Identification of cosmic-ray positrons with the transition radiation detector of the AMS experiment on the International Space Station

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Abstract: Cosmic-ray positrons have been proposed as important probes for dark matter annihilation, as well as for the presence of cosmic accelerators in the vicinity of the Solar System. The measurement of the positron fraction has therefore been the first target for the AMS experiment, installed on the International Space Station since May 2011. Because protons are more abundant than positrons by a factor of 10^4, AMS needs very good capabilities for the suppression of the proton background. The transition radiation detector (TRD) of AMS is a powerful instrument for this purpose, in addition to the electromagnetic calorimeter. We present the performance of the TRD during the first two years of the AMS flight, in particular the proton rejection and the corresponding selection efficiency for positrons, to show that the proton background has indeed been suppressed to a negligible level in the measurement of the positron fraction by AMS.

Keywords: AMS, transition radiation, positron, particle identification

1 Introduction

Positrons are a rare component in cosmic rays, their production mechanism established until now being secondary production in hadronic interactions of primary cosmic-ray particles (mostly protons and α particles) with interstellar matter. Their relative rarity with respect to electrons makes them a sensitive probe to new physics, or to the presence of cosmic accelerators in the vicinity (~ 1 kpc) of the Solar System. In fact, measurements of the cosmic-ray positron fraction in recent years have shown indications for an unexpected rise towards high energies, an observation that has triggered a long list of publications containing models proposed in explanation, ranging from the annihilation of dark matter particles (e.g. [1]) to the presence of positrons and electrons created in the magnetospheres of pulsars and accelerated in the termination shocks of the pulsar wind in the surrounding matter (e.g. [2]). The AMS Collaboration has recently published a precise measurement of the positron fraction in the energy range up to 350 GeV, showing a steadily rising positron fraction from 10 to at least 250 GeV and the absence of spectral features [3].

In the GeV energy range, the ratio of positrons to protons is on the order of $1 : 10^4$. The identification of positrons in the vast background of protons relies on two independent subdetectors of the AMS detector [4]: The electromagnetic calorimeter [5] and the transition radiation detector (TRD). In this paper, we demonstrate the capability of the TRD for particle identification.

2 The AMS-02 transition radiation detector

The AMS detector is equipped with a transition radiation detector (Fig. 1, [6]) that can distinguish light from heavy particles on their passage through the device, to allow a selection of clean positron and anti-proton samples that have to be identified in the presence of large backgrounds of protons and electrons, respectively. Among the other subdectors of AMS, an electromagnetic calorimeter provides particle identification power by measuring the shower shape and deposited energy in showers initiated by electrons, positrons, and photons. A silicon tracker measures the curvature of charged particle tracks in the field of the surrounding permanent magnet, as well as their ionization losses.

The key point in the working principle of the TRD is the efficient detection of transition radiation (TR) – a soft X-ray emission – with the smallest amount of material in the particle path. This is achieved with twenty layers consisting each of 22 mm fleece radiator and 6 mm xenon gas in straw tube proportional counters with 72 μm thin walls made of capton composite foil. To detect the ionization signal, each tube is instrumented with a wire which is centered to 100 μm precision to achieve a useful signal homogeneity. The width of the AMS TRD is 2 m, to cover the AMS acceptance, and the 5248 straw tubes have a total gas volume of 230 liters. The design value for the TRD gas composition was a mixture of 80:20 of Xe and CO_2, based on a mission duration of 3 years. After the mission duration has been extended to 20 years, and since diffusion losses in the TRD are dominated by the CO_2 component, a mixture of 90:10 is now used. The partial pressure of xenon is held around a value of 880 mbar.

3 TRD calibration

The principle of operation of the TRD relies on a measurement of the energy deposition caused by a charged particle traversing the TRD and its path length in the active gas volume of each of the 20 layers. Depending on the particle species, the energy deposition has contributions from ionization losses and transition radiation: the yield for the latter scales with the inverse of the particle rest mass, thus the transition radiation yield is strong for electrons, but suppressed for protons. In order to exploit the particle identification capabilities of the transition radiation detector, three sets of parameters have to be determined from the data taken with the TRD onboard the ISS before any physics analysis can be performed, namely alignment parameters, gain calibration constants, and probability density functions for the dE/dx per tube for the relevant particle species.

