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Progress in Physics (84)

AMS-02, the Cosmic Ray Observatory
10 Years on the International Space Station

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Abstract

The Alpha Magnetic Spectrometer (AMS-02) has been up and running on the International Space Station ISS since May 2011. The structure of the detector is similar to a scaled-down version of modern collider experiments. Its components were mostly constructed in Europe, integrated and calibrated at CERN. AMS registers and measures cosmic rays in near-earth orbit and has so far collected over 175 billion particles. Commensurate with these unique statistics, the requirements for systematic precision are high. The results of the experiment shed new light on the origin and transport of cosmic particles on their way from their sources to our Solar system. In addition to more or less conventional astrophysical phenomena, dark matter or small pockets of antimatter may contribute. After replacement of the cooling system, which posed completely new challenges for NASA, the experiment is now equipped to take data for as long as the ISS stays operational.

(Credit: NASA)

1 Cosmic Rays

Cosmic rays are high-energy, electrically charged particles which originate from cosmic and astrophysical phenomena. Most of them come from our Milky Way. When they hit the Earth's atmosphere with an intensity of around one particle per cm^2 and second, they have a long journey behind them. Guided by magnetic fields and in interaction with interstellar gas and plasma, they diffuse through our galaxy for tens of millions of years. More than 100 years after their discovery, the physics of cosmic ray sources and their voyage to us is still full of puzzles.

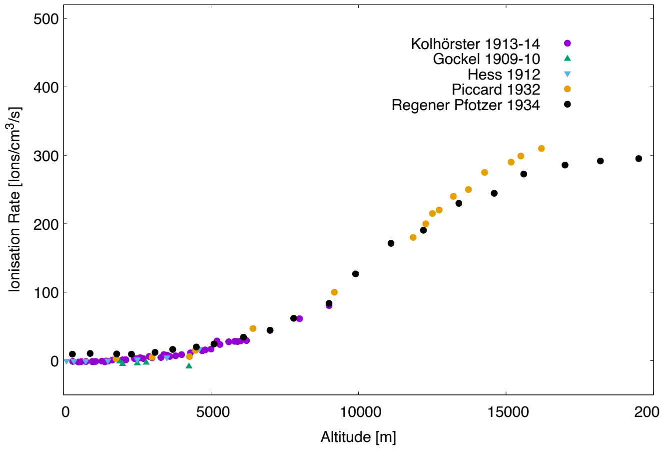

Figure 1: Ionization rate as a function of altitude above sea-level [1], measured during manned balloon flights by A. Gockel, V. F. Hess, W. Kolhörster and A. Piccard. E. Regener and G. Pfotzer reached even greater altitudes with unmanned weather balloons.

After Victor Franz Hess discovered the extraterrestrial origin of "atmospheric electricity" during his balloon flights in 1912 [1], experiments were carried out at ever increasing altitudes in the decades that followed. Figure 1 summarizes the ionization rates measured as a function of altitude, from manned and unmanned balloon flights before and after the First World War. Werner Regener and his student Georg Pfotzer were pioneers in the use of weather balloons with automatized Geiger-Müller counters in the 1930s. They measured the flux of cosmic particles – their number per unit area and time – as a function of altitude and compared it with the ionization rate. Both have the same altitude dependence, so it is in fact individual charged particles that trigger "atmospheric electricity". The results of these unmanned flights were hardly known beyond a small circle of experts. In contrast, the manned stratospheric flights by Auguste Piccard and Max Cosyns attracted unprecedented public attention. Thirty thousand spectators and numerous media watched the start of his balloon flight from the military airport of Dübendorf near Zürich, shown in Figure 2. A battalion of the Swiss Army held back the balloon and its aluminum capsule while it was being filled. The two "conquerors of the stratosphere" became public heroes in Switzerland and Belgium, Piccard was immortalised by Hergé as Pro-

