AMS, a particle spectrometer in space

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Abstract

The Alpha Magnetic Spectrometer (AMS) is designed as an independent module for installation on the International Space Station (ISS) in October 2005 for an operational period of three years. The main scientific objectives are the search for antimatter and dark matter in cosmic rays (CR) as well as the study of CR production and propagation. Selected results from the pilot AMS-01 experiment on board of the shuttle mission STS-91 in 1998 will be reviewed. I will discuss in more details the ambitious AMS-02 detector and its physics potentiality.

Key words: Cosmic rays; Space

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1 Introduction

The apparent lack of anti-matter in the Universe, the dark matter problem and the origin, composition and propagation of cosmic rays are questions adressed by AMS. Direct measurements of the spectra of different nuclei composing of CR above a few tens of GeV have so far been limited due to the exponentially falling flux as a function of energy. The AMS project will improve this situation by providing a large area, high resolution spectrometer capable of performing measurements over a rigidity range from 1 GV to TV and for a period of 3 years.

A 'scaled-down' version, AMS-01, was built and flown on the Discovery shuttle for 10 days in June 1998. The heart of the prototype AMS-01 detector was a magnetic spectrometer, using a 0.15T permanent dipole magnet in magic ring configuration and a partially equipped six plane silicon tracking detector.

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The set-up was completed by a two double layer scintillator time-of-flight system, an Aerogel threshold Cerenkov counter and veto counters located on the magnet inner wall. The detector thus measured the charge Z, rigidity $R \equiv pc/|Z|e$, velocity β and specific energy loss dE/dx of particles traversing its aperture.

The main goal of the 10 days STS-91 flight in June 1998 was docking to and resupplying the MIR station. For AMS, it was a mission to test the equipment under stringent conditions during the launch and in the space environment, and to familiarize the AMS team with operations in space. After MIR undocking, AMS had control of the shuttle orientation for ninety hours. Data were taken with variable attitudes, at altitudes between 320 and 390 km above sea level. The space shuttle's orbit covered latitudes between $\pm 51.7^{\circ}$ and all longitudes. A total of 10^8 events were registered. Results have so far been obtained on rates and spectra of electrons and positrons [1], protons [2,3], antiprotons and deuterons [6], helium [4] and the search for antihelium nuclei [5] as well as heavy anti-ions [7].

2 Results on Nuclei and Anti-Nuclei from AMS-01

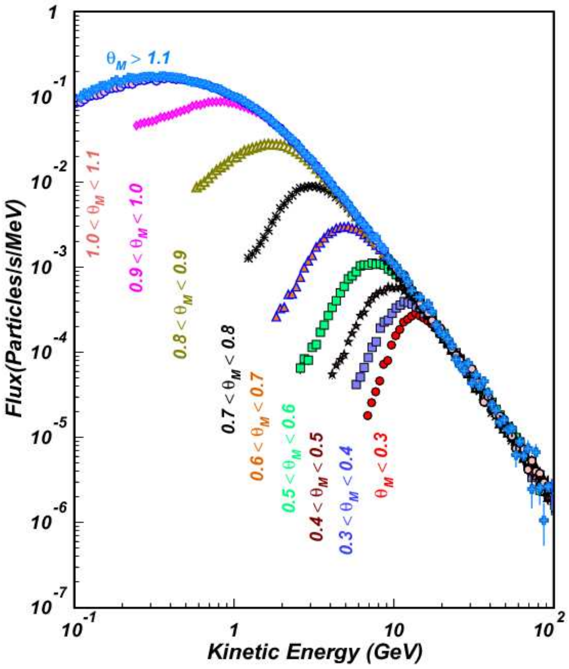

Fig. 1. Primary proton spectra obtained at various geomagnetic latitudes above the geomagnetic cut-off.

