Threshold Transition Radiation Detectors in Astroparticle Physics

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Abstract

Transition Radiation Detectors (TRDs) have been used to study highly relativistic cosmic rays in the last three decades. In recent and in future balloon or space experiments TRDs will be used as energy measuring or threshold devices with large acceptances and long flight durations. Energy measuring TRDs will be required to study the origin of high energy particles in the cosmic rays at energies near 10^{15} eV. Threshold TRDs will be used for particle identification which is a key issue for dark matter and SUSY searches relying on positron spectroscopy up to 300 GeV. This requires a proton rejection above 10^2 from the TRDs. A review will be given of the different requirements and experimental solutions for threshold TRDs and the astrophysical significance of their measurements. Special emphasis will be dedicated to the space qualification and long flight duration aspects of the AMS-02 TRD.

Key words: Cosmic Rays, Transition radiation detectors, Particle identification, Space detectors
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1 Introduction

During the last decades, transition radiation detectors (TRDs) became practical and powerful devices for particle detection and identification. The typical TRD configuration consists of a radiator of foils, foam or fibers, followed by a gaseous X-ray detector. The intensity of transition radiation depends on the Lorentz-factor $\gamma = E/mc^2$ of the primary particle. The TR X-rays are emitted in the forward direction. In the detector the X-ray signal is superimposed upon the ionization signal of the primary particle.

With threshold and energy measuring TRDs the TR X-rays can be observed above a Lorentz factor threshold γ_0 (typically $\approx 10^3$). The saturation point γ_{sat}

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occurs rapidly over a small range in γ (one order of magnitude) for threshold TRDs whereas for energy measuring devices the location of γ_{sat} depends on the physical properties of the radiator (1) and can be optimized to meet specific design requirements.

2 Energy Measuring TRDs

Energy measuring TRDs will be required to study the nature and origin of high energy particles in the cosmic rays at energies near 10^{15} eV, known as the "knee". The knee is the energy range in which measurements of the spectra of individual elements are expected to provide crucial clues to the details of the acceleration mechanism. The measurements done by the Cosmic Ray Nuclei Detector (CRN) (2), using an energy measuring TRD in space, indicate that all cosmic ray species are generated at the acceleration sites with the same source energy spectrum which has a power law shape of $\approx E^{-2.2}$, close to supernova-shock acceleration theories predictions. Long duration balloon or space experiments with large area TRDs like the TRACER, CREAM or ACCESS experiment are described in (3; 4; 5; 6).

3 Threshold TRDs

Threshold TRDs are used to identify particles and to distinguish between particles of the same energy but with different masses, for instance between electrons and antiprotons or positrons and protons. The indirect searches for dark matter candidates with high statistic measurements of positrons from neutralino annihilations (7) require experiments with large acceptance factors and long flight duration operation. The dominating proton background has to be reduced by a factor 10^6 to reach the required precision in e^+-spectroscopy in the momentum range between 10 and 300 GeV.

The WIZARD collaboration has performed the TS93-experiment to measure the e^+-spectrum in the energy range of 4 - 50 GeV (8; 9). The TS93-apparatus was flown by balloon from Ft. Sumner on September 8th 1993 at a constant altitude of 36 km for 25 hours. The experiment (fig. 1) combined a superconducting magnet spectrometer, a Time-of-flight system on top and bottom of the spectrometer, a silicon-tungsten imaging calorimeter at the bottom and a transition radiation detector above the spectrometer. The TRD had an active area of 76×80 cm^2, a weight of 237 kg and a power consumption of 100 W for 2560 electronic channels. The detector consisted of 10 layers of carbon fiber radiators, each followed by a multiwire proportional chamber (MWPC) with 256 gold plated tungsten wires of 25 μm diameter (tensioned to 70 g). The MWPCs were filled with a xenon/methane (80 %/20 %) mixture. The TRD signals during flight were processed by different analysis techniques, leading to a rejection power of $<$ 100 against hadrons at an electron efficiency

