LARGE AREA TRANSITION RADIATION DETECTORS
FOR COSMIC RAY OBSERVATIONS IN SPACE

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ABSTRACT

The characteristic dependence of x-ray transition radiation on the Lorentz factor of the parent particle can be utilized in cosmic-ray observations on balloons or in space in order to discriminate between relativistic electrons and hadrons, or to determine the energy spectra of heavy cosmic-ray nuclei at very high energies. To obtain statistically meaningful results, exposure factors of the instruments of the order of 100-1000 m^2sr days are essential. While the intrinsic weight of transition radiation detectors is low, this requires novel approaches and precludes the use of heavy pressurized containers for the instrument. We have developed a system using large arrays of xenon filled proportional tubes as detectors which can operate in a zero pressure environment. We shall discuss this design and present results from prototype evaluations. Finally, we shall describe the capabilities of a practical detector system that will measure the elemental composition and individual energy spectra of heavy cosmic ray nuclei up to energies around 10^{15} eV.

Keywords: cosmic-ray, transition radiation.

1. INTRODUCTION

Transition radiation (TR) refers to the emission of electromagnetic radiation when a charged particle traverses the interface between dielectrically different materials. For highly relativistic particles, the radiation is mostly emitted in the x-ray region (~ 10 keV) and its intensity depends on the Lorentz factor $\gamma = E/mc^2$ of the particle: in typical arrangements it becomes observable for $\gamma = 500$, the intensity then increases with γ until saturation may be reached around $\gamma = 50{,}000$ [1]. Thus, a measurement of the TR intensity in this region can provide an estimate of γ, and if the mass m is known, of the particle energy E. An efficient transition radiation detector (TRD) usually consists of a radiator of plastic material with many interfaces (such as foams or blankets of fibers), followed by a gaseous detector (such as a multiwire proportional chamber [MWPC]) containing xenon for efficient x-ray detection. For redundancy, a practical TRD may exhibit a sequence of such radiator/detector combinations.

The accuracy in the determination of the particle energy from the TR intensity is limited by statistical fluctuations: usually, the TR signal in the detector is superimposed upon the ionization signal of the primary particle and the TR signal is subject to Poisson-fluctuations in the number of x-ray photons, while the ionization signal exhibits Landau-fluctuations. For singly charged particles, the magnitude of these fluctuations does not to permit an *accurate* energy measurement, but a well proven application is the use of a TRD as a threshold counter to distinguish between particles of high and low Lorentz factors, respectively. For instance, TRD devices are very effective in discriminating electrons and positrons from protons and pions of comparable energy. Thus, in measurements of cosmic ray electrons and positrons TRD's have been successfully used to remove the large background of protons and pions [2].

0-8194-2194-4/96/$6.00

Figure 1

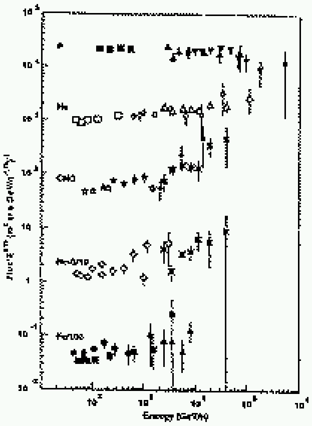

Figure 2

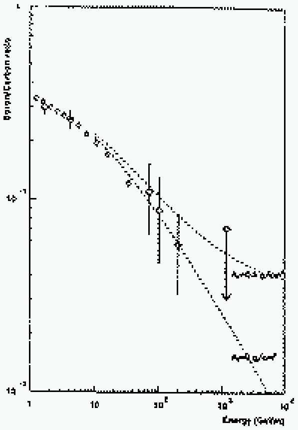

Figure 1. Differential energy spectra for protons, helium, and groups of heavier nuclei. Fluxes are multiplied by $E^{-2.75}$ *and the scales for (Ne-S) and Fe are divided by factors of 10 and 100, respectively.*