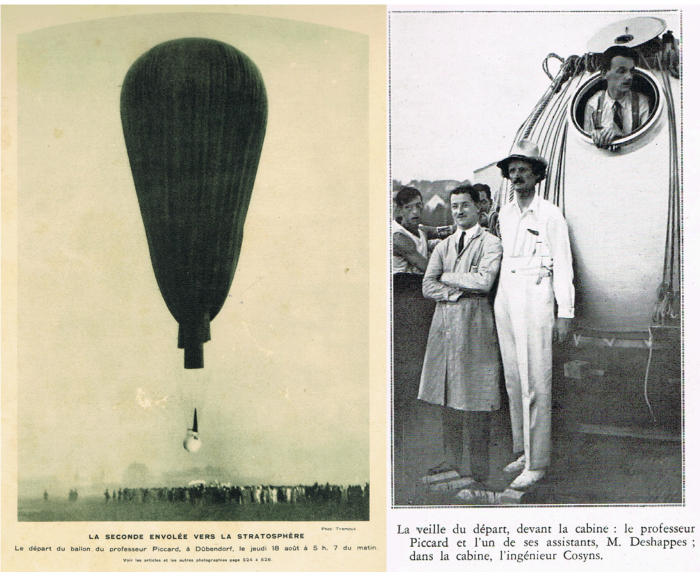

Figure 2: Left: Photo from the title page of the French magazine "L'Illustration" of August 27, 1932, showing the lift-off of Auguste Piccard's stratospheric mission from Dübendorf. Right: Auguste Piccard in front and Max Cosyns inside the pressurised aluminum capsule, from the same issue of "L'Illustration". (Credit: Author's collection)

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[1] For early Swiss contributions to this discovery, see e.g. J. Lacki, "Albert Gockel: from atmospheric electricity to cosmic radiation", *SPG Mitteilungen* 38 (2012) 25-29

fessor Calculus (professeur Tournesol in the original) in the famous “Adventures of Tintin” comics. Regener, whose balloon launches from the courtyard of his Stuttgart institute were only witnessed by his colleagues and students, was pushed out of his academic position by the Nazi regime. Today he is considered one of the pioneers of geophysics.

At altitudes of around 20 km, the rate of ionization by cosmic rays reaches the so-called Regener-Pfotzer maximum and then decreases. James Van Allen took the first measurements outside the Earth’s atmosphere in 1947 with a V2 rocket confiscated during the occupation of Germany. He found that the counting rate plateaued beyond about 50 km altitude, at about half of its maximum level. He was probably the first who actually observed mainly primary cosmic radiation, and not particles released in cosmic atmospheric showers. Subsequently, especially during the geophysical year 1958 with the Explorer and Pioneer missions, Van Allen discovered the Earth’s radiation belts named after him – geomagnetic regions in which secondary particles of cosmic radiation are trapped like in a magnetic bottle. He can thus be considered the pioneer of cosmic ray research in space. In the following decades, measurements in space were continued with the Soviet Proton and Sokol missions.

From the observations at great altitudes, a kind of consensus model has emerged in the last few decades, which qualitatively summarizes the gross features of cosmic rays in the energy range up to a few 10^6 GeV:

- This radiation comes mainly from supernovae in the Milky Way, so it consists of stellar material, atomic nuclei [8, 9] and electrons. The sources are randomly distributed in the galaxy. The density and rate of supernovae are large enough to explain the observed energy density of cosmic rays.

- The acceleration of individual particles to high energies takes place in plasma shock waves, which emerge from supernovae. The so-called Fermi mechanism causes the particle flux Φ – defined as the number of cosmic rays per unit area, time and solid angle – to follow a power law as a function of energy. The differential flux $d\Phi/dE$ indicates the particle flux per energy interval. It decreases like $d\Phi/dE \propto E^{-\gamma}$, with the so-called spectral index γ, a term borrowed from spectroscopy of electromagnetic radiation. A larger index corresponds to a softer spectrum, a smaller index to a harder one. One expects $\gamma \simeq 2$ at the source for all particle species with unit charge.

- The particles then diffuse through the material and plasma of the Milky Way and remain stored in the galaxy for tens of millions of years. They are thoroughly swirled so that directional information is lost. The result is a roughly isotropic and homogeneous interstellar particle flux.

- Particles lose energy in this process and the spectral index increases by about 0.7 for nuclei, and 1 for electrons and positrons, which lose energy more easily. In the Solar system one thus expects $\gamma \simeq 2.7$ for primary nuclei and $\gamma \simeq 3$ for primary electrons.

