OG 4.1.17

An Application of the Direct Coulomb Electron Pair Production Process to the Energy Measurement of the "VH-Group" in the "Knee" Region of the "All-Particle" Energy Spectrum

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Abstract

The "all-particle" cosmic ray energy spectrum appears to be exhibiting a significant change in the spectral index just above ~ 3000 TeV. This could indicate (1) a change in the propagation of the cosmic rays in the galactic medium, and/or (2) the upper limit of the supernova shock wave acceleration mechanism, and/or (3) a new source of high-energy cosmic rays. Air shower and JACEE data indicate the spectral change is associated with a composition change to a heavier element mixture whereas DICE does not indicate this. A detector concept will be presented that utilizes the energy dependence of the production of direct Coulomb electron-positron pairs by energetic heavy ions. Monte Carlo simulations of a direct electron pair detector consisting of Pb target foils interleaved with planes of 1-mm square scintillating optical fibers will be discussed. The goal is to design a large area, non-saturating instrument to measure the energy spectrum of the individual cosmic ray elements in the "VH-group" for energies greater than 10 TeV/nucleon.

1 Introduction:

1.1 Science Objectives: The "knee" or transition region of the "all-particle" cosmic ray energy spectrum is of interest for several reasons. The "all-particle" cosmic ray energy spectrum appears to steepen above ~ 3000 TeV. The supernova shock acceleration mechanism is expected to have an upper limit $\approx Z*100$ TeV where Z is the cosmic ray charge (Lagage and Cesarsky, 1983). Based on this model the cosmic ray composition should transform to a heavier element mixture as the energy approaches the "knee" region. However, the first results from the Dual Imaging Cerenkov Experiment (DICE- a ground based air shower experiment) shows no evidence for an increase in the average mass of the cosmic rays in the "knee" region (Boothby et al.,1997). The original Lagage and Cesarsky model can be extended to higher energies by various means as outlined by (Cherry and Wefel for the JACEE Collaboration,1998). The change in the spectral index could also indicate a change in the propagation of cosmic rays in the galactic medium or a change in the acceleration mechanism at the source or a new source of high-energy cosmic rays or, perhaps, there is a deviation from the standard model describing the hadronic interactions in this high energy region. Measuring the cosmic ray elemental composition directly to as high an energy as possible will permit a comparison to the overlapping indirect measurements of the large, ground based air-shower arrays.

2 The Fundamental Cosmic Ray Energy Measurement Technique:

The electromagnetic phenomenon proposed to measure the energy of the cosmic rays is based on the creation of electron-positron pairs from the virtual photon field of a relativistic ion while encountering the field of a stationary nucleus. The direct electron pair production cross-section, described by the perturbative two-photon Feynman diagrams, including the exchange term, can be evaluated by the Monte Carlo integration method (Wu et al.,1992, Bottcher and Strayer,1989). This approach has the advantage of extracting the pair momentum and emission angle distributions of the pairs while simultaneously calculating the total cross-section for pair production. The theory predicts that the direct electron pair yield does not saturate at high Lorentz factors so that it is possible to apply this electromagnetic process to the energy measurement of the heavy cosmic rays above 10 TeV/nucleon.

2.1 Monte Carlo Simulation of a Candidate Direct Electron Pair Detector: A Monte Carlo simulation of one concept for a direct electron pair detector is illustrated in Figure 1. The case treated in Figure 1 is a normally incident Fe nucleus at an energy of 100 TeV/nucleon.

