strip tracker planes to precisely measure each particle's position at several points.

If positrons and electrons were the only particles entering the AMS, the magnet and tracking system would suffice to determine the positron fraction as a function of energy. In reality, some 15 000 protons and a smattering of other nuclei enter the AMS for each positron that does so. Those background particles are also highly relativistic—their kinetic energy is much greater than their rest energy. Therefore, a proton, say, with a given energy will respond to the AMS magnet in the same way as a positron; to obtain the positron fraction at its extraordinary precision, the AMS needs to reject all but 1 in 10^6 of an overwhelming number of impostor events caused by protons and heavier nuclei.

The particle rejection is accomplished with two components of the AMS: the transition radiation detector and the electromagnetic calorimeter. As shown in figure 2, those elements are the first and last modules seen by a particle traversing the AMS.

The principle behind the transition radiation detector is that charged particles moving quickly enough emit x rays when passing between mediums that have different indices of refraction. The lighter electrons and positrons are fast enough; the heavy particles, even though relativistic, don't radiate.

Before leaving the AMS, electrons and positrons deposit much of their energy in the electromagnetic calorimeter. In doing so, they generate a shower of electrons, positrons, and photons. Protons and heavier particles, by contrast, bull through the calorimeter, depositing a much smaller portion of their energy while creating their own, qualitatively different shower. The AMS recognizes an event as being caused by an electron or positron only if the energy deposit and the shower are characteristic of the lighter particles.

Figure 1. The Alpha Magnetic Spectrometer, seen mounted to the left of two solar panels, aboard the International Space Station, 29 June 2012. (Courtesy of NASA.)

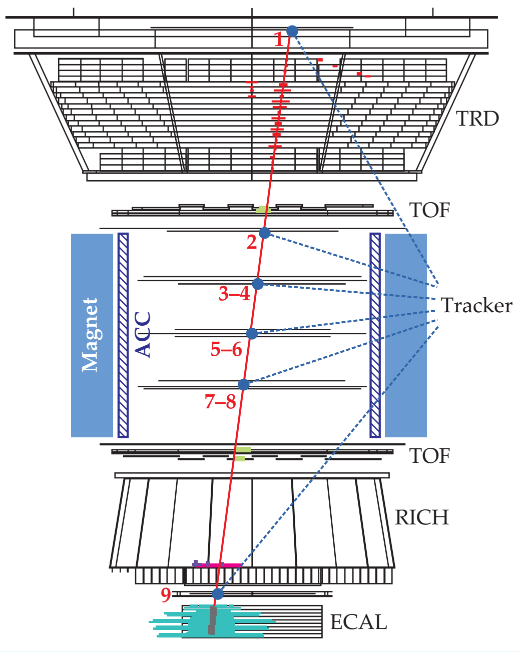

Figure 2. An electron as seen by the Alpha Magnetic Spectrometer. Although it appears straight, the 4-m-long electron track (orange) is actually slightly curved. From the nine position measurements, the experimenters can determine the curvature of the track and extract the particle's charge and momentum. Characteristic signatures of energy dumped into the transition radiation detector (TRD) and electromagnetic calorimeter (ECAL) allow electrons and positrons to be distinguished from protons and heavier nuclei. The other elements shown here, defined in the text, allow for additional charge and energy checks and ensure that particles traverse the detector from top to bottom. (Adapted from ref. 1.)

The ring imaging Cherenkov detector (RICH) and the time-of-flight (TOF) detector illustrated in figure 2 provide additional checks on particle and energy identification. In addition, the TOF detector ensures that accepted events traverse the AMS from top to bottom. Otherwise, upward-moving electrons might be identified as downward-moving positrons. The anticoincidence counter (ACC) just within the AMS magnet rejects potentially confusing events caused by particles that enter the detector from the sides.