- Through interaction with interstellar matter secondary particles are produced. The spectra of these secondaries are softer, since they result from inelastic scattering, i.e. they have a larger spectral index. However, their spectral index should increase by the same amount $\Delta\gamma$ with respect to primaries for all secondary species.

Direct observation at high altitudes is so far limited to energies up to a few TeV, since balloon and space missions do not allow very large detectors. Higher energies have only been accessible to indirect observation via atmospheric showers. As an example, Figure 3 shows the fluxes of selected nuclei and the only definitely detected antinucleus $\overline{\mathrm{H}}$. As one can see in the double logarithmic plot, the differential particle fluxes do decrease with energy according to a power law, by almost three orders of magnitude per energy decade above 10 GeV. The fluxes of the few electrons and positrons drop even more steeply. The counting rate of an experiment – and thus its range in terms of energy – is determined by the acceptance, which roughly corresponds to the product of its area and the solid angle covered. The exposure time is of course also decisive for the overall statistics.
Figure 3 shows how the results of AMS-02 cover this research field in the energy range up to a few TeV. What cannot be appreciated in this representation is the far superior accuracy of AMS results compared to previous experiments. Spectra and composition contain information about production, acceleration and transport mechanisms, but details re-

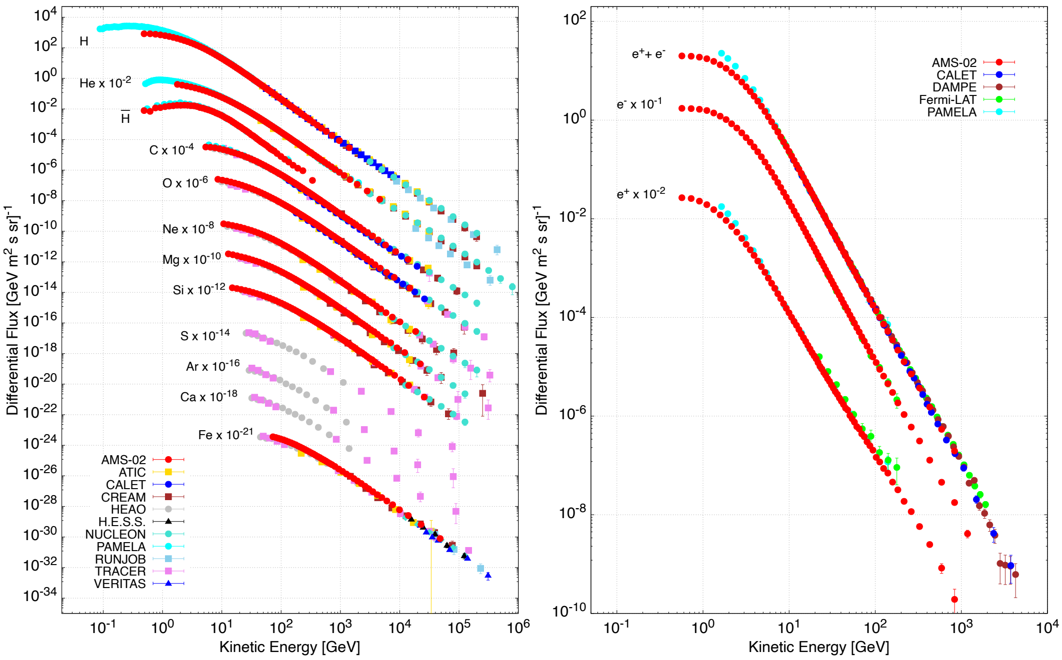


Figure 3: Differential flux of cosmic nuclei and anti-nuclei (left), electrons and positrons as well as the sum of the two (right), as a function of their total kinetic energy. Results of selected balloon experiments are represented with squares (■), space experiments with points (●), atmospheric shower experiments with triangles (▲) [1]. Most error bars, especially for AMS results, are smaller than the symbol size.

main hidden in a double logarithmic plot. And it is precisely the details that provide information about astrophysical phenomena important for cosmic rays.

