Antimatter Search with AMS (Alpha Magnetic Spectrometer) during STS-91 Precursor Flight

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The Alpha Magnetic Spectrometer (AMS) is designed to study the antimatter, matter and dark matter in space. AMS successfully flown on space shuttle Discovery during precursor flight STS-91 in a 51.7° orbit at altitudes between 320 and 390 km. No antimatter nuclei with $Z \geq 2$ were detected. In this report we present the AMS performances during shuttle flight and we give new limits on antimatter/matter flux ratio.

1. INTRODUCTION

There are four large–scale phenomena that characterize the present state of the universe: Hubble expansion, the isotropic microwave background radiation, relative abundances of light isotopes and the ratio of the total baryon number to the photon density of about $N_B/N_\gamma \sim 10^{-9}$.

The first three phenomena find explanation in standard Big-Bang model which also requires the matter and antimatter to be equally abundant at very early stage of the universe [1–3].

Measurements to search for evidence of antimatter of cosmic origin have been carried out mostly by stratospheric balloons and satellite experiments. Up to date, the results seem to exclude antimatter existence up to the scale of supercluster of galaxies (about 10 Mpc) making the observed baryon asymmetry ($N_B \neq 0$) one of the most important astrophysical puzzles [4–8]. The baryogenesis, which is the evolution of a symmetric universe into an asymmetric one, requires the baryon number and CP to be violated [9]. The CP non conservation has already been observed in K and B systems but the amount of the measured non conservation is not enough to explain the observed baryon asymmetry.

The observation of the rotational velocity of stars in spiral galaxies enables us to calculate the mean density of matter as a function of distance from the galactic center. The matter distribution obtained this way is in strong disagreement with the observed distribution of luminous matter [10–12]. This disagreement is atributed to the existence of a halo of invisible (dark) matter. The nature of the dark matter which dominates the mass of the galaxies is another important unsolved problem of modern cosmology and astrophysics.

The AMS experiment is mainly designed to study these two major problems, namely, to search for antimatter of cosmological origin with an unprecedented sensitivity, and to study the composition of the cosmic rays to understand the nature of dark matter [13–15].

The first phase of the project has successfully been completed and AMS has shown no major problems during the STS-91 precursor flight on space shuttle Discovery (2nd-to-12th of June 1998). Its three years long data taking on International Space Station (ISS) has already been approved by NASA and its installation has been scheduled for 2003. In this report we will discuss the operational performance of AMS during precursor flight and present new limits for antimatter/matter flux ratio.

2. AMS DESIGN PRINCIPLES AND ITS PERFORMANCE ON STS-91

The AMS configuration flown on STS-91 is shown in Figure 1.

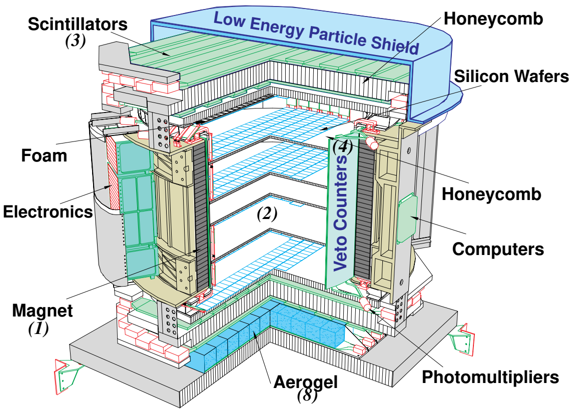

Figure 1. AMS configuration for the June 1998 Shuttle precursor flight (STS91).

The experiment consists of the following elements;

- A cylindrical permanent magnet of about 1.8 tons made out of premagnetized highest grade rare earth Nd–Fe–B pieces providing a dipole field prependicular to cylinder axis. The inner diameter and height were 1134 mm and 800 mm respectively and the field strength at the center was about 0.14 T giving a resolving power of $BL^2 = \ 0.14\ Tm^2$.

