The AMS experiment : first results and physics prospects

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abstract

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THE AMS EXPERIMENT : FIRST RESULTS AND PHYSICS PROSPECTS

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Abstract. The main physics goal of the AMS experiment is the search for primordial antimatter, non-baryonic dark matter, and the measurement with high statistics and high accuracy of the electrically charged cosmic ray particles and light nuclei in the extraterrestrial space beyond the atmosphere. AMS is the first magnetic spectrometer which will be flown in space. It will be installed for 3 years on the international space station (ISS) in 2003. A precursor flight with the space shuttle DISCOVERY took place in June 1998. 100 millions particles were recorded during the test flight and unexpected physics results were observed on fluxes of protons, electrons, positrons, and helium nuclei. These results are described below, and the physics prospects for the second phase of the experiment on the space station as well.

1 Introduction

In the early age of the cosmic ray physics, most of the experiments where looking at charged particles, and at the showers in the atmosphere produced by the interaction of these particles. When it became possible to launch detectors in the outer space beyond the atmosphere the new generation of experiments looked at high energy gamma rays, and many discoveries were done. Gamma rays propagation in the intergalactic and interstellar medium is not affected by magnetic fields, and thus it was possible to point at sources of gamma rays and to identify it.

On the contrary, the information of direction of the sources of charged particles is washed out by the propagation in the galactic and intergalactic magnetic field. Near the earth, the fluxes of charged cosmic rays are disturbed by the solar activity which produces the solar wind, a plasma made mainly of protons and electrons which behaves like a shielding for the earth. Furthermore, the earth magnetic field bends the trajectories of particles coming from the outer space and sends them back to space when the energy is below a threshold that depends on the impinging angle and the geomagnetic latitude of the particle. The earth magnetic field is in first approximation a dipole inclined of about 11^o with respect to the earth rotation axis,

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with the dipole axis shifted by about 400 kms from the center of the earth, and the south magnetic pole near the north geographic pole. Near the magnetic poles the kinetic energy threshold is as low as 10 MeV while at the magnetic equator it raises to 10 GeV. Despite these effects, charged cosmic rays contain physics information on the dynamics of galaxies (cosmic wind, confinement, origin of charged cosmic rays) and on primordial universe that cannnot be found elsewhere.

Due to the difficulty to build a magnetic spectrometer and operate it in space, former experiments on charged cosmic rays in space were only measuring particles by range, and therefore they could not distinguish positive from negative charge particles. Several balloon borne experiments aimed at measuring electrically charged cosmic rays, but they suffer from two drawbacks : i) balloons are limited in altitude to about 40 Kms, and there is still 5 g/cm^2 of atmosphere above, thus inducing interactions of primary cosmic rays which give a lot of background particles ii) The duration of balloon flights is so far limited to 2 to 3 weeks, hence these experiments cannot get high statistics, which limits the sensitivity reachable even with an ideal detector. For the study of rare phenomena, it is mandatory to be in the outer space beyond the atmosphere, to have a detector with a large acceptance, and to gather data for a long time

AMS will be the first magnetic spectrometer in space for a long duration, 3 to 5 years. The main goal of the experiment is the search for primordial antimatter, for non-baryonic dark matter, and the high precision and high statistics measurement of electrically charged cosmic ray particles and light nuclei in a very wide range of energy, from a few hundred MeV up to a few TeV in momentum.

2 The physics of AMS

2.1 The primordial antimatter

It was demonstrated by A. Zacharov [1] that to generate an asymmetric universe made of matter only, starting from a symmetric universe, i.e. an universe in which there is the same amount of matter and of antimatter, as it is in the big-bang theory at the very beginning of the universe, 4 conditions must be fulfilled : i) Violation of the baryonic number ii) Violation of the charge conjugation C iii) large CP violation iv) Baryogenesis out of the thermal equilibrium. These conditions are in contradiction with the experimental observations. The first condition means that the proton should be unstable; the experimental limit on the lifetime proton is very high [2], around 10^{33} years, which almost exclude the first condition. The CP violation observed in the K system are too small to account for the condition iii). Furthermore, in the Minimal SuperSymmetric Model, from the condition iii) one can derive an upper limit of about 60 GeV for the mass of the lightest Higgs boson [3] , while the recent LEP results put a lower limit of 88.3 GeV on this mass[b]. The theoretical attempts to find a way to make the antimatter disappearing like in the inflation model have not yet found a natural way. On the other hand, the absence of observation of gamma ray peaks from matter-antimatter annihilation excludes the presence of large quantity of antimatter within a distance of the order of 10 Mpc from the earth.