2 The AMS Project

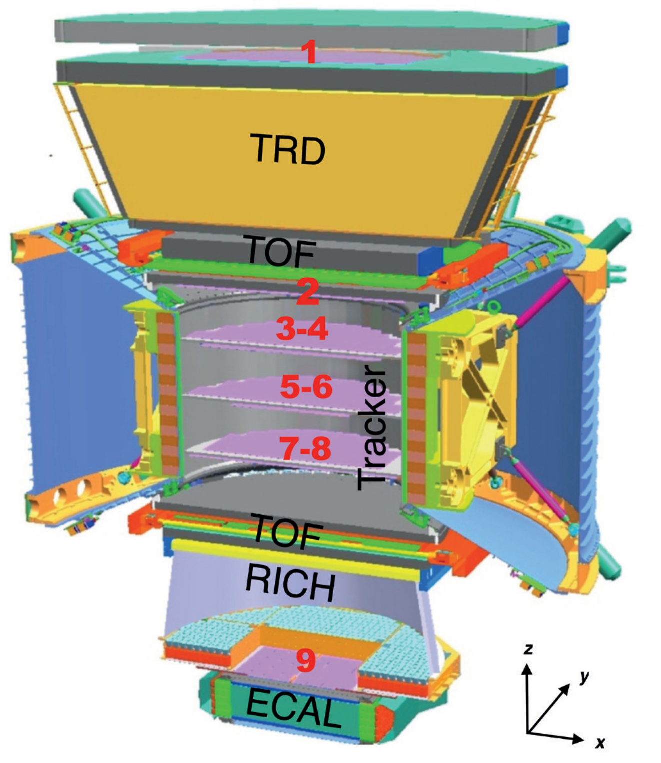
Complex detector systems, as we know them from accelerator particle physics, are a relatively new resource in cosmic ray research. One of the reasons is that conditions prevail during a balloon flight, and even more so during a rocket launch, that few detectors survive unscathed [2]. In orbit, very technology-hostile conditions reign in terms of temperature fluctuations and radiation exposure. Space experiments which meet the requirements of a typical collider experiment are therefore as rare as opportunities to fly them.

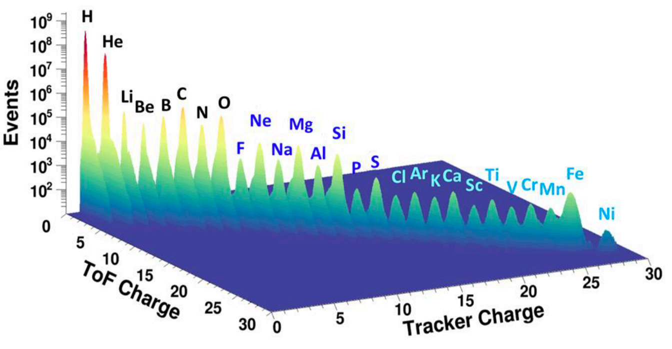
In a magnetic spectrometer, charged particles are directed onto a curved path by a magnetic field. The radius of curvature determines the magnetic rigidity $R = p/Z$, the ratio of momentum p and electric charge Z. To do this, one needs a magnet with a precisely known field and track detectors to measure the path of the particle. A pioneer in the field of space-based spectrometers was the PAMELA experiment of the WiZARD collaboration, which relied on long experience with balloon and collider experiments alike. Modern technology and analysis methods from particle physics at accelerators thus found their way into the systematic research of cosmic rays [3].

In 1994, Samuel C. C. Ting proposed to build a spectrometer with a hundred times greater acceptance and a complete set of detectors for particle identification, to be acommodated on the International Space Station ISS. The proposal was enthusiastically supported by NASA under Dan Goldin, Administrator from 1992 to 2001. The project was named Alpha Magnetic Spectrometer (AMS), after the code name “Alpha Station” for one of the numerous iterations of the ISS concept. The international collaboration, responsible for construction and operation of AMS, today includes around 500 scientists and engineers from 56 institutions in 16 countries. The dimensions of AMS with (5 × 4 × 3) m^3 and a weight of 7.5 t are adapted to the capacity of the now historical space shuttle (Space Transport System STS).