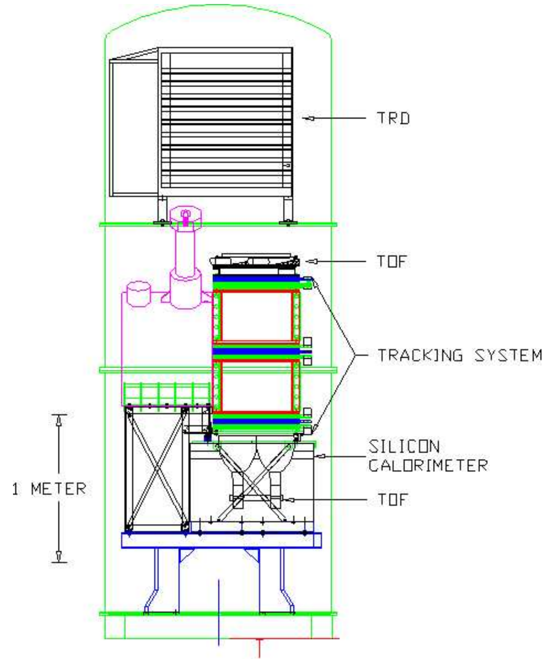

Fig. 1. Schematic diagramm of TS93-experiment (8).

of 70 %. The combination of the electromagnetic calorimeter and threshold TRD reached an overall rejection factor for protons of $3 \cdot 10^4$ in the momentum range 4-50 GeV/c.

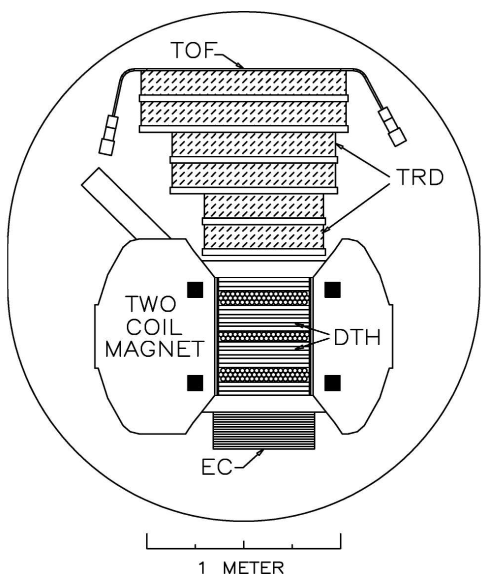

Fig. 2. Schematic diagramm of HEAT-experiment (10).

The High Energy Antimatter Telescope (HEAT, fig. 2) experiment was optimized for the detection of cosmic-ray $e^{\pm}$ below 100 GeV by using a combination of a superconducting magnet spectrometer ($\sim$ 1T magnetic field), time-of-flight scintillators, a threshold TRD and an electromagnetic calorime-

ter (10; 11). The balloon instrument was first flown on May 3rd 1994 from Ft. Sumner, New Mexico, and collected data for 29.5 hours at float altitudes of 3.8-7.4 g/cm^2 of residual atmosphere and again on August 23rd 1995 from Lynn Lake, Manitoba, for a data taking period of 26 hours at 3.3-6.8 g/cm^2.
The TRD is comprised of six modules, each module consists of a radiator and a multiwire proportional chamber (MWPC). The 12.7 cm thick radiators are composed of polyethylene fiber blankets with an effective fiber diameter of 21 μm and a mean fiber spacing of 380 μm.
The MWPCs had a thickness of 2 cm and employed 13 μm diameter gold-plated tungsten wires, with a 5 mm spacing between wires. The chosen gas was a xenon/methane (70 %/30 %) composition. The chambers were operated in proportional mode at a high voltage of 3700 V at 1 atm. The TRD signals were processed by a likelihood analysis, leading to a rejection power of 170 against protons at an electron efficiency of 90 %.
The combination of the ECAL and the TRD reached an overall hadron rejection power of $8 \cdot 10^4$ in the energy range of 5 to 50 GeV (10).

