A NEW MEASUREMENT OF THE COSMIC RAY ELECTRON SPECTRUM FROM 10 GeV TO 300 GeV

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We have measured the spectrum of cosmic ray electrons with a new instrument that combines a transition radiation detector with a shower detector. The transition radiation detector provides unique identification of individual electrons and good discrimination against protons. At the same time, it allows the construction of a large area instrument (0.48 m^2 ster) and consequently makes possible a measurement of improved statistical accuracy. The instrument has been calibrated with electron beams of 5-300 GeV at Fermilab, thus eliminating energy dependent biases. A first balloon flight yielded 30 hours of data at an altitude of 5 g/cm^2. We shall describe the design of the instrument, the accelerator calibrations, and the analysis of the balloon flight data. The spectrum of electrons is found to be significantly steeper than that of protons over the whole energy range.

1. Introduction. The shape of the spectrum of high energy cosmic ray electrons has remained controversial for many years. The important question is the existence of a possible steepening of the spectrum which may occur as a result of radiative energy losses of electrons in the interstellar magnetic and photon fields. Such a steepening would provide significant information about the propagation and lifetime of cosmic rays in the galaxy. Most of the electron data until the early 1970's (including, for instance, the measurements of Anand et al. (1973) and the previous results of Müller and Meyer (1973)) supported an electron spectrum that has the same slope as the proton spectrum (differential spectral index $\alpha \approx 2.7$). Some of the more recent results are consistent with steeper spectra: Silverberg (1976) and Matsuo et al. (1975) have reported $\alpha \approx 3.1$-3.2, and Meegan and Earl (1975) found a spectral index $\alpha \approx 3.4$. Significant discrepancies exist not only with respect to the slope of the spectra but also with respect to the absolute electron fluxes. This situation is undoubtedly caused by experimental difficulties, most importantly the following:

(1) In the shower detectors used in previous measurements, interacting protons may masquerade as electron showers, leading to a substantial background that is difficult to correct for. With shower detectors, individual electrons cannot be identified, unless the interaction is made visible in a nuclear emulsion.

(2) Until recently, detectors could be calibrated at accelerators only up to electron energies of 20 GeV. The energy response and shower characteristics had to be empirically extrapolated to higher energies.

(3) The small flux and limited detector size made large statistical errors unavoidable.

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To overcome these difficulties, we have constructed a new detector of very large area (geometric factor 0.48 m^2 ster), that is able, with the aid of transition radiation detectors, to identify individual electrons, and that also has been calibrated at Fermilab with electron-beams covering the energy range 5 to 300 GeV. This instrument has been exposed in a first balloon flight in October 1975, for 30 hours at 5 g/cm^2 of residual atmosphere above Palestine, Texas. In the following, we shall present preliminary results from this experiment.