A clear signature of the existence of islands of antimatter in the universe would be the observation of antinuclei of Helium or Carbon, since such nuclei cannot be produced by interaction of cosmic rays with the interstellar medium. They can only be produced in the furnace of a star of antimatter, and be ejected in the outer space in a supernova explosion. Balloon borne experiments have searched for such antinuclei for more than 20 years with negative results [5, 6, 7]. AMS is designed to reach a sensitivity of 10^{-9} on the ratio antihelium/helium, better by 3 orders of magnitude than the existing experiments.

2.2 The Dark matter

From the motion of the spiral arms of galaxies and of the cluster of galaxies it can be deduced that about 90% of the mass of the universe is non-radiating, and therefore is invisible to classical astrophysics experiments. The nature of this so-called dark matter is not yet known. This missing matter could have been due to brown dwarfs, stars with a mass too small to ignite the nuclear reaction.Several [8] experiments have searched for such object by using gravitational lensing,

[b]The limit on $M-h$, mass of the lightest boson in the MSSM model published by the L3 Collaboration [4] is $M_h > 77.1 GeV$ at 95% confidence level using the data with an energy in the center of mass up to 189 GeV. Quite recently, the new preliminary value of $M_h > 88.3 GeV$ was obtained by combining the data of the 4 experiments at LEP, with the data at 192, 196, 200, and 202 GeV in the center of mass from year 1999 (A. Quadt, talk at the XXXV Rencontres de Moriond, Electroweak session, March 2000)

but from the spectrum of microwave background one can put a limit of about 20% on the fraction of dark matter which is baryonic (the so-called cold dark matter). Therefore most of the dark matter is of non baryonic origin. These objects are called WIMP's. In supersymmetric theories, a good candidate for WIMP's is the neutralino χ, lightest supersymmetric particle. This particle could have accumulated in the halo of galaxies and be observed through the annihilation with its antiparticle from which particles like antiprotons, positrons, and gammas are produced and can be observed above the flux of the same particles produced in the interaction of cosmic rays of high energy with the interstellar medium [9]. AMS will measure with high statistics and high resolution the fluxes of antiprotons, positrons, and gamma rays from .5 GeV/c to 1 TeV/c.

2.3 And the ordinary matter

A big amount of information on the mechanisms of galaxies is buried in the abundance and in the spectra of ordinary charged particles and nuclei. The spectra of charged cosmic rays at high energy falls off according to a power law, and the slope contains information about the source of such cosmic rays, either primary or secondary. Unexpected phenomena could show up as a distortion of such spectra, but this implies a high precision and high statistics measurement on a broad range of energy. For light nuclei it is of chief importance to disentangle the isotopic content, which contains information on the confinement of cosmic rays in the galaxy. The unstable isotopes act like a clock which gives the time spent in the galaxy by the nuclei between their production and the measurement. This is especially the case for the Be^9 and Be^{10}, of which the ratio of abundances gives a direct measurement of the confinement time. To have a complete information in order to test theoretical model, this ratio must be measured as a function of the energy of the nucleus, on a range of kinetic energy from low energies few tens of MeV/N up to around 15 GeV/N.

The experimental measurements on nuclei isotopes done up to now by satellites have very limited range in energy since they are using the range of nuclei in matter to disentangle the various isotopes, and they suffer from low statistics: at the time of the AMS proposal, there was only 14 Be^{10} nuclei measured world wide in 40 years, while AMS was expecting to measure 400 per day. High statistics, high precision, good identification power, and broad energy range are the key parameter to reach the physics content in this area, and these are the parameters by which the design of the AMS experiment is driven.