During the ten days mission a statistically and systematically accurate measurement of the proton and Helium spectrum has been obtained, both above and below the geomagnetic cut-off [2,3]. A charged particle approaching the Earth must have a minimal rigidity in order to overcome the Earth's magnetic field. This limit depends on the geomagnetic latitude; for example the cut-off rigidity is zero at the geomagnetic pole and 15 GV at the geomagnetic equator. Figure 1 shows the primary proton spectra for events above the geomagnetic cut-off in various bins of geomagnetic latitude. Its high energy part ($\geq$ 10 GeV), i.e. well above the cut-off and above the energies where solar modulation matters, can be fitted by a power law in rigidity with spectral index $\gamma = 2.780 \pm 0.009(\mathrm{fit}) \pm 0.019(\mathrm{sys})$. This flux is in excellent agreement, in normalisation as well as in shape, with recent results of the BESS balloon experiment [8]. These data are relevant for the evaluation of the atmospheric neutrino flux [9].

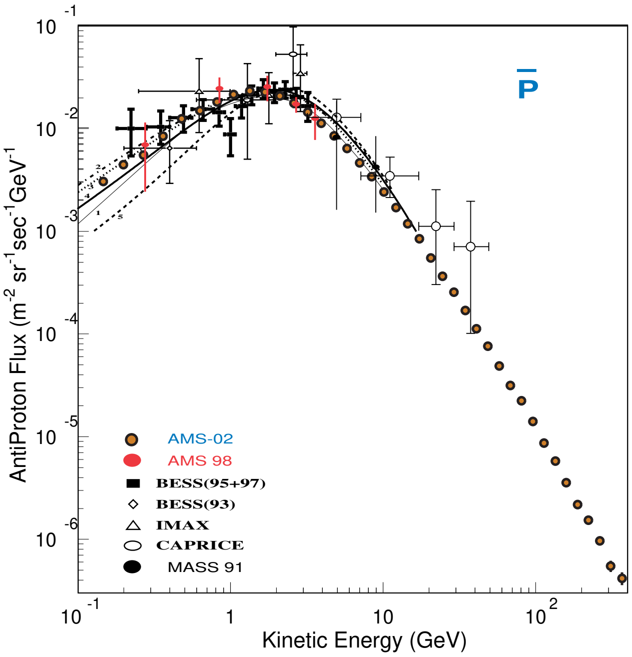

Fig. 2. Antiproton spectrum obtained by AMS-01(AMS 98), compared to results from balloon spectrometers. Also shown is a simulation of measurements expected from AMS-02 covering the high energy end of the spectrum.

The AMS-01 hardware only allowed a low statistics measurement of the antiproton flux at modest energies. The result is shown in Figure 2, together with the corresponding results from BESS [10], IMAX [11], CAPRICE [12] and MASS [13] as well as expectations for AMS-02. The spectrum peaks at 2 GeV which is a characteristic feature of secondary antiprotons produced by the interaction of galactic high energy cosmic rays with the interstellar medium. It thus neither indicates the presence of significant amounts of antimatter nor the need for non-standard antiproton production mechanisms. Such mechanisms might in fact contribute at energies above a few ten GeV, where no measurement exists so far (see Section 4).

While antiprotons are of conventional origin, secondary production of heavier antinuclei is severely suppressed. Thus, though helium is an important component of the cosmic ray flux, antihelium nuclei have never been observed. A total of 2.86×10^6 helium events were observed by AMS-01, but not a single acceptable antihelium candidate was found. Assuming equal spectral shape for nuclei and antinuclei, this leads to a 95% CL upper limit on the flux ratio of $\Phi(\overline{\mathrm{He}})/\Phi(\mathrm{He}) < 1.1 \times 10^{-6}$, extending up to 140 GV. Recent BESS measurements [14] have slightly improved on this limit, though at lower rigidities as shown in Figure 3. All these limits are conservative in the sense that the minimum of the acceptance is applied to the whole rigidity range quoted.