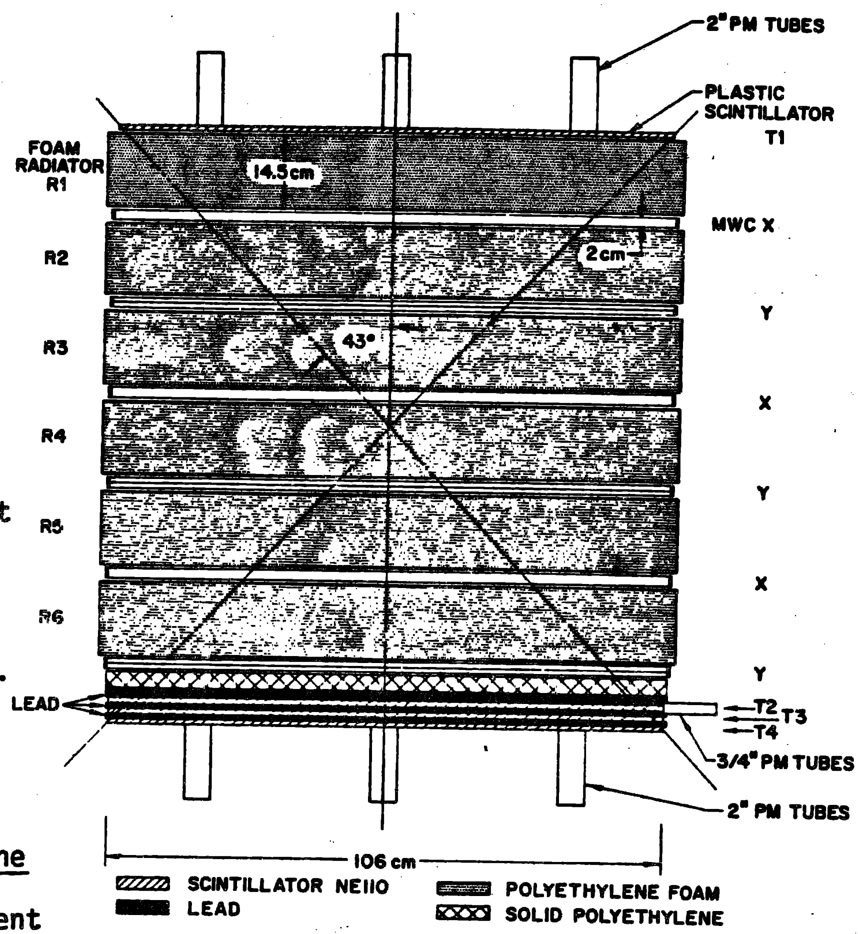

Figure 1
Schematic cross section of the instrument

2. Description of the Instrument. A cross section of the instrument is shown in Figure 1. The main components are:

(1) A scintillator telescope consisting of plastic scintillators T1, T2, T3, and T4.

(2) A transition radiation detector of 6 plastic foam radiators, each followed by a multiwire proportional chamber.

(3) A shallow shower detector that is formed by lead plates above scintillators T2, T3, and T4.

All counter elements are pulse height analyzed. A time of flight measurement between T1 and T4 identifies those particles that traverse the detector in the downward direction. The wire directions of consecutive proportional chambers are orthogonal to each other, and groups of 5 adjacent wires are connected to a common amplifier. All wire groups are individually pulse height analyzed, and therefore trajectory and pulse height information is measured (with a spatial resolution of 5 cm) for each particle traversing the instrument.

The shower counter employs a total of 8 radiation lengths of lead (the shower is sampled after 4, 6 and 8 r.l.). The photomultiplier tubes were individually calibrated with a nanosecond light source in order to insure linear response beyond the largest expected shower signals.

In order to accept a particle as an electron, the following criteria have to be met:

(1) A particle, identified as singly charged by the pulse height in T1, must traverse the detector in the downward direction. The trajectory of the particle must be uniquely defined from the signals of the multiwire chambers.

(2) The pulse heights in the shower counter (T2, T3, T4) must be consistent with the profile of an electromagnetic cascade. The shower signals also measure the electron energy.

(3) X-ray transition radiation must be detected in the transition radiation detector. Only particles with Lorentz factors $\gamma = E/mc^2 \gtrsim 10^4$ will produce transition radiation in saturation. Therefore, the transition radiation detector acts as an efficient discriminator between protons and electrons, and can positively identify those interacting protons that lead to shower signals that might otherwise be indistinguishable from electron showers.

