The Alpha Magnetic Spectrometer on the International Space Station

B. Borgia on behalf of AMS Collaboration

***Abstract*—The Alpha Magnetic Spectrometer (AMS) is a particle physics detector designed to measure charged cosmic ray spectra up to the TV region, with high-energy photon detection capability up to few hundred GeV. AMS is a superconducting spectrometer with large acceptance, long duration (at least three years for the magnet) and state of the art particle identification techniques. AMS will investigate the composition of cosmic rays with high statistics and provide the most sensitive search for the existence of antimatter nuclei and for the nature of dark matter. The detector is being constructed with an eight-layer Silicon Tracker inside a large superconducting magnet, providing a ~ 0.8 Tm^2 bending power and an acceptance of ~ 0.4 m^2 sr. A Transition Radiation Detector and a three-dimensional Electromagnetic Calorimeter allow for electron, positron and photon identification, while a Time of Flight scintillating system and a Ring Image Cerenkov detector perform independent velocity measurements. This complex apparatus will identify and measure nuclei up to Iron. We will describe the overall detector construction and performance, which is due to be completed by 2006. The detector will be installed on ISS (International Space Station) in 2008.**

***Index Terms*—Anti-matter, cosmic rays, dark matter, neutralino, space detector, space station, superconducting spectrometer.**

I. Introduction

THE Alpha Magnetic Spectrometer (AMS) is a high-energy particle physics experiment in space to be placed on the International Space Station (ISS) in 2008 for a mission of at least three years. The main physics goals are searches for anti-matter and dark matter. Physics objectives dictate instrumental requirements, and due to conditions in space, the detector has to fulfill more special requirements. The payload is limited to 7 tons and 3 kW power consumption. Construction of sub detectors is well underway. Here we report beam test results that confirm projected performances.

II. Physics Goals and Detector Requirements

Until now, a consistent theory of baryogenesis has not been proposed, as present experimental data do not support these models. The main ingredients of the Sakharov [1] model are baryon nonconservation and large CP-violation but these are not observed. For the last 20 years, cosmic ray searches for antinuclei have given negative results but have been unable to fully probe the universe. Experimental input is essential, either with a positive or a negative outcome, if sensitivity is high enough. A major objective of the physics program of the AMS experiment is to search for cosmic ray antinuclei. Detection of a few anti-He nuclei will be clear evidence of the existence of antimatter domains, since their formation in conventional processes is largely suppressed.

Present search limits on anti-He are at the level of 10^{-6} [2], [13]–[16] therefore, to increase the sensitivity for antimatter up to very far distances, greater than 20 Mpc, AMS has to reach a rejection factor for He of 10^{-9}. A high value of the magnetic field B and a large magnetic volume are the first requirements for this goal, since momentum resolution is proportional to BL^2. A low material budget along the particle trajectory minimizes the probability for large angle nuclear scattering, which could be confused with the signal of anti-nuclei. Track reconstruction with redundant points will add strong constraints to the charge sign determination. Time of flight and Cerenkov measurements determine the up-down direction of the particle and so bending sign.

Several observations indicate that the Universe should include a large amount of unknown dark matter (DM). It could be composed of nonbaryonic Weakly Interacting Massive Particles (WIMP). The Lightest Supersymmetric Particle in R-parity conserving SUSY models [3], [17]–[19] may be a WIMP candidate. SUSY dark matter can be searched in decay channels from neutralino annihilation

$$\chi+\chi\rightarrow e^{+}+\cdots$$
$$\chi+\chi\rightarrow \bar{p}+\cdots$$
$$\chi+\chi\rightarrow \bar{d}+\cdots$$
$$\chi+\chi\rightarrow \gamma+\cdots$$

A simultaneous measurement of all channels will add confidence to the result. Cosmic Ray spectra over the energy range 1–100 GeV show the ratio of proton/positron of the order of 10^3 to 10^4, the proton/antiproton ratio varies between 10^5 and 10^3 and the electron/antiproton from 10^3 to 10^2. A detector aiming to search for a neutralino signal through annihilation products therefore needs an excellent proton and electron identification along with good charge sign determination, of the order of 10^5. While charge sign determination is already required for the antimatter search, particle identification requires dedicated detectors. Emission of transition radiation is proportional to the Lorentz factor γ; therefore AMS incorporates a detector based on this effect. Comparison of momentum with total energy deposited in the electromagnetic calorimeter adds a large proton rejection factor against electrons.