Figure 2. Energy dependence of the boron/carbon abundance ratio. The dashed cures corresponds to a propagation pathlength of $\Lambda = AE^{-0.6} + \Lambda_o$ *with* $\Lambda_o = 0$ *(lower curve) and* $\Lambda_o = 0.5\ g/cm^2$ *(upper curve), respectively.*

The situation is different for particles with larger charge number Z: The TR intensity scales with Z^2, and consequently the relative magnitude of fluctuations decreases as 1/Z. This important fact permits the use of TRD's to measure the energy of the heavier and multiply charged cosmic-ray nuclei. It has been shown that even for lithium-nuclei (Z = 3), an energy measurement becomes possible and, of course, that for iron (Z = 26), the fluctuations are negligible as compared to other systematic uncertainties. The first TRD system designed for such measurements has been flown on Spacelab-2 in 1985 and has led to a measurement of the elemental composition of the heavier primary cosmic-ray nuclei up to energies around 10^{12} TeV/nucleon [3]. The upper energy limit is due to counting statistics from the limited exposure factor of that experiment. In the present paper, we shall discuss an approach to substantially extend the range of these measurements, even if only balloons are available as carriers above the atmosphere.

2. SCIENTIFIC GOALS

Detailed studies of the elemental composition of cosmic rays are essential for the understanding of the origin of these particles and of the processes governing their propagation through the galaxy. It is now generally believed that first-order Fermi acceleration in supernova-driven shocks in interstellar space may account for the generation of the bulk of the cosmic-ray flux. However, it is also believed that this acceleration mechanism becomes inefficient at energies above ~ $Z \cdot 10^{14}$eV (where Z is the elemental charge of the nucleus) [4]. Consequently, the origin of particles at still higher energy remains essentially unknown. A conspicuous steepening (the "knee") in the all-particle energy spectrum above 10^{15}eV may well indicate a qualitative change in the particle population at these energies. It is important to seek evidence for such changes in the cosmic-ray composition, but precise composition measurements do not extend much beyond ~ 10^{13} eV.

To infer information about cosmic-ray sources, the measured data must be corrected for changes during the propagation of cosmic rays through the interstellar medium. When this is done, one concludes that the composition of the cosmic ray source is independent of energy, and that the relative elemental abundances are similar to the "universal" abundance scale, albeit depleted for elements with high first ionization potential. The propagation correction is model-dependent, but all reasonable propagation models lead to the conclusion that the energy spectrum generated at the source decreases much less steeply with energy ($\propto E^{-2.15}$) than that of the ambient particle flux ($\propto E^{-2.75}$) [5]. The experimental evidence for this behavior is the observed decrease with energy in the production of secondary cosmic rays by interstellar spallation which, in turn, indicates a propagation pathlength Λ depending on energy as Λ (E) $\propto E^{-0.6}$.

While this brief summary might indicate that a fair amount of information is available about the generation and propagation of cosmic rays in the galaxy, we must re-emphasize that all detailed information is restricted to energies below about 10^{13} eV per particle. To illustrate this, we show in figure 1 a compilation of data of the energy spectra of protons and helium, and of groups of heavier elements, and in figure 2 measurements of the relative abundance of the secondary element boron (the B/C ratio). There may be an indication of change in the spectral slopes at the highest energies, but the observational uncertainties preclude any definitive statement. Similarly, the propagation pathlength Λ(E) (which follows the B/C ratio at high energies) is unknown above ~ 10^{12} eV per particle. Thus, as the energy range approaches the region of the "knee", and the region where changes in the particle composition may be expected due to the limitations of the shock acceleration process, no data of any precision exist. Conversely, if new measurements in this region became available, significant constraints on present cosmic ray models would be obtained.

3. DESIGN CRITERIA FOR NEW MEASUREMENTS

The steeply falling energy spectrum of cosmic-rays mandates that any new measurement attempting to reach higher energies cannot be succesful unless the detector exhibits very large collection area and is exposed to the cosmic-ray flux for a sufficiently long period of time. At the highest energies, this requirement can only be fulfilled with ground based air shower detectors which however, are severely limited in their capability of determining the identity of the primary particle.

