Search for Fractional Charges in Cosmic Rays with AMS

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\textbf{ABSTRACT}

Preliminary results on the flux of non strongly-interacting, fractionally charged particles in primary cosmic rays at 400 Km above sea level are given. Cosmic ray data collected by AMS-01 in June 1998 have been analysed on the hypotheses of $2/3$ charged leptons. The search is carried on by looking at the energy deposition measurements by the time of flight system scintillator counters. A preliminary flux limit is given.

\textit{keywords:} AMS, TOF, fractional charge.

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1. Introduction

Many historical experiments stated that the charge of matter comes in discrete units, and determined the amount of those ‘quanta’ of charge (by Millikan \textsuperscript{1}). Later on, several researches have been made in order to test if, in some circumstances, a fractional amount of that elementary charge could be produced.

From the theoretical point of view, in the Standard model of quantum chromodynamics, there is space only for colour singlet particles. Although the quarks, which are the bricks of the model, come with fractional charge, up to now they have been seen to be confined into mesons and baryons integrally charged. Few grand unified theories, anyway, account for color singlet particles with fractional charge (see \textsuperscript{2}, \textsuperscript{3} and \textsuperscript{4}). Moreover, some theories of spontaneously broken QCD have predicted free quarks \textsuperscript{5}, although in the standard quark interactions scheme, those free quarks should soon strongly interact with matter, and would hardly penetrate a particle detector.

Leptons known so far, are only neutral or with charge multiple of e. Anyhow, a fractional lepton could produce ionization in a detector, penetrating a large amount of material, leaving an energy proportional to $Q^2$ and, in some cases, passing the detection efficiency of the apparatus. So, it is worthwhile searching for lightly ionizing particle among the whole data taken by a particle detector although it was born with another aim. Any observation of fractional charge, in fact, would be a direct evidence of physics beyond the standard model.

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2. The AMS-01 time of flight (TOF)

In June 1998, the Alpha Magnetic Spectrometer, in its first version (AMS-01), was carried for ten days on board of the shuttle space mission (STS91), collecting an amount of 100 millions of cosmic rays.

The detector of AMS-01, whose configuration is shown in figure 1, consists of: a permanent magnet equipped with six layers of silicon tracker, that measures the trajectory of relativistic particles with an accuracy of 10 µm in the bending direction and 30 µm in the non-bending one; a scintillator system for the rejection of events due to interaction in the magnet inner walls; a threshold Areogel Cerenkov system, and a Time Of Flight (TOF) system.

The TOF consists of four planes which measure the transit time of charged particles with a resolution of 120 ps over a distance of 1.4 m. The TOF also yields multiple layers energy loss measurements, providing the fast trigger for the AMS experiment. Four TOF scintillators layers and up to eight silicon tracker layers, in fact, measure $dE/dx$, allowing a multiple determination of the absolute value of the particle charge.

The AMS trigger logic can be divided in these steps: first the scintillator data are processed in a very fast way, and perform what is called the Fast Trigger (FT), that gives the ‘time zero’ of the experiment. The first level trigger, that together with the presence of the FT also asks for the absence of the anticoincidence data. Then, the third level that precesses the data from the various detectors: asks for AND of same counter sides in the TOF, applies a cut on the maximum curvature of the trajectory in the tracker (this request leaves about 14% of the total triggers), controls that the track from tracker fits with the track from TOF.

The Fast trigger is thus made only by the TOF, when at least one side of one counter, in each plane, has gained the “High Threshold” (HT) of 150 mV. The Ams data are recorded when also other trigger levels are gained (except for the so called ‘prescaled events’, about 1/100 of the total, where only the fast triggers was requested). Usually, the requirement for the trigger were three over four planes of the TOF. In correspondence of a trigger, however, all of the four planes were always recorded, thus allowing the search for “rare events” in the whole data taken during the STS91 flight so far.

Figure 1. The AMS detector for the STS-91 mission (AMS-01).

Figure 2. Logic of the TOF counters readout board.
3. Hypothesis for the analysis

In order to give a limit on the flux of rare events, it has been made the hypothesis that the fractional charges \((2/3 \, e)\) have an energy loss distribution which is a ‘properly scaled’ proton Landau. Moreover, it has been used the same Acceptance as for the AMS-01 proton analysis (and so the cuts). For this analysis, finally, only the Fast Trigger efficiency changes and has to be computed.

A cosmic ray flux is given by:

\[
\phi = \frac{N_{obs}}{\varepsilon \cdot A \cdot T}
\]  

(1)

where \(A\) is the Acceptance, \(T\) is the observation time, \(N_{obs}\) is the events observed. Thus, being:

\[
\varepsilon = \varepsilon_{FT} \cdot \varepsilon_{LV,3} \cdot \varepsilon_{cut}
\]

And, for our assumptions, being

\[
A \cdot \varepsilon_{LV,3} \cdot \varepsilon_{cut} \simeq 0.15 \text{ m}^2 \text{sr}
\]

then, in our analysis, it had to be computed only the fast trigger efficiency and the observation time.

