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Precision X-ray transition radiation detectors for cosmic rays

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Abstract. Precision transition radiation detectors (TRDs) can be an effective tool for determining the energy spectra of cosmic ray nuclei up to the energies of the knee. They offer unique measurement capabilities and embody design principles which are somewhat different from those of the threshold TRDs used in accelerator experiments. We will discuss some of the characteristics of these instruments, including the relevant design principles and the properties which determine their performance.

1 Introduction

Precision transition radiation detectors (TRDs) represent a powerful technology for the measurement of cosmic ray nuclei (see, *e.g.*, Swordy et al. (1990); Gahbauer et al. (1999); Wakely (2001)). Unlike the threshold devices used in accelerator based high energy physics (see *e.g.*, Dolgoshein (1993)), precision TRDs are designed to make high resolution energy measurements of high-Z particles across wide ranges of Lorentz factor.

Precision TRDs have many features which make them attractive for cosmic ray research. For instance, the generation of TR is not destructive to the measured particle, so TRDs can be used as components in larger instruments, providing information complementary to other detectors. Additionally, the TR process is purely electromagnetic, so detectors can be constructed with relatively little "target" mass, allowing for geometric factors much larger than possible with methods such as calorimetery. Also, because TR has a well-understood dependence on charge, TRDs can be fully calibrated prior to deployment by using singly-charged particles at accelerator sites.

Precision TRDs are not simply threshold TRDs applied to the measurement of high-Z particles. Each device addresses a different application, and therefore utilizes some unique design parameters. In this paper, we will briefly discuss the design of precision TRDs, including an examination of performance factors, and the physics of the underlying processes.

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2 Properties of X-ray Transition Radiation

When crossing the interface between two media of differing dielectric constant, a particle of charge Z and Lorentz factor γ may generate transition radiation photons. For highly relativistic particles, the photons will typically be in the X-ray range of 1 – 100 keV. As the Lorentz factor of the particle increases, the yield and average energy of the X-rays will increase. Therefore, measuring the total energy of the emitted photons provides an estimate of γ.

TR X-ray emission is peaked in a sharply forward direction, with the bulk of the yield centered near $\theta \approx 1/\gamma$. As a consequence, the emitted photons are co-incident with the primary particles, and in most practical detector configurations, cannot be separated from them. This recommends the use of thin high-Z gas detectors to collect the X-rays, while minimizing the ionization background deposits.

The per-interface yield of TR is intrinsically small. For a transition between typical materials, the photon production probability for singly-charged particles is of the order $\alpha \approx 1/137$. This leads to the traditional TRD "radiator" design, in which many thin slabs (*i.e.*, foils) of material are fixed within a volume of light gas or vacuum. The total TR yield from such a radiator is determined by the interference of the emission amplitudes from all 2N faces of the radiator slabs. If certain design constraints are respected (see, *e.g.*, Cherry et al. (1974)), the yield from an N-foil TRD radiator can approach 2N times the yield from a single interface. This important result is the reason that practical instruments can be made using the TR technique. Without this multiplication of yield, the output would be too small to be useful.

In general, the behavior of TR emission is determined by the physical properties of the radiator. This includes the thickness (l_1) and spacing (l_2) of the foils, as well as the plasma frequencies of the gap (ω_2) and foil materials (ω_1).