- Six planes of double-sided silicon microstrip detectors to track the trajectories of particles traversing the magnet free bore hence measure their momenta, the absolute value and the sign of the charge. The total amount of the material within the tracker volume seen by incoming particle is 3.2% of X_0. The tracker alignment is performed through pre and post-flight surveys and using the high momentum particles at CERN PS test beam. The calibration data are used to improve the fitting parameters of flight data. The momentum resolution of the silicon spectrometer has been studied using helium and carbon beams at GSI in Darmstad. For rigidities (p/Z) between 3 and 10 GV the resolution is measured to be about 8%, for lower momenta the resolution is limited by multiple scattering, while the expected maximum detectable rigidity is about 500 GV. The momentum resolution of silicon tracker exposed to 10 GeV protons is shown in Figure 2. Important parameters of the tracker are listed in Table 1. During the STS-91 mission tracker was equipped with about 45% of the total sensitive area.

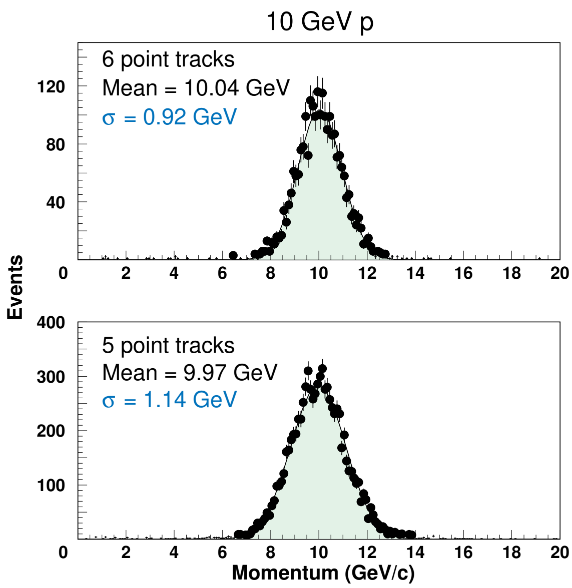

Figure 2. The tracker momentum resolution at 10 GeV with protons at CERN PS test beam.

Table 1
AMS silicon Tracker parameters for STS-91 flight.

Number of planes	6
Accuracy (bending plane)	10 μm
Accuracy (non bending plane)	30 μm
Number of channels	58368
Power consumption	180 W
Weight	130 kg
Silicon Area (double sided)	2.4 m^2

- Four layers of scintillators (S1 to S4) providing the first level trigger, time of flight measurements and particle direction. The typical resolution of time of flight is measured to be 120 ps.

  The separate measurements of $\frac{dE}{dx}$ in tracker and in ToF give the possibility to determine the magnitude of particle charge,Z. The energy loss measurements for light nuclei obtained with silicon tracker is shown in Figure 3.

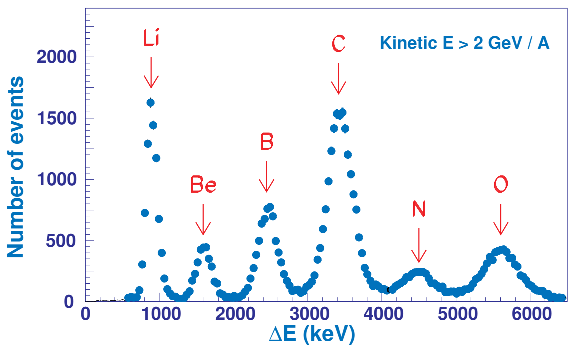

Figure 3. The measurement of energy losses of light nuclei in silicon tracker.

The particle mass is obtained by combined measurements of velocity (ToF) and rigidity (silicon tracker) (see Figure 4).