3 AMS precursor flight on shuttle DISCOVERY

3.1 The AMS01 detector

Since it was the first time that a magnetic spectrometer was to be flown in space for a long time, it was decided to have a precursor flight of a few days on board of the space shuttle DISCOVERY in order to test the detector behavior and performances under actual space flight conditions, to gather data on the background sources, and to study the operating parameters of the experiment. The detector was flown in June 1998, in the mission STS-91 of the shuttle DISCOVERY with an orbit inclined by 51.6^o on the geographic equator, at an altitude varying between 320 kms and 390 kms. More than 100 millions triggers were gathered during the data taking. Most of the data were collected with the shuttle attitude such that AMS z-axis was pointing toward the zenith, within an angle of 45 degrees. However 4 hours of data taking were done with the axis pointing toward the center of the earth in order to have a measurement of the fluxes of upward moving particles.

For this precursor flight, AMS consisted mainly of a permanent magnet, a silicon tracker, time of flight hodoscopes, anticoincidence counters, and an aerogel threshold Cerenkov counter. The acceptance was about 0.3 m^2sr. The permanent magnet was made of 1.9 tons of Nd-Fe-B in the shape of a cylindrical shell of inner diameter 1115 mm and length 800 mm. The Nd-Fe-B was magnetized to 46 MGOe with the direction varying in order to provide a dipole field in the x direction perpendicular to the cylinder axes, with a value of 0.14 Tesla in the center of the magnet and an analysis power BL^2, parallel to the magnet axis z of 0.14 Tm^2. The trajectory of particles traversing the magnet bore was measured by six planes of double sided silicon microstrip detectors put inside the magnet perpendicular to the axis, the outer layers being just outside the magnet cylinder, above and below. From the deflection the rigidity $\mathrm{R} = \mathrm{pc}/|Z|\mathrm{e}$ (GV) was measured. The tracker had an accuracy of about 10 microns in the bending plane and 30 microns in the other one. The tracker provided

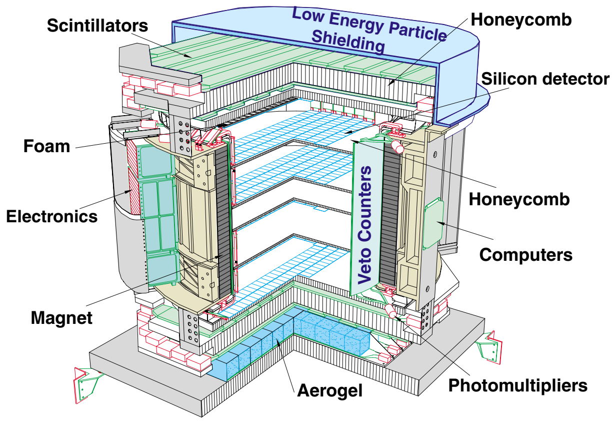

Figure 1: The AMS01 detector

also a determination of the charge $|Z|$ through multiple measurements of energy loss. The total amount of material of the tracker as seen by a particle parallel to the axis of the magnet was only 3% of radiation length, in order to minimize interactions and multiple scattering.

The particle velocity and direction of motion were measured by a time-of-flight system made of four layers of scintillation counters, 2 above and 2 below the magnet. Each layer consisted of 14 paddles of 10 mm thickness and 110 mm width overlapping in such a way to provide a hermetic coverage. The typical accuracy on the time measurement was 120 psec for particles of unit charge, and 105 psec for charge $|Z| = 2$, allowing to separate electrons from protons up to 1.5 GeV/c. The pulse height information from each plane provided additional determination of the charge $|Z|$. The velocity measurement was complemented by a threshold Cerenkov counter with an aerogel radiator of refractive index n=1.035, giving a separation between electrons and protons up to 3.7 GeV/c. A layer of anticoincidence scintillation counters lined the inner surface of the magnet to get rid of the background caused by particles passing through or interacting in the magnet walls and support structure. Finally, the detector was also shielded from low energy (a few MeV) particles by thin carbon fiber walls.

During the construction, the detector components went successfully through extensive space qualification tests (acceleration, vibration, thermal vacuum, electromagnetic interference, and radiation).

