AMS Experiment on the International Space Station

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Abstract: Alpha Magnetic Spectrometer (AMS-02) is a general purpose high energy particle detector which was successfully deployed on the International Space Station (ISS) on May 19, 2011 to conduct a unique long duration mission of fundamental physics research in space. Among the physics objectives of AMS are a search for an understanding of Dark Matter, Antimatter, the origin of cosmic rays and the exploration of new physics phenomena not possible to study from ground based experiments. This article reviews the performance of the AMS-02 detector on ISS, as well as the first results based on data collected during the first weeks of operation in space.

Key words: cosmic rays, dark matter, antimatter, space-born magnetic spectrometer

1 Introduction

Tremendous interest to space-borne particle physics experiments stems from the unique features of experimentation in space: possibility of studying primordial particles created in the early Universe in a clean, almost background free environment. Success of the first space-borne particle detectors such as IMP-5,7,8, HEAO-3, ACE, EGRET \textsuperscript{1]} lead to proposals of a more complex experiments (PAMELA, FERMI, AMS) \textsuperscript{2, 3}. These new experiments address the most intriguing questions of the modern cosmology — baryon asymmetry of the Universe and its mass density composition.

AMS is an international collaboration composed of 60 institutes from 16 countries. The detector was successfully launched onboard STS-134 mission on May 16, 2011 and deployed on the International Space Station on May 19, 2011. Since its activation on ISS, AMS is steadily collecting data at a rate of $1.4 \times 10^9$ events per month. The technical goals of AMS are to reach a sensitivity of antimatter search $10^{-10}$ (ratio of anti-helium to helium), an $e^+/p$ rejection of $1/10^6$ and to measure the composition and spectra of charged particles with an accuracy of 1%. This represents a considerable sensitivity improvement compared to the previous experiments with space-borne magnetic spectrometers.

There is a strong demand for precision measurements of cosmic rays in the energy region from 10 to 1000 GeV as the recent measurements of $e^+/(e^++e^-)$ by AMS-01, HEAT and PAMELA \textsuperscript{4]} indicate a large deviation of this ratio from the production of $e^+$ and $e^-$ predicted by a model that includes only ordinary cosmic ray collisions. These measurements are both at too low energy and of too limited statistics to shed the light on the origin of this significant excess. AMS-02 detector is expected to provide definitive answers concerning the nature of this deviation.

2 AMS Detector

AMS-02 is a general purpose detector to study primordial cosmic ray particles in the energy range from 0.5 to 2000 GeV. In order to ensure that technologies used in the detector construction work reliably in space, a scaled down detector (AMS-01) was built and flown in 1998 on board the STS-91 mission for 10 days \textsuperscript{3}. Layout of the AMS-02 detector for long duration mission on ISS is presented in Figure 1. It consists of a Transition Radiation Detector; four planes of Time...
of Flight counters; a Permanent Magnet; a precision silicon Tracker; an array of Veto Counters, surrounding Tracker; a Ring Image Cerenkov detector; and Electromagnetic Calorimeter. The front-end electronics consist of 650 microprocessors that reduce raw data volume by factor 1000 without loss of physics information, and downlink collected data to the ground at an average rate of 10 Mbit/s.

2.1 Transition Radiation Detector

The Transition Radiation Detector, TRD, is mounted on top of AMS-02 (see Figure 1). It is designed to distinguish between light particles and heavy particles of equal charge and momentum, specifically between positrons and protons, which give the same signal in the silicon tracker but need to be separated to search for signals from dark matter annihilation in the cosmic ray spectra.

The TRD consists of 5248 straw tubes of 6 mm diameter. Sixteen straws are arranged in a module and mounted in 20 layers, each with a fiber fleece radiator of 20 mm thickness. Each straw tube is filled with a Xenon/CO\textsubscript{2} gas mixture; xenon efficiently captures the transition radiation generated in the radiator. Leak rate of the gas from TRD was measured to be 5μg/s. It is dominated by CO\textsubscript{2} diffusion through the straw tube walls. With 5 kg of CO\textsubscript{2} onboard, this leak rate corresponds to the lifetime of 30 years in space.

