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# ENERGY SPECTRUM OF COSMIC-RAY IRON NUCLEUS OBSERVED WITH EMULSION CHAMBER

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## ABSTRACT

Energy spectrum of cosmic-ray Fe-nucleus has been measured from 4 GeV per nucleon to beyond 100 GeV per nucleon. The data were obtained using emulsion chambers on a balloon from Sanriku, Japan. The energies were estimated by the opening angle method after calibrated using 1.88 GeV per nucleon Fe collisions. The spectrum of Fe is approximately $E^{-2.5}$ in the range from 10 to 200 GeV per nucleon. This result is in good agreement with those of other experiments.

## 1. Introduction.

The current experimental data on the primary spectrum above 1 GeV/n are recently reviewed[1]. Concerning iron nucleus spectrum, it is interesting to establish the spectrum above 100 GeV/n, because the propagation and escape of cosmic rays from galactic confinement would make a effect on the primary spectrum above 100 GeV/n on basis of energy dependent L/M and sub-iron/iron ratio. But, the statistics of high energy data around 100 GeV/n is not sufficient for the discussion. The recent spectrum results have been obtained using instruments such as ionization spectrometers[2], gas Cerenkov counters[1,3,4], magnetic spectrometers[5], and emulsion chambers[6,7]. There were some differences between different techniques. In this experiment, we used an emulsion chamber and applied the opening angle method for estimating the primary energy. In an emulsion chamber experiment, there were three problems to be solved: (1) The shortening of the scanning time for nucleus-nucleus collisions. (2) Charge determination of heavy nuclei. (3) Energy determination of primary nucleus, whose problem was pointed out by Kullberg et al.[8]. By developing a new detection method with plastic detector CR-39, the scanning time was shortened[9]. To reach the reliable results on 2) and 3) problem, the calibration experiments were carried out by exposing the same type of chambers as the balloon-borne one to 1.0 GeV/n and 1.88 GeV/n Fe beams at LBL heavy iron accelerator.

## 2. Experimental procedure

A schematic diagram of the instruments is shown in Fig.1. The emulsion chamber consists of 9 plastic track detector CR-39 plates, 27 nuclear emulsion plates and 20 polyethylen target plates. which are piled alternately. The CR-39 plates are about 1.7 mm thick. The emulsion plate is coated with 50 $\mu$m thick nuclear emulsion gel on both sides of a 1.0 mm thick lucite plate. The target plates are 1.0 mm thick polyethylen. The overall size of 6 chambers is 1.5 m x 0.8 m x 8.9 cm and the total depth is 8.3 g/cm$^2$ . These chambers have been exposed by balloon flight at Sanriku Balloon Center, Japan, for about 15.5 hours at an altitude of 7.6 g/cm$^2$ .

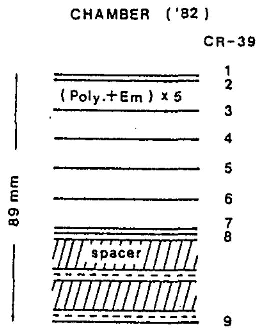

Fig.1 Chamber design.

A CR-39 sheet at the top of chamber was generally scanned with a microscope of 40 magnification and the radius of located cones was measured on an adjacent downstream CR-39 plate. The charge resolution is about $\Delta Z$=+/-1 . Selected cones of charge Z=26+/-1 were followed downstream using CR-39(No.3,5,7). Collisions were found by checking whether or not the cone became smaller or disappeared downstream. The angles of secondary particles and fragments were measured in nuclear emulsion plates.

For iron nucleus of Z=26+/-1, the integral flux is obtained using collision mean free path of $\lambda$= 15.6 g/cm$^2$ for Fe-air collision as follows;

$$I(>= 4.0\ \mathrm{GeV/n}) = (1.2 +/- 0.1)\times 10^{-1}\ (m^2\cdot str\cdot sec)^{-1}$$

where 4.0 GeV/n is vertical-cut-off kinetic energy at Sanriku.

