Observation of High Energy Cosmic-Ray Electrons by Emulsion Chamber

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Abstract

A series of emulsion chamber exposures, beginning in Japan in 1968, and continuing with the participation of US group, has yielded a total exposure factor of $4\cdot 10^5$ m^2-sec-str, namely 10 times of the exposure obtained by other experiments. Using this large statistical base, the primary electron spectrum can be reliably plotted by combining data from 30 to 1000 GeV.

The electron spectrum derived by combining data from all our chambers exposed from 1968 to 1977, is well represented by

$$J = 1.7\cdot 10^{-4}(100\ \mathrm{GeV}/E)^{3.3\pm0.2}(m^2 \mathrm{sec}\cdot\mathrm{str.}\ \mathrm{GeV})^{-1},$$

in the energy range 30-1000 GeV, being essentially the same to that presented at the time of Plovdiv Conference.

The most probable life time for cosmic electrons derived from our data combining with other authors is

$$\tau_0 = 5\cdot 10^6 - 3\cdot 10^7 \text{ yrs} \quad \text{with } \delta = 0.2 - 0.7 ,$$

if one assumes the energy dependent leaky box model, but other possibilities can not completely be excluded. It is also pointed the astrophysical implications of electron spectrum in the energy range beyond 1 TeV.

1. Introduction

It has long been hoped that the studies of the primary electron spectrum would answer important questions regarding the propagation of cosmic rays and the structure of the Galaxy.

Emulsion chambers can easily be constructed with large geometric acceptance angle so that reliable statistics can be obtained even for low intensity components like the primary electrons. The identification of the event is clear by the visual inspection through microscope at the starting point of each event. The energy determination has been confirmed by calibration experiments using 50-300 GeV electron beams at Fermilab.

The experiments described here began in Japan in 1968, and they were continued on an expanded scale with the collaboration of US group after 1975.

Additional two exposures had been performed in 1977 and 1979 after the Plovdiv Conference, yielding exposures of 29 hrs 20 min and 28 hrs each at the balloon altitudes of about 4 mb. Thus our total exposures is now about $4\cdot10^5$ m^2-sec-str, which is about 10 times greater than that of other experimental groups. Table 1 lists the flights in this series, which provides data on the electron spectrum between 30 and 1000 GeV.

Table 1. Lists of Exposures

Chambers	Size (m^2)	T (min.)	Av. Alt. (mb)	SΩT (m^2-sec-str.)	Launching Place
1968	0.05	380	6.0	1826	Haranomachi, Japan
1969	0.05	267	7.0	1283	"
1970	0.05	1136	6.0	5460	Sanriku, Japan
1973	0.20	833	8.0	19335	"
1976	0.40	1526	3.9	70841	Palestine, U.S.A
1977	0.78	1760	4.4	159128	"
1979	0.80	1680	4.0	155790	"
Total				413663	

2. Experiments

2-1. Experimental Apparatus

The detector for this experiments is the emulsion chamber, consisting of a sandwitch of nuclear emulsion plates, X-ray films and lead plates. In Fig.1, a typical chamber is shown. The detectors used in the 1977 and 1979 flights had cross sectional area of 40 x 50 cm^2 and 23 film packets sandwiched between 22 lead plates. In the direction normal to the plates, the detector had 8.2 radiation lengths of lead. Each of the film packets consisted of two high-sensitive X-ray films and a Fuji ET7B nuclear emulsion plate double coated on a plastic base 800 microns in thickness.

The emulsion chambers were assembled upside down in boxes provided with carefully-machined plastic liners. Prior to pouring, the plastic emulsion base plates were machined to fit the liner within tolearances better than 25 microns.

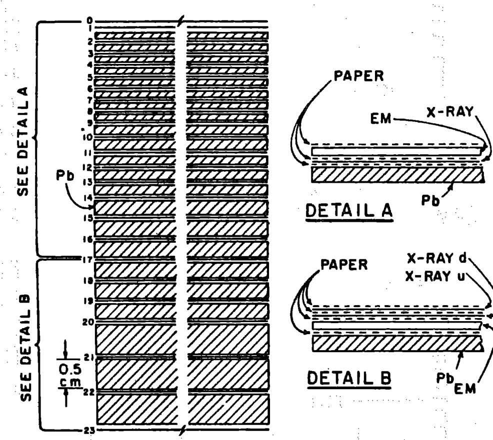

Fig. 1 Configuration of Detector

2-2. Exposures

Two additional exposures were performed after Plovdiv Conference by balloons launched from NCAR SBF at Palestine, Texas. 4 chambers are assembled in each flight. The first flight was performed on Sep.28,1977 and leveled for

29 h 20 min at an average altitude of 4.4 mb. The second flight was on May 15, 1979 at an average level altitude of 4 mb for 28 hrs.