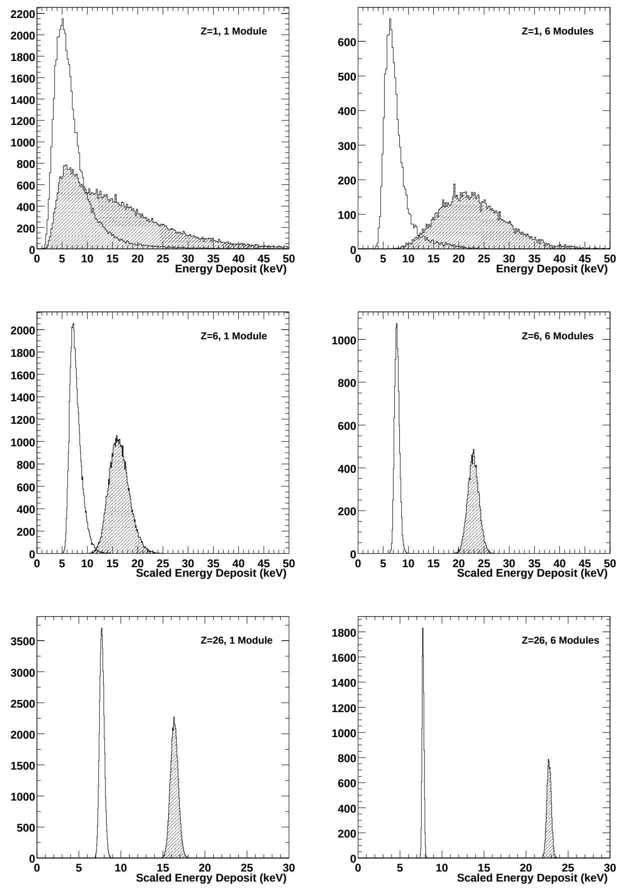

Fig. 1. Simulated deposited-energy distributions for particles at two different Lorentz factors. The unshaded histograms represent nuclei at $\gamma = 100$, while the shaded histograms are for $\gamma = 1000$. The upper left panel shows protons as detected by a single TRD module with one 1 cm thick layer of 100% Xenon. The upper right panel shows protons as detected by a six-module TRD with six 1 cm Xenon layers. The middle and lower panels show the same information for Carbon nuclei ($Z = 6$) and Iron nuclei ($Z = 26$), respectively. All histograms are scaled by $1/Z^2$, and by their module count. Note the change in scale for the lower histograms.

One of the most important properties of a radiator is its saturation limit. This is the particle energy beyond which the TR yield from the radiator ceases to increase. This saturation phenomenon effectively restricts the application of TRDs to limited windows of Lorentz factor and provides one of the principle constraints in the design process. The effect of saturation can be seen in the response curves of Figure 2. The saturation limit is given by $\gamma_{sat} \approx 3.0(\hbar\omega_1)\sqrt{l_1 l_2}$, where the l_i are measured in μm, and $\hbar\omega_1$ in eV (Cherry et al., 1974).

2.1 Application to Cosmic Nuclei

A fundamental limitation of the TR technique for singly-charged particles is the intrinsic smallness of the TR yield. Even when using multi-foil radiators, the TR signals are quite small, and subject to large fluctuations. The subsequent deposited energy distributions are very wide and unsuitable for precision energy measurements. Furthermore, TR signals are generally measured against a background of ionization energy loss from the primary particle itself. For thin gas detectors, this background has a broad, Landau-like distribution with an amplitude roughly equal to that of the signal. It is for these reasons that the traditional use of TRDs has been limited to threshold applications. Note that while the use of multiple detector modules improves resolution, practical restrictions on the detector length generally limit TRDs to under 10 modules.

However, both the TR and ionization processes scale strictly as Z^2. With this scaling, there comes a subsequent reduction in the relative widths of the deposited energy distributions from each process. For ionization losses, the behavior is the same as is seen in the familiar transition from Landau-like to Gaussian distributions when increasing the thickness of an absorber layer. The identical transition occurs for the TR process, allowing a dramatic reduction in the overall relative signal width as the charge of the measured particles increases.

This is illustrated in Figure 1, which shows deposited-energy distributions for Hydrogen, Carbon and Iron nuclei. The unfilled histograms represent ionization energy deposit alone, while the filled histograms show both ionization and TR deposits. The relative widths of the distributions scale according to $1/Z$. This behavior, which has been experimentally verified in previous detectors (Swordy et al., 1990), is the fundamental reason why high-resolution measurements can be achieved using precision TRDs.

3 TRD Design

A typical TRD instrument consists of one or more modules comprising two components each: a radiator volume containing multiple interfaces to generate TR photons, followed by a detector suitable for collecting these photons. Both of these components have several design parameters which must be optimized to construct an effective TRD. Among them are: radiator material, gap material, effective foil thickness, effective gap thickness, interface count, detector type, and detector geometry. Additionally, the module count, total stack height, desired geometric factor, and signal processing technique must be considered. Many of these parameters are closely inter-related, such that choices made for one will impact the options available for the others.

3.1 Common Design Features

In terms of the most fundamental design parameters, there is much in common between threshold and precision TRDs. The radiator material must represent a compromise between high density, which provides an improved TR yield, and low atomic number, which minimizes the re-absorption of X-rays in the foils. This suggests light low-Z metals, such as Li, or high-density hydrocarbons such as Mylar or polyethylene.

