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Results of the AMS experiment(*)

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Summary. — The Alpha Magnetic Spectrometer (AMS) was flown in June 1998 on the space shuttle Discovery during flight STS-91 in a 51.7° orbit at altitudes between 320 and 390 km. The major detector elements were a permanent magnet with an analyzing power $B*L^2$ of 0.14 Tm^2, a six-layer, double-sided silicon tracker, time-of-flight hodoscopes, a Čerenkov counter and anti-coincidence counters. A total of 2.86×10^6 He nuclei were observed in the rigidity range 1 to 140 GeV. No $\overline{\mathrm{He}}$ nuclei were detected at any rigidity. The upper limit on the flux ratio of $\overline{\mathrm{He}}$ to He is 1.1×10^{-6}. The proton spectrum in the kinetic energy range 0.1 to 200 GeV was measured, and is parameterized by a power law above the geomagnetic cutoff. Below the geomagnetic cutoff, a substantial second spectrum was observed concentrated at equatorial latitudes with a flux of $\sim 70\,\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$. The lepton spectra in the kinetic energy ranges 0.2 to 40 GeV for electrons and 0.2 to 3 GeV for positrons were measured. Two distinct spectra were observed, a higher energy spectrum and a substantial second spectrum with positrons much more abundant than electrons. Tracing leptons from the second spectra shows that most of these leptons travel for an extended period of time in the geomagnetic field and that the positrons and electrons originate from two complementary geographic regions. Long-lived secondary spectra protons (antiprotons) originate from the same regions as positrons (electrons).

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1. – Introduction

AMS is an international collaboration spanning 3 Continents, 13 Countries, 33 Institutions. It is based on an agreement between NASA and DOE. It is a CERN Recognized

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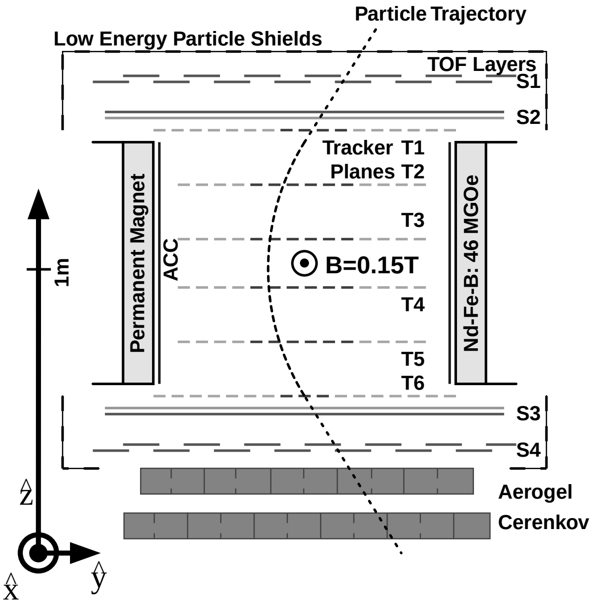

Fig. 1. – Schematic view of AMS as flown on STS-91.

Experiment. First results are published in [1-3], which can be consulted for details. The apparatus, as flown on STS-91, is described in detail in [4] (see fig. 1).

The purpose of the AMS experiment is to study the antimatter composition of the primary cosmic rays. The existence (or absence) of antimatter nuclei in space is closely connected to the theories of elementary particle physics, like CP-violation, baryon number nonconservation, Grand Unified Theory (GUT), etc. Balloon-based cosmic ray searches for antinuclei at altitudes up to 40 km have been carried out for more than 20 years; all such searches have been negative.

The Alpha Magnetic Spectrometer (AMS) is scheduled for a particle physics program on the International Space Station. Using a high-precision, large acceptance magnetic spectrometer, searches for dark matter, the origin of cosmic rays, and for antinuclei are foreseen.

The AMS flight on the space shuttle *Discovery* (STS-91 in June 1998, see fig. 2) was primarily a test flight to verify the detector's performance under actual space flight conditions.

2. – Data taking

After the shuttle had attained orbit, data collection commenced on 3 June 1998 and continued over the next nine days for a total of 184 hours, resulting in 100 million triggers recorded, half during the MIR docking period. Around 12% of physics data were sent via slow links to various NASA/USAF ground stations and were delivered in almost real time.