2-3. Scanning

For the detection of electron showers above 500 GeV, scanning was performed by naked eye on the X-ray films, and the corresponding showers were found in the emulsion plates. For showers with energies below the detection threshold of the X-ray film, scanning was also performed using a microscope directly on the emulsion plates with suitable scanning criteria according to the minimum energy to be detected. Recent efforts were mostly expended to the energy region near 1 TeV as well as near 200 GeV to have better statistics in the corresponding energy region.

The detected shower events were traced back to the top emulsion layer of the chamber. The originating particles were identified by examining the detailed structure of their starting points and shower development to distinguish electron, gamma-ray and hadron events.

2-4. Energy Detemination

The experimental procedure for the energy determination of electron showers is the same to that of our preceding paper (Nishimura et al, '77,'79). Namely we count the number of shower tracks within a circle of radius of 100 microns in each layer of nuclear emulsion plate.

Six small chambers identical configuration to our chamber were exposed at Fermilab to electron beams of 50, 100 and 300 GeV energies. The data in Fig. 2 are the results from the calibration and the solid lines are the results of analytical calculations for the corresponding chamber configuration (Nishimura, '64). The results are in good agreement with the analytic theory. An individual shower, however, has large fluctuations around the average values. Number of tracks at the shower maximum is sometimes used by various authors, but it is known to be subjected by the fluctuation.

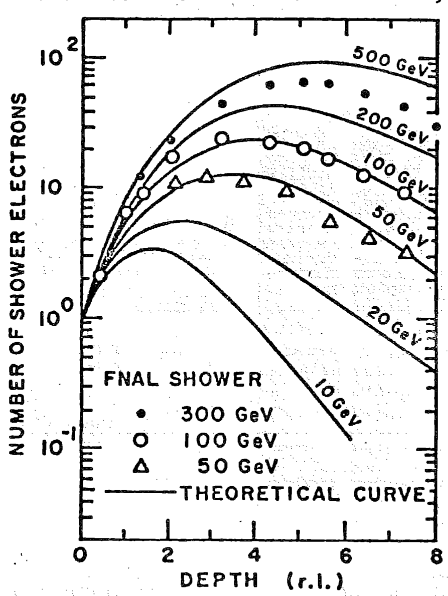

Fig. 2 Transition curve of electron shower

In order to avoid the effect of such fluctuation, the restricted track length is used in our case for the energy determination of the individual shower. Thus we calculate the track length in such a way,

$$Z_\pi = \Sigma a_i N_i ,$$

and used the relation,

$$Z_\pi = 1.20 (E_0 / \text{GeV}) ,$$

to determine the energies of primary electrons in this experiment, where N_i is the number of tracks and a_i is the weight parameter for the i th layer in the chamber.

In fact about 80 % of the showers observed in the calibration chambers are distributed within the error of 10% in the track length. Therefore we are confident that the energy estimation of electron showers in our series of experiment is quite accurate.

3. Results and Discussion

The chambers for flights in 1977 and 1979 shown in Fig. 1 have area $S = 0.2\ m^2$, and the angle of acceptance were 60°. Four such chambers were flown at once. This can be compared, to the most recent values for detectors used by other workers ranging $5\cdot10^2 - 5\cdot10^4\ m^2$-sec-str. The value of $S\Omega T$ is also given in Table 1. Such large exposure factors yield improved statistics which allow us to extend the energy spectrum of primary electrons beyond 1 TeV region. Also the improvement of the statistics beyond 200 GeV is now in progress by the microscope scanning.