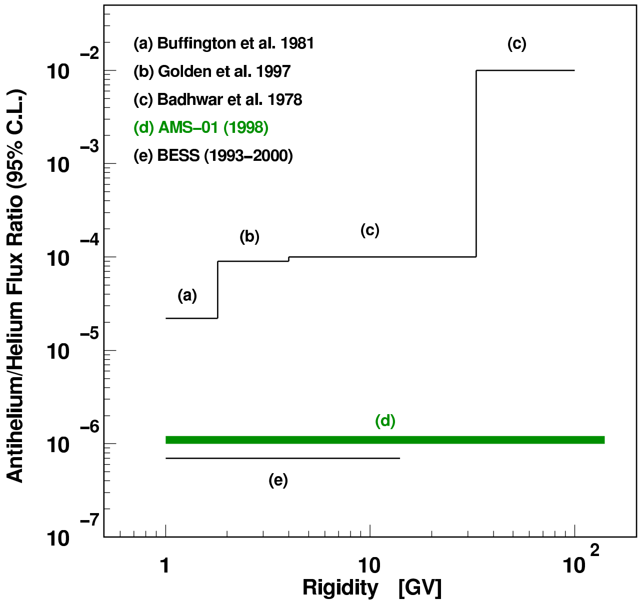

Fig. 3. Experimental upper limits on the antihelium to helium flux ratio assuming equal spectral shape.

3 The AMS-02 detector

Following the experience gathered during the AMS-01 mission, a more ambitious detector with extended rigidity range was designed for installation on the ISS. This detector, AMS-02, is based on a spectrometer with a superconducting magnet. Its main components are shown in Figure 4. In addition to providing an extended rigidity range for charged particles, it also implements more performant particle identification, additional redundancy for the measurement of charge and velocity and less trigger bias against heavy elements.

The magnet consists of 2 dipoles and 2 series of 6 smaller racetrack coils circumferentially distributed, cooled by superfluid helium at 1.8 K. This configuration was chosen for 3 reasons: to increase the overall dipole field, to

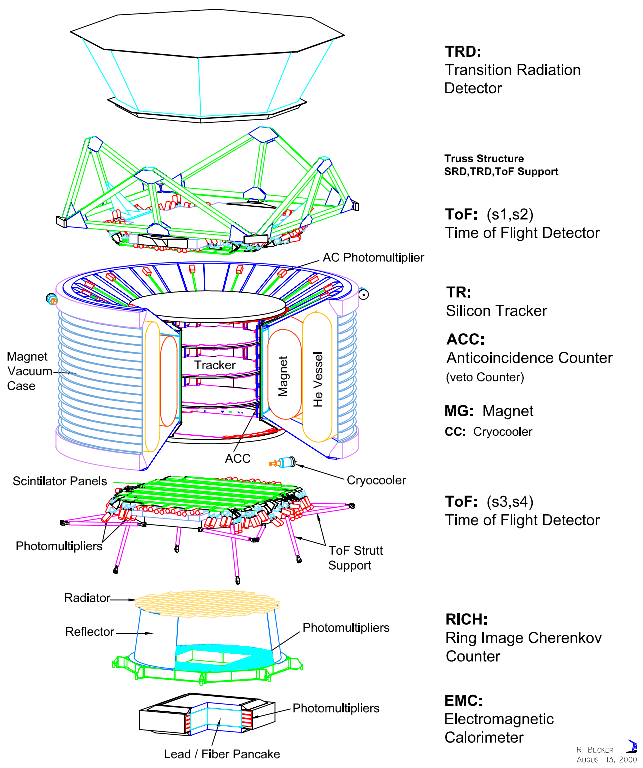

Fig. 4. Exploded view of the AMS-02 detector layout identifying its major components.

reduce the stray field and to suppress the torque resulting from the interaction the magnetic moment of the magnet with the Earth magnetic field. The magnetic field reaches 0.8T close to the center, six times the field strength of the AMS-01 permanent magnet. It is thermally connected to a 2500 l vessel of liquid helium for about 3 years of operation without refill.