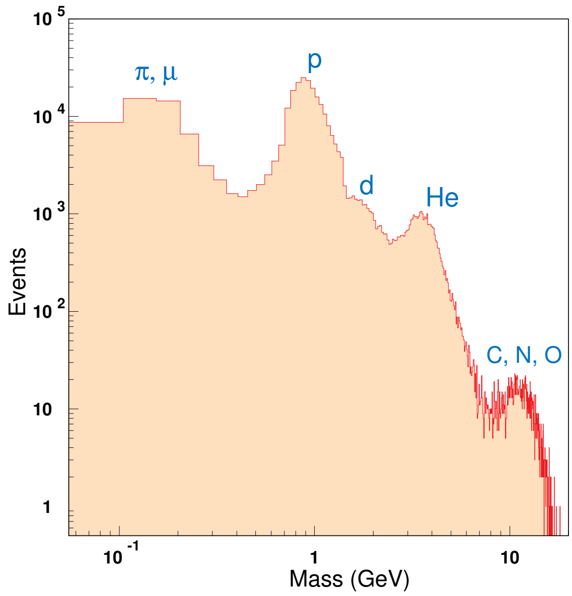

Figure 4. The mass spectrum measured online by the combined measurement of the silicon tracker (R) and the time of flight (β).

- Aerogel Čerenkov counters (C1 and C2) with refractive index of 1.035 to improve the albedo rejection and the determination of the particle mass by measuring its velocity, hence, to extend the electron-proton separation capability up to 3.5 GeV/c.
- Anticoincidence counters surrounding the inner wall of the magnet to reject background induced by the passage of charged particles through the magnet.
- A thin carbon fiber shield for low energy particles (LEPS) covering the sensitive areas of the detector.

During the construction phase all detector elements were extensively tested in order to have qualification for an operation in space. The detector performance including the temperature,current and magnetic field values were monitored on-line. A total of about 100 million triggers have been recorded with an data acquisition rate ranging between $\sim 100\ Hz$ at the equator to $\sim 700\ Hz$ at $\pm 51.7^o$.

During STS-91 flight the Discovery was docked to MIR station for about three days. The AMS has been operational before, during and after the docking including 11 hours for albedo measurement. Total useful data taking time was about 135 hours.

Over almost the entire mission period about 10% of the total collected data was sent to ground in real time allowing to monitor the operating conditions of AMS.

After the flight the detector has been exposed to ion and proton beams to perform extensive post flight calibrations.

The results obtained during all phases have largely shown a good mechanical stability of the detector and an excellent electrical performance.

3. EVENT SELECTION FOR ANTIMATTER SEARCH

The antinuclei search in AMS has been carried out according to the following procedure:

- Particle rigidity (R) measurement, obtained from silicon tracker, requiring hits in at least four tracker planes. It is reconstructed using two different fitting algorithms of which results were required to agree.

- Particle velocity (β) is measured by ToF system determining also the particle direction (up/downward).

- Particle absolute charge ($|Z|$) determination is obtained by the separate $\frac{dE}{dx}$ measurements in ToF and in silicon tracker systems.

The sign of the charge is derived from the deflection in silicon tracker system and the mass was calculated from $|Z|$, R and β.

On sample events with $|Z| \geq 2$ detailed investigations on the charge magnitude and on its charge determinations were performed.

The probability to assign a wrong charge magnitude to a proton to mimic an antihelium nuclei by combined measurements of ToF and silicon tracker systems was estimated to be less than 10^{-7}.

The determination of charge sign is done through ;

- correct measurement the particle direction. A particular care was taken to investigate a possible confusion between different charge sign values.

- identification of the large angle single nuclear scattering events in one of the inner tracker planes which may cause a wrong measurement of the charge sign. To suppress this background a cut was applied on the estimated rigidity error. In addition, the rigidity and charge sign were measured by fitting first three (R_1), last three (R_2) and all (R) hits along a track. The measured quantities are required to give same charge sign and consistent rigidity values. The comparison of the relative rigidity error $\frac{\Delta R}{R}$ with the rigidity asymmetry $A_{12} = (R_1 - R_2)/R_1 + R_2)$ was rejecting most of the large angle scattering events by leaving uneffected the real signal.

- identification and rejection of the background due to an interaction of the primary nuclei in silicon tracker material causing a displacement of the measured track point from that of the real trajectory. To suppress this background the events with very high energy observed within $5mm$ of the track were rejected.