The size of the gaps between foils must strike a balance be-

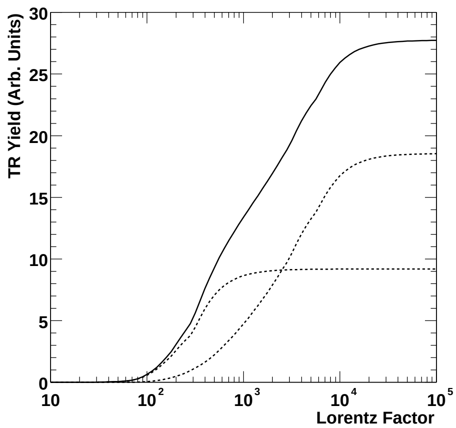

Fig. 2. Simulated response of a two-part composite radiator. The solid line is the response of the full composite radiator. The dashed lines are the contributions of the individual radiator components. The effects of X-ray detection efficiency and absorption in the down-stream radiator volume are included.

tween extending the response at high Lorentz factors (large l_2), and maintaining an acceptable number of foils. These goals cannot be realized simultaneously without increasing the detector height, which reduces the geometric factor. The detector foils themselves can be increased in thickness to produce harder X-rays, but only at the cost of increased re-absorption in the radiator.

The TRD X-ray detector should maximize the absorption of X-rays, while simultaneously minimizing the ionization energy deposit due to the primary particle. This favors gas-type detectors with high-Z fill gases, such as Xenon. In a recent innovation for balloon or space-based instruments, the traditional multi-wire proportional chambers are replaced with layers of pressurized proportional tubes, eliminating the need for massive pressure vessels (Gahbauer et al., 1999).

An important benefit of using gas-filled detectors is that they exhibit a relativistic rise in ionization energy losses. This well-known effect has an onset near $\gamma \sim 4$, and saturates near $\gamma \sim 1000$, where the TR yield generally begins to become appreciable. This makes it an ideal complement to the TR process in a precision TRD (See Figure 3, and Hörandel et al. (2001)).

3.2 Precision TRD Features

3.2.1 Response Window

The primary difference between a precision TRD and a threshold TRD is in the size of the active response window. This is simply the region of the response curve which has non-zero slope, providing finite detector sensitivity. In a threshold TRD, the size of this window is ideally zero, and the slope of the response curve is infinite. However, in a precision TRD, the active response window must be kept as large as possible.

The size of the response window is determined by the physical properties of the radiator, in particular, the ratio of the gap spacing to the foil thickness, $\kappa = l_2/l_1$. In general, the larger this ratio, the larger the response window. For threshold TRDs, κ tends to be relatively small ($\kappa \lesssim 10$). In a precision TRD, κ should be larger, preferably $\gtrsim 100$. This is generally achieved by increasing the size of the foil gap. This requires a reduction in the foil count (assuming the detector height is fixed), and so must be balanced against the subsequent loss of yield.

3.2.2 Composite Radiators and Feedthrough

In practice, satisfactory yields cannot be provided by a single radiator over greatly-extended ranges of Lorentz factor. Therefore, a large response window is best achieved by the use of *composite* radiators. A composite radiator is one in which two or more radiator volumes are stacked to form a single radiator. The parameters of each sub-radiator are chosen to provide superior response within a limited range of Lorentz factor. By combining multiple radiators with overlapping but offset response windows, an aggregate response superior to that of the individuals is possible. Figure 2 shows the response curve of a typical two-part composite radiator.

Note that the response of a composite radiator is not simply the sum of the responses from the components. The absorption of TR X-rays in down-stream radiator volumes can significantly impact the yield of the initial radiator segments. To minimize this effect, those radiator subsections producing the hardest (most penetrating) radiation should be placed at the top of the radiator stack. Radiators generating soft X-rays can then be placed as close to the photon detector as possible.

This configuration reduces the loss of X-rays in subsequent radiator volumes, and takes advantage of the so-called *feedthrough* effect. Feedthrough occurs when X-rays generated in an upper TRD module pass unabsorbed through the detector of that module to be absorbed in a downstream detector. This process enhances the importance of upstream radiator components, and plays an important role in precision TRD design.

3.2.3 Signal Processing

An additional point of distinction between precision and threshold TRDs concerns the form of signal processing used to analyze the detector signals. In threshold TRDs, the so-called "cluster-counting" method (Ludlum et al., 1981; Fabjan et al., 1981) is frequently used to help reduce ionization backgrounds, or provide fast triggering capabilities. With this technique, total-deposited-energy information (which is used in traditional processing methods) is discarded in favor of a simple discrimination technique: counting the number of ionization clusters above a given threshold.

For the cosmic-ray nuclei measured in a TRD, however, there is a large range of particle charges. When measuring particles of higher charge, the number of ionization clusters increases as Z^2, and individual clusters can no longer be resolved.