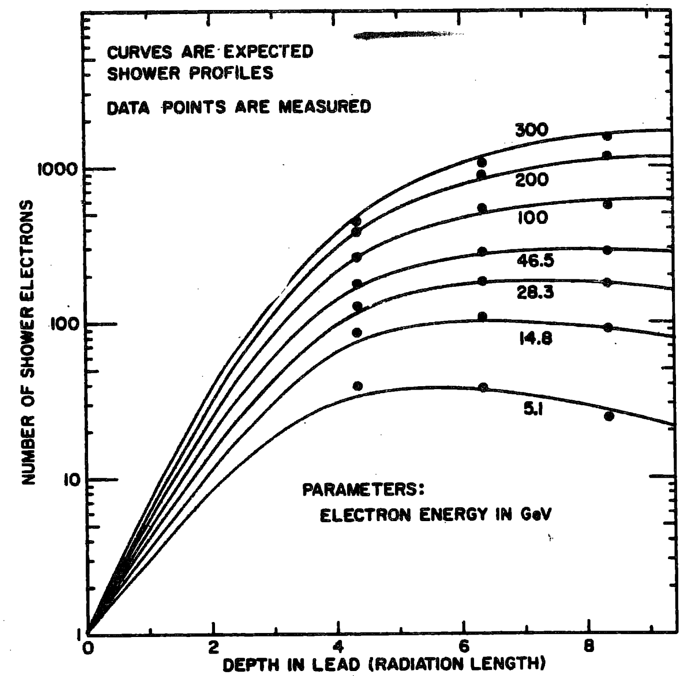

Figure 2

Comparison of measured and expected shower signals

The major new element of this instrument is the transition radiation detector. Its design is based on results of extensive accelerator studies of transition radiation (Cherry et al. 1974b and Prince et al. 1975). We have learned in these studies that polyethylene foam (Dow "Ethafoam") can be used as a particularly simple but efficient radiator material, and that the combination chosen in this experiment, 15 cm thick radiators with 2 cm thick xenon-filled proportional chambers with rather thin windows, yields an optimum x-ray signal under the geometric constraints of a balloon borne instrument. We shall discuss at this conference some further details of such detectors in the paper by Cherry et al. (1977).

3. Accelerator Calibrations. Realizing the crucial importance of accelerator calibrations of any new cosmic ray detector, we have exposed our instrument at Fermilab to beams of electrons, pions, and protons covering the entire energy range from 5 to 300 GeV. These calibrations yield the following information:

(1) Shower signals: The average shower signals observed in the shower counters T2, T3, and T4 were measured as a function of the electron energy. It is not possible to analytically calculate these signals (i.e. the number of secondary electrons) with the required accuracy. However, we were pleased to observe that our measured shower signals are well represented by the results of an earlier extrapolation (Müller 1972) that was based on measurements below 15 GeV. This is shown in Figure 2. The "shower sum", i.e. the

sum of the pulse heights from T2, T3, and T4, is a monotonic function of the electron energy, the energy resolution being constant at about 30% FWHM over the whole energy range.

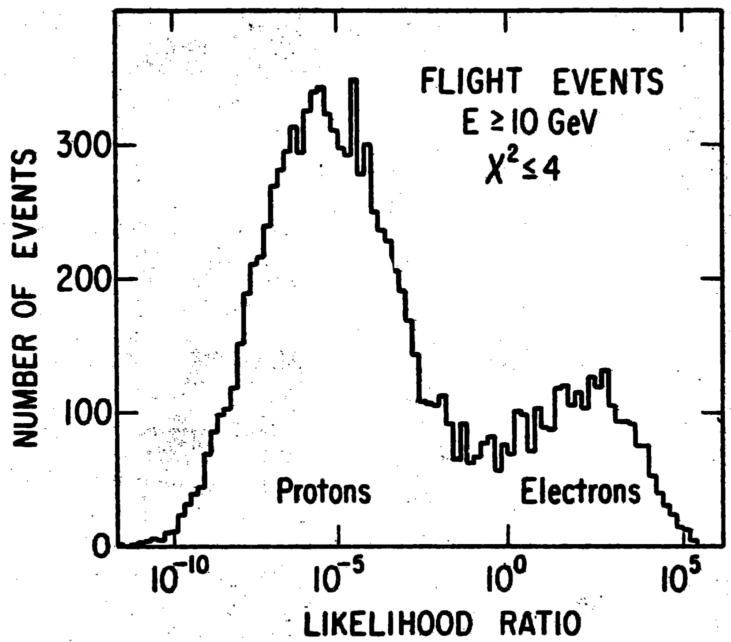

Figure 3

Likelihood ratio histogram of a sample of flight data. The likelihood ratio is a measure of the transition radiation signal. The events in this histogram are due to singly charged particles with unique trajectories which have a total shower signal greater than 10 GeV electrons and fairly good shower fits ($\chi^2 \leq 4$).

(2) Transition radiation signals: An electron, accompanied by transition radiation x-rays, yields pulse heights in the proportional chambers that are larger than the ionization signal alone by a factor of about 2. The transition radiation signal reaches saturation for electron energies above 5 GeV ($\gamma \approx 10^4$), and remains constant up to the highest electron energies covered (300 GeV, $\gamma \sim 6 \times 10^5$). Details of this behavior are discussed by Cherry et al. (1977).