Since AMS will take data for at least three years with magnetic field and possibly more without it, it will record cosmic

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ray spectra with very high statistics and high precision, allowing possible discovery of new phenomena or new particles.

In addition to the mass determination for antimatter search, in order to study fundamental topics in astroparticle physics such as the relative abundances of light isotopes and charged nuclei, it is necessary to have a precise measurement of the masses of charged particles. For instance the ratio $^{10}\mathrm{Be}/^{9}\mathrm{Be}$ allows the determination of the cosmic ray confinement time in the Galaxy and of the mean density of interstellar material traversed by cosmic rays [4], [20]. For this purpose a Ring Imaging Cerenkov Detector was designed with a large geometrical acceptance to operate in the environmental conditions in space.

Following the above requirements and guidelines, the AMS Collaboration is constructing a large superconducting magnetic spectrometer with outstanding particle identification of positrons, antiprotons, gammas and nuclei. The main components are:

- a Transition Radiation Detector (TRD) with capability to reject protons with a factor greater than 10^2 up to 250 GeV/c;
- the central spectrometer, magnet and silicon tracker. It allows rigidity (momentum/charge), charge and sign measurements;
- time of Flight scintillation counters (TOF). They will measure particle speed and absolute value of charge through dE/dx deposited in the scintillators;
- Ring Imaging Cerenkov Counter (RICH) measuring independently speed and charge;
- electromagnetic calorimeter (ECAL) with three-dimensional (3-D) sampling, It will measure total electron and gamma energies and will reject protons with a factor greater than 10^3;
- anticoincidence counters (ACC) will provide rejection of sidetracks or scattered particles in the mechanical supports or magnet.

Fig. 1 shows a cut-through view of the detector.

Due to the space environment, the transport by the Space Shuttle and the installation on the ISS, the construction of the AMS detector has to fulfill requirements for safety and mission success. All parts must undergo testing against radiation damage, vibration, thermal and vacuum operations. In addition specific tests are required, for instance the liquid Helium vessel should be safe against micrometeorite impact or at least He should vent in a controlled way.

Being attached to the ISS, the detector will receive power and commands, will transmit data, but no direct human intervention is foreseen for all three years of flight. Therefore the liquid He supply must last for the entire period, electronics has to have redundant communication channels and the gas supply for the TRD should last much longer than three years.

III. Detector Components

A. Transition Radiation Detector

The Transition Radiation Detector (TRD) [5] consists of 20 layers of 6 mm diameter straw tubes alternating with 22 mm layers of polyethylene/polypropylene fleece radiator. An 80%/20% mixture of Xe/CO_2 at 1.0 bar absolute fills the

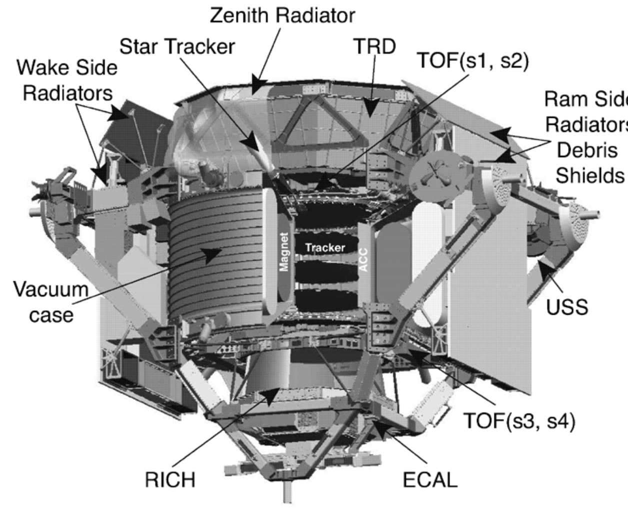

Fig. 1. AMS detector in a cut-through view. USS is the support structure. See text for sub-detectors acronyms. Overall dimensions are 3m × 3m × 3m.

straw tubes from a recirculation gas system designed to operate in space much longer than three years. The straw tubes are built as modules of 16 tubes. In all, there are 328 modules, for a total of 5248 straws. Each straw is tested and accepted only with a He leak rate below 10^{-5} liter at 1 mbar per second per meter length of the straw tube. This is followed by a serial test of dark current and corona and the gas gain is measured as a function of high voltage with an ^{55}Fe source and with an Ar/CO_2 gas mixture. All straw modules were produced and tested by July 2004.