3.1 Alignment

As the first step in the calibration, the TRD has to be aligned with respect to the coordinate system defined by the silicon tracker. This is vital for a precise determination of the path length. The complex thermal environment onboard the ISS caused by orbital variations of the exposure to the Sun and by variations of the operation parameters, such as changes in the attitude of the ISS and in the positioning of the solar arrays, leads to thermal expansion and contraction of the aluminum support structure of the TRD and as a consequence, movements of the TRD with respect to the silicon tracker on a typical scale as large as 1 mm. Using the alignment procedure, the residual misalignment is reduced to the level of 20 μm, allowing for a precise determination of the path lengths inside the TRD straws. Details on the TRD operation and the alignment procedures developed to cope with the changing thermal environment are given in a dedicated contribution [7].

3.2 Gain calibration

The second step in the calibration procedure is the determination of the gas gain. The primary ionization in the TRD straw tubes is amplified by the avalanche process induced in the large electric field close to the wire at the center of each straw. The amplification factor is called gas gain and depends mainly on the voltage applied, the xenon density and the fraction of CO_2. Because of unavoidable diffusion losses through the straw tube walls, the gas composition inside the TRD modules changes continuously. The high voltage is therefore adjusted on a daily basis in an effort to keep the gas gain constant. Once per month, the TRD gas is replenished from the supply containers mounted to the TRD.
For gain calibration, clean proton events are selected based on the absence of an electromagnetic shower in the ECAL and the charge measurements in the silicon tracker. The distributions of the dE/dx values, corrected for the dependence of the ionization losses on particle momentum according to the Bethe-Bloch formula, are accumulated for each module over a time of $\sim$ 1 hour and a Landau distribution is then fitted to each of them. Gain correction factors can then be extracted that normalize the most probable value of the gain distribution to the value of 100 ADC counts/cm. Figure 2 illustrates the behavior of gas gain with time for all the modules and the quality of the calibration: On the left-hand side of the figure, the fitted most probable values in the proton dE/dx distributions are shown, plotting the values for all 328 TRD modules in the same figure.

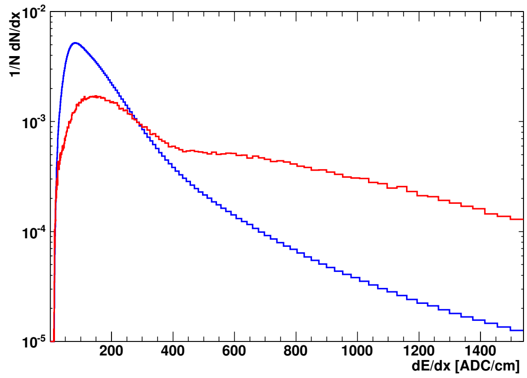

Figure 3: Probability density functions for energy depositions in the TRD, for electrons (p_e, red) and protons (p_p, blue), as obtained from ISS flight data. In order to have high-statistics curves, the electron pdf was averaged over the last ten layers of the TRD, where the transition radiation component is in saturation, and the proton pdf was averaged over the momentum range from 6.7 to 14.3 GeV/c.

After the end of the commissioning phase, from June 15th, 2011, the TRD was first operated with weekly adjustments of the high voltage, so that diffusion losses caused a gradual increase of the gas gain. This strategy was changed effective October 26th, 2011, and daily adjustments of the high voltage are now being done, in order to keep the gas gain at a constant level. Stronger variations in the gas gain are apparent for short intervals roughly once per month, during gas refill operations on the TRD.

The right-hand of the figure demonstrates the quality of the gain calibration, based on an independent sample of events for which the procedure was repeated after the gain calibration factors determined in the first step have been applied. Except for the commisioning phase and the brief refill periods, the behavior is extremely smooth. After calibration, the remaining r.m.s. variation is at the percent level, at 1.7 ADC counts/cm.

