The Alpha Magnetic Spectrometer on the International Space Station

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***Abstract*--The Alpha Magnetic Spectrometer (AMS) is a particle physics detector designed to measure charged cosmic rays spectra up to TV region, with high-energy photon detection capability up to few hundred GeV. AMS is a superconducting spectrometer with large acceptance, long duration (3 years) 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 anti matter nuclei and for the origin of dark matter. The detector is being constructed with an eight layers Silicon Tracker inside a large superconducting magnet, providing a ~ 0.8 Tm^2 bending power and an acceptance of ~ 0.5 m^2 sr. A Transition Radiation Detector and a 3D Electromagnetic Calorimeter allow for electron, positron and photon identification, while independent velocity measurements are performed by a Time of Flight scintillating system and a Ring Image Cerenkov detector. This complex apparatus will identify and measure nuclei up to Iron.**

This contribution will describe the overall detector construction and performance, which is due to be completed by 2005.

The detector will be installed on ISS (International Space Station) in 2008.

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 three years mission. The main physics goals are the anti-matter and the dark matter searches. Physics objectives dictate instrumental requirements. Due to conditions on space, the detector has to fulfill more special requirements. Payload is limited to 7 tons and power to 2.2 kwatt. Construction of sub detectors is well underway. Expected performances and test results will be reported in the following.

II. Physics Goals and Detector Requirements

Until now, a consistent theory of baryogenesis has not been yet proposed, as these models are not presently supported by experimental data. Main ingredients of Sakharov [1] model are baryon non-conservation and large CP-violation but they are not observed. All last 20 years cosmic ray searches for antinuclei have given negative results. Experimental input is essential, either with positive or 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 few anti-He nuclei will be a clear evidence of existence of antimatter, since their formation in conventional processes is largely suppressed.

Present limits on anti-He search are at the level of 10^{-6} [2] therefore to increase the sensitivity for antimatter domains up to very far distances, greater than 20 Mpc; AMS has to reach a rejection factor for He of 10^{-9}. High value of magnetic field B and large magnetic volume are first requirements for this goal, since momentum resolution is proportional to BL^2. Low material budget along 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 constraint to charge sign determination. Time of flight measurement determines up-down direction of the particle and then bending sign.

Several observations indicate that the Universe should include a large amount of unknown dark matter (DM). It should be composed of non-baryonic Weakly Interacting Massive Particles (WIMP). The Lightest Supersymmetric Particle in R-parity conserving SUSY models may be a WIMP candidate. SUSY dark matter can be searched in three decay channels from the neutralino annihilation:

$$\chi + \chi \rightarrow e^+ + \ldots\ldots\ldots$$

$$\chi + \chi \rightarrow \overline{p} + \ldots\ldots\ldots.$$

$$\chi + \chi \rightarrow \overline{d} + \ldots\ldots\ldots.$$

$$\chi + \chi \rightarrow \gamma + \ldots\ldots\ldots.$$

A simultaneous measurement of all channels will add confidence in the result. In the energy range 1 to 100 GeV of Cosmic Rays spectrum, ratio of proton/positron is of the order of 10^3, 10^4, proton/antiproton ratio varies between 10^5, 10^3 and electron/antiproton 10^3, 10^2. A detector aiming to search 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 should be already achieved for antimatter search, particle identification requires dedicated detectors. Emission of transition radiation is proportional to the Lorentz factor γ, therefore a specialized detector should be chosen. Comparison of momentum with total energy deposited in the electromagnetic calorimeter adds a large proton rejection factor.

In addition, since AMS will take data for at least three years with magnetic field and possibly more without it, it will record cosmic ray spectra with very high statistics and high precision,

Manuscript received November 1, 2004. This work was supported in part by INFN, Italy.

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allowing possible discovery of new phenomena or new particles.

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

- 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). It 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 3D sampling, It will measure total electrons and gammas energy and will reject protons with a factor greater than 10^3.
- Anticoincidence counters (ACC) will provide rejection of side tracks or scattered particles in the mechanical supports or magnet.