A 20-layer prototype was built and tested in the CERN beam between 10 and 250 GeV. At 90% electron efficiency and at energy of 250 GeV, the proton rejection factor achieved by means of a likelihood method is 140 (see Fig. 2).

B. Superconducting Magnet

The superconducting magnet [6] is a major enterprise for a space experiment that needs detailed analysis and design not only for its performance, but even more for safety issues.

The AMS magnet consists of two dipole coils with two sets of 6 racetrack coils for field return. This arrangement suppresses the overall dipole magnetic moment and stray field is limited to less than 300 Gauss in its vicinity. Coils kept cooled to 1.8 K by means of 2500 L of superfluid He. The magnetic field achieved is 0.86 T. Superfluid helium, or He II, has several advantages, has zero viscosity, is denser than He I, has a high thermal conductivity and low thermal capacitance. The inner free bore of the magnet is a cylinder with a diameter of 1.1 m.

All coils are manufactured and dipole coils are tested to the maximum mechanical load. Operation of coils after an induced quench was also tested. A special test was performed on the vacuum vessel to insure that micrometeorites will not puncture the enclosed vessel holding liquid helium.

C. Silicon Tracker

The silicon tracker [7] is composed of 2500 double-sided silicon micro-strip sensors, 300 μm thick. The n-type, high resistivity (>6 kΩ) sensors are biased with the punch-through

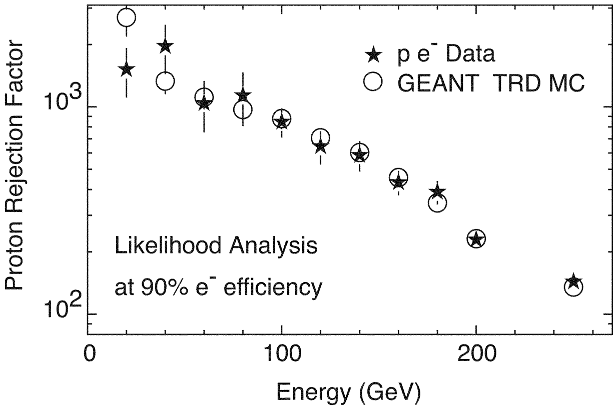

Fig. 2. TRD proton rejection factor at 90% electron efficiency.

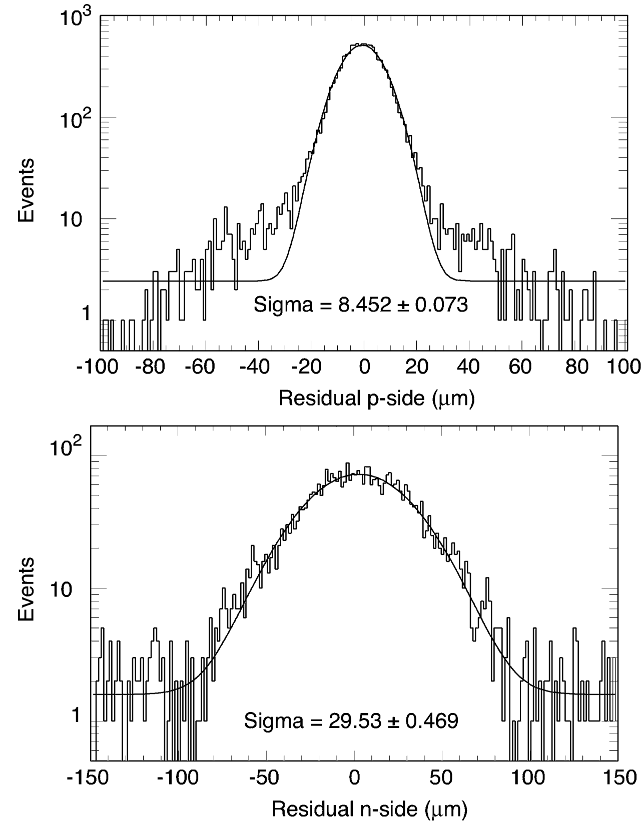

Fig. 3. Residual distributions with respect to reference position on prototype ladder. Top plot is p-side and bottom plot is n-side.