## 3. Energy determination and correction.

We carried out an experiment using 1.88 GeV/n Fe beam at LBL to calibrate the primary energy estimated by the opening angle method. There are two methods to estimate the incident energy from the emission angle of alpha particles and heavy fragments. One is by the mean angle and the other is by root-mean-square angle. The incident kinetic energy can be calculated by the following relations;

$$P_o = \langle P_t \rangle / \langle \theta \rangle \quad , \quad P_o = \sqrt{\frac{M \langle E_k^* \rangle}{3}} \Big/ \sqrt{\langle \theta^2 \rangle}$$

where $P_0$ is incident momentum, and $\langle P_t \rangle$ and $\langle E^*_k \rangle$ are parameters. As it is very difficult to measure the incident axis of interaction in the cosmic ray, emulsion chamber experiment, we must take the center of geometrical weight of heavy and alpha fragments in the forward cone as the axis of interaction. The parameters were calculated for the events of Nh+$N_\alpha$ >= 3, where Nh means number of heavy fragments with charge greater than 3 and $N_\alpha$ is number of alpha particles. They are shown in Table 1 for each charge range of fragment.

| Zf | < Pt > (MeV/c) | < $E^*k$ > (MeV) |
|---|---|---|
| 2 | 86.7 +/- 6.5 | 33.5 +/- 5.1 |
| 3 - 8 | 64.6 +/-11.4 | 18.7 +/- 7.5 |
| 9 - 12 | 61.4 +/- 4.4 | 17.4 +/- 2.8 |
| 13 - 15 | 54.0 +/- 5.5 | 14.2 +/- 3.1 |
| 16 - 21 | 37.3 +/- 4.1 | 5.9 +/- 1.2 |

Table 1. Parameters for primary energy estimation.
Zf means a charge of fragment.

Using these parameters, we can conversely estimate the incident energy from experimental values of $\langle\theta\rangle$ and $\langle\theta^2\rangle$, and can obtain the error distribution of estimated energy when the incident energies are known. Figure 2 shows $E/E_0$ distribution for 114 events with $N_h + N_\alpha >= 3$ obtained by the above two methods, where E means the estimated primary energy and $E_0$ means the beam kinetic energy of 1.88 GeV/n. The mean values of estimated energy are larger than beam energy. It is mainly due to the tail of angular distribution of alpha particles and fragments at large angles. So, if we apply the opening angle method to observe the primary energy spectrum of heavy nuclei, we must be careful of the overestimation of primary energy.

To check the effect of the estimated energy error on the primary spectrum, a Monte Carlo simulation has been made assuming the integral spectrum is a $E^{-1.5}$ spectrum at high energy, which is modulated by cut-off rigidity at Sanriku, and using the $E/E_0$ distribution in Fig.2, which has an approximate form of gamma function, i.e. $f(x)= x^{a} \cdot \exp(-bx)$ with a=3.1 and b=0.42 . It is also assumed that a form of $E/E_0$ distribution does not vary with primary energy $E_0$ . The results is shown in Fig.3 . The spectra are multiplied by $E^{2.5}$ to emphasize spectral features. It can be seen that the observed spectrum by the opening angle method is higher than the true one. Then we must correct the observed spectrum. We can also obtain a correction factor from this simulation if spectral index is known.

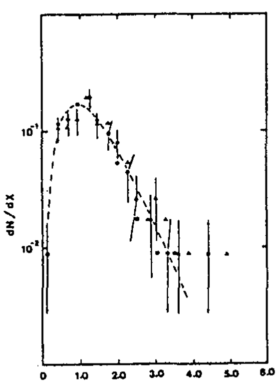


Fig.2 Estimated energy error distribution. E means the estimated primary energy and $E_0$ means the beam kinetic energy 1.88 GeV/n. ● and ▲ denotes the $E/E_0$ data obtained by mean angle and root-mean-square angle method, respectively.