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

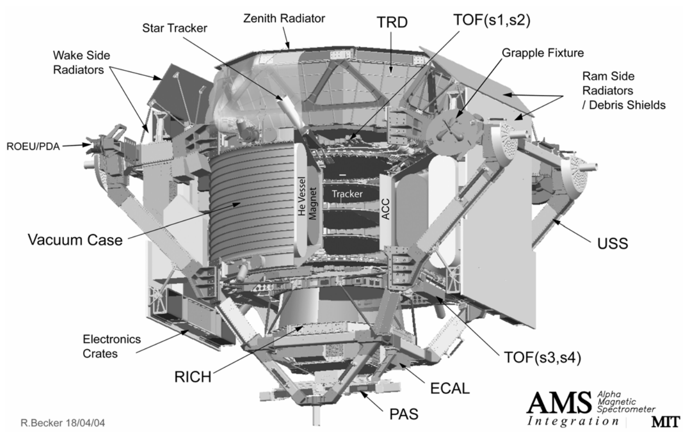

Fig. 1. AMS detector in a cut-through view. USS is the support structure. See text for sub-detectors acronyms.

Due to space environment and the attachment to the ISS, the construction of AMS detector has to fulfill requirements for safety and mission success. Radiation damage, vibration, termovacuum, all parts have to undergo these tests. In addition specific tests are required for instance liquid Helium vessel should be safe for micro-meteorites 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 3 years of flight. Therefore liquid He supply must last for entire period, electronics has to have redundant communication channels, gas supply for the TRD should last much longer than 3 years.

III. Detector Components

A. Transition Radiation Detector

Transition Radiation Detector (TRD) 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/CO2 at 1.0 bar absolute fills the straw tubes from a recirculation gas system designed to operate >3 years in space. 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} *l mbar/s/m*. 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 the Ar/CO_2 gas mixture. All straw modules were produced and tested by July 2004.

A full 20 layers prototype was built and tested on CERN beam. At 90% electron efficiency, between 10 and 250 GeV the proton rejection factor achieved by a likelihood method is 140.

B. Superconducting Magnet

The superconducting magnet 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 set of 6 racetrack coils for field return. This arrangement suppresses the dipole magnetic moment and stray field is limited to less than 300 Gauss in its vicinity. Coils are cooled at 1.8 K by means of 2500 litres 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.

Al coils are manufactured and dipole coils are tested to the maximum mechanical load. Operation of coils after induced quench was also tested. A special test was performed on vacuum shield to insure that micro-meteorites will not puncture the vacuum vessel holding liquid helium.

C. Silicon Tracker

The silicon tracker 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 technique and 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 selection 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 (<5µm), and minimize the degradation of the electrical performance due to handling and ultra-sonic bonding.

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, 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. The cooling liquid, CO_2 at 23 to 50 bar, is circulated by a pump. 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 of 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.

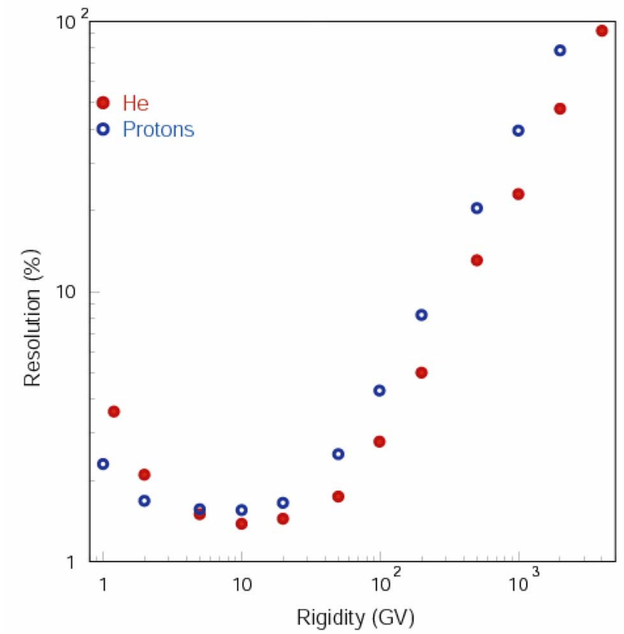

Fig. 2. Expected rigidity resolution of protons and He in AMS.

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). Rigidity resolution for protons and He ions is shown in Fig.2.

By November 2005 the system will be completed.