technique; p+ blocking strips, implanted on the n-side, are used to minimize the influence of surface charge on the position measurement obtained from the ohmic side. The sensor design uses capacitive charge coupling with implantation (readout) strip pitches of 27.5 (110) μm for the p-side and 104 (208) μm for the n-side. The finer pitch p-side strips are used to measure the bending, or y, coordinate and the orthogonal n-side strips measure x. More than 4000 sensors have been produced to select the 2500 highest quality sensors required to assemble the Silicon Tracker. All the sensors were tested twice to ensure that electrical parameters and performance specifications meet the space qualification requirements, for example that the number of noisy strips was less than 0.6% per sensor. The long-term electrical stability of a sample of sensors is also monitored. This large number of sensors makes the Silicon Tracker the largest precision tracking detector ever built for a space application. Silicon sensors are assembled first in ladders. The principal goals of the ladder fabrication are to guarantee the required precision for the relative alignment of the silicon sensors (<5 μm), and minimize the degradation of the electrical performance due to handling and ultra-sonic bonding. Then ladders are assembled onto support honeycomb planes.

The tracker support structure is divided into three sections: a carbon fiber cylindrical shell which supports the planes 2 to 4 located inside the magnet, and two carbon fiber flanges which support the exterior planes 1 and 5. With respect to the AMS-01 configuration [8], [21] the number of silicon layers has been increased from 6 to 8 by suppressing one internal plane and equipping both sides of the remaining three internal planes with silicon ladders.

The Tracker Thermal Control System (TTCS) is a two-phase, mechanically pumped loop system. A pump circulates the cooling fluid, CO_2, at 23 to 50 bar. It enters into the tracker volume at a temperature just below the boiling point and passes by thermal bars on the outer and outermost inner planes, where the heat from front-end hybrids is collected in series. At each heat input, a small fraction of the liquid is evaporated. The tracker volume is isothermally cooled and the cooling hardware located in the tracker volume minimized. Outside the tracker volume, the fluid passes through a heat exchanger to keep the incoming fluid just at the boiling point while minimizing the pre-heater power required. It is then directed to condensers on the tracker thermal radiator panels facing deep space. There, the vapor/liquid mixture is cooled to below the boiling point, and then returns to the pump input, closing the circuit. This system removes 144 watt of Tracker power.

A measurement of the position resolution was provided by a dedicated setup consisting of a reference telescope composed of four single-sided silicon sensors with 50 μm pitch readout and an AMS prototype ladder. The detectors were placed in 120 GeV muon beam at CERN. The residual distributions of the ladder are described by a Gaussian function and flat background. The widths of the Gaussians are 8.5 and 30 μm respectively for the p- (bending plane) and n-sides (non bending plane) (Fig. 3). Fig. 4 shows expected rigidity resolution for protons and He ions.

Ionization energy deposited in the tracker sensors is proportional to Z^2. This property is used to determine the ion charge Z by measuring the charge collected by the junction side and by the ohmic side of sensors. Six ladders were exposed to a fragmentation beam originated by 135 GeV/A Indium ions impinging on a beryllium target. An independent measurement was performed by the RICH prototype at the same time (see Fig. 7).

D. *Time of Flight Counters*

Two sets of double scintillation counter planes provide a fast trigger and time of flight measurement [9]. Each plane is divided into 8 or 10 paddles, 12 cm wide, 1 cm thick, and are disposed crosswise along x and y directions. Physics requirements demand a time of flight resolution of 120 ps. Downward

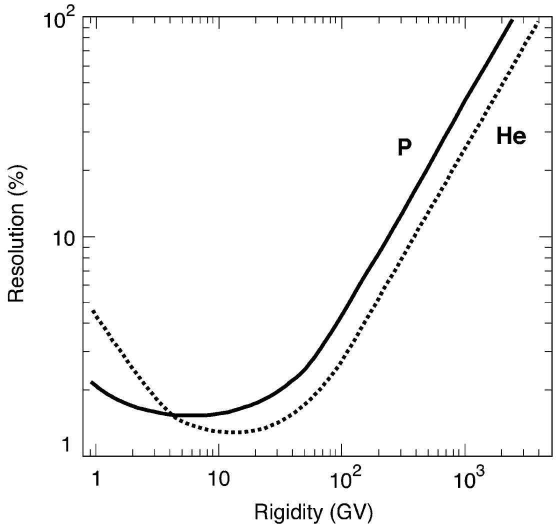

Fig. 4. Expected rigidity resolution of protons and He in AMS.