Thus, the foremost experimental challenge is to devise instrumentation that can be carried above the atmosphere for direct measurements and whose energy range overlaps the range of air shower detectors as far as possible. At the same time, of course, the detector must be limited in weight, size, power and consumables, commensurate with the limitations of balloons or spacecraft. In order to reach energies around 10^{15} eV per particle, a statistically meaningful measurement requires exposure factors of the order of 100-1000 m^2sr days (geometric factor × time) for the major primary cosmic ray nuclei and significantly more for less abundant components, such as the important secondary species Li, Be and B. Thus if the detector is flown on balloons for an accumulated duration of ~ 10 days, geometric factors of the order 10-100 m^2sr are needed, while for a year long satellite flight a smaller instruments might suffice. However, spallation production in the residual atmosphere at balloon altitude leads to limitations in the measurements of rare secondary cosmic-ray components. Space flight is especially important for such observations but then again, very large area instruments are needed.

The detector must determine two quantities for each cosmic ray particle, the nuclear charge, Z, and the energy, E. Charge measurement can be accomplished through measurement of the specific ionization in scintillators or gas counters, or through measurement of Cherenkov light. In both cases, the signal scales as Z^2, and the techniques are relatively well established. Measurements of the energy represent a greater challenge. A serious problem is the fact that accelerator beams of nuclei with sufficiently high energy do not exist. Therefore, the calibration of conventional detectors that require a nuclear interaction of the particle (such as calorimeters and air shower detectors) is subject to uncertainties as it must depend on extrapolations from lower energies and on Monte Carlo simulations. In particular, fluctuations in the detector response

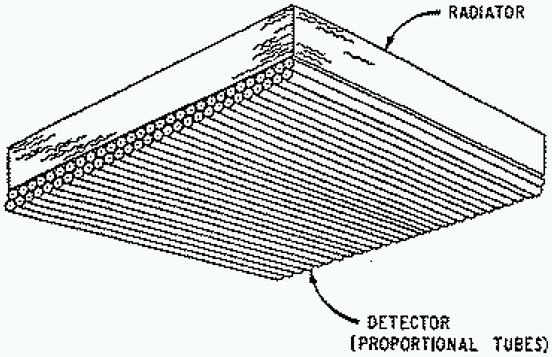

Figure 3. View of a TRD radiator/detector combination that uses single wire proportional tubes for x-ray detection.

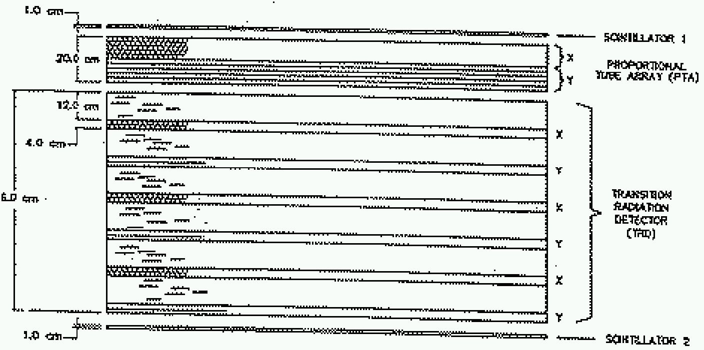

Figure 4. Cross-section of a detector consisting of scintillators, proportional tube array, and 6-layer transistion radiation detector. Tubes are laid out in two orthogonal directions (x and y directions). Height and width are drawn with different scales.

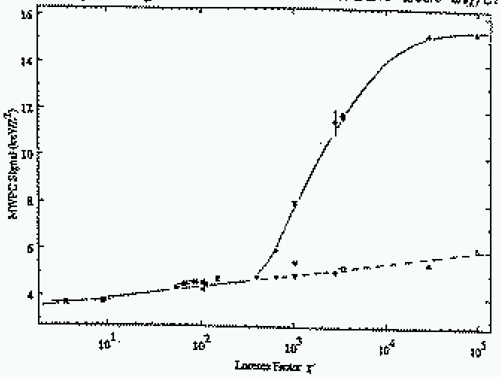

Figure 5. TRD signal as a funcion of Lorentz factor γ. Upper curve: TRD response, lower curve (dashed): ionization signal only, without TR. Data from Fermilab calibration.

may be difficult to predict, but knowledge of those is essential for the correct determination of the shape of the energy spectra.