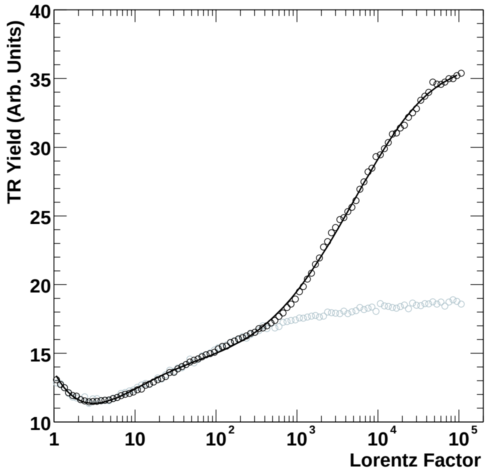

Fig. 3. Full simulation of a three-component, six-module composite TRD, including TR and relativistic rise processes. The energy deposit is normalized to a single 2 cm chamber of 100% Xenon. Each point represents the average of 10000 simulated events. To accentuate the relativistic ionization contribution, the response both with (dark circles) and without (light circles) TR generation is shown. The line is an approximate fit to the TR data.

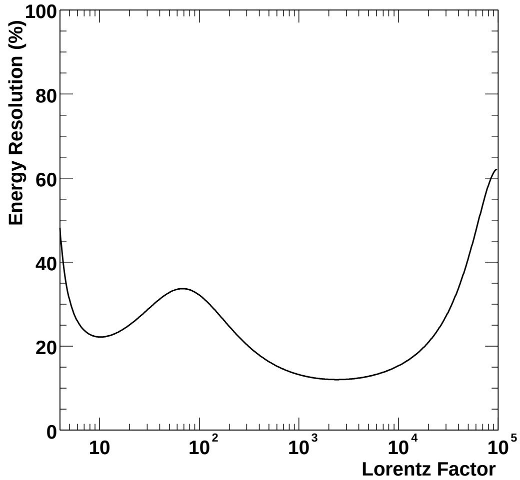

Fig. 4. Simulated relative energy resolution for Iron nuclei incident on a six-module composite TRD, including TR and relativistic rise processes. The energy resolution is calculated from the fit in Figure 3.

4 TRD Performance

4.1 Energy Resolution

The performance of a precision TRD may be best characterized by an energy resolution curve. This curve shows the relative precision of energy measurements as a function of Lorentz factor. The form of the resolution curve is determined by the slope of the detector response, and the magnitude of the fluctuations of the signal according to the expression $(\Delta E/E) = (1/E)\Delta\Re(E)/\Re'(E)$. Here $\Re(E)$ represents the response function, $\Re'(E)$ the slope of the response function, and $\Delta\Re(E)$ the RMS signal width at energy E.

The energy resolution can be improved by reducing the fluctuations in the deposited signal, or by increasing the slope of the response curve. The signal fluctuations decrease with increased particle charge, such that for high-Z particles, the intrinsic resolution of the X-ray detector may become the limiting factor.

Increasing the slope of the response curve, however, requires either a reduction in the size of the response window or an increase in the maximum TR yield. In this way, we see that the global performance of the TRD is determined by the area under the response curve. Without increasing the total area by increasing the yield at saturation, the energy resolution cannot be improved at one point without worsening it at another. Indeed, in this sense, a threshold TRD can be considered a precision TRD which has traded infinite resolution at the threshold point for zero resolution elsewhere.

Figure 3 shows the full simulated response of a multi-radiator composite TRD. This TRD features six radiator and detector pairs, with three sub-radiators in each pair. Both TR and ionization energy loss (including relativistic rise) processes are included in the simulation. From the approximate fit to this response function, we can generate a relative energy resolution curve. This is shown in Figure 4, assuming particles of charge $Z = 26$ (Iron). This design demonstrates that excellent energy resolution can be achieved over nearly four orders of magnitude using a precision TRD.

5 Conclusions

Precision transition radiation detectors can be a powerful tool for the measurement of the energy spectra of cosmic ray nuclei. Unlike threshold TRDs, which are built to discriminate between particle species, precision TRDs are explicitly designed to make high-resolution measurements of particle Lorentz factors. This is possible due to a qualitative change in the behavior of energy loss distributions between singly-charged particles and particles of higher charge. With these particles, there is a Z^2 increase in the relevant energy loss rates (TR and ionization), as well as a $1/Z$ decrease in the relative distribution widths. By exploiting these features, a precision TRD can provide high resolution energy measurements over large ranges of Lorentz factor.

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