D. Time of Flight Counters

Two double planes of scintillation counters provide fast trigger and measurement of time of flight. Each plane is divided in 8 or 10 paddles 12 cm wide 1 cm thick and are disposed crosswise along x and y directions. The resolution in the time of flight needed to satisfy the physics requirements is 120 ps. Downward 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 has been a primary design consideration in the construction of the TOF system.

The TOF counters were tested in ion beams at CERN in again in 2003. 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. As the measurement in AMS will be done with four independent measurements, the time resolution which can be inferred is of the order of 130 ps for a MIP.

E. Ring Imaging Cerenkov Detector

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 determination of the masses of charged particles. For this purpose a Ring Imaging Cerenkov Detector (RICH) has been designed with a large geometrical acceptance to operate in the environmental conditions of the outer space.

The properties of Cerenkov cone depend on the velocity of the charged particle and the refractive index of the material, n(ω). 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 dω 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 estimation of the charge of the incoming particle.

Particles traverse 3 cm of Aerogel radiator with n=1.03 emitting a Cerenkov cone collected by 800 photomultipliers directly or reflected by a conical mirror. Each phototube is divided further into 4 × 4□□□□□□s. The intersection of the light cone with the phototube plane will form a ring which radius is proportional to particle speed. Eventually the speed is measured with an accuracy $\delta\beta/\beta = 0.1\%$.

Charge can be clearly separated up to Z ~ 26 (Fe).

By September 2005 the RICH counter will be completed.

F. Electromagnetic Calorimeter

The Electromagnetic Calorimeter (ECAL) of the AMS experiment is a fine grained lead-scintillating fiber sampling calorimeter that allows precise, 3-dimensional 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. ECAL consists of a lead/scintillating fiber sandwich with an active area of 648 x 648 mm2 and a thickness of ≈ 16 X_0. The calorimeter is composed from "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 (4 layers) and y-axis (5 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 x 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.

After cell by cell and layer equalization the calorimeter has reached an energy resolution of

$$\sigma / E = [(10.2 \pm 0.3\%)/\sqrt{E(GeV)}] \otimes (2.31 \pm 0.05\%)$$

for electrons and an angular resolution for gamma rays of

$$\sigma(\theta) = [(8.0 \pm 0.1°)/\sqrt{E(GeV)}] \otimes (0.57 \pm 0.04°)$$

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 track fitting with variable points, all with consistent charge sign, cut on energy deposition on the silicon sensors to reject nuclear interactions and kinematical fit to cut masses lower than He mass. The present detector will have a BL^2 six times 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. 3.

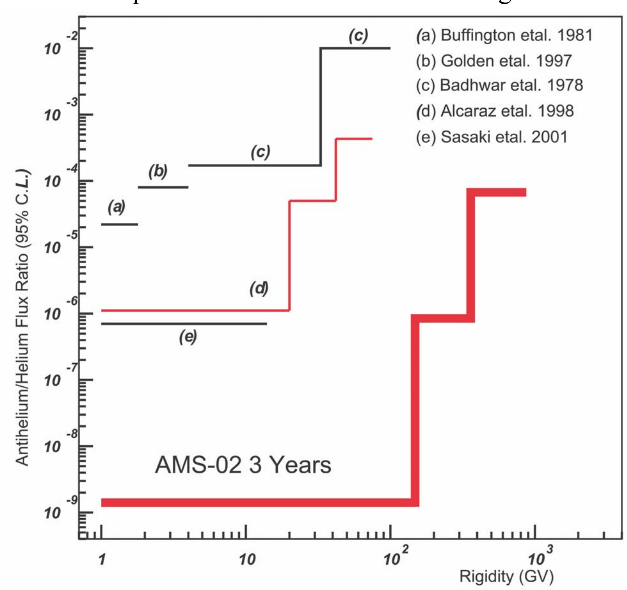

Fig. 3. Projected AMS limits on anti-He/He flux ratio compared to previous measurements [2] [3] including AMS-01.

B. Dark Matter Search

Positron signal is the most promising among the neutralino annihilation various channels. 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. 4 shows the expected signal due to the annihilation of a neutralino with mass of 130 GeV/c^2.