The basic trigger was made of the coincidence of signals in 3 out of 4 of the TOF planes, with a veto on a signal in the anticoincidence counters. During the flight, the detector performances as well as temperature and magnetic field were monitored continuously, and the alignment of the tracker was also continuously monitored with an infrared laser system. After the flight, the detector was checked and calibrated again first in an ion beam of Helium and Carbon at GSI-Darmstadt, then with an high energy pion and proton beam at CERN-PS, confirming that the detector performances remained the same before, during, and after the flight.

4 First physics results

At the time of this conference, the analysis of the data gathered by AMS was not yet finished. However, results were already available on antimatter search, on fluxes of protons, of electrons and positrons, and on flux and mass spectrum of helium. For the analysis, the data gathered above the area of the South Atlantic Anomaly were excluded. Apart from results on antihelium and proton spectra, the results presented below are preliminary.

4.1 Search for antihelium

For this search, the sample was restricted to data taken with the shuttle attitude such that the z-axis of AMS was pointing toward the zenith within an angle of 45 degrees. Events were selected after full reconstruction (momentum, sign, velocity, direction upward or downward, energy loss in the tracker and in the TOF) and were required to give hits in at least 4 tracker planes out of 6, and to have an energy loss in tracker and in TOF, each calculated from truncated mean, compatible with Z=2 charge. The latter criteria rejected the background of electrons with wrongly measured charge, since the combined charge confusion probability was found to be less than 10^{-7} (fig 2). The possibility of misidentifying the direction upward or downward of the cosmic ray was found to be negligible from a control sample. To get rid of large angle nuclear scattering on one of the tracker plane, it was also requested that the parameters of the track reconstructed with the first 3 hits, the last 3 hits, and using all the hits in the tracker be compatible. To remove events with colinear delta rays which could disturb the reconstruction a last cut was applied on

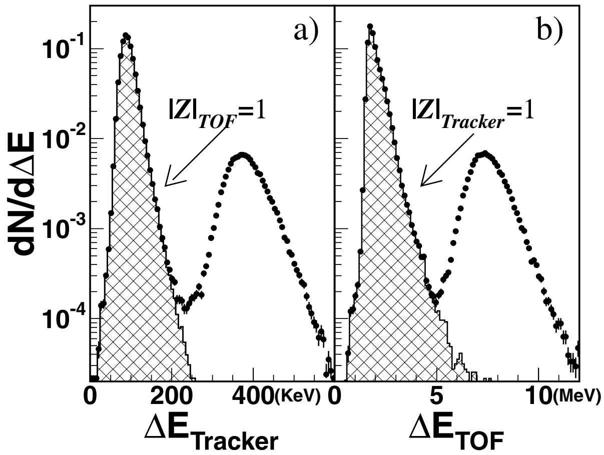

Figure 2: Energy loss measurements in tracker and TOF

events with an excess of energy deposited within $\pm$ 5 mm of the track. Finally a probability function was constructed from the measurement of velocity, rigidity, and energy loss to to check the compatibility of the track with the passage of an helium or antihelium nuclei with A=3 or 4. While this last cut removed the 4 remaining antihelium candidates, the Helium sample was very little affected. A total of $2.8 \cdot 10^6$ He was obtained in a rigidity range of up to 140 GV while there was not antihelium at any rigidity(fig 3). The limit on antihelium is: N(antihelium)/N(helium)$< 1.1 \cdot 10^{-6}$ over the range 1 to 140 GV in rigidity. The same study applied to nuclei with $|Z| > 2$ gave $1.56 \cdot 10^5$ events in the same rigidity range and no antinucleus candidate. Eventually, after the flight, AMS was put in an ion beam at GSI Darmstadt to confirm that the performances on charge separation and mass reconstruction were thoroughly understood.

