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# Search for exotic particles with the AMS experiment

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**Abstract.** Two very important open items in modern physics are the existence of Dark Matter and free quarks. A search for slow-moving charged massive (SCM) particles ($10^4 < m < 10^{10}\ GeV$ and $\beta = 10^{-4} \div 10^{-2}$) and free fractional charges ($q = 2/3e$) among Cosmic Rays has been performed with the AMS detector, using a special set of data taken during the first flight of June 1998. The analysis and the limits on the fluxes of SCM particles ($F_{lux} \leq 1.5 \cdot 10^{-6}\ cm^{-2}s^{-1}sr^{-1}$) and free quarks ($F_{lux} \leq 3.1 \cdot 10^{-6}\ cm^{-2}s^{-1}sr^{-1}$) are presented.

## 1 Introduction

The Alpha Magnetic Spectrometer, AMS, is the first large acceptance (0.65 $m^2$) particle detector designed to operate in space (S. Ahlen *et al.*, 1994). It will be installed on the International Space Station (ISSA) and will start data taking from march 2004 for 3 years. The AMS experiment will address two fundamental questions in astroparticle physics: the possible presence of cosmological antimatter in the universe and the nature of the so-called "Dark Matter".

A precursor (AMS-01) of the final detector (AMS-02) had a successful flight on the Space Shuttle mission STS-91 in June 1998, when it was carried in the cargo bay and observed for ten days in both the Zenith and Nadir directions (J. Alcaraz *et al.*, 1999). The AMS-01 configuration, shown in Fig.1, consists of a permanent magnet equipped with six layer of silicon tracker, that measures the trajectory of relativistic particles with an accuracy of 10 $\mu m$ in the bending direction and 30 $\mu m$ in the non-bending direction, a scintillator system for the rejection of events due to interactions on the magnets inner walls, a threshold Aerogel Cerenkov system and a Time-of-Flight (ToF) system. The four scintillator planes of the ToF measure the transit times of charged particles with a resolution of 120 ps over a distance of 1.4 m. The ToF also yields multiple energy loss measurements and provides the fast trigger to AMS (D. Alvisi *et al.*, 1999).

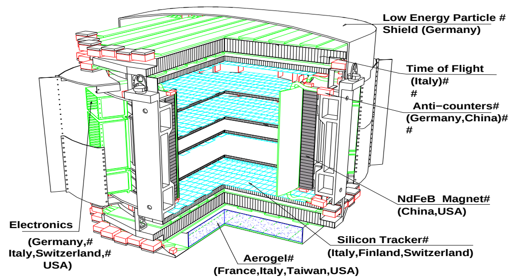


**Fig. 1.** Scheme of the AMS-01 detector.

## 2 Read-out electronics

The ToF data acquisition is performed by an electronics module, equipped with 4 channels. Each channel, coupled to one scintillator side, receives in input 2 signals, anode and dynode, and provides on output:

- a trigger signal, corresponding to a threshold of 150 mV on the input anode signal, which is sent to the AMS general trigger system
- a high-resolution (25 ps bin size) time measurement (Time Expansion) of the delay between the input anode signal (above a threshold of 30 mV) and the trigger signal coming back from the general AMS trigger
- the amplitude of the integrated input anode signal
- the amplitude of the integrated input dynode signal
- a time-over-threshold (history) signal which gives a rough estimate of the signal time (with 1 ns bin size) to tag "off-time" events in a time interval of 10 $\mu s$ before and 6.5 $\mu s$ after the trigger.

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### 2.1 The off-time signals

During normal data acquisition operations, the 4 channels are free to accept inputs until the trigger is produced. At this time the Time Expansion channel is blocked, and cannot receive any more input signals until the arrive of a *clear* signal, but the ToF system can continue to accept and record signals in a 16.5 $\mu s$ window around the trigger (about 10 $\mu s$ before and 6.5 $\mu s$ after), via the anode, dynode and history channels, and to measure their times (with 2.2 ns precision) and pulse-high (PH). Thus if one or more particles pass through the detector within the 16.5 $\mu s$ window, as much signals are generated in these channels: these signals are called *off-time* events.

## 3 Analysis

### 3.1 Search for slow-moving charged massive particles

If a particle with $\beta = 10^{-2} \div 10^{-4}$ and M=$10^4 \div 10^{10}$ $MeV$ (e.g. a magnetic monopole or a charged component of the DM) passes through AMS, it will have a time of flight inside the detector of $4.5 \div 9$ $\mu s$. The width of the trigger time-window ($\simeq$ $55$ $ns$) prevents AMS to trigger directly on these particles, but on the hypothesis that SCM particles delivers a signal comparable or large than 1.7 MeV (that corresponds to the ToF energy response to a Minimum Ionizing Particle (MIP) of unitary charge), their signals can be recorded by the ToF as off-time signals.