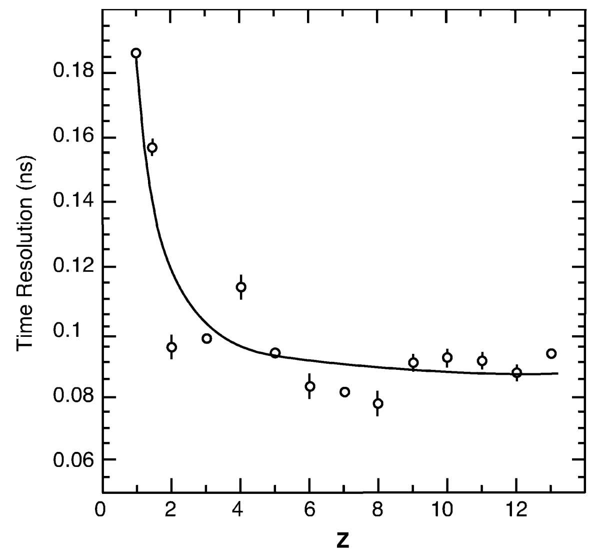

Fig. 5. Time of flight resolution between only two counters versus particle charge Z. Point at $Z = 1.4$ correspond to two protons crossing the counters simultaneously.

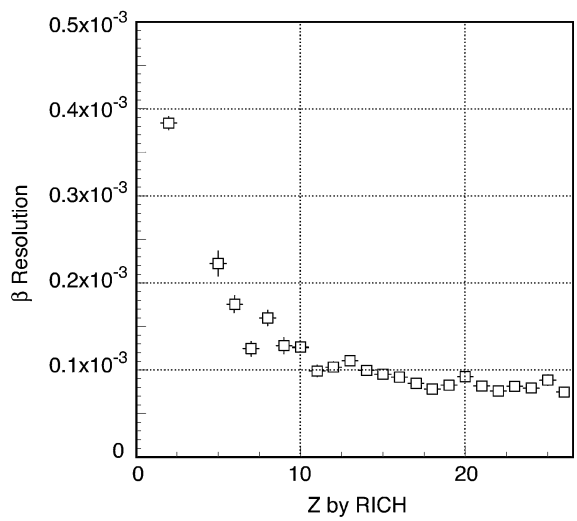

Fig. 6. RICH velocity resolution vs particle charge Z.

going charged particles are distinguished from upward going at the level of 10^9.

The system measures the energy loss by a charged particle (to first order proportional to Z^2) with a resolution sufficient to distinguish nuclei up to charge $Z \sim 20$. Taking into account the attenuation along the counters, and the need to have a good measurement of single charged particles, a dynamic range of more than 10 000 in the measurement of the pulse height is required. Within AMS, this measurement complements those made by the Silicon Tracker and RICH. The TOF counters must operate in the stray field of the AMS cryomagnet. The use of magnetic shielding is precluded because of the large weight required and the induced forces on the assembly. Consequently, a thorough investigation selected a PMT, which can operate under these conditions, the Hamamatsu R5946, provided the PMT axis is aligned within 45 degrees of the field direction. This was a primary design consideration in the construction of the TOF system.

The TOF counters were tested in CERN ion beams. The beams were obtained by the fragmentation of the primary SPS Pb beam at 20 and 158 GeV/c/A against a Be or Pb target, within different momentum per nucleon windows using the H8 selection line. Four counters with different configurations of the light guides were tested. Fig. 5 shows time of flight resolution between two counters as function of particle charge Z. In AMS four independent combinations of the four counter planes will measure the time of flight. Therefore the time resolution that can be inferred is of the order of 130 ps for a minimum ionizing particle.