During data taking the shuttle altitude varied from 320 to 390 km and the latitude ranged between ± 51.7°. Before the rendezvous with the MIR space station the attitude of the shuttle was maintained as to keep the z-axis of AMS pointed within 45 ° of the

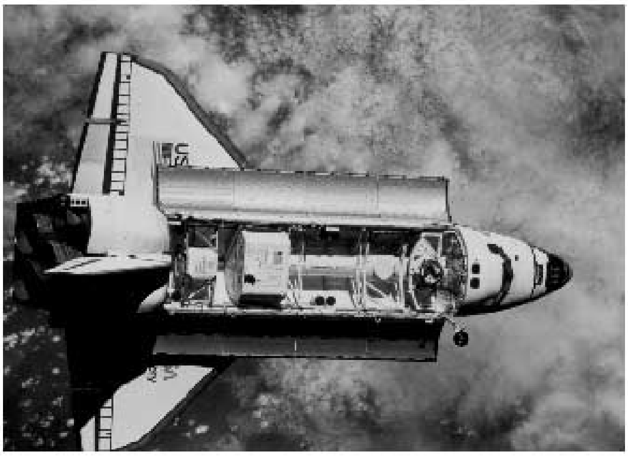

Fig. 2. – AMS (near the tail) as seen from MIR during STS-91 docking on June 4, 1998.

zenith. While docked, the attitude was constrained by MIR requirements and varied substantially. After undocking the pointing was maintained with a precision of 1° at 0°, 20° and then 40 ° of the zenith. Shortly before descent the shuttle turned over and the pointing was towards the nadir.

Events were triggered by the coincidence of signals in all four TOF planes consistent with the passage of a charged particle through the active tracker volume. Triggers with a coincident signal from the anti-counters (ACC) were vetoed.

The detector performance as well as temperature and magnetic field were monitored continuously.

3. – Event reconstruction

- The sign of the particle charge Z was derived from the deflection in the rigidity fit and the particle direction.
- The particle mass was derived from $|Z|R$ and β.
- The particle rigidity, $R = pc/|Z|e\,(\mathrm{GV})$, was obtained from the measurement of the deflection of the trajectory measured by the tracker in the magnetic field. Hits in at least four tracker planes were required and the fitting was performed with two different algorithms, the results of which were required to agree.
- The particle velocity, β, and direction, $\hat{\mathrm{z}} = \pm 1$, was obtained from the TOF, where $\hat{\mathrm{z}} = -1$ signifies a downward-going particle in the AMS coordinate system.
- The magnitude of the particle charge Z was obtained from the measurements of energy losses in the TOF counters and tracker planes (corrected for β).

4. – Search for antihelium in cosmic rays

The results of our search are summarized in fig. 3. As seen, we obtain a total of 2.86×10^6 He events up to a rigidity of 140 GV. We found no $\overline{\mathrm{He}}$ event at any rigidity.

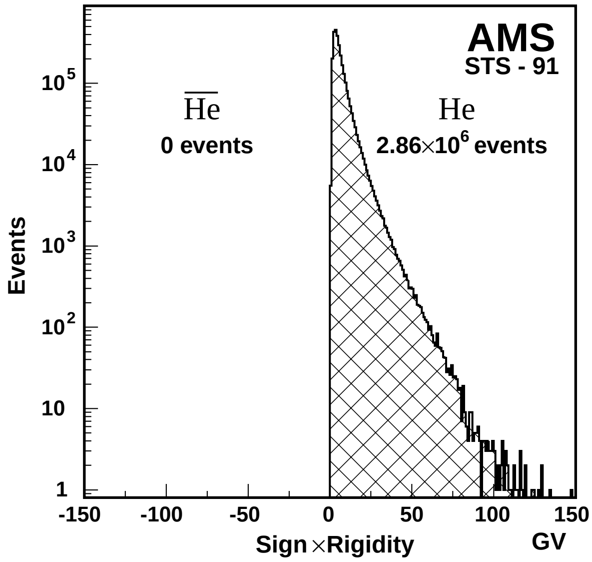

Fig. 3. – Measured rigidity times the charge sign for selected $|Z| = 2$ events.