Trajectories of charged particles are localised by double sided silicon sensors, arranged in eight layers of about one m^2 each on five planes of an ultra-light support structure. Close to 2500 sensors provide a tracking resolution of $\sim$10μm in the bending direction, $\sim$30μm orthogonal to it. Together with the improved magnet, the spectrometer thus measures rigidity up to a few TV, as shown in Figure 5. The measurement of specific energy loss, $dE/dx \sim |Z^2|$, in the silicon serves to identify nuclei. The tracker also measures the direction and energy of photons, converted in the material above the first tracker layer, with excellent directional resolution and good energy resolution.

Separation between light and heavy particles is provided by the Transition Radiation Detector on top of the set-up, which measures the radiation emitted by particle upon changes in the index of refraction of the traversed medium. The detector features 20 layers of fleece radiator and proportional straw tubes for X-ray detection. It will separate baryons from electrons up to energies of 300 GeV. It will also help in the tracking of charged particles, identify photon

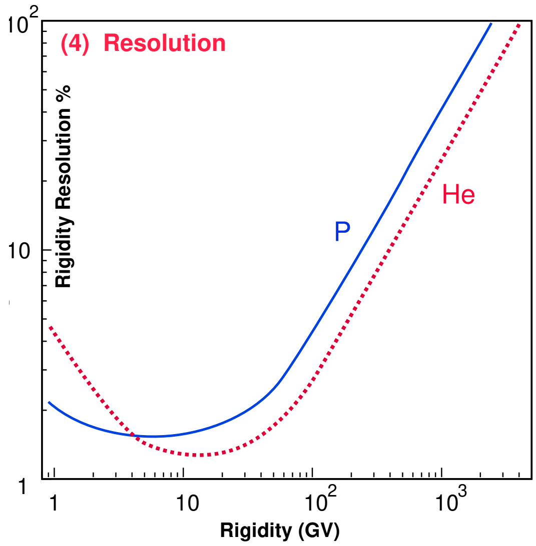

Fig. 5. Expected rigidity resolution of the AMS-02 superconducting spectrometer as a function of rigidity, for protons and helium.

conversion points and measure dE/dx.

As in AMS-01, two crossed double layers of scintillators provide time-of-flight and thus measure particle velocity. Due to the higher magnetic stray field of the AMS-02 superconducting magnet, the phototubes have to be aligned more carefully with the local magnetic field. A timing resolution of ~ 140 ps is nevertheless expected. In addition to measuring the velocity of particles and their direction, the time-of-flight system provides a redundant measurement of dE/dx with about 10% resolution for minimum ionising particles. It is also the principle trigger detector for charged particles.

Below the spectrometer, a ring imaging Cerenkov detector provides further velocity and charge measurement. Light emitted in the combined Aerogel ($n = 1.035$) and sodium-fluoride ($n = 1.336$) radiator on the top is detected as a circle of photons by an array of position sensitive photo multipliers on the bottom, occasionally after reflection off a conical mirror. The emission angle measures velocity, with an expected resolution of $\delta\beta/\beta \simeq 10^{-3}$. The number of photo-electrons measures dE/dx with a resolution of about 8%, thus providing an independent measurement of the charge up to iron.

At the very bottom, an electromagnetic calorimeter made of 640 kg of lead scintillating fiber sandwich completes the set-up. The calorimeter reconstructs the shower with three dimensional sampling using crossed layers. Its energy resolution for electromagnetic showers is expected to be $\delta E/E \simeq 12\%/\sqrt{E} + 2.8\%$ (with E in GeV). It distinguishes hadronic from electromagnetic showers by their lateral and longitudinal shape, thus suppressing protons by a factor of 10^{-4} up to several hundred GeV. The calorimeter will also serve as an independent photon detector, with an angular resolution of about $\sim 1°$.