3.3 Probability density functions

With the calibrated energy depositions dE_i and the path lengths dx_i, determined from the trajectory extrapolated from the silicon tracker, in all of the TRD tubes that show a non-zero energy deposition, a statistical analysis can be performed to identify the species of a passing particle. For this purpose, the probability density functions (pdfs) for the dE/dx per tube for each particle species have to be known. They are obtained by selecting clean samples of electrons, protons, Helium and nuclei up to $Z = 6$, based on the information provided by the ECAL and the silicon tracker. A new technique developed to extend the range of nuclear charges that can be identified with the TRD, based on the amount of δ-rays produced inside the TRD, is presented elsewhere [8]. To account for the dependence of the average dE/dx on momentum, the proton curves are determined in bins of momentum, while the electron probability density functions are stored as a function of the TRD layer number, since the amount of transition radiation produced depends on the total amount of radiator traversed. For illustration, Figure 3 shows typical probability density distributions for electrons (p_e) and protons (p_p) as obtained from flight data. Both particle species show the peak and Landau-shaped tail

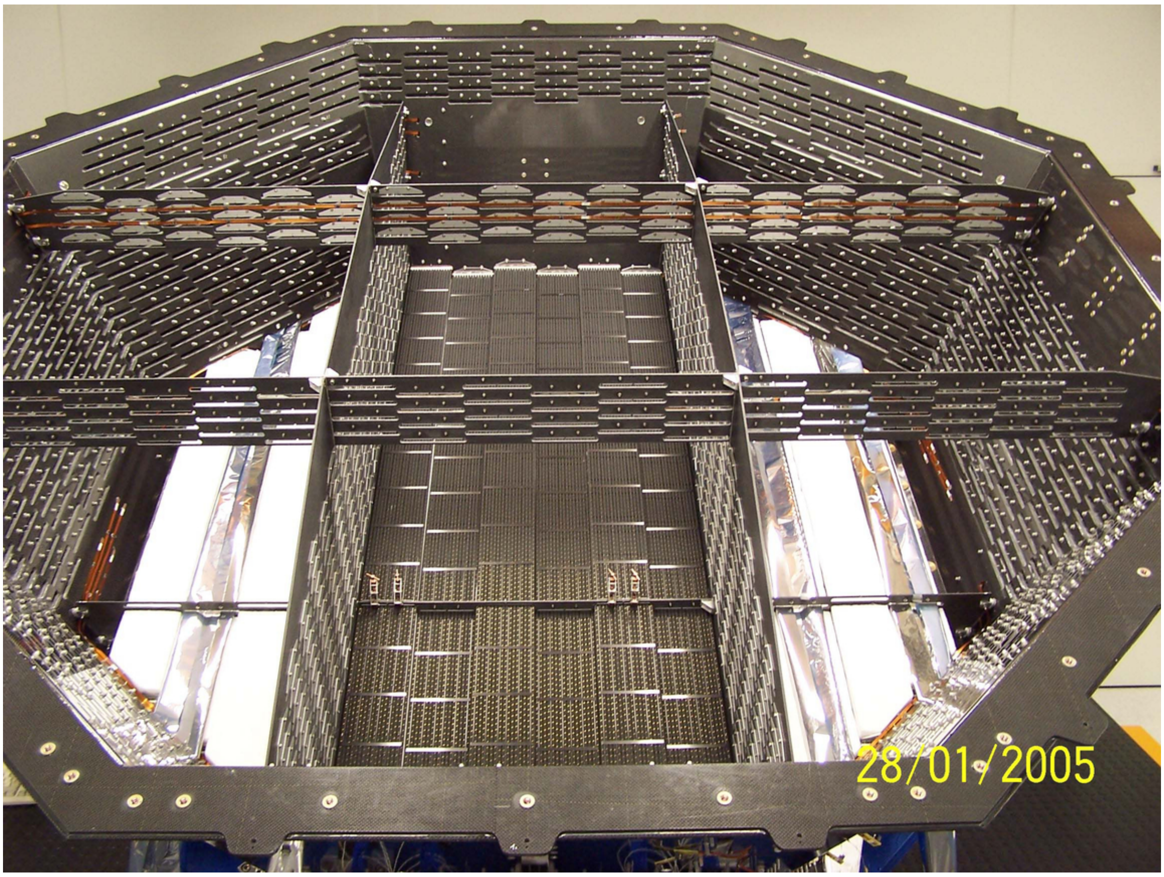