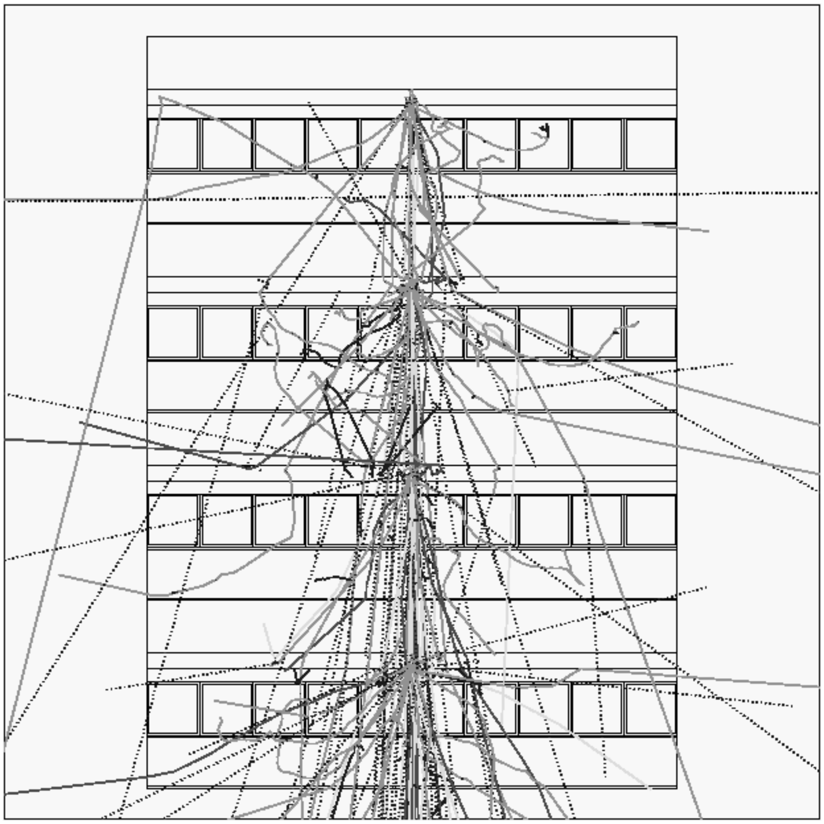


Figure 1: A concept for a direct electron pair detector consisting of thin Pb target foils (300 μm) interleaved with *x*,*y* planes of 1.0 mm square plastic scintillating optical fibers and low mass density spacers to influence the spatial dispersion of the tracks.

The solid tracks include the direct electron pairs, the knock-on electrons, and the secondary delta rays. The direct electron pairs were generated with no cutoff energy while only the knock-on electrons with energies > 1.0 MeV were followed. The dotted tracks are the secondary photons. The CERN/GEANT (V3.21) computer program was used to trace the particles through the detector geometry. The cutoff energy for tracing all the particles was set to 10 keV resulting in a good estimate for the energy deposition in the fibers. The first three simulation cases treated were normally incident Fe nuclei for the energies 1,10, and 100 TeV/nucleon. When the Fe nuclei ≥ 10 TeV/nucleon had penetrated roughly 2.0 radiation lengths of the Pb target, the simulations showed that the electromagnetic cascade produced by the direct electron pairs dominated the one due to the background knock-on electrons. This can be qualitatively understood by comparing the physical properties of the direct pairs with the knock-on electrons (Derrickson,1995).For an energy ≥ 10 TeV/nucleon, the direct electron pair member angular distribution is sharply peaked in the forward direction and the energy distribution exhibits a high energy tail. Both of these features are more pronounced as the primary cosmic ray energy increases. This contrasts with the physical properties of the knock-on electrons where mostly lower energy electrons with larger emission angles are produced for the same primary cosmic ray energy. Presented in Table 1 are the average numbers of direct pairs and knock-on electrons produced in 300 μm of Pb for the three simulation cases. Even though the knock-on electron flux exceeds the direct electron pair member value, the direct pair induced electromagnetic cascade is dominant for energies above 10 TeV/nucleon.

