Transition Radiation Detectors for Cosmic Rays Near the Knee

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Abstract

Precise observations of the energy spectra and relative abundances of cosmic-ray nuclei require instruments that exhibit individual charge resolution and a calibrated energy response. If energies up to $\sim 10^{15}$ eV are to be covered, the low intensity of the heavier nuclei (Z $\gtrsim$ 3) also mandates detector areas of several square meters. X-ray transition radiation detectors (TRDs) appear to provide the only practical means of fulfilling all of these requirements for balloon or space-borne instruments. However, for measurements up to the cosmic-ray "knee", care must be taken that the energy response of the TRD does not saturate for Lorentz factors less than $\sim 10^5$. We have designed detectors to meet this goal, and have successfully tested prototypes at an accelerator beam at CERN. We shall present and discuss the results of these measurements.

1. Introduction

The determination of the energy spectra and composition of the elements in cosmic rays at very high energies, i.e., approaching the knee region above 10^{15} eV, has been a long-standing goal in cosmic-ray astrophysics. Achieving this goal with direct measurements requires instruments which are not only very large, but which have an extended and well-understood response. Precision TRDs can meet these requirements [4,5]. Because the TR process responds to Lorentz factor ($\gamma = E/mc^2$), rather than energy, calibrations at ground-based facilities may be performed prior to the deployment of the instrument. Furthermore, because TR emission is not a nuclear effect, TRDs do not require large masses of "target" material. This allows for relatively large detector areas for a given mass.

Unlike accelerator-oriented threshold TRDs, precision TRDs are employed to make accurate measurements of Lorentz factors over large ranges of energy. This is possible because the transition radiation yield scales with nuclear charge, as Z^2 [3]. However, if energies as high as the cosmic-ray knee are to be reached, a TRD must be carefully designed to maintain sensitivity up to Lorentz factors of $\gamma \sim 10^5$, *while retaining effectiveness at lower Lorentz factors,* $\gamma \lesssim 10^3$.

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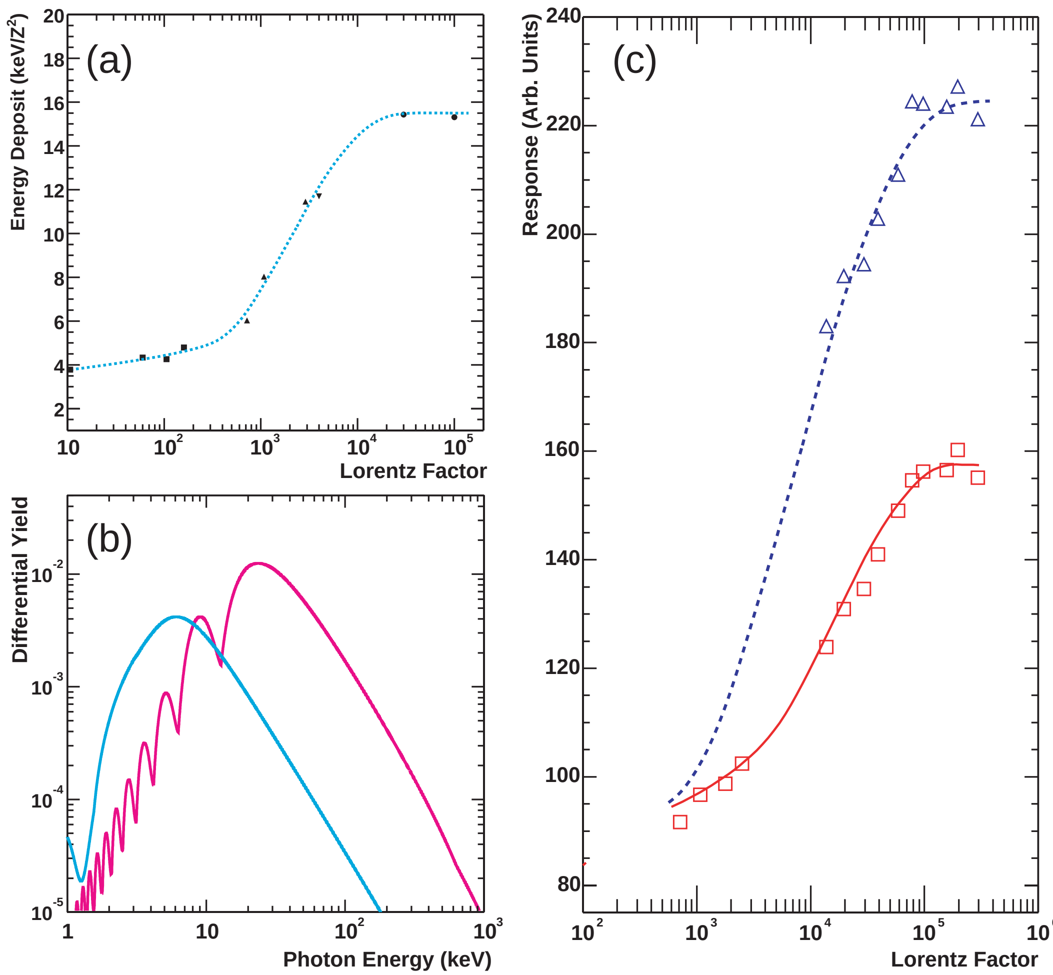

Fig. 1. Panel a: The response curve of the CRN TRD [2]. Panel b: Differential TR spectra. Panel c: The TRD response curve for two detector prototypes. Squares: Configuration A. Triangles: Configuration B. Solid line: Simulation. See text for details.