In these areas, transition radiation detectors offer a distinct advantage. The TR effect is purely electromagnetic and, as mentioned, depends on the Lorentz factor γ. Therefore, the TR intensity scales strictly with Z^2 [6], and further, accelerator beams of electrons and pions in the appropriate Lorentz factor range are readily available for calibrations. Thus, TRD's maybe fully calibrated, both with respect to their γ-dependence, and with respect to fluctuations in response. Their limitations comes from the fact that they are difficult to use for low-Z particles such as protons and He - nuclei, and that their signal saturates for high γ. Another important advantage of TR devices is the fact that they are very light in weight, so that detectors of very large area can readily be constructed. As we shall show, instruments with geometric factors of 10 - 100 m^2sr are quite feasible.

4. THE "TRACER" CONCEPT

Based on these considerations, we have devised the concept of an instrument which we call TRACER ("Transition Radiation Array for Cosmic Energetic Radiation") and whose design we shall describe below. This concept builds on experiences gained with the CRN detector flown on Spacelab-2 [2], but incorporates several features that permit reaching a much larger geometric factor. A major limitation of CRN was the fact that this instrument, as is typical for almost all cosmic ray detectors flown previously above the atmosphere, was enclosed in a gas-tight pressurized container ("gondola") to permit operation in an environment at atmospheric pressure. Clearly, weight and cost of such a container become prohibitive if one wants to accommodate a detector with very large area. Thus, the first requirement for TRACER is that it be operated in the ambient environment at balloon or spacecraft altitude. We choose TRD for energy measurements, but we cannot use thin-walled, parallel cathode MWPC's which were successfully employed for TR - detection in CRN. A ready solution is the replacement of the MWPC's with arrays of thin-walled single wire proportional tubes as shown schematically in figure 3. Such tubes, spiral-wound from aluminized mylar, are easy and inexpensive to manufacture, may have typical diameters of ~ 2 cm and considerable length (up to ~ 5 m), become rather rigid at internal over-pressures and, most importantly, can easily withstand overpressures of several atmospheres. Issues of concern are the pathlength variations of cosmic-ray particles through the tubes, and the sizeable number of electronics channels needed for individual signal readout.

In addition to TRD's, the CRN instrument employed gas Cherenkov counters for energy measurements in the range around $\gamma \approx 100$, below the onset of TR, and in order to reduce the abundant low energy background for the TR measurement by requiring saturated Cherenkov signals for valid TR - events. Such Cherenkov counters become more and more difficult to construct as the desired area of the instrument increases and, again, cannot easily be operated in external vacuum. For TRACER, their function will be assumed by an array of gas filled proportional tubes where the relativistic rise in the ionization signal will be utilized for an estimate of γ below the TR region. More detail about this important aspect will be given below.

Figure 4 shows the schematic cross section of the TRACER instrument. Its main components are (1) two large square scintillator sheets on top and bottom, to be used as instrument trigger and for charge determination; (2) a proportional tube array (PTA) of 10 layers to determine the charge and to estimate the energy from the relativistic rise in the specific ionization, and (3) a transition radiation detector for energy measurements at high energy ($\gamma > 500$), consisting of 6 pairs of radiator/detector combinations with each detector being composed of a double layer of proportional tubes. The radiators are battings of polyethylene fibers, each about 12 cm thick.

The overall dimensions of the detector can be chosen almost at will but are constrained by the permissible overall weight.

5. SOME TECHNICAL DETAILS

5.1. Charge Measurement: TRACER uses two devices to determine the charge Z of cosmic ray nuclei, plastic scintillators and proportional tubes. For relativistic particles, the scintillator signals scale with Z^2 (the relation is not quite linear at larger Z values due to the density effect). With appropriate optimization of the placement and readout of photomultiplier tubes, and with the application of corrections for the inclination of the particle trajectory and for spatial non-uniformities over the scintillator area, a charge resolution $\delta/\delta Z \approx 0.25$ charge units can be achieved. Instead of scintillators, plastic Cherenkov counters may also be used and would be advantageous if TRACER is flown in regions with low geomagnetic cut-off rigidity.