Additional χ^2 cuts were then applied to the quantities measured in ToF and silicon tracker systems. A probability function was then introduced to evaluate the compatibility of the measurements with those of a He, or heavier nucleus passing through the detector. Tighter cuts were used for events with hits in only four tracker planes. After the cuts, no $\bar{H}e$ event was observed over the entire rigidty range. About 2,8 M He events were survived giving a total detection efficiency of about 49%. Instead, 156 K events with $Z > 2$ were survived, with no negative rigidity event, resulting to an efficiency of about 56%. In Figure 5 the measured rigidity spectras were given for light nuclei which survived the above cuts. The tracker rigidity resolution is given in Figure 6.

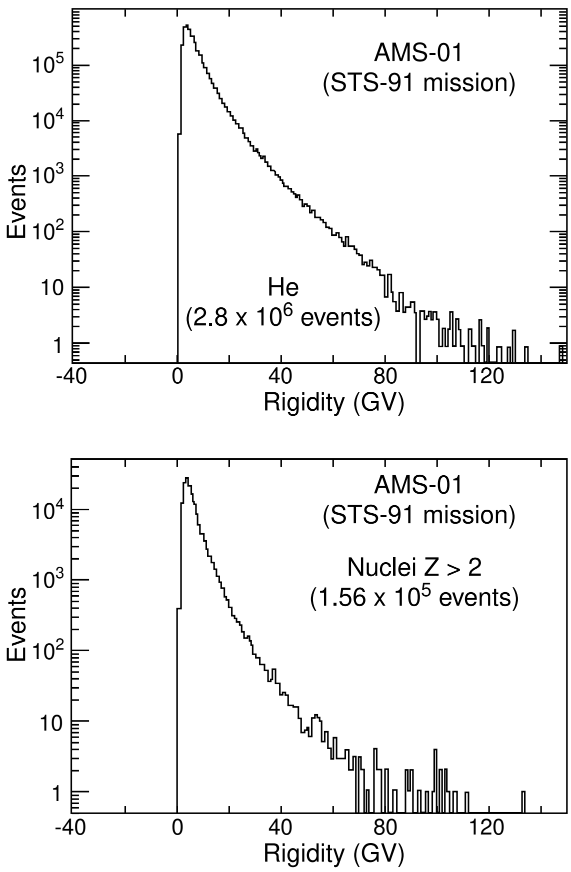

Figure 5. Measured rigidity spectras for He and $Z > 2$ nuclei after the selection cuts.

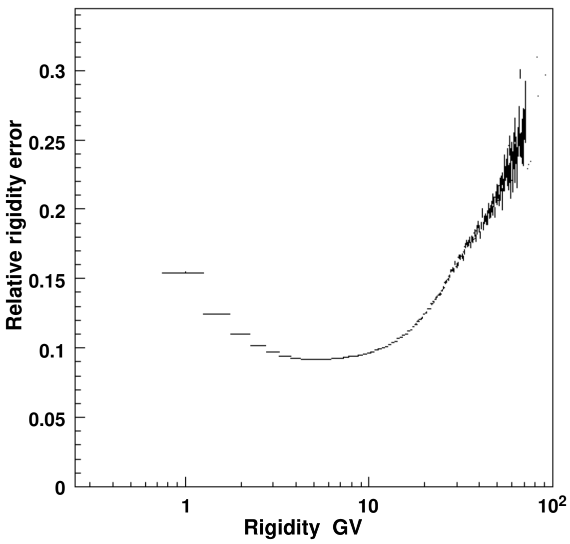

Figure 6. Rigidity resolution of the AMS silicon tracker for $Z > 1$ particles surviving the antimatter selection cuts.

4. DISCUSSION AND RESULTS

We did not observe antinuclei with $Z \geq 2$. In order to establish the antimatter/matter flux ratio limits the following different approaches were used. In calculating the antihelium/helium limits we first assumed the antihelium to have the same rigidity spectrum shape of helium. Since the incident helium nuclei flux ($\Phi_{He}(R_i)$) in any of n rigidity bins of $(R_i, R_i + \Delta R)$ is related with that of the measured one ($\Phi^m_{He}(R_i)$) as

$$\Phi_{He}(R_i) = \epsilon^{-1}_{He}(R_i)\Phi^m_{He}(R_i) \qquad (1)$$

where $\epsilon_{He}(R_i)$ is the detection efficieny in this bin, evaluated through complete Monte Carlo simulation using the GEANT [16] package. In order to obtain the detection efficieny for antihelium, $\epsilon_{\bar{H}e}(R)$, a small correction was applied to the helium efficieny, $\epsilon_{He}(R)$, because of the estimated difference between helium and antihelium absorbtion cross sections. [17].