E. Ring Imaging Cerenkov Detector

The properties of a Cerenkov cone depend on the velocity of the charged particle $v = \beta c$ and the refractive index of the material, $n(\omega)$. In particular, for an incoming particle of charge Ze, the half opening angle θ of the cone is given by $\cos\theta = 1/n\beta$; the number of radiated photons in a frequency range $d\omega$ for a traversed length dx in the material is proportional to $Z^2 \sin^2\theta$. Therefore, the velocity is determined from the measurement of the opening angle of the Cerenkov cone and, as a by-product, the number of detected photons will provide an independent estimate of the charge of the incoming particle [10].

Particles traverse either 3 cm of Aerogel radiator with $n = 1.03$ or 0.5 cm of NaF emitting a Cerenkov cone collected by 560 photomultipliers directly or reflected by a conical mirror. Each phototube is divided into 4×4 pixels. The intersection of the light cone with the phototube plane will form a ring which radius is proportional to particle speed. A counter prototype was exposed to the fragmentation beam at CERN described before (§D). Eventually the speed is measured with an accuracy $\delta\beta/\beta = 0.1\%$ (Fig. 6).

Fig. 7 shows charge measured by junction side of the Tracker sensors versus charge measured by RICH. Particle charge can be clearly separated up to Z∼26 (Fe).

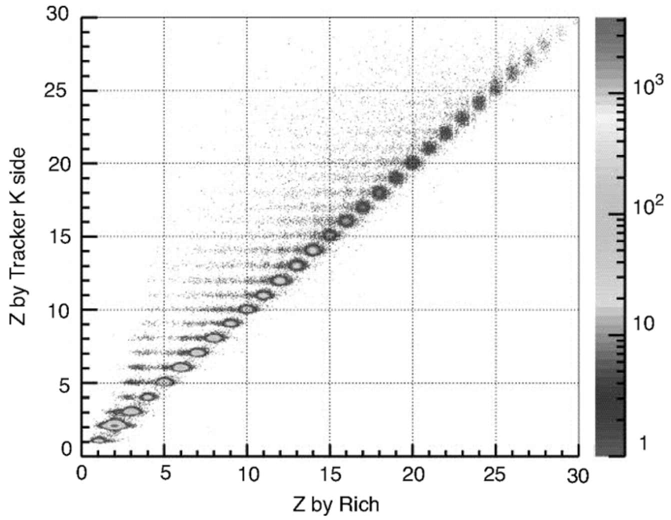

Fig. 7. Charge correlation measurement in a 135 GeV/A fragmentation beam: Tracker (junction side) versus RICH.

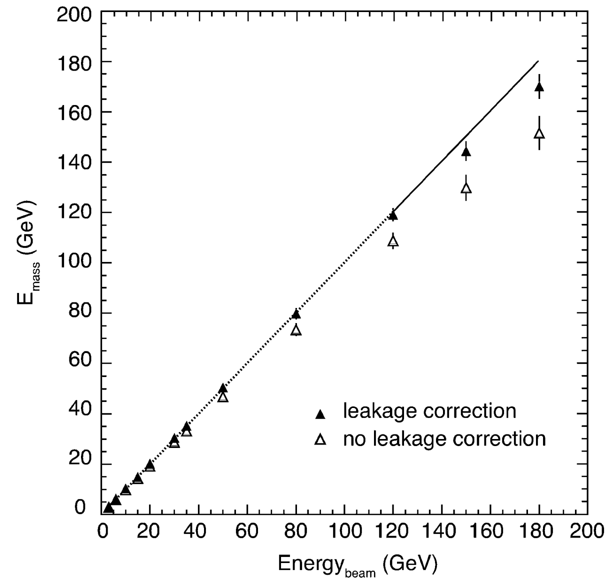

Fig. 8. ECAL energy linearity response before and after leakage correction.