The ionization signals in the PTA also scale with Z^2 but exhibit a "logarithmic rise", an increase of about 50% from minimum ionizing to highly relativistic particles. For a given energy, and with knowledge of the pathlength of the particles through the PTA (see below), the charge resolution will again be about $\delta Z \approx 0.25$ charge units. The relativistic rise in the PTA signal is important as it permits the rejection of low energy background for the TRD analysis: candidate TR events ($\gamma \geq 500$) will only be accepted if the PTA signal also indicates highly relativistic energy. This greatly reduces the possibility that a low energy particle masquerades as a TR event due to statistical fluctuation in the TRD response. On the other hand, the relativistic rise also compromises the uniqueness in the charge determination with the PTA alone; this ambiguity is resolved with the signals of the scintillation counters.

5.2. Energy Measurement: The energy measurement for large γ is provided with the TRD system. A typical response curve for the TRD, obtained with accelerator measurements at Fermilab, is shown in figure 5. The figure shows that at low energies, the signal is just due to ionization loss of the particle in the detector, but that at $\gamma = 400$ a rapid increase due to TR photons sets in until saturation is reached around $\gamma \approx 40{,}000$. Thus, the maximum energy that can be measured is $E \approx 6 \times 10^{14}$ eV for oxygen, and $E \approx 2 \times 10^{15}$ eV for iron.

We have studied the response and energy resolution of the detector in figure 4 in a complete Monte Carlo simulation. The simulation assumes an isotropic flux of cosmic-ray nuclei, and includes a reconstruction of the particle trajectories as described below. The simulation shows that the energy resolution of the TRD depends both on Z and on E. For instance, for carbon and iron at $\gamma = 3000$, we obtain $\delta\gamma/\gamma\ (1\sigma) = 15\%$ and 7%, respectively. An important feature of the TRD system is the redundancy which is achieved through the use of six independent measurements which also permits the determination of intrinsic fluctuations of the detector with data obtained in flight.

5.3. Trajectory and Pathlength Determination: For the correct interpretation of the measurements, the trajectory through the instrument must be well known in order to determine the pathlength through individual tubes. We therefore have developed a tracking algorithm which uses the fact that, within fluctuations, tube signals are proportional to the pathlength within each tube. We have tested the algorithm with a Monte Carlo technique that generates events for the detector shown in figure 4, assuming an isotropic flux of cosmic ray particles and taking realistic levels of signal fluctuations into account. We find that the reconstructed trajectories reproduce the incoming track with an accuracy in the x - and y - direction of 0.4 mm for carbon, and 0.3 mm for iron (1σ). This excellent reconstruction permits us to normalize the total ionization and TR signals to the total pathlength traversed in the tubes, and, consequently, to achieve the resolution in charge and energy quoted above. Figures 6 and 7 show examples of signal distributions obtained in these simulations.

Figure 6

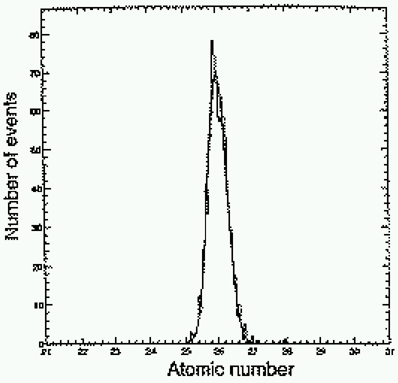

Figure 7

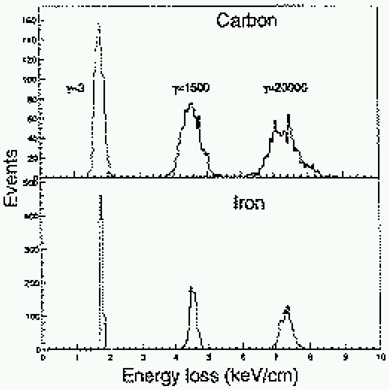

Figure 6. Reconstructed charge, Z, for iron nuclei traversing isotropically 12 layers of 2 cm thick proportional tubes. (Result of a Monte Carlo simulation).