Since no $\overline{\mathrm{He}}$ nuclei were observed, we can only establish an upper limit on their flux. If the incident $\overline{\mathrm{He}}$ spectrum is assumed to have the same shape as the He spectrum over the range $1 < R < 140\,\mathrm{GV}$, then one obtains at the 95 % C.L. a limit of

$$\frac{N_{\overline{\mathrm{He}}}}{N_{\mathrm{He}}} < 1.1 \times 10^{-6}.$$

5. – Protons in near earth orbit

Data were collected in the cosmic ray proton spectrum region from kinetic energies of 0.1 to 200 GeV, taking advantage of the large acceptance, the accurate momentum resolution, the precise trajectory reconstruction and the good particle identification capabilities of AMS.

The high statistics ($\sim 10^7$) available allow to determine the variation of the spectrum with position both above and below the geomagnetic cutoff. Because the incident particle direction and momentum were accurately measured in AMS, it is possible to investigate the origin of protons below cutoff by tracking them in the earth's magnetic field.

The spectrum above cutoff is referred to as the "primary" spectrum and below cutoff as the "second" spectrum.

5˙1. *Properties of the primary spectrum.* – The primary proton spectrum can be parameterized by a power law in rigidity, $\Phi_0 \times \mathrm{R}^{-\gamma}$. Fitting the measured spectrum over the rigidity range $10 < R < 200$ GeV, *i.e.* well above cutoff, yields

$$\gamma = 2.79 \pm 0.012\,(\mathrm{fit}) \pm 0.019\,(\mathrm{sys}),$$

$$\Phi_0 = 16.9 \pm 0.2\,(\mathrm{fit}) \pm 1.3\,(\mathrm{sys}) \pm 1.5\,(\gamma)\,\frac{\mathrm{GV}^{2.79}}{\mathrm{m}^2\mathrm{s\,sr\,MV}}\,.$$

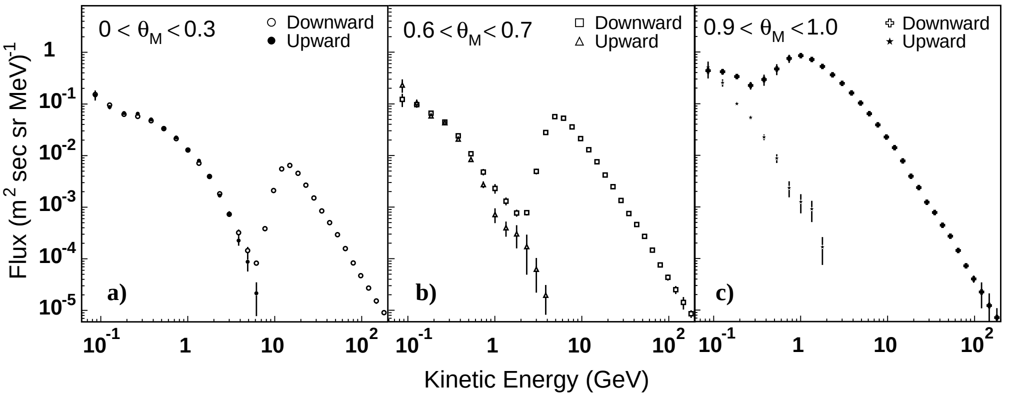

Fig. 4. – Comparison of upward and downward second proton spectrum at different geomagnetic latitudes. As seen, below cutoff, the upward and downward fluxes agree in the range $0 \leq \Theta_{\mathrm{M}} < 0.8$.

The systematic uncertainty in γ was estimated from the uncertainty in the acceptance (0.006), the dependence of the resolution function on the particle direction and track length within one sigma (0.015), variation of the tracker bending coordinate resolution by ±4 microns (0.005) and variation of the selection criteria (0.010). The third uncertainty quoted for Φ_0 reflects the systematic uncertainty in γ.

5˙2. *Properties of the second spectrum.* – A substantial second spectrum of downward-going protons is observed for all but the highest geomagnetic latitudes.

The upward- and downward-going protons of the second spectrum have the following unique properties:

i) At geomagnetic equatorial latitudes, $\Theta_{\mathrm{M}} < 0.2$, this spectrum extends from the lowest measured energy, 0.1 GeV, to ~6 GeV with a flux $\sim 70\,\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$.

ii) The second spectrum has a distinct structure near the geomagnetic equator: a change in geomagnetic latitude from 0 to 0.3 causes the proton flux to drop by a factor of 2 to 3 depending on the energy.

iii) Over the much wider interval $0.3 < \Theta_{\mathrm{M}} < 0.8$, the flux is nearly constant.

iv) In the range $0 \leq \Theta_{\mathrm{M}} < 0.8$, detailed comparison in different latitude bands (fig. 4) indicates that the upward and downward fluxes are nearly identical, agreeing within 1 %.