4.2 Systematic measurement of proton spectra

Protons are easy to study since they are the most abundant singly charged particles, all the other fluxes being orders of magnitude lower. The huge statistics gathered by AMS allowed to study the proton energy spectrum as a function of the latitude and the high accuracy of the measurement allowed to trace backward the particles recorded in AMS. The sample was restricted to the period in which the z-axis

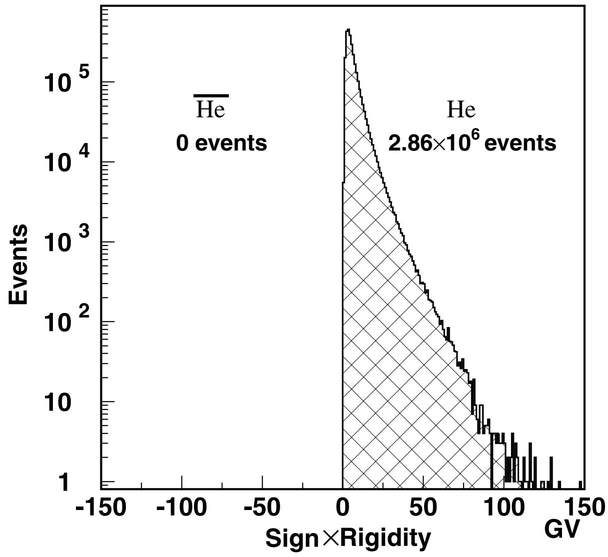

Figure 3: Measured rigidity times the charge sign for selected $|Z| = 2$ events

was pointing within 1^o of the Zenith to measure the downward going particles and to the period in which the z-axis was pointing within 1^o of the Nadir to measure the upward going particles. After reconstruction, tracks were selected with at least 4 hits in the tracker in the bending plane and a measured charge from energy loss compatible with Z = 1. The remaining background events from pions produced in the top part of AMS was found to be less than 0.5% below 1 GeV and vanishing rapidly with energy, while the contamination of deuterons was reduced to a negligible level by requiring the measured mass to be within 3 standard deviations of the proton mass. The measured spectra were corrected for the differential acceptance estimated from Monte-Carlo simulation, giving a contribution to the total systematic error of 5%, then the effect of detector resolution was unfolded using resolution functions obtained from the simulation and checked at several energy from test beam measurement (fig 4). The effect of geomagnetic cutoff shows up very neatly as a function of geomagnetic latitude. At high energy all the spectra have the same behavior. Surprisingly, a second (secondary) spectrum starts below the geomagnetic cutoff with a rate about an order of magnitude below. Near the equator the secondary spectrum has a distinct struc-

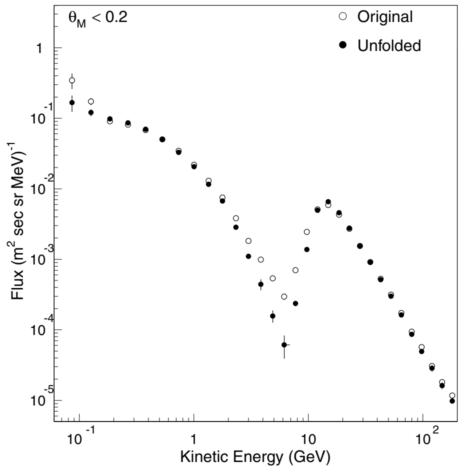

Figure 4: Original and unfolded proton spectrum near the geomagnetic equator

ture. In this region, the spectrum extends from the lowest measured energy, 0.1 GeV to about 6 GeV, with a rate of $70m^{-2}.sec^{-1}.sr^{-1}$. In all the bins in latitude up to $\Theta_M = 0.7$ the secondary spectrum of downward particle has a flux equal to the upward particles flux measured with the detector pointing toward the earth (fig 5). By tracing back 10^5 protons of the secondary flux in the earth magnetic field and stopping the extrapolation, either when the particle reach the top of atmosphere defined at 40 kms, or when the flight time reached 10 seconds, it was found that all the protons from the secondary spectrum originate in the atmosphere. 30% of the protons flew for less than 0.3 seconds and their origin in the atmosphere is uniformly distributed around the globe reflecting the shuttle orbits. The remaining 70% flew for more than 0.3 sec and originate from a restricted geographic zone, which could be related to the South Atlantic Anomaly.