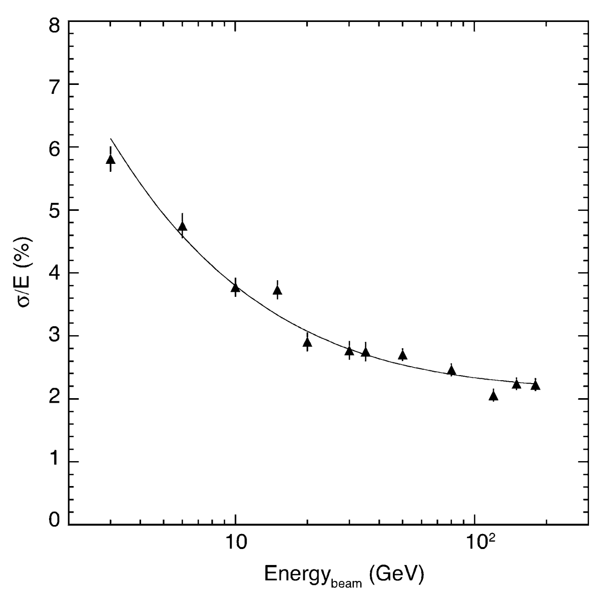

Fig. 9. ECAL energy resolution versus energy after data corrections. Solid line represents fitted formula of text.

F. Electromagnetic Calorimeter

The Electromagnetic Calorimeter (ECAL) of the AMS experiment is a fine grained lead-scintillating fiber sampling calorimeter [11] that allows precise, 3-D imaging of the longitudinal and lateral shower development, providing high ($\geq 10^6$) electron/hadron discrimination in combination with the other AMS detectors and good energy resolution. The calorimeter also provides a standalone photon trigger capability to AMS. The ECAL consists of a lead/scintillating fiber sandwich with an active area of 648×648 mm^2 and a thickness of ≈ 16 X_0. The calorimeter is composed of "superlayers", made of 11 grooved 1 mm thick lead foils interleaved with layers of 1 mm diameter scintillating fibers and glued together with epoxy. In each superlayer, fibers run in one direction only. The detector imaging capability is obtained by stacking superlayers with fibers alternatively parallel to the x-axis (four layers) and y-axis (five layers). Fibers are read out, on one end only, by four anode Hamamatsu R7600-00-M4 photomultipliers; each anode covers an active area of 9×9 mm^2, defined as a cell. In total the ECAL is subdivided into 1296 cells and this allows a sampling of the longitudinal shower profile by 18 independent measurements. This sampling allows a proton rejection of 10^3.

A full size prototype was exposed to electron and proton beams. Corrections to raw data were applied for light attenuation along the fiber and then cell by cell and layer equalization. Last sampling method is applied to correct energy leakage at higher energies. Fig. 8 shows the calorimeter linearity before and after correction.

The calorimeter reaches an energy resolution of

$$\sigma/E + \{[(10.2 \pm 0.3\%)/\sqrt{E(\mathrm{GeV})}]^2 + (2.31 \pm 0.05\%)^2\}^{1/2}$$

for electrons (see Fig. 9) and an angular resolution measured with electrons (Fig. 10) as

$$\sigma(\theta) = \{[(8.0 \pm 0.1^\circ)/\sqrt{E(\mathrm{GeV})}]^2 + (0.57 \pm 0.04^\circ)^2\}^{1/2}.$$

Resolution is defined as the angular distance from incoming beam that contains 68% of the events.

IV. Detector Performance

A. Antimatter Search

The precursor flight AMS-01 in 1998 has not observed any anti-He and put a limit of 10^{-6} to anti-He/He ratio. Selection criteria were based on 1) track fitting with variable points, all with consistent charge sign, 2) cut on energy deposition on the silicon sensors to reject nuclear interactions and 3) kinematical fit to cut masses lower than He mass. The present detector will have a BL^2 six times larger than the value of AMS-01 and 8 planes of silicon detectors instead of 6. Simulation by Monte Carlo method shows that no false candidates will be found in 10^9 He events, therefore we expect to reach the limit shown in Fig. 11.

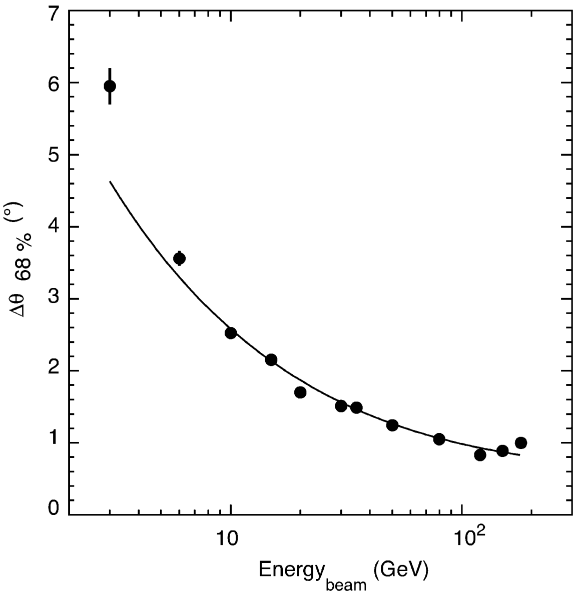

Fig. 10. ECAL angular resolution versus energy. Resolution is defined as the angular distance from incoming beam that contains 68% of the events.