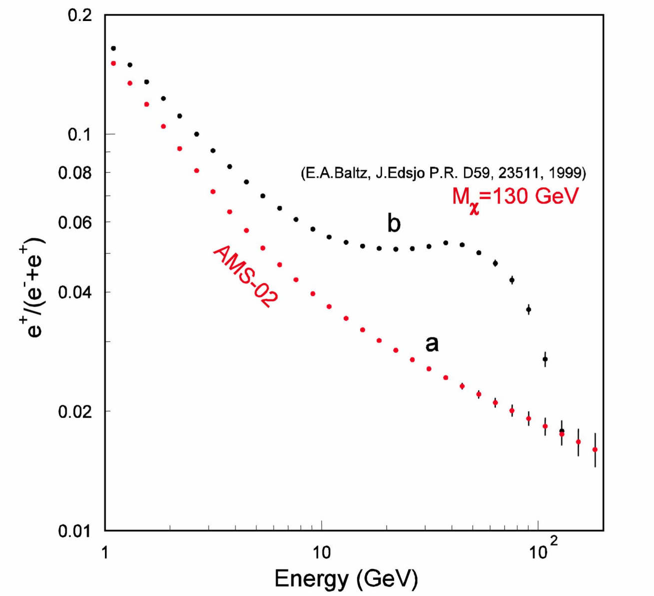

Fig. 4. Simulated positron spectrum measurement in the absence (a) or presence (b) of a neutralino with mass 130 GeV/c^2.

V. Summary

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

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 by orders of magnitude.

VI. . Acknowledgment

The construction of AMS is an undertaking of many individuals and organizations. The support of NASA and the U.S. Dept. of Energy has been vital in the inception, development and fabrication of the experiment. The interest and support of Mr. Daniel S. Goldin, former NASA Administrator, is gratefully acknowledged. The dedication of Dr. John O'Fallon, Dr. Peter Rosen and Dr. P.K. Williams of U.S. DOE, our Mission Management team, Dr. Douglas P. Blanchard, Mr. Mark J. Sistilli, Mr. James R. Bates, Stephen Porter, NASA, Dr. Susan Breon, GSFC-NASA, Mr. Kenneth Bollweg and Mr. T. Martin, Lockheed-Martin, the support of the space agencies from Germany (DLR), Italy (ASI), France (CNES), Spain (CDTI) and China (CALT) and the support of CSIST, Taiwan, have made the construction possible.

The support of GSI--Darmstadt, particularly of Dr. Reinhard Simon made it possible for us to test electronics components for radiation effects.

The support of INFN, Italy, IN2P3, Region Rhône-Alpes and Haute Savoie, France, CIEMAT and CICYT, Spain, LIP, Portugal, CHEP, Korea, the Chinese Academy of Sciences, the National Natural Science Foundation and the Ministry of Science and Technology of China, Academia Sinica, Taiwan, the U.S. NSF, M.I.T., ETH-Zurich, the University of Geneva, National Central University and National Cheng Kung University, Taiwan, Moscow State University, SEU, Nanjing, Shanghai Jiao Tong University, RWTH-Aachen, the University of Turku and the University of Technology of Helsinki, is gratefully acknowledged.

We are also grateful for the strong support and interest shown from the private sector, including Dr. E. Ettlinger, Linde, Dr. R. Herzog, ILK, Dresden, Mr. J. Ross, Mr. S. Milward and Mr. S. Harrision of SCL, Culham, UK, Mr. M. Molina, CGS, Milan, Mr. F. Petroni, CAEN, Viareggio, Mr. A. Poseda, CRISA (Astrium), Madrid, Ing. A. Pontetti, G&A Engineering, Italy, Dr. E.A. Werner and Dr. J. Krieger, ISATEC, Aachen, and Dr. H. Bieri, Bieri Engineeering, Switzerland.

We thank Professors A. De Rujula, J. Ellis, A. Guth, L. Maiani, for many interesting discussions and support.

VII. References

[1] A. D. Sakharov, *JETP Letters* vol. 5, pp. 24 , 1967.
[2] J. Alcaraz et al., AMS coll., *Phys, Lett.* vol. B461, pp. 387, 1999.
M. Sasaki et al., BESS coll., *Proc.* 27th *ICRC*, pp. 1711, 2001.
[3] G. Badhwar et al. *Nature,* vol. 274, pp. 137, 1978.
A. Buffington et al. *ApJ.* vol. 248, pp. 1179, 1981.
R. L. Golden et al. *ApJ.* vol. 479, pp. 992, 1997.