The diagram on the right shows a section through the AMS detector. A cylindrical permanent magnet generates a dipolar magnetic field of about 0.15 T. Its direction is horizontal in the x direction. Particles enter from above, moving in the $-z$ direction. The nine tracking layers (Tracker 1– 9), silicon strip detectors with high resolution and double-sided read out, each locate the particle passage in the bending (y) and non-bending direction (x). They also measure the absolute value of the particle charge.

The tracker is embedded in a set of detectors for particle identification, which complement each other and increase systematic reliability. A transition radiation counter (TRD) differentiates between light and heavy particles. Four layers of time-of-flight scintillators (TOF) determine the direction of flight, velocity and charge. The ring-imaging Cherenkov detector (RICH) also determines velocity and charge. Finally, an electromagnetic calorimeter (ECAL) measures the energy of electrons, positrons and photons and distinguishes them from hadrons. The absolute value of the electrical charge is determined by practically all detectors with different resolutions. Details about the detector and its performance can be found in a comprehensive report [7].





Redundancy of measurements – for energy/momentum, velocity and electrical charge – is a key strength of the AMS detector. As an example, the plot above shows the nuclear charge measured in the TOF system against the one obtained from the tracker sensors.

The track detector produces around 140 W of heat inside the magnet bore. In order to keep the temperature of the spectrometer constant, two-phase cooling with liquid CO_2 transports the heat to the outside, where it is dissipated by radiators. Its four redundant pumps showed signs of wear and tear since 2015, and a replacement was necessary for long-term operation. An improved replacement cooling system was thus sent to the ISS, along with specially developed tools. In a complex operation in January 2020, the exchange was accomplished during four space walks. This was the first time that a high-pressure system was cut open in space and re-welded, arguably the most challenging operation since the repair of the Hubble telescope.

NASA initially required a pilot experiment in the cargo bay of a shuttle to ensure the feasibility of the design and the capabilities of the collaboration. This prototype detector, called AMS-01, flew aboard Space Shuttle Discovery in June 1998 on the last American mission to the Russian space station MIR. In ten days the experiment registered about 70 million cosmic particles [4].

Based on this success, the collaboration decided to build a more ambitious detector, AMS-02, for long-term measurements on the ISS. It was initially intended to replace the permanent magnet with a more powerful superconducting electromagnet [5]. The majority of detector components was produced in Europe. The entire detector was integrated with the electromagnet at CERN in 2009 and calibrated in CERN particle beams. AMS is an excellent example of how CERN technology, expertise and infrastructure helps projects in neighbouring fields to succeed. Consequently, it was the pioneer of a new category of projects at CERN, the so-called recognised experiments, which by now has many prominent members [6].

When testing the thermal properties of AMS in vacuum at ESA-ESTEC in the Netherlands, it turned out that the 2500 l supply of superfluid helium for cooling the magnet would only allow operation for about two years, too short for the planned research program. Since an in-orbit refill was deemed unfeasible, the electromagnet was abandoned and the detector adapted to the permanent magnet of AMS-01. The Info Box describes the final detector.

However, the installation on the ISS was anything but guaranteed for several years. After the accident of space shuttle Columbia in 2003, in which seven astronauts lost their lives, NASA decided to reduce the space shuttle program and discontinue it by 2010. Many flights were removed from the flight schedule, including the one for AMS. Sam Ting, however, organised support from influential US senators. In 2008, both houses of parliament passed a budget law which required NASA to transport AMS-02 to the ISS. In January 2009, three days after President Obama took office, AMS-02 was back on the flight schedule, with an additional shuttle flight STS-134.

On August 26, 2010, AMS-02, carefully recalibrated, was transported from CERN to Kennedy Space Center. After installation in the cargo bay, it was launched on May 16, 2011 with the last mission of space shuttle Endeavor. Three days later, robotic arms transported the detector to its anchor point on the starboard side of the ISS transverse truss. A few hours later, AMS-02 registered the first helium nucleus. The photo at the begin of the article shows AMS-02 in position. The results of the first seven years on the ISS have recently been summarized [7]. A few highlights are presented below.