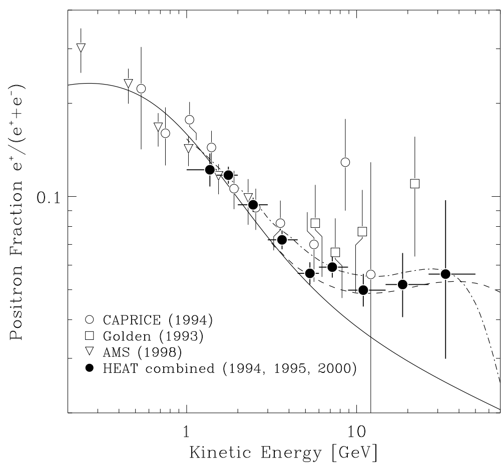

Fig. 3. The e$^+$-fraction as a function of energy for the HEAT-, TS93- and the AMS-01-data compared to model predictions (12).

The results of the e$^+$-fraction as a function of energy measurements for the Heat- and the TS93-data follow the general trend of a computation of cosmic-ray secondary e$^\pm$ spectra in a diffusive model for Galactic cosmic-ray propagation (14) up to a few GeV. One explanation for the enhancement of the observed e$^+$-fraction at higher energies is the annihilation of dark matter candidates, the supersymmetric neutralinos (7).
Threshold TRDs in space should improve the counting statistics and should extend the measureable energy range to higher energies around 300 GeV. In addition these experiments should be free of systematic uncertainties due to e$^+$-production in the residual atmosphere at balloon altitudes. The challenge is to build such a detector in a space qualified way with strict limits on gas tightness, weight, power consumption and outgassing whilst assuring structural safety and gasgain homogeneity in a harsh environment during payload

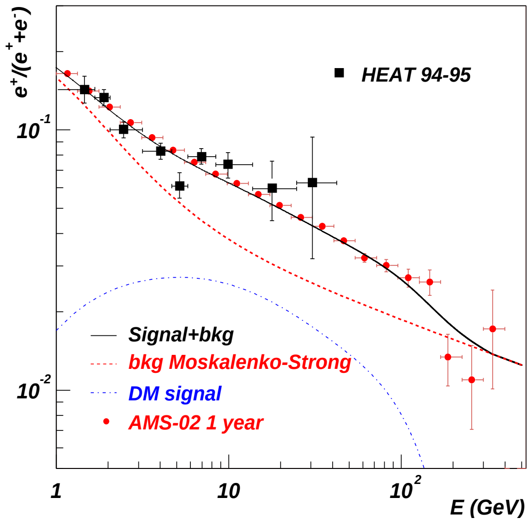

Fig. 4. The expected e$^+$-fraction accuracy from AMS-02 after 1 year on the ISS compared to the HEAT-data and model predictions (13).

lift and on orbit without the possibility of further access to the detector. This involves detailed finite element calculations, vibration and thermo-vacuum tests.

A space qualified threshold TRD is the one which was foreseen for the PAMELA instrument. This TRD has been designed to reach a hadron rejection of 20 at an electron efficiency of 90 % (15; 16).

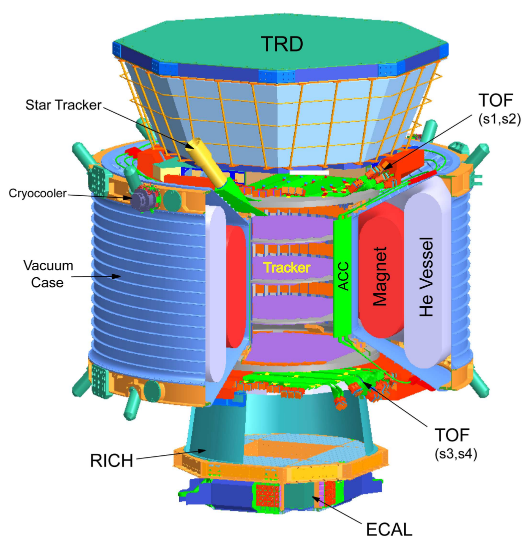

Fig. 5. The 3-dimensional view of the AMS-02 experiment.