The $raw$ data were analyzed and the off-time signals with:

- *at least* 1 hit in both sides of the same counter,
- *at least* 1 hit on each of the first 3 ToF planes

have been selected. The 4th plane was excluded from the analysis, since it was switched off 15 hours after the beginning of the flight, and the signals in the time interval (-1,+2) $\mu s$ around the trigger time are not considered, to avoid contaminations by spurious hits connected with on-time events.

Then the value of the energy loss $dE/dx$, in MeV, the time and the coordinates, have been evaluated for each plane. The errors for space-time coordinates are also estimated: as shown in Fig.2, the error on the times is about 1.6 ns, while the error on the longitudinal coordinates is about 17 cm. ¿From the knowledge of the space-time coordinates and errors, the $\beta$ of the track is evaluated thorough a linear fit. The $\chi^2$ of the fit and the $1/\beta$ resolution are also estimated, the last is about 50% of the measured value at $\beta \simeq 1$, Fig.3.

4% of the initial events passed the first selection.

To search for SCM particles, the tracks selected have been re-analyzed and the events with:

- $only$ 2 fronts on the anode integrator channel
- $only$ 1 events per counter
- $only$ 1 signal per plane
- no signals on the anti-coincidence counters

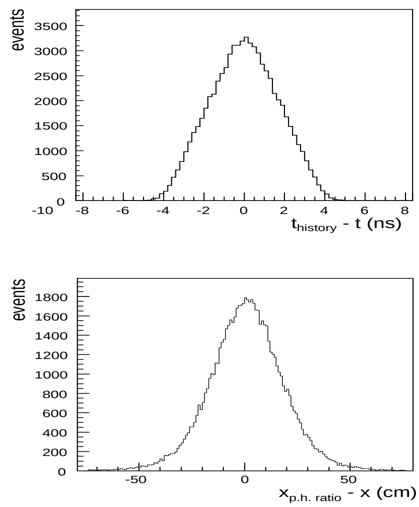


**Fig. 2.** Counter time resolution (top) and position resolution (bottom) along the counter.

- $\beta > 0$ (i.e. coming from outer space)

have been selected. They are about 5% of the initial events.

Fig.4 shows the behavior of the $\log_{10}(\beta)$ as a function of $\log_{10}(\chi^2)$ for events passing the cuts, and the two projections, corresponding respectively to the $\log_{10}(\chi^2)$ and the $\log_{10}(\beta)$ distributions. Is possible to distinguish $three$ different zones:

1. $\beta > 0.3$ and $\chi^2 < 4$ (with $\chi^2/N \simeq 1$ if $\chi^2 \leq 4$, being $N$ the number of the freedom degrees) (red box). The events in this zone are called *good events*: they correspond to physical particles arrived late with respect to the particle that produced the trigger.
2. $\chi^2$ $>>$ $4$ (green box). The events in this region are called *random events*, and correspond to three uncorrelated hits on the three planes.
3. $\beta < 0.3$ and $\chi^2 > 4$ (blue box). The events in this zone are called *mixed events*, they are a combination of the two previous cases.

The region with $\beta < 0.01$ and $\chi^2 < 4$ (yellow box) is where SCM particles candidates should be found. A value of $\beta <$ $0.01$ corresponds to a time of flight between the 1 and 3 ToF planes from 4.5 to 9 $\mu s$.
11 events with $\beta < 0.01$ and $\chi^2 < 4$ are present on the data.

### 3.2 Background evaluation

The Monte Carlo simulation of AMS does not reproduce "off-time" events, thus a "new" $ad$ $hoc$ MC has therefore been written.

In this program the three classes of events are generates, each class having only one hit for plane, as the data. The $good$ events are simulated generating 3 hits correlated each other on the 3 different ToF planes. The position on the first

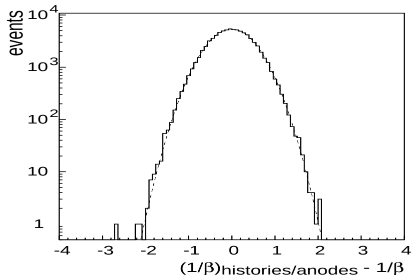


**Fig. 3.** $1/\beta$ resolution.

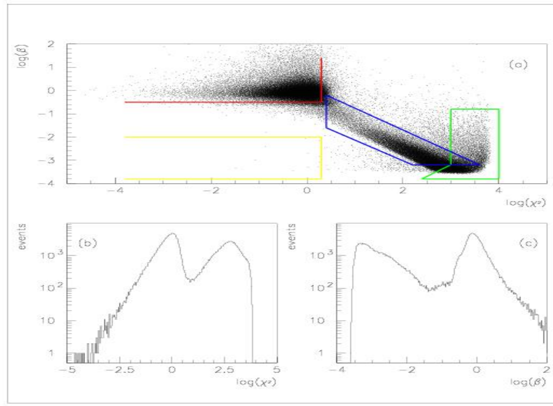


**Fig. 4.** (a) $\log_{10}(\beta)$ as a function of $\log_{10}(\chi^2)$ for events that passed the cuts. Behavior of $\log_{10}(\beta)$ (b) and $\log_{10}(\chi^2)$ (c).