Figure 7. Expected signal distributions for carbon and iron nuclei of different Lorentz factors traversing isotropically a 6-layer TRD system. (Result of a Monte Carlo simulation).

5.4. Some Technical Issues: The detector shown in figure 4 can be implemented, for instance, with an area of 4m × 4m, and a total height of ~ 1.2 m. This would yield a large geometric factor of ~ 28 m^2sr, and yet a manageable total weight of about 1,500 kg. The mechanical design of the proportional tubes for PTA and TRD will be identical. The scintillators require a fairly large number of photomultiplier tubes (~ 50 - 100). The number of proportional tubes is very large (~ 4400), each tube being 4m long. Thus, we presently develop techniques that permit an easy but reliable mass production of tubes. As each tube must have its individual signal readout, a large number of electronics channels is necessary, calling for use of VLSI electronics in order to keep cost and power requirements manageable. An instrument of this type can easily be flown on conventional balloons, or on long duration flights with supperpressure balloons once this capability becomes available. It also could be carried in space, for instance on the space station or a co-orbiting platform. The modular nature of the TRACER concept would permit on-orbit assembly.

6. CONCLUSIONS

The TRACER concept offers an attractive possibility for measurements of the individual energy spectra of cosmic ray nuclei, up to energies close to 10^{15} eV per particle. It permits the construction of detectors of very large area, hence good collection efficiency for rare particles. Its major limitation is the fact that it is not designed to detect the lightest nuclei, protons and α-particles. For these, calorimetric techniques seem to remain the only method to determine the energy spectra.

To illustrate the performance of the TRACER configuration described above, we show in figure 8 simulated results for the nuclei boron to oxygen, for a flight duration of 2 days. The simulation uses realistic assumptions about detector response and fluctuations, and about the expected particle spectra and composition. It demonstrates the well extended and resolved "tails" of high energy particles with large TRD signals. The energy scale is indicated by the lines in the figure.

If this detector were flown in space, it would yield an unprecedented exposure factor of ~ 10,000 m^2sr days. Such a flight would lead to major progress in the understanding of propagation of cosmic rays in the galaxy. This is illustrated in figure 9 where we show expected results on the relative abundance of spallation produced Boron nuclei. The question whether the cosmic ray propagation pathlength continues to decrease $\propto E^{-0.6}$ ($\Lambda_0 = 0$), or whether it reaches a constant asymptotic level (e.g. $\Lambda_0 = 0.5$ g/cm^2) is one of the key questions in cosmic ray astrophysics. Figure 9 shows that this question would be answered by a space flight of TRACER.

Figure 8

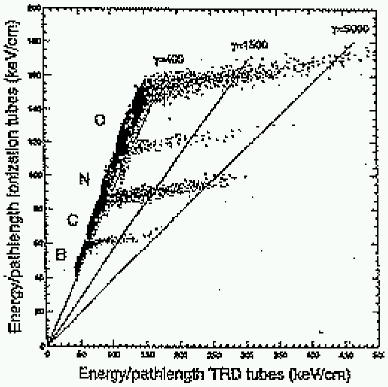

Figure 9

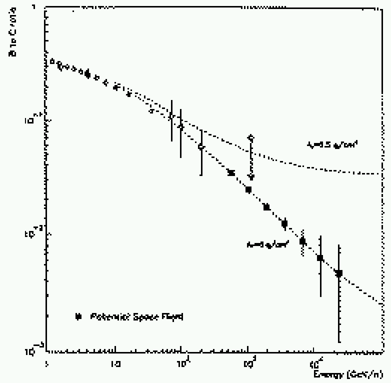

Figure 8. Cross correlation of PTA vs TRD signals for some elements from a Monte Carlo simulation. (for computational reasons, the flux of particles with $\gamma < 100$ is suppressed by a factor of 100).

Figure 9. Potential measurements of the B/C ratio from a one year space flight.

7. ACKNOWLEDGMENTS

This work has been supported through NASA grant NAGW-1982

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