3 Cosmic Nuclei

The analysis of cosmic ray composition affords us a look into the cosmic nuclear physics laboratory, and its functioning from shortly after the Big Bang until today [8, 9]. Hydrogen and helium nuclei originate mainly from bario- and nucleosynthesis a few minutes after the Big Bang [10]. The ratio of their abundances is indeed one of the pillars of Big Bang theory. Like all other nuclei, they are accelerated to high energies by turbulent magnetic fields, such as those found in shock waves following supernovae. Since this is a magnetic mechanism, the magnetic rigidity $R = p/Z$ (measured in Gigavolts, GV) is the suitable variable for describing their spectra.

Significant deviations from a simple power spectrum are already evident in the dominant components. Figure 4 shows the proton spectrum as an example, multiplied by $R^{2.7}$ so that details can be seen on a linear scale. Above about 200 GV, the spectrum becomes significantly harder. Calorimetric measurements confirm this trend.

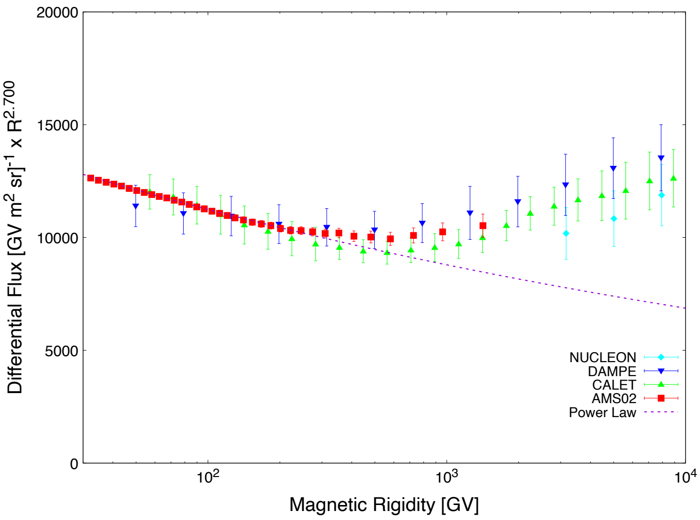


Figure 4: Differential flux of protons as a function of the magnetic rigidity R, scaled with $R^{2.7}$, from recent measurements by space experiments [1].

Light nuclei such as lithium, beryllium and boron come at most partially from primordial nucleosynthesis. They are raw materials and intermediate products in the breeding of heavier nuclei inside stars, and therefore strongly underrepresented in stellar matter. They are found three orders of magnitude more often in cosmic rays, thanks to the splitting of heavy nuclei by spallation on the way from their source to us. Stable primary products of stellar nucleosynthesis – such

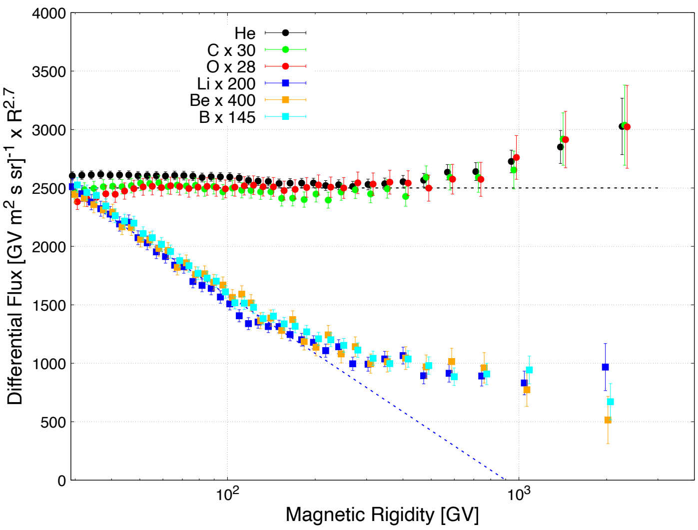


Figure 5: Differential flux (times $R^{2.7}$) as a function of magnetic rigidity for primary nuclei (He, C, O) and secondary products of interactions with interstellar matter (Li, Be, B) [7]. The fluxes from AMS-02 are scaled so that they roughly match the helium flux at low energies. The lines indicate the dependency expected with a constant spectral index.

as helium, carbon or oxygen, even iron – all show roughly the same power spectrum, although their abundance decreases drastically with increasing mass. Secondary spallation products, on the other hand, have a significantly softer spectrum, as shown in Figure 5.

