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Charge Spectrum, Mean Free Paths, and Flux of Heavy Primary Cosmic Rays at the Top of the Atmosphere

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This investigation is restricted to primary cosmic rays of nuclear charges equal to or greater than ten at the geomagnetic latitude of 41 degrees north. Data were obtained from thick emulsions exposed at high altitudes over Texas. The flux, extrapolated to the top of the atmosphere, was found to be 2.65±0.3 particles/m^2 sec sterad. The distribution histogram for the charge spectrum is included. The attenuation mean free paths for three groups were 28.5±2.8, 26.7±2.9, 23.6±3.7 g/cm^2 for $Z=10$–11, 12–14, 15–26, respectively.

INTRODUCTION

The heavy primary component of the cosmic radiation studied in this paper includes particles having $Z\geq 10$. At balloon altitude, passage of these heavy primaries through finite thicknesses of air has caused changes in the character of the heavy primary beam. Besides this, measurements of the very small flux of heavies are easily influenced by extraneous variables. Therefore ideal values of flux, mean free path (MFP), and the charge spectrum of the heavy nuclei have not yet been obtained. Increased accuracy requires both better statistics and further improvement in methods. This study has the dual purpose of determining the charge spectrum with good statistics (total tracks considered: 1887), and determining the attenuation MFP for several different charge groups.

EXPERIMENTAL METHOD

Six different plates or groups of plates were exposed to the cosmic radiation at 41 degrees north geomagnetic latitude (Texas) at altitudes ranging from 90 000 to 115 000 feet, with the exception of one series of plates (3200 series) which was exposed at 70 000 feet. Complete flight data are given in Table I.

With the exception of plate 2588, the delta-ray counting method exclusively was used to determine the relative characteristics of the tracks. Plate 2588 was a composite emulsion consisting of Ilford G-5 and G-0 emulsions sandwiched together. On this plate grain counts were also made. Upon the completion of scanning, each track found was counted for delta rays under a total magnification of 1250. The delta-ray counting criteria developed by this laboratory and based on a 4-grain convention were closely adhered to throughout.[1]

In order to identify charge, and to decide whether or not certain tracks were relativistic, measurements of the deflections of tracks in the emulsions caused by multiple scattering were taken. While there are several methods of measuring this scattering, the method used in this experiment was the coordinate method.[2]

Systematic errors inherent in the measurement of scattering may be classified as statistical and nonstatistical. Errors of the first type result from uncertainties in setting the filar micrometer hairline on the center of the track and also from the apparent scattering which results from uneven stage motion. Assuming these errors are distributed normally we may consider them as statistical noise, and call spurious scattering of this type "noise level." These errors were corrected by the method of different cell sizes,[3] or by the use of third differences obtained in the coordinate method.[4] Distortion of emulsions is the most important source of the second type of error, and can be detected by noting runs of positive and negative signs of the second differences. It can be corrected by subtracting from each second difference, the average of the algebraic values of the second differences.[2] The above process of correction was carried through where such error was detected.

Identification of Particles

The cutoff energy at 41°N geomagnetic latitude is approximately 1.5 Bev per nucleon—the velocity of nuclei having this energy being $0.931c$; consequently the delta-ray density on a track produced by a particle having this velocity is about 15% greater than the delta-ray density of a truly relativistic track. But on the average, the nuclei will have a velocity of about $0.97c$ since many of the nuclei will have relativistic velocities, and not merely that allowed by the cutoff value. We

Table I. Flight data.

Plate No.	Altitude in g/cm^2	Geomag. lat. and location	Date	Effective flight time in hours	Area scanned in cm^2	Emul. type
2601	17.46	Texas 41°N	Unknown	6.0	34.70	G-5
1423	15.43	same	March ?, 1952	7.7	32.14	G-5
1480	15.40	same	May 8, 1952	7.5	60.00	G-5
4001	7.74	same	June 3, 1955	9.0	21.70	G-5
3200	52.80	same	January 24, 1955	8.0	280.40	G-5
HHN11	9.98	same	February 11, 1955	8.4	23.78	G-5
2588	11.43	same	November 18, 1954	6.2	23.45	G-5 and G-0

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[1] O. B. Young and W. C. Ballowe, Am. J. Phys. **24**, 157 (1956).
[2] P. H. Fowler, Phil. Mag. **41**, 169 (1950).
[3] M. G. K. Menon *et al.*, Phil. Mag. **42**, 932 (1950).
[4] J. E. Moyal, Phil. Mag. **41**, 1058 (1950).

TABLE II. Calibration constants.

Plate	2601	1423	1480	4001	3200	HHN11	2588
a	0.057	0.075	0.081	0.082	0.072	0.082	0.065
b	0.2	0.2	0.2	0.23	0.2	0.2	0.2

may assume then that the discrepancy introduced by the assumption that all nuclei are relativistic is well within the limits of experimental error at 41°N. On this basis, the delta-ray density of tracks will vary directly with Z^2 since βc approaches one in the formula

$$N=\frac{aZ^2}{\beta^2}\left(\frac{1}{W_1}-\frac{1}{\beta^2}\right),$$

where N is the number of delta rays per unit length having an energy greater than W_1 produced by a nucleus of charge Ze. This relation is independent of the precise energy value. Therefore, we may write

$$N=aZ^2+b,$$

where a and b are constants of the plates, b representing the background delta-ray counts.[5] Thus we have a calibration relation usable without restriction at 41°N for very high altitudes (i.e., altitudes above 90 000 feet).