The new detector thus features sophisticated particle identification devices that will allow to discriminate the small amount of antiprotons against the large background of electrons, as well as positrons against the overwhelming background of protons, up to high energies. It will also have two ways of measuring high energy photons, by conversion in the tracker and in the electromagnetic calorimeter, which will allow systematic observations of the gamma ray sky.

4 Physics with the AMS-02 detector

The observation of antimatter suppression to the 10^{-9} level in the universe cannot be explained by the CP-asymmetry in the K and B-meson system. A locally broken matter-antimatter symmetry would imply regions of the universe consisting of matter and others of antimatter. From measurements the presence of a significant amount of anti-matter up to the scale of 15 Mpc is excluded. The observation of light anti-nulei like $\overline{\mathrm{He}}$ would be the proof for the existence of anti-matter domains whereas heavier anti-nuclei like $\overline{\mathrm{C}}$ would originate from anti-matter supernovae. Figure 6 shows the expected He spectrum for AMS-02 up to TV rigidity: this is a factor thousand increase in statistics compared to AMS-01 and a large increase in momentum reach. With these data, tiny amounts of antimatter can be discovered if it exists and can reach the vicinity of Earth. Otherwise it will improve current limits on the antimatter to matter flux ratio by three orders of magnitude, and up to TV rigidities.

More than 90% of the matter in the universe is believed to be a non-luminous, non-baryonic substance of yet unknown nature. One of the promising candidates for cold dark matter is provided by supersymmetry, in particular the lightest supersymmetric particle which often is taken to be the lightest neutralino, $\tilde{\chi}_1^0$. The concentration of WIMPS around galaxies may provide sufficient density to cause its indirect observation via annihilation reactions, $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow W^+W^-$, ZZ or $f\bar{f}$. All of these reactions may cause an excess in antiparticle spectra over standard physics expectation. As an example, Figure 7 shows the expected signal from two different heavy Higgsino-like neutralino contributions to the antiproton flux (dashed lines) and how it distorts the secondary antiproton flux [15]. Similar features are expected in the positron spectrum [16] due to boson and fermion production and decay from neutralino annihilation. WIMP annihilation into photons is expected to give much weaker signals [17].

The spectra and composition of cosmic rays will give important information on more conventional astrophysics, like the sources, acceleration and transport of cosmic rays inside our galaxy [18]. The chemical composition is observed

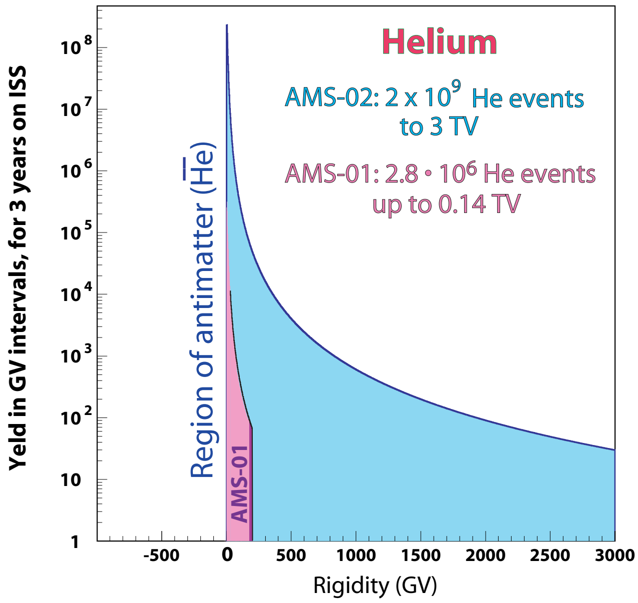

Fig. 6. Expected rigidity distribution of helium nuclei with AMS-02, compared to the AMS-01 result, in the absence of an antimatter signal.