3.1. Typical energy loss in TOF planes

The typical energy loss of triggered particles traversing the TOF planes is given in figure 3. As you can see, the Most Probable Value (MPV) of 1 MIP, in each plane, is about 1.8 MeV. From now on, we can pass to MIP units, in the whole analysis.

3.2. Fast trigger efficiency

It is possible to compute the FT efficiency for detecting particles with low charge depositions in each of the four planes of the TOF. To do this, the method of the “spectator plane” is used: everytime a plane is not in the 3/4 triggered planes, it is possible to look at its recorded data to see if the HT was passed or not. In this way at the end we have the FT efficiency of the plane, in MIP units, shown in figure 4.

Later on, the total FT efficiency is the sum over the combinations of three planes, formally:

\[
\varepsilon = \left( \frac{3}{4} \right) \left( \varepsilon_{pl1} \cdot \varepsilon_{pl2} \cdot \varepsilon_{pl3} + \varepsilon_{pl2} \cdot \varepsilon_{pl3} \cdot \varepsilon_{pl4} + \varepsilon_{pl1} \cdot \varepsilon_{pl2} \cdot \varepsilon_{pl4} + \varepsilon_{pl1} \cdot \varepsilon_{pl3} \cdot \varepsilon_{pl4} \right)
\]
4. Expected energy loss distribution for $\frac{2}{3}e$

considering the energy loss distribution of $\frac{2}{3}e$ charges, as a “scaled proton landau”, and taking into account the efficiency of each plane, we can get the expected energy loss distribution of those fractional charges, in each plane (see, for plane 1, figure 6). From that figure it is evident that, if we put a cut at 0.7 MIP, we can be confident to be away from the proton background. Then, dividing the integral of the expected flux that is on the left of the cut, by the total integral of the “scaled” proton landau, we get the FT efficiency for $\frac{2}{3}e$ for that plane.

5. Lightly ionizing particle in the TOF

It has been plotted the energy released in the TOF planes, after some canonical cuts (the same used for the AMS-01 proton analysis) shown in figure 7, looking at the low energy losses. The “canonical cuts” consist basically in asking for data taken away from the south atlantic anomaly, with at least 1 cluster per TOF plane, and with only 1 TOF bar involved in each cluster. Later on, only few tracker cuts are added (“track quality” cuts), but they just reduce the events of a 10%. The plots are shown in figure 7 with a mark at 0.7 MIP.

We now have to compute the fast trigger efficiency for detecting $\frac{2}{3}e$. It is possible to think on the expected energy loss of $\frac{2}{3}e$ as a properly scaled proton landau, as you can see in figure 6.

Here are the various plane efficiencies calculated in the mentioned way:

$$
\varepsilon^{pl1} = 0.43 \\
\varepsilon^{pl2} = 0.71 \\
\varepsilon^{pl3} = 0.68 \\
\varepsilon^{pl4} = 0.47
$$

that led to the combined efficiency of FT, for detecting fractionally charge: $\varepsilon_{FT}^{\frac{2}{3}e} = 0.18$

6. Analysis and results

The AMS-01 data have been analyzed using basically the same cuts that have been used in the proton AMS-01 official analysis. They consist on data taken away from the south atlantic anomaly, no overlaps of the TOF counters, and finally only few ‘track quality cuts’ of tracker, that reduce of a 10% only the events. At this last point has been evaluated the low energy loss
in the TOF planes (plotted in figure 7). As you can observe from the plot, below the 0.7 MIP there are still some candidates in the four TOF planes. Nevertheless, if we require a low energy loss simultaneously in the first three TOF planes, then the bulk of candidates disappears.

In such cases of counting “rare events”, where a poisson variable $n$ counts signal events with unknown mean $s$ (and with $θ$ prior) as well as background with mean $b$, then, in the absence of a clear discovery (e.g., when $n=0$ or if $n$ is compatible with the expected background), it is possible to give an upper limit on $s$. In substance, when $n = 0$, the mean $s$ is, at 95% of C.L., less than 3. This results from even bayesian approach than frequentists one (7, 8).

We finally calculated the observation time, which in this case is $T = 36436 s$.

7. Conclusions

Looking at the energy lost in the four planes of the Time of Flight of the AMS-01 experiment (on the test flight of 1998) and selecting the events triggered only by the TOF (the ‘prescaled events’), it has been possible to put an upper limit on the $\tilde{2}e$ lepton-like particles flux is:

$$\phi < 3.0 \times 10^{-7} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$$

at 95% of Confidence Level.

This upper limit could be lowered extending the analysis on all the AMS-01 data (about factor of 10). Moreover, with the AMS-02 experiment on the International Space Station which will last for three years, the same limit can improve another factor of 100.

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Figure 7. Energy released in TOF (in MIP units) with mark at 0.7 MIP, the analysis is made on the first 12 hours of AMS-01 data.
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