Plate Calibration

The primary method of calibration used was that proposed by Dainton *et al.*,[6] and confirmed by Tidman *et al.* on an experimental basis.[7] In this method, long, fast tracks made by alpha particles and lithium nuclei are found either by scanning or from stars caused by heavy nuclei. The tracks are counted for delta rays, thus giving the delta-ray density for nuclei with a Z of 2 and 3. The value of minimum ionization is obtained for single charged particles from observations of decay electrons from mu mesons. In addition to this, long tracks from the CNOF (carbon, nitrogen, oxygen, fluorine) group are counted, and then all are measured for multiple scattering. If N_δ, the number of δ rays per hundred microns is then plotted against $\bar{\alpha}$, the scattering per hundred microns, on a log-log scale, these points will always show clearly resolved lines, provided of course, that the total number of tracks is large. Hence, the above formula is a calibration relation for relativistic tracks. Considering the fact that the average energy of the particles makes them somewhat less than relativistic, a value which was 5% higher than the first constant in the above formula was used. Thus, the formula becomes

$$N=0.082Z^2+0.2.$$

A star caused by a heavy nucleus in which the conservation of charge between the incident nucleus and the outgoing jet of fast particles could be seen was found on this plate. Four alpha particles, three protons in the narrow forward cone, and one more proton which made a large angle with the primary incident nucleus were observed. The count on the incident nucleus was 9.54 delta rays/100 microns. Assuming no meson production and that the target nucleus was a proton, the charge of the incident nucleus should be eleven. On this basis, the calibration constant should be 0.077. From the angular distribution of secondary particles, the energy of the primary nucleus could be estimated as 7 Bev using the relation $\langle\theta^2\rangle^{\frac{1}{2}}=0.056/E$, where θ is the root-mean-square angle.[8] This value agrees well with the results obtained from scattering measurements.

The results of the calibrations for all plates are shown in Table II.

Calibration of HHN11

This calibration will be given as an example of the general method by which the plates were calibrated. Figure 1 shows the results of both multiple scattering measurements and delta-ray counts on tracks having a delta-ray count between 0.5 and 7 per hundred microns which were more than 5000 microns long. From this it is clear that the delta-ray density of the track of a nucleus at the mean scattering angle of 0.01° per hundred microns can be expressed by the following formula:

$$N=0.078Z^2+0.2,$$

the constants a and b being derived from

$$a=\tfrac{1}{3}(N_2-N_1)=\tfrac{1}{5}(N_3-N_2),$$
$$b=N_1-a=N_2-4a.$$

Charge Spectrum

A summary spectrum is shown in Fig. 2. The 3200 series is omitted in the summary since the light end contains many secondary particles. No nuclei were

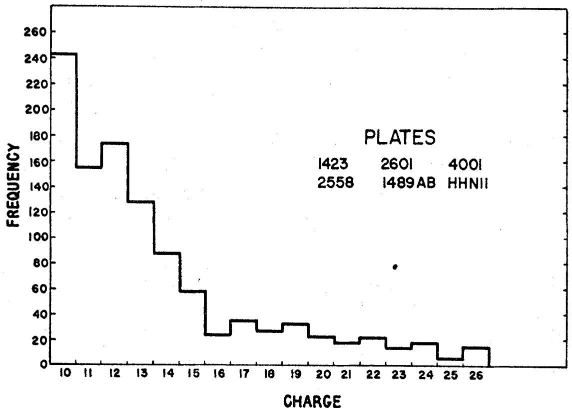

FIG. 1. Summary charge spectrum.

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[5] H. L. Bradt and B. Peters, Phys. Rev. **77**, 58 (1950).

[6] A. D. Dainton *et al.*, Phil. Mag. **42**, 317 (1950).

[7] Tidman, George, and Hers, Proc. Phys. Soc. (London) **A66**, 1019 (1953).

[8] Kaplan, Peters, Reynolds, and Ritson, Phys. Rev. **85**, 295 (1952).

found which had a delta-ray density significantly greater than that which the plate calibrations allowed for iron. No predominance of nuclei carrying an even charge was seen. A general decrease in frequency of particles from a Z of 10 to 15 is seen, at which point the spectrum shows a flattening out though there is a slight general decline in frequency. However, it can be seen in all individual plate histograms except the 1480 series and plate 2588 that there is a considerable peak at a Z of 26 compared to the preceding Z which is manganese. As could be expected, the 3200 series (alt: 70 000) shows a much lower value at its heavy end indicating that many of the heavier particles have broken up and added a secondary flux to the light end.

The summary spectrum is given in percent in Table III.

TABLE III. Abundances of elements in heavy cosmic rays from $Z=10$ to $Z=26$ inclusive for 1082 tracks.