Figure 1: The TRD during the construction phase. In the central part one sees the first installed straw modules. The white material on the left and right is the fiber fleece radiator which covers each module plane. After completion the carbon fiber support structure was filled with 328 straw modules and closed also from the top with an aluminum honeycomb / carbon fiber composite plate.

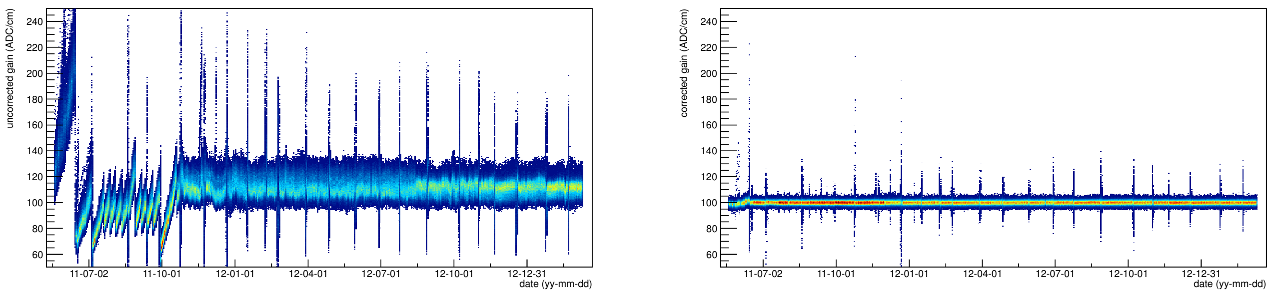

Figure 2: Left: Gain calibration constants (most probable value of Landau distribution) for all 328 TRD modules as a function of time, as determined by the TRD calibration procedure. Right: Validation of gain calibration procedure using an independent test sample of events, again showing all 328 TRD modules in one plot. The gain calibration is performed such that the most probable value of a proton dE/dx distribution is scaled to a value of 100 ADC/cm.

from ionization losses. In addition, the shoulder caused by transition radiation and extending towards higher energy depositions is clearly visible in the electron distribution.

4 Electron-proton separation with the TRD

The key figure of merit of the TRD is its separation power between electrons and protons. This is usually expressed as the proton rejection $R = 1/\varepsilon_p$, where ε_p is the probability for a proton to pass the TRD selection at a given electron efficiency ε_e. To identify electrons and protons, an electron and proton likelihood are calculated based on the calibrated dE/dx values and the probability density functions $p_{e,p}$ found in the calibration,

$$L_{e,p} = \sqrt[n]{\prod_i^n p_{e,p}(dE_i/dx_i)} \qquad (1)$$

where n is the number of TRD layers traversed by the particle. A cut is finally applied on the ratio