3-1. Electron Spectrum

The differential electron spectrum data obtained by combining results from all emulsion chambers exposed from 1968-1977 is shown in Fig. 3 along with results from other authors. The energy value for each electron has been corrected for energy loss in overlaying atmosphere, taking into account the approximate slope of the energy spectrum. The resulting spectrum is well represented by:

$$J = 1.7\cdot10^{-4}(100\ \mathrm{GeV}/E)^{3.3\pm0.2}\quad (\mathrm{GeV\text{-}m^2\text{-}sec\text{-}str})^{-1}$$

which is essentialy the same to our results at the time of Plovdiv Conference.

3-2. Atmospheric Gamma Rays

Gamma rays by π° mesons produced in the atmosphere were also observed inside our chambers. The resutls are compared with those of theoretical expectation (Orth and Buffington,'76; Badhwar et al, '77; Murakami, '79) in Fig. 4. Fair agreement is observed as shown in Fig. 4, indicating the accuracy of our energy determination as well as the correctness of our identification of the events.

4. Discussions

The conventional plot shown in Fig. 3 obscures the substantial differences between the results of various groups, so the data is replotted in Fig. 5, with the vertical scale expanded by a factor E^3. The presence of unresolved systematic errors in some of the published data is obvious.

Since Tata (Anand et al, '73) data was obtained by nuclear emulsion detector similar to us, it has to be compared to our data. Their data gives higher flux by a factor of about 2 from the flux of our experiment.

First their energy determination depends upon a Monte Carlo simulation above 30 GeV (Anand, '73). A chamber identical to their configuration was also exposed to 300 GeV electron beam at Fermilab at the time of our calibration experiments. Counting of the shower tracks were made under the same criteria as in their paper. The results show their simulation overestimates shower energy by a factor of 1.2-1.3. Our Monte Calro results

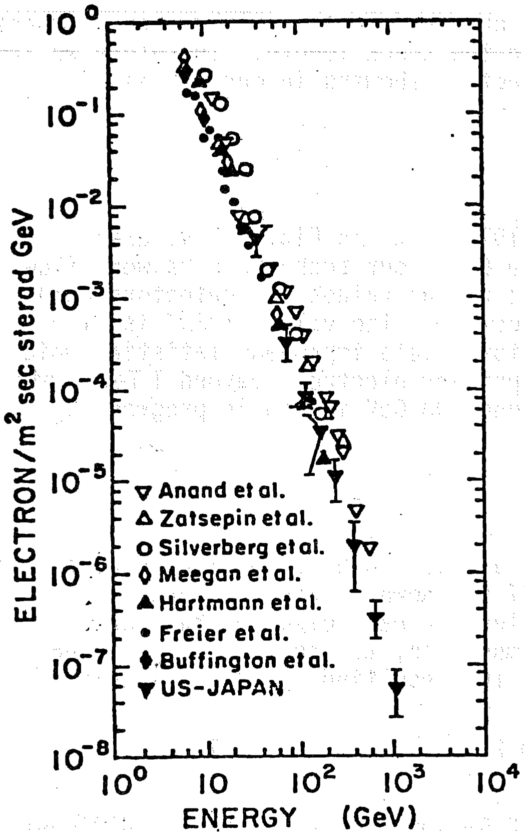

Fig. 3 Energy spectrum of electrons

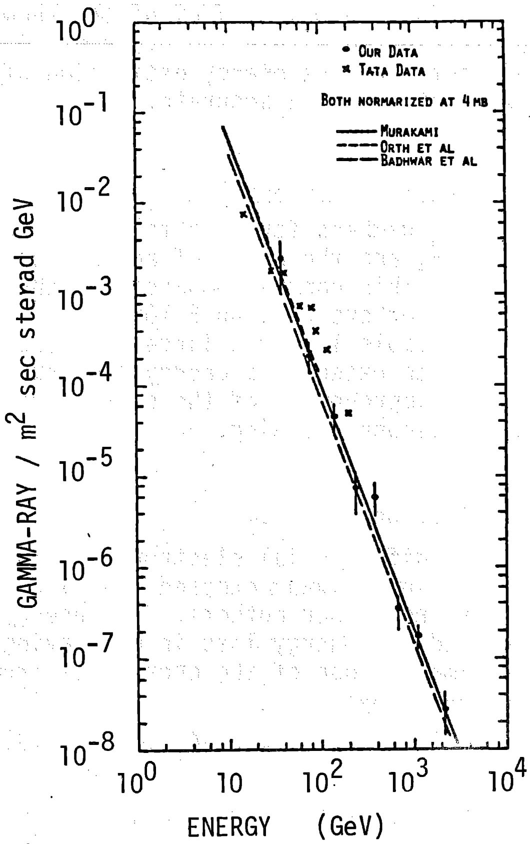

Fig. 4 Atmosphere Gamma-rays normarized at 4 mb

also show the same conclusion.