Table 1: THE <NUMBER> OF DIRECT PAIRS AND KNOCK-ONS PRODUCED BY AN Fe NUCLEUS IN A 300 μm Pb FOIL

PRIMARY ENERGY OF Fe	<DIRECT PAIR MEMBERS>	<KNOCK-ON ELECTRONS>†
1 TeV/nucleon	**4.7**	**13.8**
10 TeV/nucleon	**5.6**	
100 TeV/nucleon	**9.6**	

† $\beta \sim 1.0$ **FOR ALL 3 SIMULATION CASES**

3 Laboratory Studies for a Pair Detector:

In conjunction with the Monte Carlo simulations of a direct electron pair detector, a high gain photon imaging system (GEN I demagnifying electrostatic image intensifier/GEN II image intensifier/CCD camera) is being tested for its capability to detect minimum ionizing particles (MIP) in large area, scintillating optical fiber arrays. The objective is to separate as much as possible the direct electron pair induced electromagnetic cascade signal from the neighboring heavy ion response. This requires a highly segmented detector which means using smaller fibers (e.g., 0.5 mm) and yet still be capable of detecting ≤ 1.0 MIP. The gain of this imaging system will be adjusted so that the useful dynamic range will cover ≤ 1.0 MIP to several hundred MIP. This will take into account the attenuation in the fibers over several meters and the fluctuations in the light output.

A complementary lower gain imaging system consisting of linear multi-anode photomultiplier tubes will be optically coupled to the opposite end of the fibers. The gain will be adjusted so that the dynamic range covers the charge interval silicon to nickel. Normally incident silicon deposits roughly 250 MIP in a 1.0 mm fiber.

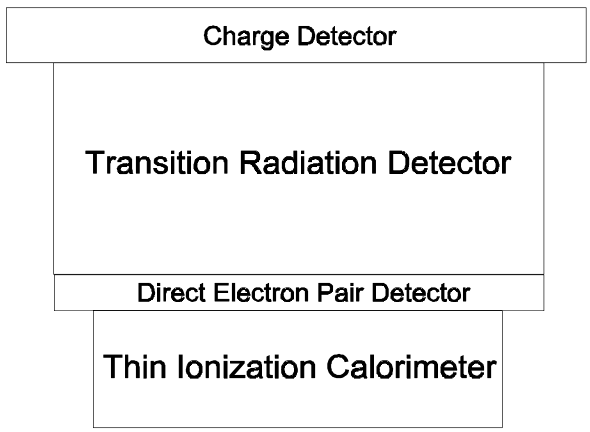
As part of the detector development, the frequency of occurrence of peripheral nuclear fragmentation events will be estimated and their physical characteristics studied in order to develop methods to discriminate against them.

4 Future Applications:

The ultimate goal is to design an instrument possessing a large collection factor, elemental charge resolution, and good energy resolution (≈ 30 %) in order to measure the energy spectra of the heavy cosmic rays, specifically the “VH-group” in the “knee” region of the “all-particle” energy spectrum. Since the direct electron pair method can not be verified at an accelerator, either long duration balloon flights or space flight experiments are options. A balloon instrument with a geometry factor of 16.2 $m^2 \bullet sr$ (i.e.,2.5 m x 2.5 m x 0.25 m) exposed at an altitude of 5 g/cm^2 for 100 days will collect ≈ 60 Fe events above 10 TeV/nucleon. This integral Fe flux estimate assumes a differential power law spectrum of $E^{-2.6}$ and is based on the measurements of Simon et al.,1980.

Currently the transition radiation method and "ionization" calorimetry are the only visible techniques for the direct cosmic ray composition energy measurements in the "knee" region. Figure 2 shows a detector concept that includes a direct electron pair detector along with a transition radiation detector (TRD) and a thin "ionization" calorimeter. One option might be the removal of the low Z target in the thin "ionization" calorimeter thereby extending the direct electron pair detector depth in Pb to cover a larger cosmic ray charge range. This configuration would have the added benefit of cross calibrating the direct electron pair method with both the transition radiation method, especially in the energy region where the TRD output begins to saturate (≈ 20 TeV/nucleon, Müller et al.,1997), and the "ionization" calorimetry method that depends on the hadronic interaction for the energy measurement.

A Cosmic Ray Detector Concept Utilizing the Direct Electron Pair Method



Goals : (1) Measure the energy spectra of the cosmic ray elements Si,S,Sub-Fe, and Fe
(2) Cross calibration with the transition radiation measurements
(3) Cross calibration with the ionization calorimeter measurements

Figure 2: An instrument that incorporates a direct electron pair detector for an ultra long duration balloon flight.

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