2. Transition Radiation Properties

Transition radiation is emitted in the x-ray region when a relativistic charged particle traverses a dielectrically inhomogeneous radiator, such as a stack of foils stretched in air, or a volume of plastic foam or fibers. The energy yield of the TR varies with the Lorentz factor of the primary particle, allowing estimates to be made of particle energy. However, the range of Lorentz factors over which such estimates can be made is limited. In practice, for any given radiator, *saturation* effects will set in, reducing its sensitivity at higher energies. This can be seen in Figure 1a, which shows the response curve (detector signal versus Lorentz factor) of the CRN instrument [2]. This instrument was designed to provide excellent response at lower Lorentz factors. Consequently, the TR signal becomes noticeable around $\gamma \gtrsim 500$, and saturates around $\gamma \gtrsim 2 \times 10^4$.

The properties of the TR emitted from a radiator are affected by the geometric configuration of the radiator, i.e., on the thickness, spacing, and total number of interfaces in the volume, as well as the plasma frequencies of its materials (for a review, see [1]). An example can be seen in Figure 1b, which shows the differential emission spectra of two radiators differing only in their foil thickness. The light line is for ~ 5 μm Mylar foils, and the darker line is for thicker foils, ~ 50 μm. Self-absorption effects have been included, reducing the emission at low energies. As can be seen, the radiation yield peaks at considerably lower x-ray energy for the thin-foil radiator than for the thick-foil configuration. This dependence can be exploited to shift the emission spectrum of a radiator to features in the photoelectric response of the detector gas.

This provides a certain freedom in the "tuning" of a radiator to achieve the performance goals required for any specific purpose. In particular, by varying the thickness and spacing of the radiator's interfaces, it is possible to raise and lower the sensitive region (in Lorentz factor) of a given radiator. By *combining* radiators with different tunings, it is possible to build an instrument with an aggregate response which extends beyond that of any of its component parts. These designs are called composite, or graded radiators.

3. Prototype Design and Measurements

One may try to push the saturation point of a TRD to $\gamma \sim 10^5$ by increasing the distance between the interfaces within a radiator [5]. However, for a fixed detector height, this requires a reduced number of interfaces, and therefore, a diminished TR yield. Alternatively, one may increase the thickness of the foils in the radiator. This, however, also increases the hardness of the radiation, making it more difficult to detect. In practice, achieving a high saturation point requires some compromise between thicker foils (lower detection efficiency) and larger gaps (smaller TR yield).

Just such a compromise is possible by using foils which have been selected specifically to target the highest-energy absorption edge of the detector gas. In the case of a Mylar radiator and xenon detector gas, for instance, this suggests foils of ~ 75 μm thickness. Such foils, when combined with a spacing of several mm, should be able to provide a high saturation energy. This idea is tested in our first prototype TRD, Configuration A. This radiator comprises 51 76 μm (3 mil) Mylar sheets, spaced at 15 mm. The simplicity of this design facilitates easy comparisons with simulations.

A radiator specialized for high Lorentz factors is not expected to perform as well at lower Lorentz factors. Therefore, to achieve a truly extended response, one should combine multiple radiators with different regions of sensitivity. For example, Configuration B combines the foils of Configuration A with additional pieces of radiator material, including a 5 cm block of DOW Ethafoam 220 and a 7.6 cm blanket of 17 μm-thick Herculon fibers. The addition of this radiator material is meant to increase the total TR yield while improving the response at lower Lorentz factors.

Measurements of these configurations were carried out at CERN in the autumn of 2001. Pions and electrons ranging in Lorentz factor from $\gamma \approx 7 \times 10^2$ to 5×10^5 were used in the tests. The radiator materials were placed in front of a 2 cm thick multiwire proportional chamber (MWPC) filled with a xenon-methane mixture (95%/5% by volume).

4. Results and Discussion

Figure 1c shows the detector signal versus Lorentz factor for the two test TRD configurations. Configuration A (open squares) has data for nearly three orders of magnitude in Lorentz factor. The resulting response curve does not saturate until $\gamma \gtrsim 10^5$, confirming the design principles. Superimposed on the data (solid line) is the output of a full simulation using GEANT 4.3.2. The absolute normalization to the data is arbitrary, but the agreement in shape is quite excellent.

Also shown (open triangles) in Figure 1c are the results obtained for the composite TRD, Configuration B. Once again, saturation appears at $\gamma \gtrsim 10^5$, but now, the overall TR yield has been increased substantially. Though we presently have no measurements at the lower Lorentz factors, a likely response curve (the dashed line) suggests a considerable improvement over the low-end response of Configuration A.

5. Conclusions

X-ray transition radiation detectors currently seem to offer the best option for obtaining direct measurements of the energies of heavy ($Z \gtrsim 3$) cosmic rays up to the knee region, with high statistics and sufficient energy resolution. Our measurements demonstrate that configurations can be found which exhibit excellent energy response over a large energy range, $500 \lesssim \gamma \lesssim 10^5$.

6. References

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