Since there has been no $\bar{H}e$ detection, the differential upper limit for the flux ratio at 95% CL is given by:

$$\frac{\Phi_{\bar{H}e}(R)}{\Phi_{He}(R)} < \frac{3/\epsilon_{\bar{H}e}(R)}{\Phi^m_{He}(R)/\epsilon_{He}(R)} \tag{2}$$

Assuming the $\bar{H}e$ rigidity spectrum shape to be same to He spectrum, and integrating the equation (2) over the rigidity range $1 < R < 140\ GV$ we obtain:

$$\frac{\Phi_{\bar{H}e}}{\Phi_{He}} < 1.14\ 10^{-6} \tag{3}$$

Using the same approach for $Z > 2$ data we obtain

$$\frac{\Phi_{\bar{Z}>2}}{\Phi_{Z>2}} < 1.9\ 10^{-5} \tag{4}$$

If, instead, we assume a uniform $\bar{H}e$ rigidity spectrum and use the mean value of the inverse detection efficiency ($\langle 1/\epsilon_{\bar{H}e}\rangle$) of the equation (2) we obtain $\Phi_{\bar{H}e}/\Phi_{He}$ of 1.8 10^{-6} for $R = 1.6$ to 40 GV and 3.9 10^{-6} for $R = 1.6$ to 100 GV.

Finally, in order to give a conservative upper limit which does not depend on the antihelium spectrum, the equation (2) is integrated from $R_{min} = 1.6$ GV up to variable R_{max} taking the minimum value of the efficiency, $\epsilon^{min}_{\bar{H}e}$, in the rigidity interval (R_{min}, R_{max}). This yields

$$\frac{\int_{R_{min}}^{R_{max}} \Phi_{\bar{H}e}(R)dR}{\int_{R_{min}}^{R_{max}} \Phi_{He}(R)dR} < \frac{3/\epsilon^{min}_{\bar{H}e}}{\int_{R_{min}}^{R_{max}} \epsilon^{-1}_{He}(R)\Phi^m_{He}(R)dR} \tag{5}$$

The results on the relative flux of antihelium to helium as a function of R_{max} are given in Figure 7.

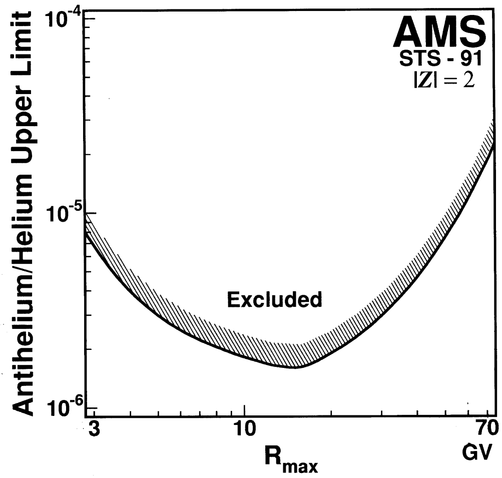

Figure 7. Antihelium/Helium flux ratio upper limit is given as a function of the rigidity interval $R = 1.6\ GV$ to R_{max} at the 95% CL.

5. Conclusion

The AMS experiment has successfully flown on space shuttle Discovery during precursor flight STS-91 in June 1998. All subsystems have shown very good performance and about 100 million primary CR triggers were recorded.

There has been no antinuclei observation at any rigidity up to about 140 GV. Assuming that the $Z = 2$ and $Z > 2$ antinuclei have the same spectral shape of their nuclei, upper limits at 95% CL on the relative antimatter/matter fluxes of 1.14 10^{-6} ($Z = 2$) and 1.9 10^{-5} ($Z > 2$) were obtained (see also [18]).

These results show that the installation of the complete version of AMS on International Space Station in 2003 will allow to search for antimatter with sensitivities orders of magnitude better than the current values.

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