The AMS-02 experiment (fig. 5) is a large acceptance particle spectrometer (0.5 m^2sr) designed to operate in space and measure cosmic ray fluxes on the International Space Station ISS for a time period of three years. AMS-02 uses

a superconducting magnet (∼ 0.9 T magnetic field), silicon strip tracker, time-of-flight scintillators, a RICH and a sampling calorimeter to detect cosmic-ray nuclei and antimatter and to search for exotic dark matter candidates in the energy range from 1 GeV up to 1 TeV (7). To reach the required precision in e^+-spectroscopy the dominant proton background has to be reduced by a factor of 10^6. This will be achieved with the AMS-02 electromagnetic calorimeter delivering 3-4 orders of magnitude and the TRD with proton rejections between 100 and 1000.
In the AMS-02 TRD, a fleece material with a density of 0.06 g/cm^3 and with 10 μm polypropylene/polyethylene fibers is used as radiator. The radiator is cleaned with CH_2Cl_2 to reach the NASA outgassing limit (17). The TR photons are detected in proportional mode straw tubes, filled with a Xe/CO_2 (80%/20%) gas mixture. The TRD consists of 20 layers, each with 20 mm fleece and modules of 16 straw tubes with 6 mm diameter made from a double layer kapton-aluminium foil of 72 μm wall thickness. For the production of gastight modules each straw was tested individually with Helium at 2.8 bar for 5 min in a setup sensitive to the gas diffusion limit through the straw wall (18). The straw modules (fig. 6) are closed with polycarbonate endpieces which serve as gas manifolds and centre the Cu-Te-crimp plugs to hold a 30 μm goldplated tungsten wire tensioned with 1 N. The modules are mechanically stabilized by longitudinal and vertical carbon fibre stiffeners. The wire positioning precision was verified with a high-resolution computer-tomography-scan (19). Each flight module is tested individually for wire tension, gas tightness, leakage current and gas gain homogeneity. In total 328 modules of lengths up to 2 m are supported by two bulkheads in a conically shaped octagon structure (fig. 7). The upper and lower four layers run parallel to the magnetic field, the others perpendicular to provide 3D tracking. The octagon is made of a carbon fibre and aluminium honeycomb machined to 100 μm precision keeping gasgain variations below 2 %. The TRD will be fully covered in a multi-layer-insulation (MLI) foil to keep the spatial and temporal orbit temperature gradient below 1 K.
The TRD gas volume of 230 l is divided into 41 separable chains each contain-

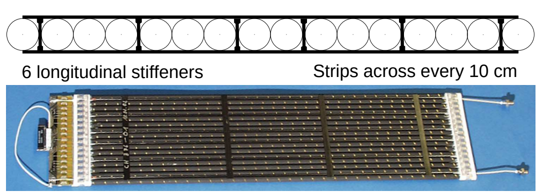

Fig. 6. AMS-02 TRD module with 16 straw tubes.

ing 8 modules connected in series. The circulating TRD gas system supplies a gas flow of 1 l/h of Xe/CO_2 (80/20) at 1 bar from two storage vessels holding 49.5 kg of Xe and 4.5 kg of CO_2 and is described in (20). Taking into account the amount of CO_2 and the gastightness of the flight straw modules the TRD could be operated for 24 years on the ISS.

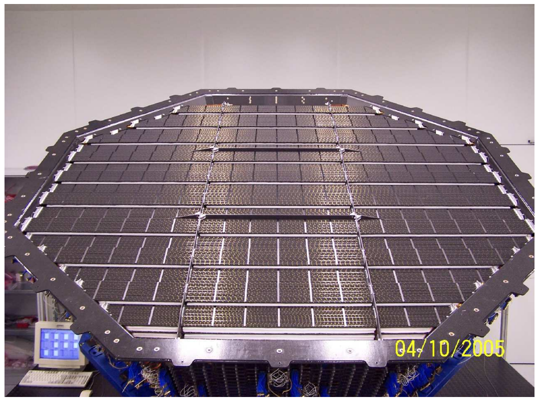

Fig. 7. AMS-02 TRD: Octagon structure with all 328 straw modules integrated.