Figure 2 illustrates quality of separation of electrons and protons with TRD using data collected by AMS on ISS.

2.2 Time of Flight Counters

The Time of Flight, TOF, system of AMS-02 provides the fast trigger to the experiment, the measurement of the particle velocity including discrimination between upward and downward going particles and a measurement of the absolute charge. Overall there are four planes of scintillators assembled into two mechanical structures — upper and lower TOF (see Figure 1). The average time resolution of each counter has been measured to be 160 picoseconds, and the overall beta ($\beta = v/c$) resolution of the system has been measured to be 4% for $\beta \sim 1$ particles, according to the design specifications.
The Anti-Coincidence Counters (ACC) surround the AMS silicon tracker, just inside the inner cylinder of the support structure, to detect unwanted particles that enter or leave the tracker volume and induce signals close to the main particle track such that it could be incorrectly measured, for example confusing a nucleus trajectory with that of an anti-nucleus. The ACC consists of sixteen curved scintillator panels of 1 m length, instrumented with wavelength shifting fibers to collect the light and guide it to a connector from where a clear fiber cable guides it to the photomultiplier sensors mounted on the conical flange of the support structure.

2.3 Silicon Tracker and Magnet

The tracker is composed of 192 ladders, which is a basic unit that contains the silicon sensors, readout electronics and mechanical support. Three planes of honeycomb with carbon fiber skin, equipped with silicon ladders on both sides of the plane, constitute the inner part of the silicon tracker. Other three planes equipped with only one layer of silicon ladders, they are located on top of TRD, on top of the Magnet and in between Ring Image Cherenkov detector and Electromagnetic Calorimeters as indicated in Figure 1.

Each ladder has strips aligned with 3μm accuracy that measure coordinates of charged particles in two orthogonal projections. Readout pitch is 110μm in the bending plane and 208μm in the non-bending plane. This granularity provides coordinate resolution of 10μm in the bending plane. Overall there are close to 200000 readout channels. Signal amplitude provides a measurement of the particle charge independent of other sub-detectors. Signal amplitude provides a measurement of the particle charge independent of other sub-detectors as presented in Figure 3.

Permanent Magnet with the central field of 1.4 kG provides a bending power sufficient to measure protons up to Maximal Detectable Rigidity of 2.14 TV. For He nuclei the Maximal Detectable rigidity is 3.75 TV.

2.4 Ring Imaging Cherenkov detector

The Ring Imaging Cerenkov (RICH) detector is designed to separate charged isotopes in cosmic rays by measuring velocities of charged particles with a precision of one part in a thousand. The detector consists of a dual dielectric radiator that induces the emission of a cone of light rays when traversed by charged particles with a velocity greater than that of the phase velocity of light in the material. The emitted photons are detected by an array of photon sensors after an expansion distance of 45 cm. The measurement of the opening angle of the cone of radiation provides a direct measurement of the velocity of the incoming charged particle ($\beta = v/c$). By counting the number of emitted photons the charge ($Z$) of the particle can be determined as illustrated in Figure 4.

The radiator material of the detector consists of 92 tiles of silica aerogel (refractive index $n = 1.05$) of 2.5 cm thickness and 16 tiles of sodium fluoride ($n = 1.33$) of 0.5 cm thickness. This allows detection of particles with velocities greater than 0.953$c$ and 0.75$c$ respectively. The detection plane consists of 10,880 photon sensors with an effective spatial granularity of $8.5 \times 8.5$ mm$^2$. To reduce lateral losses the expansion volume is surrounded by a high reflectivity reflector with the shape of a truncated cone.
2.5 Electromagnetic Calorimeter

