OBSERVATIONS OF ULTRAHEAVY COSMIC RAY PARTICLES AT 10 GV CUTOFF RIGIDITY

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ABSTRACT

Ultraheavy cosmic ray particles with Z>45 and Fe were observed in two balloon flights at a mean geomagnetic cutoff rigidity of 10 GV. Fluxes of these particles at the top of the atmosphere are presented. A ratio of (Z>45)/(Fe) is compared with other experimental results. The ratio decreases with increasing energy in the energy range from 1 to 10 GeV/amu. A possibility is presented to explain the variation of the ratio with energy.

1. Introduction. Early observations of ultraheavy cosmic ray particles (UH) were mainly made by balloon-borne track detectors at high geomagnetic latitude regions (1, 2, 3). In the observations, UH were collected enough to obtain approximate chemical compositions. Recently, more precise measurements on the abundances of UH were achieved by using electronic detector systems on board the Ariel 6 (4) and the HEAO-3 (5) satellites and a picture of the origin of the cosmic rays based on the early results was suffered significant alteration. However, to determine energy spectra of UH, more data are required.

Plastic detectors are useful instruments for measurements on the fluxes of charge groups of UH, since a large area array can be easily constructed. For observations of relativistic particles, in particular we can realize an extremely large area array, because nuclear charges of such particles can be determined with singly layered plastic sheets.

In our observations at a mean cutoff rigidity of 10 GV, no cosmic ray particles of $E \leqq 2$ GeV/amu can enter from any direction.

2. Experimental Configuration. Two arrays A_1 and A_2 were launched from Sanriku Balloon Center at a mean cutoff rigidity of 10 GV in 1976 and in 1982, respectively. A total collecting power of A_1 expanded vertically with an area of 50.4 m^2 was 846.2 $m^2 \cdot hr$ at a mean residual atmosphere of 11.2 g/cm^2 and that of A_2 expanded horizontally with an area of 28.8 m^2 was 238.5 $m^2 \cdot hr$ at a mean residual atmosphere of 7.7 g/cm^2. Each array was composed of plastic detector stacks of 40 cm × 50 cm in area consisting of three CN, two CTA and two or one PC sheets. To measure the flux of Fe, several small size stacks of emulsion and of CR-39 were also included in A_1 and A_2, respectively. In both observations, two CN sheets in each stack were used to detect tracks by ammonia vapour method and the others to determine the charges.

In the CN sheets, 9 tracks produced by UH with $Z \gtrsim 40$ were found; 5 in A_1 and 4 in A_2.

For calibrations, CN and CTA stacks were exposed to ^{40}Ar beams of 400 MeV/amu at the Bevalac. The charge resolutions were characterized by standard deviations of about 3 and 5 charge units at $Z \sim 50$ for the CN and the CTA, respectively.

3. Data Analysis. For the emulsion, δ-ray counting method were applied. On the other hand for the CR-39, using growth rate (V_t) data of etch pits, we first prepared scatter plots of normalized etch rates ($V_t/V_g - 1$) vs. $\sin\delta$, where V_g and δ are a bulk etch rate of the CR-39 and a dip angle of a track, respectively. From these analyses, frequency distributions of δ-ray densities along tracks in the emulsion and of the normalized etch rates projected on the line of $\sin\delta = 1$ were obtained. Compared with well-known chemical composition of

cosmic rays with $Z \leqq 26$, the frequency distributions were converted into charge distributions. One of the results obtained from the CR-39's data is shown in Fig. 1. No correction was made for geometric factor which varies with atomic number. The observed charge resolutions were characterized by standard deviations of 0.55 and 0.34 charge units at Fe for the emulsion and the CR-39, respectively.

The data of track etch rates in the CN and the CTA were used to determine nuclear charges of UH. No track was recorded in the PC sheets which are insensitive to relativistic particles with $Z \lesssim 70$. The track etch rate data and the charges assigned to all events are shown in table 1. In CTA, there is an apparent difference in sensitivity between front and back surfaces.

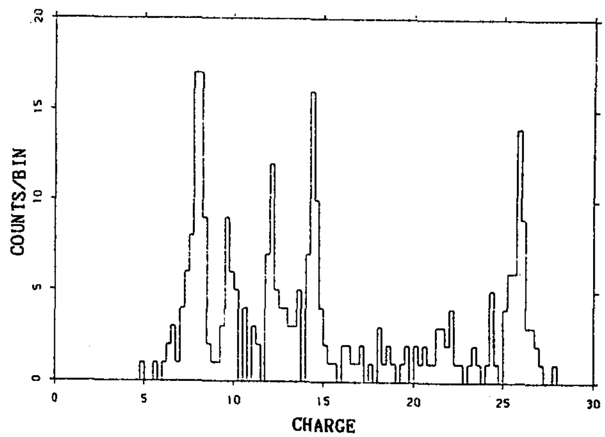

Fig. 1 Chemical composition of the particles found in the CR-39 of 100 cm².