(3) Backscatter: A certain fraction of electron showers leads to ambiguities in the determination of the electron trajectory due to additional tracks that are most likely generated by particles scattered backwards from the shower detector. Knowledge of this effect is very important, since it could lead to an energy-dependent efficiency correction in the data analysis. We measured that the fraction of electrons with unique trajectories decreases slowly with increasing energy, from 55% at 10 GeV to 21% at 200 GeV.

4. Data Analysis. The analysis of the flight data has been performed along the following steps:

(1) All events are rejected that do not exhibit a unique trajectory or that do not traverse the instrument in the downward direction.

(2) All pulse height readings are normalized, using in flight calibrations due to penetrating protons, α-particles, and heavier nuclei.

(3) The response of the shower counter is analyzed. Each set of pulse heights t_i ($i = 1...3$) measured in T2, T3, and T4, is compared with expected pulse heights $n_i(E)$ which are known, together with the expected variations $\sigma_i(E)$, from the accelerator calibrations. Minimizing the parameter $\chi^2 = \frac{1}{2}\sum[(t_i - n_i(E))^2/\sigma_i(E)^2]$ determines the energy E, and the minimum value of χ^2 measures the goodness of fit. Obviously, only events with sufficiently small values of χ^2 can be due to electrons.

(4) Likelihood techniques (Cherry et al., 1974a) are used to evaluate the transition radiation signals that are measured in the six proportional chambers. The probability that a particle without transition radiation produces a pulse height x due to ionization in the i-th chamber is given by a Landau-Vavilov distribution $P_p^{(i)}(x)$. The signal of an electron, accompanied by transition radiation x-rays, follows a different distribution $P_e^{(i)}(x)$. These distributions are known from the accelerator calibrations. For each event, we measure six pulse heights $x_i (i=1...6)$ along the trajectory of the particle. We then compute the likelihood ratio $L=\prod P_e^{(i)}(x_i)/\prod P_p^{(i)}(x_i)$ as a measure of the transition radiation signal, and, therefore, as a means to identify each individual particle. L=1 indicates equal likelihood for a proton and an electron, while L>>1 is expected for an electron (with transition radiation), and L<<1 for a proton (without transition radiation).

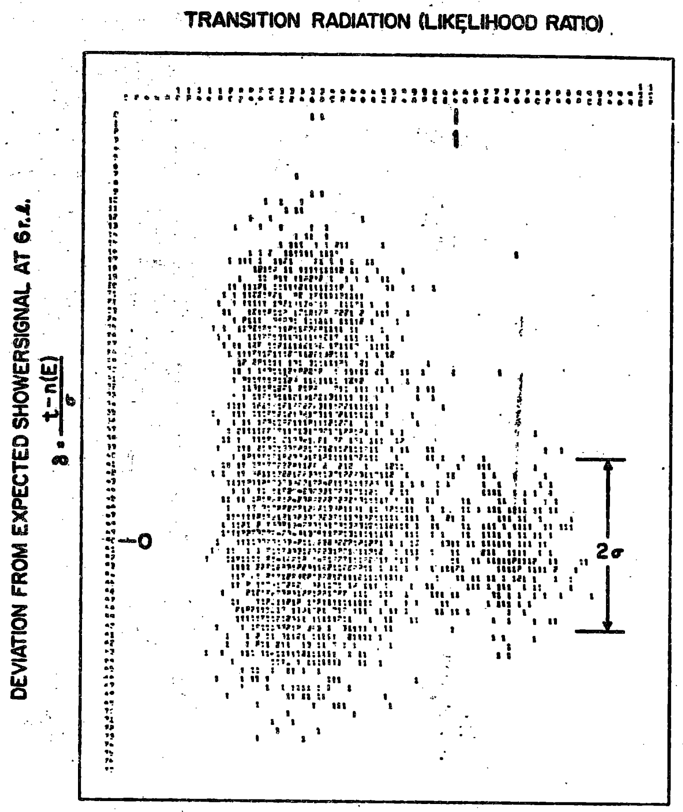

Figure 4
Correlation matrix of transition radiation signal (likelihood ratio) versus deviation from expected shower signal. Electrons should have a large likelihood ratio and a small deviation from the expected shower signal.