The AMS-02 electromagnetic calorimeter (ECAL) consists of a lead scintillating fiber sandwich with an active area of \(648 \times 648 \text{ mm}^2\) and a thickness of 166.5 mm. The calorimeter is composed of 9 superlayers, each 18.5 mm thick and made of 11 grooved, 1 mm thick lead foils interleaved with 10 layers of 1 mm diameter scintillating fibers. In each superlayer, the fibers run in one direction only. The 3-D imaging capability of the detector is obtained by stacking superlayers with fibers alternatively parallel to the \(X\) and \(Y\) axes (4 and 5, layers respectively). The calorimeter has a measured thickness corresponding to 17 radiation lengths.

Fibers are read out on one end by four anode Hamamatsu R7600-00-M4 photomultipliers (PMTs); each anode covers an active area of \(9 \times 9 \text{ mm}^2\), corresponding to 35 fibers, defined as a cell. In total the ECAL is subdivided into 1296 cells (324 PMTs) and this allows a sampling of the longitudinal shower profile by 18 independent measurements.

The signals are processed over a wide dynamic range, from one minimum ionizing particle, which produces about 8 photoelectrons per cell, up to the 60,000 photoelectrons produced in one cell by the electromagnetic shower of a 1 TeV electron. ECAL performance was studied in high energy electron and proton beams. The energy resolution for high energy electrons is measured to be \(2-3\%\) (see Figure 5), the angular resolution is \(\sim 1^\circ\) and \(e/p\) separation is estimated to be \(\sim 10^4\) for energies above 200 GeV.

3 Calibration of the AMS Detector

Various tests have been performed with the individual AMS subsystems. This includes flight qualification tests: thermal, vibration, electromagnetic interference tests; as well as studies with different beams. In addition to that, several system wide tests were performed with the AMS-02 detector: beam test at CERN as well as Electromagnetic Interference and Thermal Vacuum tests at European Space Research and Technology Center (ESTEC) in Holland.

3.1 Electromagnetic Interference and Thermal Vacuum Tests at ESTEC

AMS Detector underwent Electromagnetic Interference Test in large EMI Chamber at ESTEC in February-March 2010. The objectives of this test were to verify that the performance of the detector will not be adversely affected by the expected electromagnetic environment of the shuttle or the station and to verify that AMS will not generate electromagnetic interference that will adversely affect either vehicle. Each of the electronic subsystems designs had previously been successfully tested at “box level”. This testing of the complete detector was required as part of the NASA safety verification of AMS.

AMS Thermal Vacuum/Thermal Balance (TV/TB) test was performed in the Large Space Simulator at ESTEC, in March - April 2010. The main objectives of the test were: testing performance of the sub-detectors under vacuum in a wide range of temperatures close to those on the Space Station; verification of the operability and the performance of the AMS Thermal Control Systems; and verification of the AMS Thermal Model. In particular, AMS heat rejection capability using radiators was verified. This is a very different mechanism compared to the convective cooling which occurs during the tests at ambient conditions. Most components of AMS have already been individually tested in Thermal Vacuum chambers. The TV/TB test at the system level was required to verify the integrated performance of the detector. In particular, the functionality of AMS heaters and thermal interlocks was verified, including their impact on the overall AMS power consumption.

3.2 Beam Test at CERN

From 8 to 20 August 2010, AMS was placed in the CERN test beam with 400 GeV protons and \(10^{-9}-290\) GeV electrons. AMS detector was installed on a support structure which allows 2 axes of translation and 2 axes of rotation for exposure of the detector to particles from all directions, as in space. Figure 6 summarizes the results from the data collected in the test beam by the integrated detector, showing that the track coordinate resolution is \(10 \mu\text{m}\) (Figure 6a); the
energy resolution for electrons is 2.5 to 3% (Figure 6b); the velocity resolution is 1/1000 with 400 GeV protons (Figure 6c); and that for 400 GeV protons TRD provides a proton rejection factor of 1/120 at 90% electron selection efficiency (Figure 6d). The combined proton rejection factor (TRD and ECAL) at 400 GeV was measured to be $10^{-6}$.