Taking account of nuclear spallations in the overlaying atmosphere, we obtained the fluxes of Fe and UH at the top of the atmosphere. For the calculations of the nuclear spallations, we used Hagen's formula (6) for the total cross sections and extrapolations of Silberberg and Tsao formulae (7) for the partial ones. Scanning efficiency for lighter particles being insufficient, we restricted our attention to the particles with $Z>45$.

TABLE 1
The Track Etch Rates and The Charges Assigned to All Events

	Event No.	CN Etch Rate (μm/hr)	Z	CTA (Front) Etch Rate (μm/hr)	Z	CTA (Back) Etch Rate (μm/hr)	Z
A₁	23	27.4	46	----	--	----	--
	36	27.9	47	2.35	53	1.38	52
	62	29.5	47	2.87	52	1.83	54
	208	16.9	42	----	--	----	--
	235	12.0	40	----	--	----	--
A₂	1-19	46.1	55	2.46	54	1.43	52
	3-23	69.3	67	----	--	26.0	75
	3-27	53.1	58	2.00	52	2.57	54
	3-34	69.1	67	4.58	60	8.92	60

4. Results and Discussion. The fluxes of both Fe and UH obtained from two observations were consistent with each other. The combined values of the fluxes were as follows;

$$0.11 \pm 0.01 \quad \text{particles/m}^2 \cdot \text{sr} \cdot \text{sec} \quad \text{for Fe and}$$

$$(3.9 \pm 1.5) \times 10^{-6} \quad \text{particles/m}^2 \cdot \text{sr} \cdot \text{sec} \quad \text{for } Z>45.$$

As a flux ratio of $(Z>45)/(\mathrm{Fe})$, the following value was obtained;

$$(3.5 \pm 1.6) \times 10^{-5} \quad \text{for } R>10 \text{ GV}.$$

This value is shown in Fig. 2 with other experimental results. The datum of the

HEAO-3 was infered from a charge composition summarized by Mewaldt (8). The result of Blanford et al. (3) was that obtained from a balloon observation by using plastic detectors at a cutoff energy of 1 GeV/amu. Assuming a power law spectrum with a index of 2.6, we plotted the ratios deduced from integral fluxes at mean energies in the figure.

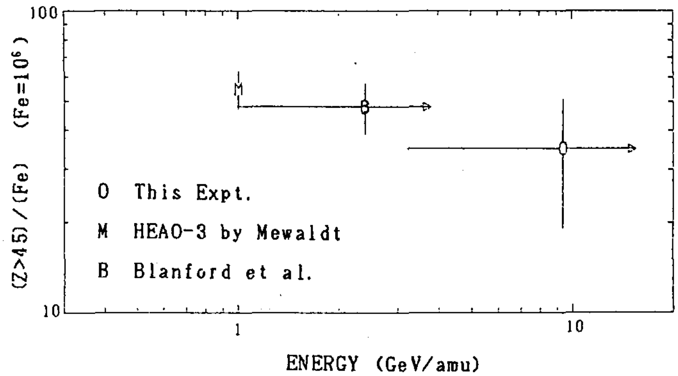

Fig. 2 Observed abundances of the particles with $Z>45$ relative to Fe ($Fe=10^6$).

It is clear in the figure that the ratio decreases with increasing energy in the energy range from 1 to 10 GeV/amu. The decrease means that the energy spectrum of UH with $Z>45$ is steeper than that of Fe. The difference in the energy spectra is to be ascribed to the effects of cosmic ray propagation in the Galaxy, if indices of injection energy spectra of all particles are assumed to be the same.

To examine the effects, propagation calculations based on a exponential path length distribution were made (9). In the calculations, we used

(1) Cameron's (10) solar system abundances for source composition,
(2) Silberberg and Tsao (11, 12) semiempirical formulae with the modifications of 1977 (13), 1979 (14) and 1983 (15), for the spallation cross-sections and
(3) the semiempirical formulae by Silberberg et al. (16) for the total inelastic cross-sectios,

and included the effects of

(1) first ionization potential enhancement and
(2) solar modulation with a deceleration parameter of 500 MV.

The effects of the ionization losses were neglected, since they are not so important in the energy range of interest.

All injection spectra were taken to be proportional to $W^{-2.2}$, where W is total energy per nucleon.

We considered collisions up to nine times and treated individually 323 isotopes from Nb to Bi, which are either stable, long lived or decayable exclusively by electron capture, and about 800 short lived isotopes produced by collisions and subsequent radio active decays.