Above the geomagnetic threshold, the proton spectrum follows a power law in rigidity $\Phi_0 \cdot R^{-\gamma}$. Fitting the parameters on the rapidity range 10 to 200 GV yields :

$$\gamma = 2.79 \pm 0.012(fit) \pm 0.019(sys)$$

$$\Phi_0 = [16.9 \pm 0.2(fit) \pm 1.3(sys) \pm 1.5(\gamma)]GV^{2.79}/(m^2.sec.sr.MV)$$

To check these results, a calibration of the AMS detector was done at CERN after the flight with 100 millions of protons and pions of energy 2,3,4,10, 14 GeV. From the beam of 10 ± 0.1 GeV protons, the tracks reconstructed gave a mean value of 10.04 GeV with a width of

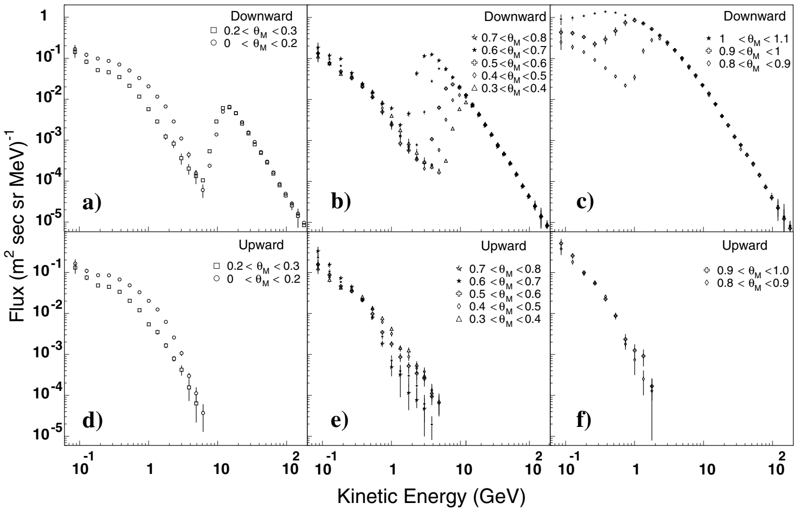

Figure 5: Fluxes of proton upward and downward in bins of geomagnetic latitude

0.92 GeV, showing that there is no bias in the reconstruction.

4.3 Electron and Positron measurements

AMS was also able to measure electrons and positrons. The electrons, thanks to their negative sign have clear identification and very small background, hence AMS was able to measure their spectra with limited statistics up to 100 GeV. For a geomagnetic latitude of $\Theta_M < 0.3$, it was found that electrons behave like protons, with a secondary flux below the geomagnetic cutoff extending up to 3 GeV (fig 6) and the same amount of electrons moving downward and upward, uniformly spread around the globe. Positrons suffer from the high flux of protons about thousand time higher in rate which gives a lot of background at high energy. Hence the study was done only below 2 GeV, where the time of flight of the particles and the signal in the aerogel counter allow to reduce the proton misidentification to a negligible level. As a consistency check, the positron fraction over the sum of positron and electron rates was compared in the polar region ($\Theta_M > 1.0$) to the previous measurements by balloon borne experiments and was found in excellent agreement.

Electrons and positrons spectra have the same behaviour in the geomagnetic equator region $\Theta_M < 0.3$ rad in the energy range 0.1 to

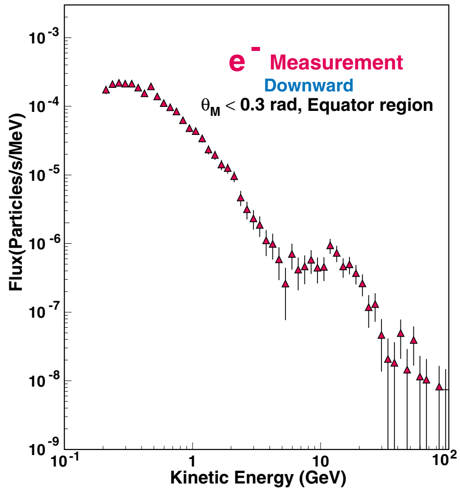

Figure 6: Flux of electrons in the geomagnetic equator region

2.5 GeV, but the flux of positrons is 3 to 4 times higher (fig 7). This was never observed before.

4.4 Measurement of Helium fluxes and mass spectrum

From the helium nuclei sample selected as explained above, it was possible to derive the helium spectra for various bins of geomagnetic latitude (fig 8). Above the geomagnetic threshold, the helium spectrum follows a power law in rigidity $\Phi_0 \cdot R^{-\gamma}$. Fitting the parameters on the rapidity range 10 to 140 GV yields :

$$\gamma = 2.65 \pm 0.014(fit) \pm 0.03(sys)$$
$$\Phi_0 = 1.45 \pm 0.06(fit) \pm 0.12(sys) \pm 0.15(\gamma) GV^{2.65}/(m^2.sec.sr.MeV)$$