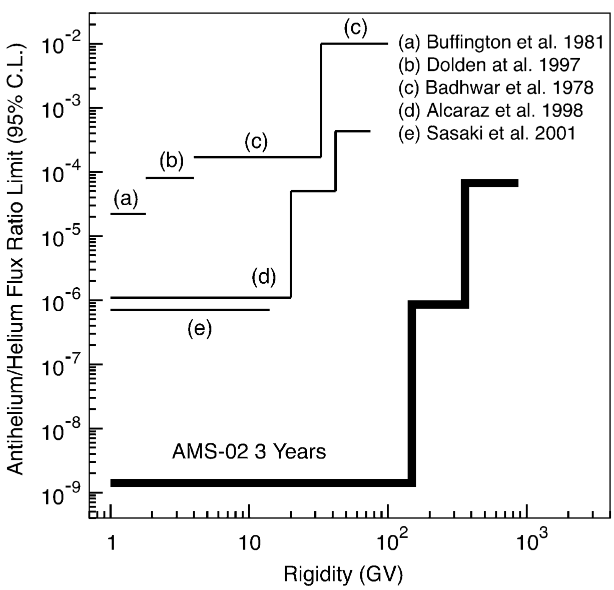

Fig. 11. Projected AMS limits on anti-He/He flux ratio compared to previous measurements [2], [13]–[16] including AMS-01.

B. Dark Matter Search

Among the neutralino annihilation channels, the positron signal is one of the most promising. Beam test data and Monte Carlo simulation have shown that proton background can be reduced by a factor 10^6 and electrons by 10^4. Fig. 12 shows the expected signal due to the annihilation of a neutralino with mass of 130 GeV/c^2 and with a specific choice of model parameters [12].

V. Summary

Detector integration is expected by the middle 2006. AMS will be ready to launch in September 2007. During the three years on the ISS, AMS will collect $\approx 10^{10}$ events.

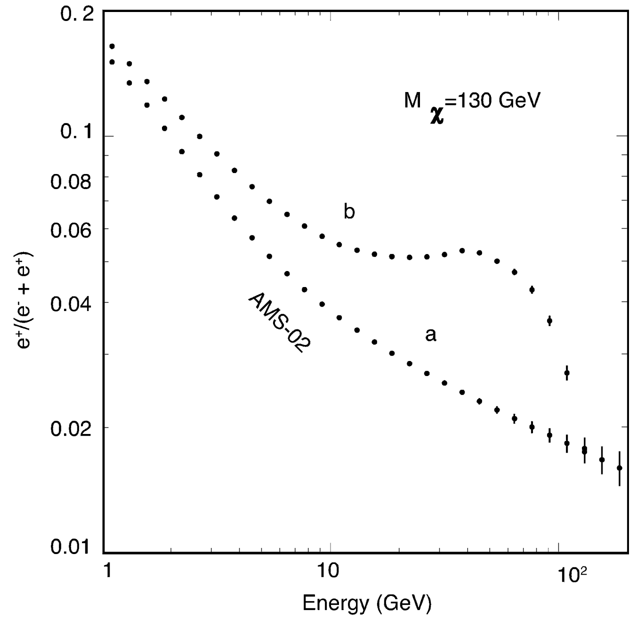

Fig. 12. Simulated positron spectrum measurement in the (a) absence or (b) presence of a neutralino with mass 130 GeV/c^2 [12].

AMS is designed to search for:

- antimatter;
- dark matter;
- new particles;
- high energy γ sources.

AMS will also measure cosmic rays with large statistics. Long time exposure in space where physics channels are measured simultaneously in the same conditions, will allow strong constraints on models and will increase discovery potential of new particles by orders of magnitude.

Acknowledgment

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