In Figure 3 we show some results of this analysis procedure. We have plotted a likelihood distribution of those events that exhibit fairly good shower fits ($\chi^2 \lesssim 4$). The clear separation between protons and electrons is well demonstrated. We also notice that the number of proton induced showers is larger than the number of electron showers. Without the transition radiation detector, a comparably clean identification of individual electrons is not possible. The good separation of protons and electrons is also illustrated in the scatter plot of Fig. 4. Here we correlate the linear deviation in the signals of one of the shower counters (at a depth of 6 r.l.) from the expected signal of "ideal" showers, with the transition radiation parameter L. Clearly, a subset of the events is well separated and distinguishes itself as electrons due to large L-values and small deviations from the expected shower signals.

5. Results. We have determined the differential energy spectrum of the electrons identified in this fashion, after taking all selection efficiencies properly into account. The resulting electron fluxes are corrected for the amount of residual atmosphere, and are plotted in Figure 5. Results from previous investigations are shown for comparison. We notice immediately that our spectrum is rather steep, significantly steeper than the spectrum of protons. Our result is in good agreement with the data of Meegan and Earl

(1975), and in qualitative agreement with the spectrum of Silverberg (1976). It is tempting to interpret the slope of our spectrum in the context of a steepening due to radiative energy losses. These aspects will be further discussed in the accompanying paper (Müller and Prince, 1977).

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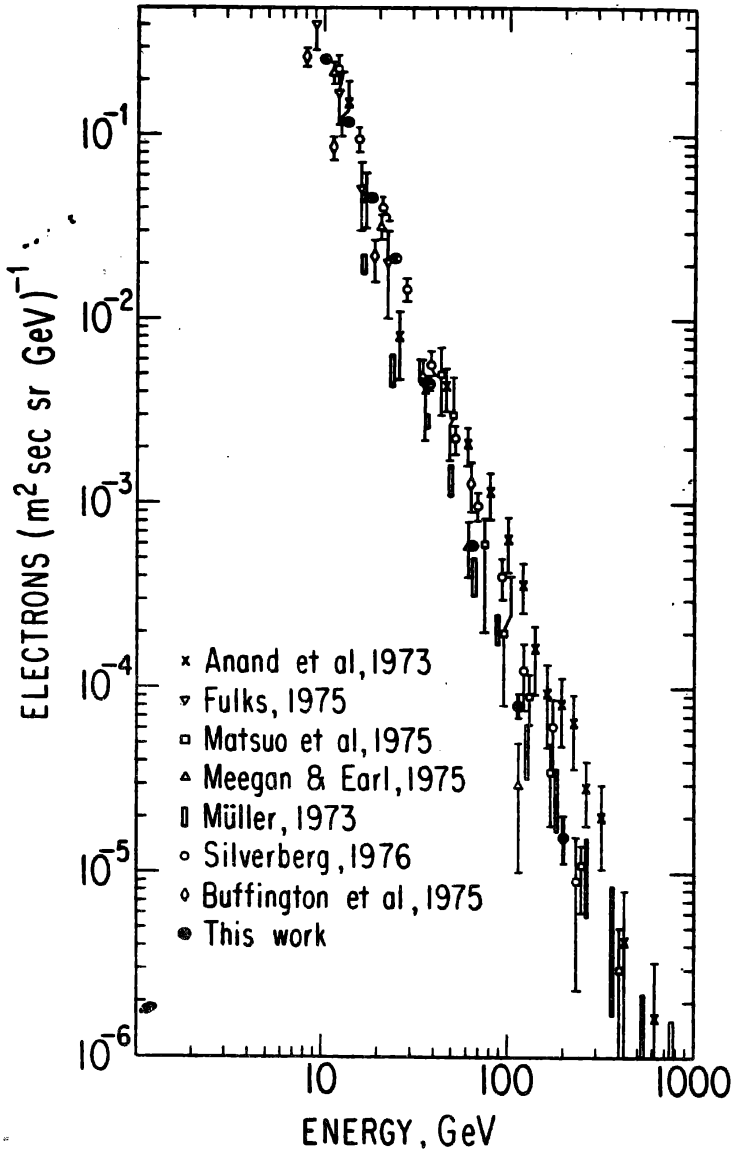

Figure 5: Differential energy spectrum of cosmic ray electrons.

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