Below the energy threshold after the fall of the primary spectrum a secondary spectrum shows up, 2 to 3 order of magnitude smaller in flux, in the equatorial region $|\Theta_M| < 0.4$ rad. Fitting the mass of helium nuclei above the threshold one gets M = 3.64 ± 0.01 GeV/c^2 in the polar region $|\Theta_M| > 0.4$ rad, and M = 3.65 ± 0.09 GeV/c^2 in the equatorial region $|\Theta_M| < 0.4$ rad. Comparing with the He^4 mass of 3.727 GeV/c^2, it shows that the content is mostly He^4. However, the same mass fitting applied to Helium nuclei below the threshold in the equatorial region gives a mass of 2.86 ± 0.04 GeV (fig 9 a and b), close to the He^3 mass of 2.809 GeV/c^2 which implies that these

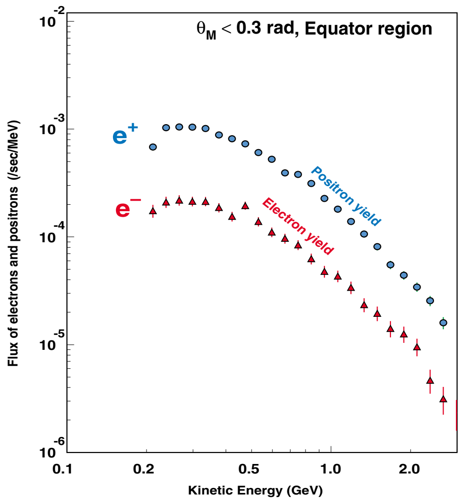

Figure 7: Relative electron and positron yield around the equator

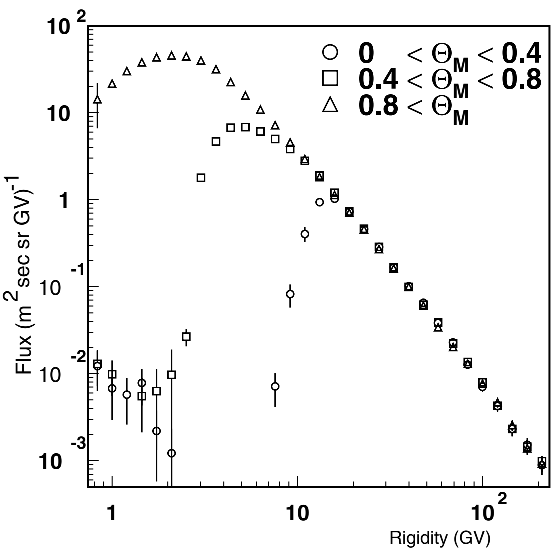

Figure 8: Spectra of Helium nuclei in bins of geomagnetic latitude

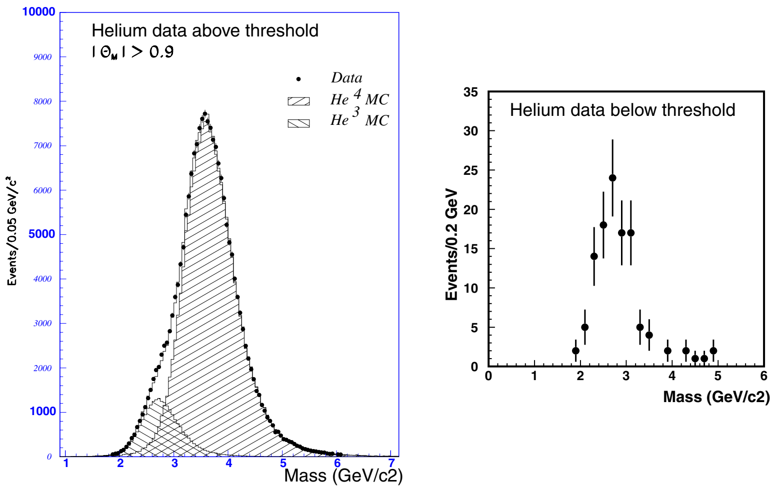

Figure 9: Helium mass spectra above and below threshold

nuclei are mostly He^3.