Secondary, their correction for overlying atmosphere does not take into account the effect of the spectral slope, and thus overestimates the energy loss by a factor of 1.1. The flux is therefore overestimated by a factor of about 2, which would almost bring their data into line with ours.

The higher flux of gamma rays beyond 30 GeV obtained by Tata group (Stephens, '70) in Fig. 4 is also interpreted by the same reason.

The shape of the spectrum of primary electrons shown in Fig. 5 is compared to the results of various models of propagation of the cosmic rays inside the Galaxy. Reasonable fit is observed, if one takes

$$\tau_0 = 1.0 {}^{+2.0}_{-0.5}\ 10^7 \text{ yrs.} \quad \text{with } \delta = 0.2 - 0.7 ,$$

in the energy dependent leaky box model, with the leakage life time

$$\tau = \tau_0 (E / 5\text{GeV})^{-\delta}, \qquad \delta = 0.2 \sim 0.7, \qquad E \geq 5 \text{ GeV} .$$

Here we take the loss of energy of the electron by synchrotron and inverse Compton processes as a commonly accepted value

$$b = 10^{-16} (\text{GeV} - \text{sec})^{-1} ,$$

assuming B = 3 micro gauss and 2.7 K radiation.

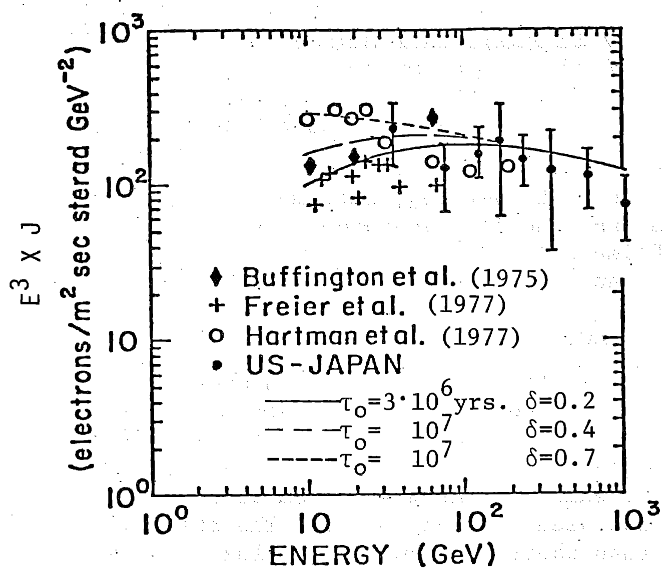

Fig. 5 E^3 times of Electron Flux

However, the spectrum of straight line in Fig. 5, which correspond to $\tau_0 \geq 5\cdot10^7$ yrs can not completely be excluded. The improvement of the accuracy of the data in the energy range below 100 GeV as well as beyond 1000 GeV is the most crucial. The relation between the leaky box model and diffusion model is discussed in a separate paper (Nishimura et al, '79a).

At higher energies, e.g. above 1 TeV, the electron life time becomes so short, it is expected that only few sources nearby solar system could contribute to the flux, if we assume electrons are accelerated by discrete sources. Large deviation is expected for the spectrum of primary electron from the average beyond 1 TeV due to few discrete sources contributing to that energy region (Shen, '70; Nishimura et al, '79b). Thus the information on the detailed shape of the electron spectrum beyond 1 TeV would give us an astrophysical implication of cosmic ray sources. More detailed discussions on this point will be presented in a separate paper in this conference (Nishimura et al, '79 b).

We believe our technique is free of serious difficulties regarding detection efficiency, discrimination of electron-simulating events, and energy estimation.

At the time of this writing, data of half of 1977 chambers are not included. After finishing the analysis of those chambers, our measurement of the primary electron spectrum will be extended beyond 1 TeV.

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