Surprisingly, however, all nuclei show a change in the spectral index at a rigidity of around 200 GV [7]. The change towards a harder spectrum is $\Delta\gamma_{\text{HeCO}} = +(0.170 \pm 0.015)$ for the lighter primary nuclei helium, carbon and oxygen. It is a little less pronounced for the heavier primaries neon, magnesium and silicon, with $\Delta\gamma_{\text{NeMgSi}} = \Delta\gamma_{\text{HeCO}} - (0.045 \pm 0.008)$. For secondary nuclei the change in spectral index is much more pronounced, with $\Delta\gamma_{\text{LiBeB}} = \Delta\gamma_{\text{HeCO}} + (0.140 \pm 0.025)$. It is not entirely clear where this turn to a harder spectrum comes from. In principle, new sources or stronger "accelerators" in the vicinity of our solar system can cause this phenomenon. However, the fact that the spectral index change is almost twice as large for secondaries compared to primaries indicates a transport effect [11]. The diffusion through the galactic disk could, for example, run differently than in the halo of the Milky Way [12]. The smaller difference between light and heavy primaries may indicate other spatial inhomogeneities in cosmic ray diffusion [13, 14], since heavier particles propagate shorter distances [15]. But these are not the only astrophysical phenomena which may be invoked to explain the unexpected deviations from the simple consensus model [16].

All this new information has to be incorporated into models such as the GALPROP code [17], which quantitatively describe the release, acceleration and diffusion of cosmic rays in the Milky Way. All available data from astrophysics, nuclear and particle physics are used to understand the formation and transport of particles from their sources to us. Precision results like those from AMS have already had a major impact on these models and will continue to do so. Only when the contributions of conventional astrophysical phenomena to cosmic radiation are understood with sufficient accuracy can potential contributions from unconventional sources – such as dark matter – be firmly established.

4 Cosmic Antimatter

But uncertainties of this kind don't really deter from the search for unconventional phenomena, especially since the energy density of dark matter considerably exceeds that of normal matter. In a search for unconventional sources of cosmic radiation, components which rarely come from normal astrophysical processes are particularly suitable. The total rate of antihydrogen nuclei $\overline{\text{H}}$, for example, is suppressed by more than four orders of magnitude with respect to hydrogen. Conventionally, antiprotons come from the production of baryon-antibaryon pairs in interactions of the – at least in our part of the cosmos – overwhelmingly dominant particles of matter. A contribution from annihilation reactions of dark matter particles, which may be their own antiparticles, is possible, but of unclear significance because of the still quite large uncertainties in the calculation of conventional contributions [18].

On the other hand, the lightest antiparticles, positrons e^+, have long been suspected to partially come from unidentified sources, already since the results of the PAMELA space spectrometer. Figure 6 shows the spectrum of positrons that AMS-02 has measured to date. For better visibility of its structure, the particle flux is multiplied by a factor E^3. There is a low-energy component which is compatible with conventional diffusion sources.

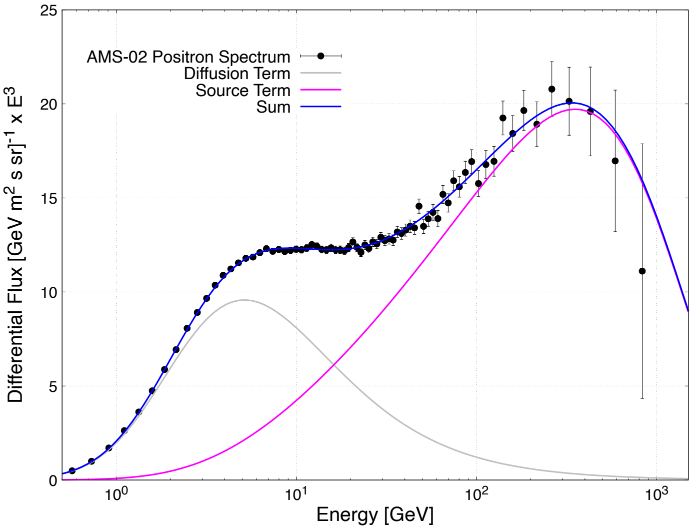


Figure 6: AMS-02 measurement of the differential flux of positrons as a function of the energy E, scaled with $E^{3.0}$ [7]. Error bars represent the total statistical and systematic errors. The diffusion term corresponds to a secondary production of positrons through the interaction of cosmic rays with interstellar matter. The source term corresponds to primary production by a new, not yet identified source.