$$L_{\mathrm{TRD}} = -\log \frac{L_e}{L_e + L_p} \qquad (2)$$

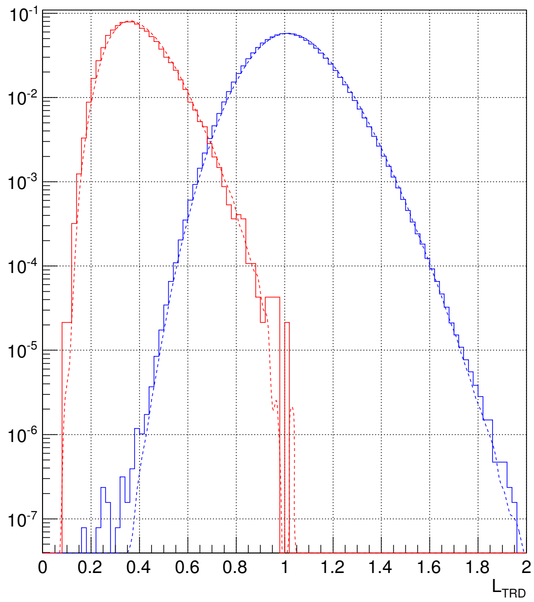

Figure 4: Normalized distributions of the likelihood ratios as defined by eq. (2) for the momentum range from 10 to 100 GeV/c. The distributions obtained from ISS flight data for electrons (red) and protons (blue) are shown as solid histograms. Overlaid as dashed lines are the corresponding toy Monte Carlo distributions as described in the main text.

to separate positrons and protons.

Figure 4 shows the likelihood ratios for ISS protons and electrons. Protons and electrons have been identified from a sample of particle tracks crossing the electromagnetic calorimeter. A pure electron sample can then be obtained by requiring an electromagnetic shower in the calorimeter, match between the energy deposited in the calorimeter and the momentum measured in the tracker, and a negative curvature in the tracker. Protons are identified by having energy depositions consistent with $Z = 1$ in all subdetectors except the TRD and the absence of an electromagnetic shower in the calorimeter.

In order to determine the proton rejection of the TRD, a cut on L_{TRD} has to be applied. The integral from zero to the value of the cut over the likelihood distributions for electrons and protons will then yield ε_e and ε_p, respectively.

To gauge the purity of the test samples of electrons and protons, and to check the internal consistency of the probability density functions with the likelihood distributions found in the data, a toy Monte Carlo study is performed. It proceeds by generating random dE/dx measurements drawn from the pdfs used in the particle identification, For every particle in the actual data, typically ten toy MC events are generated, using the momentum of the particle and the pattern of TRD layers with a non-zero energy deposition found in the event. Therefore, the toy Monte Carlo produces likelihood distributions that would be obtained in the case of complete absence of correlation between individual energy depositions in the TRD straws and a perfect description of the true (unknown) probability density functions. The toy Monte Carlo distributions for electrons and protons are also included in Figure 4, and the agreement with the distributions found for the flight data is very good. The remaining tails in the likelihood distributions are at the level of 10^{-6} for protons.

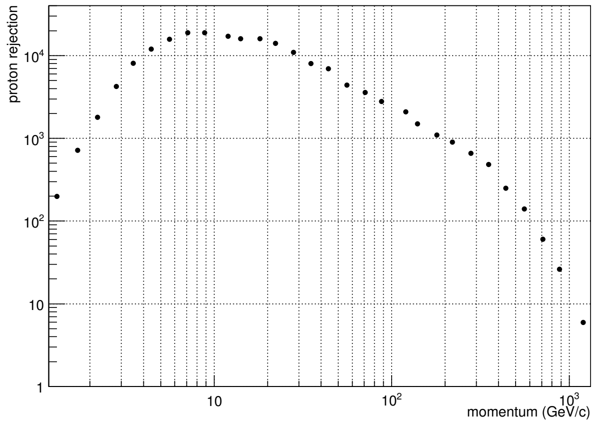

Figure 5: The proton rejection measured by the TRD as a function of track momentum at 90 % selection efficiency for electrons and positrons.

Figure 5 shows the overall TRD proton rejection in the momentum interval from 1 to 100 GeV/c, for an electron efficiency of 90 %. The electron efficiency was determined from the integral of the likelihood distribtion, i.e. after cuts on the quality of the event data in the TRD have been applied.

5 Summary

The main purpose of the transition radiation detector of AMS-02 is the robust identification of cosmic-ray positrons in the large background of protons. The TRD measures the transition radiation yield of charged particles in each of its twenty layers of straw tube modules. With the calibration, consisting of alignment, determination of gas gains, and sampling of probability density functions of energy depositions for the different particle species, a likelihood method is applied to identify electrons or positrons and protons. The resulting proton rejection power at an electron efficiency of 90 % has been shown to be better than 10^4 around 10 GeV and drops to 10^2 around a momentum of 600 GeV/c.

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