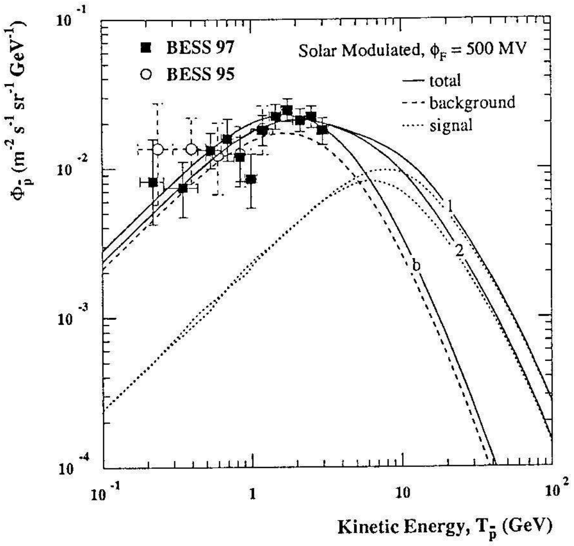

Fig. 7. Distortion of the secondary anti-proton flux (line b) induced by a signal from heavy Higgsino-like neutralinos.

to be rather similar to the solar composition, with remarkable exceptions for lithium, beryllium and boron which are neither produced in primordial nucleosynthesis nor in stars. They rather come from spallation reactions taking place in the supernovae explosion itself. A handle on cosmic ray propagation from source to Earth is given by the observation of radioactive isotopes, like ^{10}Be which has a life time comparable to the cosmic rays confinement time in our galaxy. As an example, Figure 8 shows the ratio of the ^{10}Be to ^{9}Be flux as a function of energy expected in leaky box transport models, compared to previous measurements [19] and the expected AMS-02 measurement capabilities. Such a measurement will determine the cosmic ray confinement time in the Milky Way and measure the mean density of interstellar material traversed.

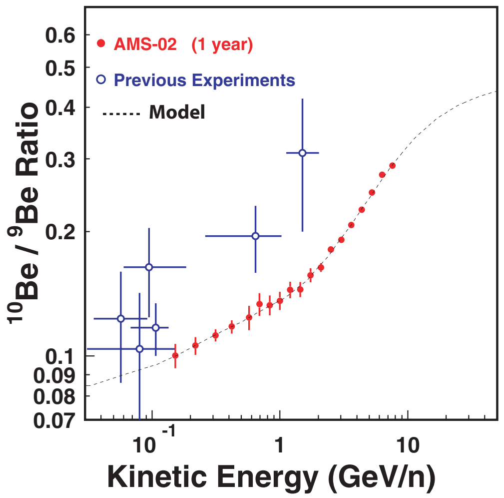

Fig. 8. Ratio of the ^{10}Be to ^{9}Be flux as a function of energy expected in leaky box transport models, compared to existing measurements and the expected AMS-02 results using isotope identification in the ring imaging Cerenkov detector.

AMS-02 will also measure the direction and energy of photons [20], by conversion in the 0.25 radiation length of material above the tracker, as well as in the electromagnetic calorimeter. A star tracker has recently been added to the AMS-02 set-up to ensure accurate knowledge about the instrument orientation, since the ISS attitude is rather variable. AMS-02 will constantly scan the whole sky and thus be well suited to follow the time evolution of variable photon sources. It will be able to study galactic photon sources like quasars as well as extragalactic sources like AGN [21], with the aim of learning more about the acceleration mechanisms at work in these objects.

5 Conclusions

AMS-02 is a complete and sophisticated detector which should be ready in October 2005 for installation on the ISS. Due to its large geometrical acceptance, large momentum range and dynamics, its particle identification capability and its long duration campaign of measurements, it will collect close to 3 orders of magnitude more statistics than in AMS-01 with much better instrumental conditions. It will contribute to the observation of cosmics rays and photons in space in an energy domain and time scale complementary to other projects.

A rich and diversified physics program will result from its three years of data taking on the ISS.

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