During processing of AMS for the Shuttle flight at Kennedy Space Center from September 2010 to March 2011 calibration parameters obtained during the CERN beam test were used to cross check the detector performance using see level Cosmic Rays. Figure 7 shows the reconstructed masses of CR muons and protons collected at KSC.

### 4 AMS Operations on ISS

AMS was installed on the International Space Station on May 19, 2011 and since that date the detector is collecting data at an average rate of 10 Mbps. Particle rates over one ISS orbit vary between 200 Hz near the equator to about 2000 Hz near the Earth magnetic poles. Data acquisition efficiency is on average 85% (it reaches 96% near the equator and 65% near the poles) resulting in an average event acquisition rate of 700Hz. Over 7 billion events have been collected during the first five months of operations in space (Figure 8). Over its lifetime of ~20 years AMS will collect 300 billion triggers. This will provide unprecedented sensitivity to search for new phenomena.

Status of all AMS subsystems is constantly monitored by the AMS shifts (5–12 people are on shift at any given time in the AMS Payload Operations and Control Center, POCC, at CERN). Dynamically changing running parameters (data downlink bandwidth, distribution of available electrical power, rotation of ISS solar panels and radiators near AMS, ...) are followed by shifters, who are also in permanent contact with NASA ground personnel on voice loops. Commands are sent to AMS from POCC in response to changing conditions, as necessary.

All AMS subsystems are fully operational with the
Fig. 8. Number of events collected by AMS on ISS as a function of calendar time.

Variations of ambient conditions (temperature in first place) are studied and will be accounted for with proper calibrations and alignments. Therefore, intensive calibration work for all detector systems is going on now in order to maximize the accuracy of the measurements.

5 AMS Physics Potential

AMS-02 is a general purpose particle detector capable of identifying and measuring simultaneously all cosmic ray particle species: photons, electrons, protons and nuclei as well as all corresponding antiparticles. This feature becomes very important for distinguishing signals from new phenomena and background processes, given a significant uncertainty in the background calculations related to the modeling of the standard processes and subsequent propagation. AMS will measure spectra for nuclei in the energy range from 0.5 GeV/n to 2 TeV/n with 1% accuracy over the 11-year solar cycle. These spectra will constitute a stringent experimental test of the assumptions that go into the background estimates. In this article only the data collected during the very first weeks of operations on ISS are presented. Example of proton rate spectra at different latitudes is presented in Figure 9, which shows the effect of geomagnetic cutoff as well as the presence of the under-cutoff spectrum — the effect already reported by AMS-01 [3].

5.1 Dark Matter Searches

The most appealing candidate for Dark Matter is a stable neutralino which is a generic ingredient of SUSY models with a breaking scale of few hundred GeV. AMS-02 has potential to study neutralino annihilation using simultaneously four different final state particles: positrons, anti-protons, anti-deuterons and photons. As seen in Figure 10, the available low energy measurements of the positron fraction indicate a strong deviation from the estimates based on the model that takes into account only cosmic ray collisions. AMS-02 will measure all nuclei spectra thus providing stringent constraints on the background estimates. It is also important to extend the energy range of the measurements to a 1 TeV range in order to assess any changes in the behavior of the positron fraction at high rigidities up to 1 TeV. This is one of the primary goals for AMS.

Fig. 9. Proton rate spectra observed by AMS at different geomagnetic latitudes as a function of measured rigidity.

Fig. 10. Data on positron fraction in Cosmic Rays [4].

Example of an event from the data sample corresponding to this analysis is presented in Figure 11. This event is identified as an electron of 240 GeV. It was collected during first few days of AMS operations in space — on May 22, 2011. It should be noted that 3D shower reconstruction in ECAL (Figure 12) provides an accurate estimate of directions and coordinates.