plane and the track direction are randomly generated, then a $\beta$, randomly extracted from a distribution obtained simulating the fluxes of primary and secondary $p$ inside AMS, is assigned to the track. Hence the coordinates and the times over the latter two planes are evaluated, assuming that the track of the particle is a straight line.

The $random$ events are composed by three uncorrelated hits on the three planes. The times of the hits are randomly chosen within the 16.5 $\mu$ $s$ time window.

The $mixed$ events are a combination of the first two: they are composed of two $good$ hits on two planes plus a random hit on the third.

The same fit procedure applied to the data, to obtain the value of $\beta$, has been used on simulated events. Fig.5 shows the plot of $\log_{10}(\beta_r)$ as a function of $\log_{10}(\chi^2)$ obtained from the simulation, for the events with $\beta$ reconstructed ($\beta_r$) $> 0$, that has the same behavior as for real data.

10.6 background events have been found, all coming from random or mixed events.

### 3.3 Flux of slow charged massive particles

The upper limit for the flux of SCM particles, has been evaluated using Poisson statistics, for the case of processes with both signal and background (P.D.G., 2000):

$$1 - \epsilon = 1 - \frac{e^{-(\mu_B+N)} \Sigma_{n=0}^{n_0} \dfrac{(\mu_B+N)^n}{n!}}{e^{-\mu_B} \Sigma_{n=0}^{n_0} \dfrac{\mu_B^n}{n!}} \qquad (1)$$

where $n_0$ is the number of observed events, $\mu_B$ is the known Poisson parameter for the background, and $\mu_S$ is the unknown Poisson parameter for the signal. The corresponding upper limit on the signal is $N = 4.3$, at 90% C.L. Since the total time of observation $T$ $\simeq$ 13383 s, the MC efficiency $\eta$ is $0.17$, and the geometrical acceptance of the detector $A$ is $0.125$ $m^2sr$ (estimated via MC), the upper limit on the flux of SCM particles, at 90% C.L., is:

$$Flux \leq 1.5 \cdot 10^{-6} \;\; cm^{-2}s^{-1}sr^{-1} \qquad (2)$$

### 3.4 Search for Free Fractional Charges q=2/3$e$ with AMS

The off-time signals selected to search for SCM particles can be used again to look for free quarks with electric charge q=2/3$e$: assuming that free fractional charges interact like leptons, a particle with charge q=2/3$e$ passing through AMS should give a peak at $q^2 \cdot 1.7$ MeV $\simeq 0.76$ MeV on the ToF planes (from the Bethe-Block formula (M.S. Longair, 1994)). This value is well below the high threshold, $1.2$ $MeV$, but exceeds the anode threshold, $0.3$ $MeV$, so they can be recorded as off-time signals by this channel.
It is impossible to perform searches for free quarks with q=1/3$e$, since their passage through AMS should produce a peak at 0.19 MeV, a value even lower than the anode threshold.

### 3.5 Search for free fractional charges

The off-time events that passed the first selection have been re-analyzed and the events with:

- $only$ 2 fronts on the anode integrator channels
- $only$ 1 signal per plane
- $only$ 1 signal per counter
- no signals on the anticoincidence counters
- $\beta > 0.3$ and $\chi^2 < 4$
- no hits on the counters with unstable signal amplitude

were selected. They are about 1.6% of the initial counts.

For these particles the energy loss deposition on every ToF plane is shown in Fig.6. Free quarks with charge q=2/3$e$, would have a PH peak corresponding to 4/9 $\cdot$1.7 MeV, (about $0.76$ MeV) over *all* the first 3 ToF plane. Since $\sigma_Z/Z \simeq 0.2$, free quarks candidates are required to have PH values between 0.59 MeV and 1.28 MeV, that correspond to an interval of 1 and half $\sigma$ around the $4/9 \cdot 1.7$ $MeV$ peak. On the whole data set, 13 free-quarks candidates have been found.