In addition, at high energies there is a component that can be heuristically described by a source term with a harder spectrum and an exponential cut-off. An example of such a phenomenon would be the annihilation of dark matter particles into electron-positron pairs. In fact, the electron spectrum also allows a similar contribution, but does not require it. One finds a cut-off energy for positrons of $(810^{+310}_{-180})\,\text{GeV}$; in a pair-annihilation reaction this would correspond to the mass of the primary particles.

However, electromagnetic processes can also generate electron-positron pairs. An astrophysical example would be the rapidly changing magnetic fields of pulsars. These are rotating neutron stars whose rotational axis does not coincide with the direction of the magnetic axis. This leads to strong fields in some regions, which can be suitable for generating high-energy positrons. Since positrons easily disappear in interaction with interstellar matter, such point sources should not be located too far from the solar system. Positrons of 100 GeV can e.g. only come from sources some ten thousand years old and located no farther than about one kiloparsec ($\simeq 3 \times 10^{16}$ km) from us [16]. One could therefore expect a slight anisotropy of their directions of incidence, which is not observed with upper limits at the percent level. How far propagation effects would wash out an anisotropy is unclear. This again points out how important it is to better understand diffusive propagation effects.

The search for heavier antinuclei, like antideuterium or antihelium, is particularly fascinating. They are extremely difficult to produce through interactions between matter particles; the probability to form them decreases by orders of magnitude with each additional antinucleon [19]. There are, however, a good handful of antihelium candidates in the AMS-02 data among 176 billion cosmic particles. Sam

Ting presented some of them in a 2018 CERN seminar [20]. The rate is roughly equivalent to one $\overline{\text{He}}$ per year, or one per 100 million He nuclei. On the one hand, this is a very small rate; the systematic significance is difficult to assess because, in particular, the expected background has to be quantified. The fact that this has not happened so far, and that there is no publication, is probably also due to the tiny rate. To ensure that there is no detector malfunction at the level of 1 in 100 million, one needs to know more about the properties of these rare events. Thus the AMS-02 collaboration does not (yet?) claim to have discovered complex cosmic antinuclei.

On the other hand, if at least some of these candidates are taken seriously, there are too many to explain them by conventional nuclear astrophysics. Thus there should be a small, ready-made supply of antimatter somewhere in the galaxy which might have been left over from the Big Bang. That motivated a new search for anti-stars in the Milky Way, i.e. stars made of antimatter. In the catalog of the Fermi satellite there are 14 objects whose photon spectra are compatible with antimatter [21], about 2.5 candidates per million normal stars at a distance between a few 10^{14} and 10^{16} km. They could be considered as sources of $\overline{\text{He}}$ if one knew the release and acceleration mechanism. According to the authors, however, it is more likely that they are normal γ-ray emitters such as pulsars or black holes.

5 Future Projects

It is not clear whether the question of the existence of cosmic antimatter – or of particles originating from dark matter – can be conclusively answered with AMS-02 alone. For the foreseeable future, it will be the only magnetic spectrometer in space, i.e. the only detector that can differentiate between matter and antimatter. Colleagues from Germany [22] and Italy [23] have therefore submitted outlines for follow-up projects in connection with the ESA program "Voyage 2050". In a nearer future, the HERD project [24] of the Chinese Space Agency – also with participation of WiZARD and AMS members – plans to install a large calorimetric detector on the Chinese space station Tianhe, which is currently under construction. It will allow to look into the spectra of electrons and positrons lumped together. The coming decades will remain exciting.

Acknowledgement

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Besides AMS, his projects include the polarimeter POLAR for hard X-rays on the Chinese space-lab Tiangong 2. He is the main author of two online courses on introductory particle physics on Coursera. In 2020, he published the book "Particles, Fields, Space-Time: From Thomson's Electron to Higgs' Boson" (CRC Press, 2020).