4.5 Conclusion on physics of AMS01.

The results on cosmic rays below threshold were not observed previously since nobody had made measurements in these conditions, and it was not expected from models. From preliminary studies of the trajectory of high energy cosmic rays in the earth magnetic field, it appears that these particles trapped at high altitude in the magnetic field are secondaries of the interaction of primary cosmic rays with the atmosphere, forming a kind of belt. The detailed analysis is underway. It must also be remarked that, though it was only a technological test flight, the limit put on the antimatter/ matter ratio was better than any other published results, which demonstrates the quality of the instrument.

5 AMS on the international space station ISS

AMS is scheduled to fly to the international space station ISS in October 2003, and to take data for 3 to 5 years. In order to fulfill the program of physics, specially for the high energy part of the cosmic

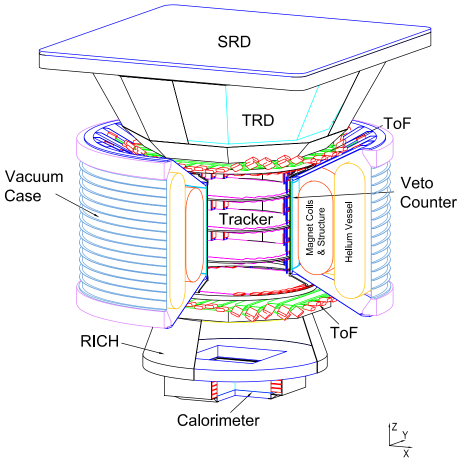

Figure 10: The AMS02 detector for the ISS

rays up to a few TeV, the instrument will be modified and completed with new detectors (fig 10) to improve measurement accuracy and particle identification.

The permanent magnet will be replaced by a superconducting magnet with the same inner volume, the same configuration of field, and a bending power 6 times higher $BL^2 = 0.86Tm^2$. This will allow to measure particle momentum with a resolution better than 2% up to 100 GeV and to have a excellent determination of the sign of electric charge up to several TeV. The tracker will be upgraded from 6 to 8 double-sided planes of silicon detectors.

A Transition Radiation Detector placed above the Time of Flight detector, made of 20 planes of straw tubes and foam, will give a separation power of nearly 200 between hadrons and electrons up to 500 GeV, and will give additional points on the trajectory of particles. Below the magnet, a RICH cerenkov counter with a double radiator of aerogel and Sodium fluoride will allow to identify nuclei up to Aluminium, and to disentangle the isotopic content up to Oxygen for nuclei with an energy per nucleon below 12 GeV. Underneath the RICH, an imaging electromagnetic calorimeter made of a sandwich of lead and scintillating fibers of depth 16.5 X_0 will measure the electromagnetic showers with an accuracy of a few percent. Thanks to its very fine granularity (18 sampling in depth, and a transverse granularity of 0.5 Mollier radius in both directions) the calorimeter will allow to achieve a rejection power hadrons/electron close to 10^4, which combined with the TRD will achieve the identification power necessary for the study of the charged cosmic rays up to TeV range. Eventually, a Synchrotron Radiation Detector placed on top of AMS will detect the synchrotron radiation produced by electrons/positrons of energy above 500 GeV in the earth magnetic field before traversing the detector and will allow to increase the range of energy covered by AMS for electrons and positrons to 3 TeV. 20000 such particles are expected between 500 GeV and 3 TeV during the 3 years of data taking.

6 Conclusion

The AMS02 experiment on the international space station will open a domain of physics yet largely unexplored. The precursor flight dedicated to test the technology and the conditions in space gave numerous original and unexpected physics results, which demonstrates the capability of the detector to fulfill its physics program.

Acknowledgments

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