Model behavior

As of April, the AMS collaboration had analyzed some 25 billion events of all kinds. Figure 3 shows the positron-fraction spectrum the team derived, along with data previously reported by the *Fermi* and PAMELA missions. Armed with the new data, particle and astrophysical theorists can better test their favorite models for explaining the excess positrons. Those models predict, in detail, how the positron-fraction spectrum eventually turns over. In particular, positrons produced via dark-matter annihilation cannot have an energy greater than the mass of the dark-matter particle. Thus, although observations to come will surely impose more stringent constraints, they promise to be particularly revealing if the flattening positron fraction is seen to fall off at higher energies.

Key components of dark-matter models are the mass of the dark-matter particle and the probabilities for two of them to annihilate into specific particle–antiparticle pairs. Astrophysical modeling is more open: Justin Vandenbroucke of the *Fermi* Large Area Telescope team notes that astrophysicists have much to learn about pulsars and how they might produce the particles that the AMS observed. Photon–photon interactions in the pulsar environment, for example, could produce electron–positron pairs, with the pulsar's strong electromagnetic field then accelerating the positrons to high energy. To fully explain the measured positron fraction, modelers have to know more than just how positrons and electrons are produced. They also need a thorough, detailed understanding of how the charged particles lose energy as they travel through galactic magnetic fields and radiation.

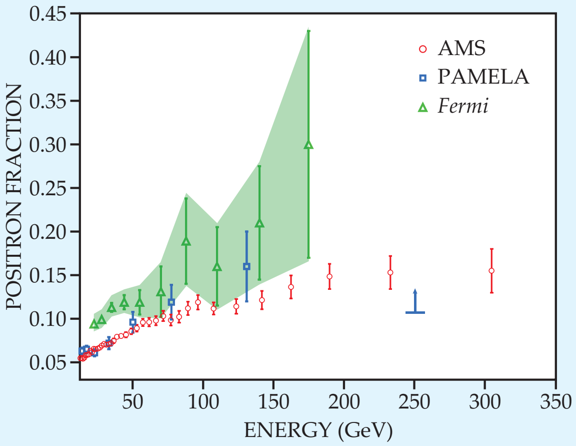

Figure 3. The positron fraction (the ratio of positrons to positrons plus electrons) as a function of energy, measured by the Alpha Magnetic Spectrometer (AMS) and the earlier PAMELA and *Fermi Gamma-Ray Space Telescope* missions. The AMS confirmed the earlier results with improved precision and observed a flattening of the spectrum at previously inaccessible high energies. At energies above 100 GeV, cosmic-ray collisions contribute less than 0.02 to the measured positron fraction. (Courtesy of Samuel Ting.)

Because of that energy loss, particles that reach the International Space Station with energies of 100 GeV or so must have been created within roughly 3000 light-years of Earth. (The Milky Way is about 100 000 light-years in diameter.) For that reason, the AMS's failure to see any evidence of anisotropy may be significant: Physicists expect that the relatively local neighborhood contributing to AMS observations has a nearly isotropic dark-matter distribution but a distinctly anisotropic pulsar distribution. On the other hand, intragalactic magnetic fields scramble the trajectories of charged particles headed toward us, so an anisotropic distribution of astrophysical particle sources could still be compatible with a nearly isotropic reception of high-energy positrons at the space station.[2]

Whatever is responsible for the AMS data and earlier results, it will have effects that extend beyond enhanced positron fractions. For dark matter, physicists are investigating astrophysical gamma-ray spectra, experiments at CERN's Large Hadron Collider, and searches for nuclear recoils arising from rare interactions of dark and conventional matter. Such a multipronged approach, says Vandenbroucke, will be necessary to solve the mystery of the cosmic-ray positron excess. "It's easy to focus on what we don't know," he continues, "but if you compare the state of our knowledge now and 5 or 10 years ago, you see we've made a big jump forward."

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References

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2. T. Linden, S. Profumo, http://arxiv.og/abs/1304.1791.