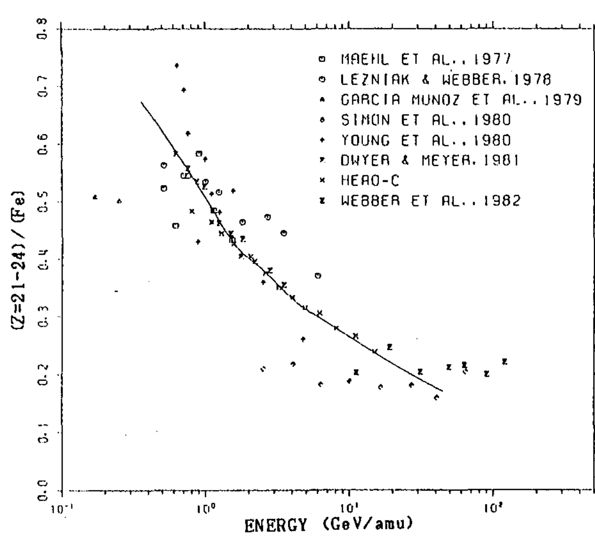

Fig. 3 The variation with energy of the (sub-Fe)/(Fe) ratio.

The following energy dependent escape mean free path λ_e was determined to explain the experimental results for the ratio of (sub-Fe)/(Fe) in the energy range from 0.6 to 30 GeV/amu;

$$\lambda_e = \begin{cases} 8.0 & \text{g/cm}^2 \quad \text{for } E \leq 2 \text{ GeV/amu}, \\ 8.0\,(E/2) & \text{g/cm}^2 \quad \text{for } E > 2 \text{ GeV/amu}. \end{cases}$$

Figure 3 shows the variation with energy of the (sub-Fe)/(Fe) ratios. The predicted curve is consistent with the experimental results over the above range of energy.

The result of the calculation is presented for the $(Z>45)/(Fe)$ ratio on

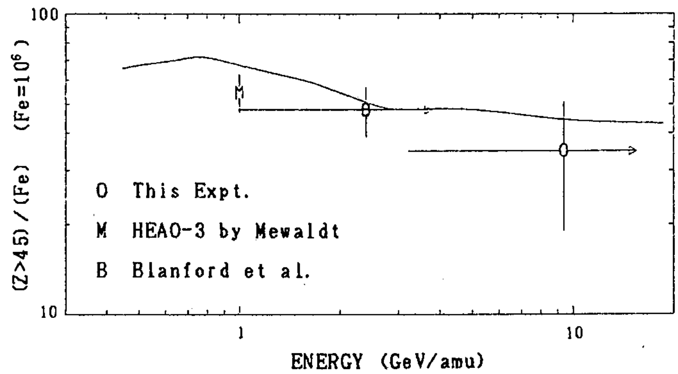

Fig. 4 The variation of the predicted ratio of (Z>45)/(Fe) compared with the observed data.

Fig. 4 and compared with the experimental data. The curve reproduces well the variation of the observed ratios. An increase around 800 MeV/amu is due mainly to similar increases in the spallation cross-sections of heavy nuclei around 1 GeV/amu. An increase in the partial cross-sections in the mass range of 10<ΔZ<40 at 1 GeV was shown in the measurements of Kaufman and Steinberg (17) on the spallation of ^{197}Au. The data obtained from the measurements were incorporated into the semiempilical formulae by Tsao et al. (15).

A possible interpretation of the variation with energy of the (Z>45)/(Fe) ratio shown by the propagation calculation is as follows.

The ratio of (secondaries with Z>45)/(Fe) increases significantly around 1 GeV/amu because it depends strongly on the spallation cross-sections. The alternative ratio of (primaries with Z>45)/(Fe) depends on the attenuation and the escape mean free paths and varies with a simple manner with energy. And the calculations showed that the secondaries are dominant in UH at 1 GeV/amu. Therefore, the (Z>45)/(Fe) ratio in the interstellar space increases at 1 GeV/amu. The effects of the solar modulation shift the increase to lower energy side.

Above 3 GeV/amu, where the spallation cross-sections change little with energy, the (primaries)/(Fe) ratio increases with increasing energy, while the (secondaries)/(Fe) ratio continues decreasing, because the interstellar matter traversed by cosmic rays decreases with increasing energy. As a result, the (Z>45)/(Fe) ratio decreases gradually with increasing energy at least up to ~10 GeV/amu.

The increase around 800 MeV/amu dominates the variation of the ratio of (Z>45)/(Fe). It results mainly from the increases in the spallation cross-sections at 1 GeV/amu. This emphasizes the importance of another measurements of the spallation cross-sections.

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