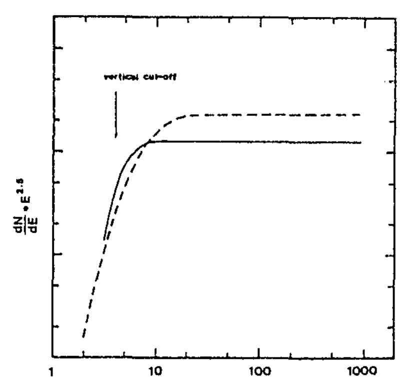


Fig.3 Results of a simulation. A differential spectrum is assumed to be $E^{-2.5}$ . The broken curve is a estimated spectrum using the error distribution in Fig.2.

## 4. Results and discussion.

We observed 294 events of primary charge, Z=26+/-1, which make a collision in a chamber and have secondary fragments of $N_h+N_\alpha >=3$ . The primary energies of these events were calculated from mean emission angle and root-mean-square angle, respectively, using parameters shown in Table 1. The spectral index is consistent to -2.5 within an experimental error by comparing the experimental with a Monte Carlo simulation of spectral index of -2.3,-2.5 and -2.7 . Using this index, the simulation makes it possible to correct the observed spectrum. The corrected energy spectrum is shown in Fig.4 along with some data from other groups. The agreement between different measurements is quite good within the quoted errors. This experiment shows that an iron spectrum has a spectral index -2.5 in the range from 10 GeV/n to 100 GeV/n. The present data do not suggest that iron spectrum gradually becomes steep to an index -2.7 above 100 GeV/n, which is expected from a conventional leaky box model, although the statistics is not yet sufficient.

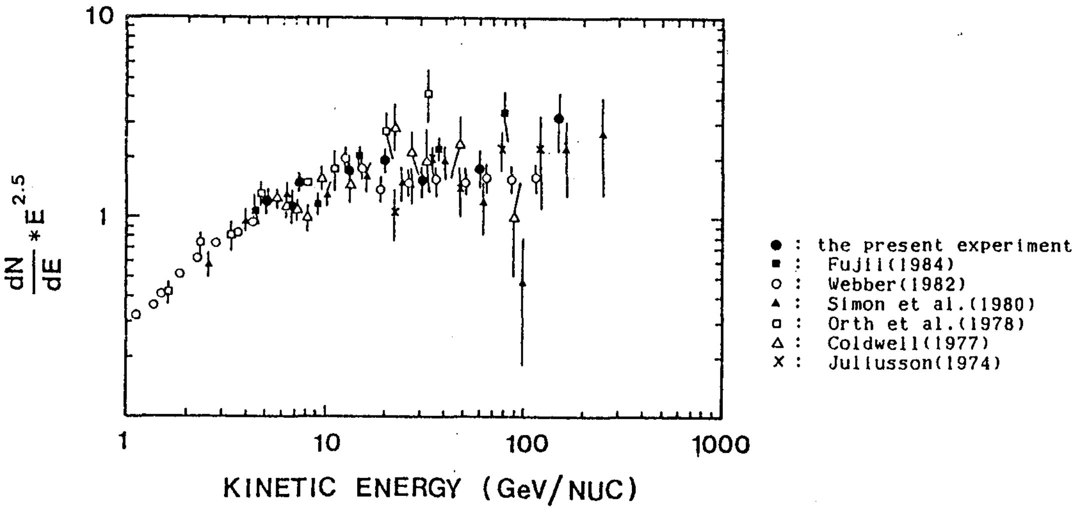


Fig.4 The iron spectra as compared with measurements of other values. The spectra have been multiplied by $E^{2.5}$ (kinetic energy) to emphasize differences. The intensities are in particles/$m^2$·str·sec·GeV per nucleon and kinetic energy is in GeV per nucleon.

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