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Fig. 11. Two projections of the electron candidate detected by AMS on May 22, 2011.

Fig. 12. Electron candidate detected by AMS on May 22, 2011: electromagnetic shower development in two transverse and in the longitudinal directions are consistent with an electron of 240 GeV.

The reconstructed shower axis can be traced back to match with the information from other AMS sub-detectors. For electron/positron candidates there are matching traces in the TRD, TOF and Tracker, for photon candidates these matching traces in other AMS-02 sub-detectors are absent.

5.2 Anti-Matter Searches

Conditions that are required for the baryon asymmetry in the Universe have no experimental support: to date neither strong CP-violation nor proton decays are observed experimentally. Therefore existence of large anti-matter domains in the Universe a-priori may not be ruled out. Such domains, if exist, would emit anti-particles which will eventually reach the Earth through a diffusion process. Production of anti-helium or heavier anti-nuclei in the interaction of ordinary matter in space is totally negligible; therefore observation of single anti-helium in space would constitute a strong argument in favor of such anti-matter domains.

One of the goals of AMS is to improve the sensitivity of a direct anti-matter search by 3 to 6 orders of magnitude (depending on the rigidity range) and increase the current search range to 1 TeV as demonstrated in Figure 13. In this figure there are no assumptions that He and anti-He spectra are identical.

Example of a high charge particle detected by AMS during the first days of operations is shown in Figure 14. The radius of the RICH ring measures the velocity (or energy) which agrees with the Tracker momentum measurement of 136 GeV. The thickness
of the ring shows $Z = 14$ in agreement with $dE/dx$ charge measurement in the Tracker. Presented in Figure 15 is also determination of cosmic ray relative nuclear abundances by the RICH and Silicon Tracker using the correlation between particle charges measured in the RICH and in the Silicon Tracker.

![Fig. 14. 136 GeV ion with $Z = 14$ (Si) observed by AMS in the first days of operations on ISS.](image)

5.3 Strangelets

AMS represents an unprecedented opportunity to explore the unknown. One example is the search for new types of matter such as strangelets [5]. Strangelets, or Strange Quark Matter (SQM), are new types of matter composed of three types of quarks ($u, d, s$) which may exist in the cosmos. Both lattice QCD and phenomenological bag model calculations indicate that SQM could be stable with lower energy levels than usual matter. SQM has a very low $Z/A$ ratio, typically less than 0.13 compared to the $\sim 0.5$ of normal nuclei. Attempts to detect SQM production in accelerators are negative, which agrees with calculations that indicate they cannot be formed there by coalescence nor distillation (the minimum stable size, $A > 8$, is too large). Neutron stars could in fact be one large strangelet at low “vapor” pressure, providing a source of SQM in cosmic rays. Searches for SQM on Earth and in lunar samples are negative but of limited sensitivity (e.g., large strangelets are so dense they would sink to the center of gravity). AMS-01 has observed a potential strangelet candidate with $Z = 2$ and mass of 16.5 GeV, with the estimated flux of $5 \times 10^{-5}$ (sr m$^{-2}$ s$^{-1}$). AMS-02 will provide much improved sensitivity for the search of this new type of matter.

![Fig. 15. Correlation between charges measured in Tracker and RICH. The data sample corresponds to first 5 days of operations on ISS, with raw data summed up over all energies.](image)

6 Conclusions

At present ISS operations are approved till 2020 and intensive discussions are going on between ISS Space Agencies to certify on-board elements through 2028. These discussions are further stimulated by a significant enhancement of ISS scientific program with the deployment of AMS-02 detector onboard ISS. Therefore, at this time, we assume that AMS-02 will collect data over 18 years of the Station lifespan. Given unprecedented statistical significance of AMS-02 data sample, AMS Collaboration is fully focused now on understanding effects related to dynamically changing ISS environment and sets calibration of the detector as its highest priority in order to maximize the accuracy of the measurements.

References