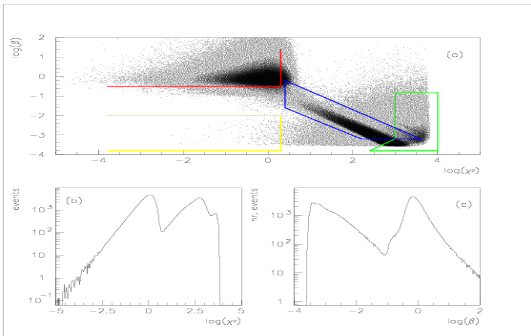


**Fig. 5.** (a) $\log_{10}(\beta)$ as a function of $\log_{10}(\chi^2)$ for MC events with $\beta_r > 0$. Behavior of $\log_{10}(\beta)$ (b) and $\log_{10}(\chi^2)$ (c).

### 3.6 Background evaluation

To simulate events with PH smaller than 1.7 MeV the official AMS MC, have been used, but all trigger thresholds have been lowered to 35 mV, corresponding to the anode discriminator threshold.

Different kinds of particles have been simulated with initial directions uniformly distributed, crossing AMS from the top, and the following momentum range: $p/\overline{p}$ (0.1 - 100 GeV/c), $e^-/e^+$ 1 MeV/c - 1 GeV/c), $\pi_+/\pi_-$ (0.1 - 100 GeV/c), $\mu_+/\mu_-$ (0.1 - 100 GeV/c) and $\gamma$'s (0.1 - 500 GeV/c), proportionally to their relative abundances at the altitude of the shuttle flight (320-390 km on the Earth's surface).

The same cuts of the data have been applied to the MC events: in particular, for the $\beta$ fit only times and coordinates measured by ToF system have been used. The comparison between the PH distributions obtained from data and from MC is shown in Fig.7. Low PH events are mainly coming from interactions of soft primaries, in particular, from protons with momentum smaller than 1 GeV/c.
The number of events expected from the background is 15.2.

### 3.7 Flux of free fractional charges

The upper limit for the flux of free fractional charges has been evaluated using again the eq.(1).

In this case $N = 3.9$, at 90% C.L., and the upper limit on the flux, at 90% C.L., is:

$$Flux \leq 3.1 \cdot 10^{-6} \ \ cm^{-2}s^{-1}sr^{-1} \qquad (3)$$

being $T = 13383\ s$, $A = 0.104\ m^2sr$ and $\eta = 0.09$, for $\beta > 0.3$ (evaluated from MC).

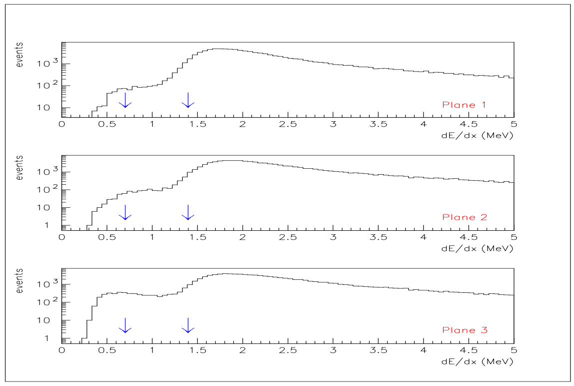


**Fig. 6.** Energy loss distribution on the first 3 ToF planes. The arrows indicate the boundaries of the 0.59-1.28 MeV interval. The events with PH lower than 1.7 MeV on the 3rd plane are about 3 times more than the low PH events on the first plane.

## 4 Conclusions

These limits constitute the first measurements of SCM particle and free quark fluxes performed outside the Earth's atmosphere. The large values obtained are mainly due to the short observation time, and already from the increased duration of data-taking, in AMS-02, it would be possible to lower them by 2-3 order of magnitude. Moreover some improvements to the future experiment, as a dedicated trigger for free fractional charges, and the possibility of having the same bin size resolution for off-time and on-time events, will allow to further lower the results of 3-4 order of magnitude.

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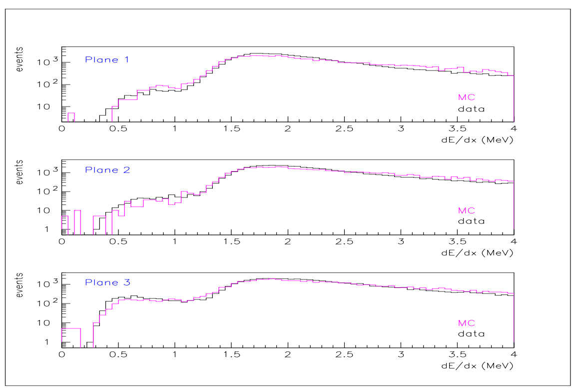


**Fig. 7.** Comparison between energy loss distribution in data (black line) and MC (purple line).