To understand the origin of the second spectrum, we traced back 10^5 protons from their measured incident angle, location and momentum, through the geomagnetic field for 10 s flight time or until they impinged on the top of the atmosphere at an altitude of 40 km, which was taken to be the point of origin. All second spectrum protons were found to originate in the atmosphere, except for few percent of the total detected near the South Atlantic Anomaly (SAA).

The trajectory tracing shows that about 30 % of the detected protons flew for less than 0.3 s before detection. The origin of these "short-lived" protons is distributed uniformly around the globe.

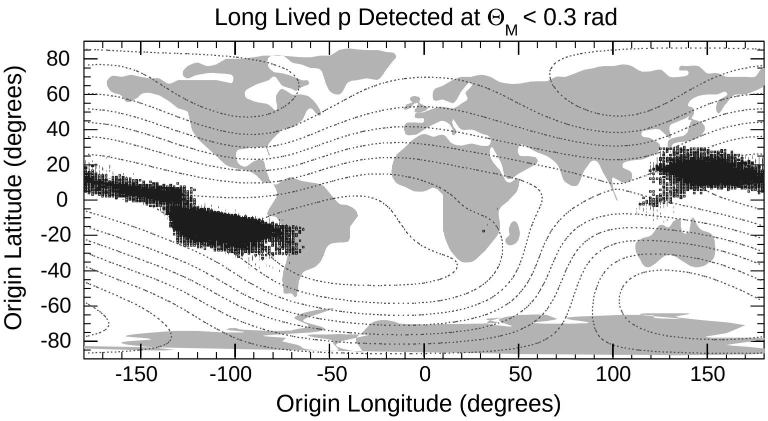

Fig. 5. – Origin of long-lived protons ($\Theta_{\rm M} < 0.3, p < 3$ GeV/c) in geomagnetic coordinates.

In contrast, the remaining 70 % of protons with flight times greater than 0.3 s, classified as "long-lived", originate from a geographically restricted zone. Figure 5 shows the strongly localized distribution of the point of origin of these long-lived protons in geomagnetic coordinates. Though data is presented only for protons detected at $\Theta_{\rm M} < 0.3$, these general features hold true up to $\Theta_{\rm M} \sim 0.7$.

6. – Leptons in near earth orbit

Data were collected to study the spectra of electrons and positrons in cosmic rays over the respective kinetic energy ranges of 0.2 to 40 GeV and 0.2 to 3 GeV, the latter range being limited by the proton background. The large acceptance of AMS and high statistics ($\sim 10^5$) enable us to study the variation of the spectra with position and angle both above and below the geomagnetic cutoff. The origin of particles below cutoff can be obtained by tracking them in the geomagnetic field.

For this study the acceptance was restricted to events with an incident angle within 25° of the positive z-axis of AMS and data from four periods are included. In the first period the z-axis was pointing within 1° of the zenith. Events from this period are referred to as "downward" going. In the second period the z-axis pointing was within 1° of the nadir. Data from this period are referred to as "upward" going. The effect of the geomagnetic cutoff and the decrease in this cutoff with increasing $\Theta_{\rm M}$ is particularly visible in the downward electron spectra. The spectra above and below cutoff differ. To understand this difference the trajectory of electrons and positrons were traced back from their measured incident angle, location and momentum, through the geomagnetic field. This was continued until the trajectory was traced to outside the Earth's magnetosphere or until it crossed the top of the atmosphere at an altitude of 40 km. The spectra from particles which were traced to originate far away from Earth are classified as "primary" and those from particles which originate in the atmosphere as "second" spectra. In practice, particles below the geomagnetic cutoff are from the second spectra, however this classification provides a cleaner separation in the transition region.

Similar to the procedure for second spectra protons, leptons with flight times < 0.2 s are defined as "short-lived", the remaining as "long-lived". For $\Theta_{\rm M} < 0.3$, most (75% of e^+, 65% of e^-) leptons are long-lived.