The gas gain homogenity of the flight straw modules is measured as a function of position along the straws and for each straw of the module before installation in the octagon structure on a precision granite table block and after installation inside the octagon. The straw signals are caused by converted 5.9 keV photons of an Fe^{55}-source. The mean homogenity of all measured gas gains is ~ 0.6 %.
Space qualification tests have been carried out for eight 0.7 m long straw modules. The modules underwent vibration tests (a 0.5 g sine sweep followed by a 6.8 grms random test followed again by a 0.5 g sine sweep), 8 cycle thermovacuum tests (between -40° C and $+60^{\circ}$ C) followed again by vibration tests. No significant changes in gas tightness, gas gain or eigenfrequencies were observed.
To separate protons from positrons, wire signals from ionization losses alone have to be distinguished efficiently from signals containing both dE/dX and absorbed TR-photons with a pulse height readout. The digitization of the signals from the 5248 straw tubes is done in the frontend-readout. Equipped with a 12-bit ADC covering a dynamical range of 40 mips (at gas gain 3000, HV=1480 V), each frontend board serves four TRD modules. The data reduction and low/high voltage supply units are situated in separate crates next to the TRD. The frontend-readout is mounted directly on the octagon inside the MLI to assure an electrical shielding for a noise level below 2 ADC-channels. The TRD readout electronic components have been space qualified by vibration, thermo-vacuum and electromagnetic interference tests (19; 21).
The proton rejection power of the AMS-02 TRD design has been verified with a full 20 layer prototype in testbeams (13; 22). Protons are separated from electrons with a combined neural network analysis. The tube-energy spectra (fig. 8) are used as probability densities $p(E)$. For proton beam energies between 15 and 250 GeV the proton rejection is well above 100 (fig. 9) at an electron efficiency of 90 %.

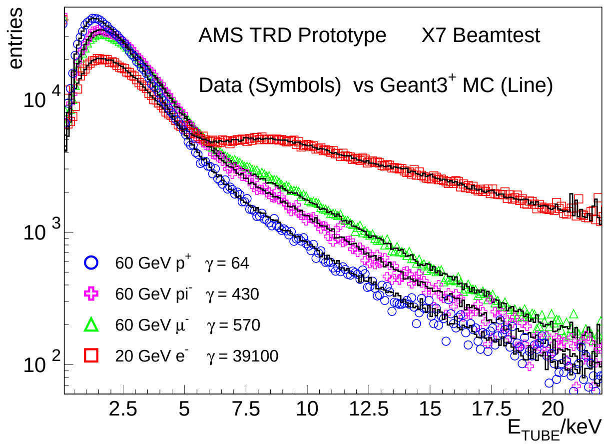

Fig. 8. Clean-single-track tube-energy-spectra.

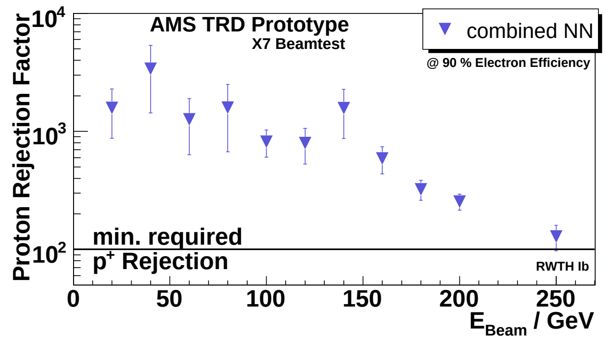

Fig. 9. AMS-02 TRD proton rejection.

4 Conclusions

The transition radiation technique has been developed for a variety of measurements in astroparticle physics. Energy measuring and threshold TRDs will continue to play an important role in astroparticle physics. The long-duration balloon experiments TRACER and CREAM use large area TRDs to study the origin and propagation of highly relativistic heavy nuclei. The spacecraft experiment AMS-02 uses a threshold TRD for $e^{\pm}$-spectroscopy to search for dark matter candidates. The AMS-02 TRD and the TRD designed for PAMELA demonstrate that it is possible to construct and build a space qualified experiment.

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