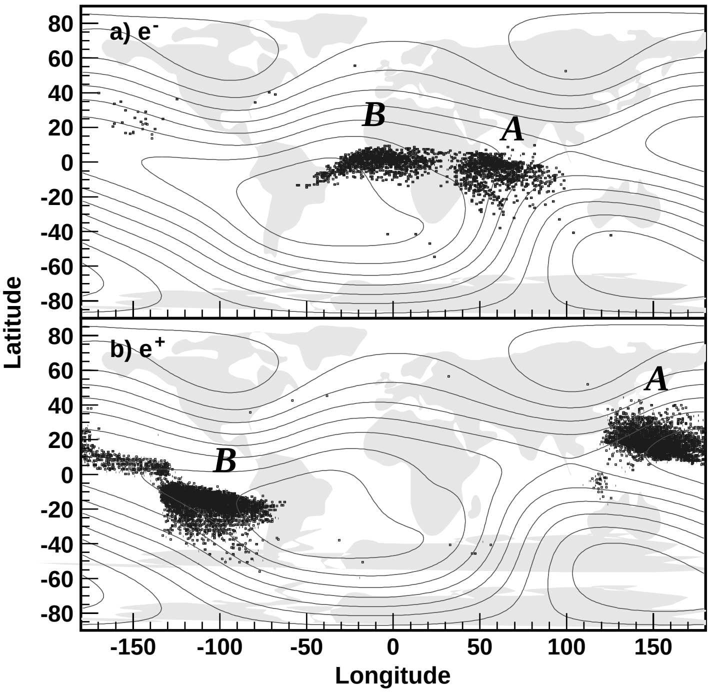

Fig. 6. – The geographical origin of long-lived second spectra leptons (< 3 GeV).

6˙1. *Origin of long-lived leptons*. – Figure 6 shows for long-lived second spectra leptons (< 3 GeV) the geographical origin of (a) electrons and (b) positrons. The lines indicate the geomagnetic field contours at 380 km. One can see the strongly localized distributions of the point of origin for long-lived leptons. Tracking shows that regions of origin for positrons coincide with regions of sink for electrons and vice versa.

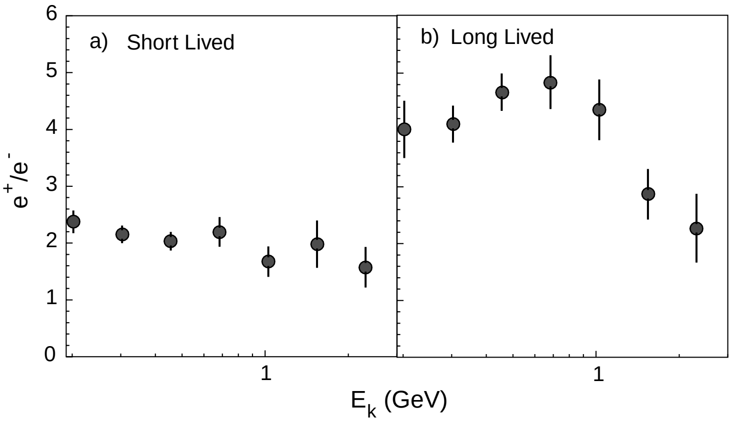

Fig. 7. – The e^+/e^- ratio of second spectra leptons (< 3 GeV, $\Theta_M < 0.3$) as a function of energy.

Long-lived second spectra positrons have the same points of origin as long-lived second spectra protons.

6˙2. *Lepton charge ratio.* – An interesting feature of the observed second lepton spectra is the predominance of positrons over electrons. The energy dependence of the e^+/e^- ratio for 0° attitude and $\Theta_M < 0.3$ is shown in fig. 7. As seen, short-lived and long-lived leptons behave differently. For short-lived leptons the ratio does not depend on the particle energy in the range 0.2 to 3 GeV but for long-lived leptons the ratio does depend on the lepton energy, reaching a maximum value of ~ 5.

7. – Conclusion

- The short test flight of the AMS detector has shown its viability for an extended period of several years of data taking at the International Space Station (ISS).
- The detector is undergoing several upgrades, the most prominent one being a superconducting magnet.
- It will be ready for its next flight and installation on the ISS, foreseen for October 2003.

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