Element	Z	Abundance (%)
Ne	10	23.0
Na	11	14.4
Mg	12	16.4
Al	13	12.0
Si	14	8.0
P	15	5.3
S	16	2.3
Cl	17	3.1
A	18	2.3
K	19	3.1
Ca	20	1.9
Sc	21	1.7
Ti	22	2.1
V	23	1.3
Cr	24	1.6
Mn	25	0.5
Fe	26	1.4

Mean Free Paths by Groups

The ultimate goal in calculating MFP by groups is the eventual calculation of MFP for each Z value. Presently this is not possible for two reasons: (1) the difficulty of absolute Z calibration, and (2) the difficulty of obtaining statistics enough to give reliable values.

In this paper, the spectrum was broken into three groups, each containing approximately the same number of particles. The grouping was as follows: Group I: $Z=10$–11; Group II: $Z=12$–14; Group III: $Z=15$–26.

Method of Mean-Free-Path Calculation

If the flux at the top of the atmosphere is assumed to be isotropic (with respect to zenith angle), then the formula

$$I(\theta)=I_0\exp[(-d/\lambda)\cos\theta] \tag{1}$$

gives the flux at zenith angle θ, and atmospheric depth d, in terms of I_0, the flux at the top of the atmosphere. The number of particles in a unit angle interval at zenith angle θ, is given for a plate in the vertical position by

$$N(\theta)=4ATI(\theta)\sin^2\theta, \tag{2}$$

where A is the area of the emulsion in cm^2, T the flight time in seconds, and I the flux at a zenith angle θ, in particles per cm^2 sec sterad. Combining Eqs. (1) and (2) and taking the common logarithm,[9] we have

$$\log\left(\frac{N(\theta)}{\sin^2\theta}\right)=\log(4AI_0T)-\left(\frac{\log e}{\lambda}\right)\frac{d}{\cos\theta}.$$

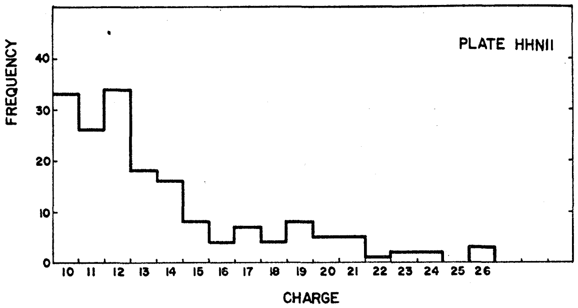

FIG. 2. Charge spectrum.

A plot of this function gives $-(\log e)/\lambda$ for the slope and for the intercept at $d/\cos\theta=0$ the value $\log(4AI_0T)$. The best-fit straight line was found by the least-squares method.[10] The end points of the graph shown in Figs. 3 and 4 were obtained by taking the antilogarithms of the end points of the above.

Combination of Plates and MFP Calculation

The plates were combined by plotting on logarithmic paper the flux *vs* the atmospheric path length ($d/\cos\theta$). Of course, this leaves the possibility of errors caused by time variation. However, at present it appears that the chief variations are caused by variations in solar emissions, and apparently the flux of heavies is much less affected than that of alphas and protons; also it was determined that no unusual solar activity was seen on the dates on which the flights of the plates used (first four plates in Table I: total tracks 941) took place. This leaves the possibility of diurnal variation but in view of the studies of Lal *et al.*,[11] and Freier *et al.*,[12] who estimate an upper limit of variation between night and day flux as 10% and 20%, respectively, the variation between the different flights should be small since all are day flights.

Under the above considerations, the attenuation MFP

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[9] A. D. Dainton and D. W. Kent, Phil. Mag. **41**, 963 (1950).

[10] R. T. Birge, Phys. Rev. **40**, 207 (1932).

[11] Lal, Pal, Kaplon, and, Peters, Phys. Rev. **86**, 569 (1952).

[12] Freier, Anderson, Naugle, and Ney, Phys. Rev. **84**, 322 (1951).

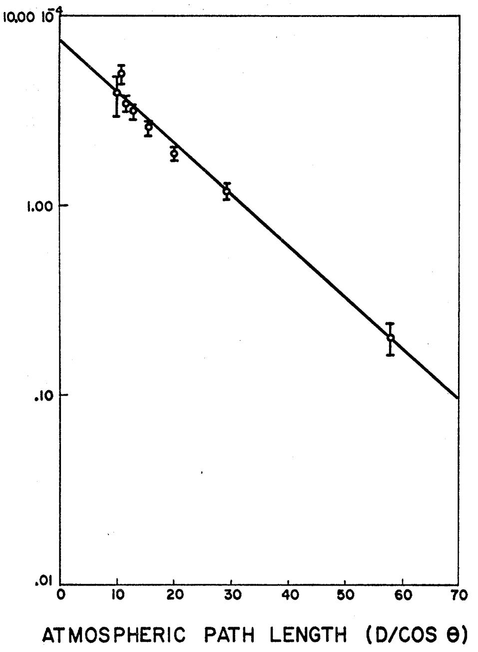

FIG. 3. Flux of CNOF (carbon, nitrogen, oxygen, fluorine) on plate HHN11.

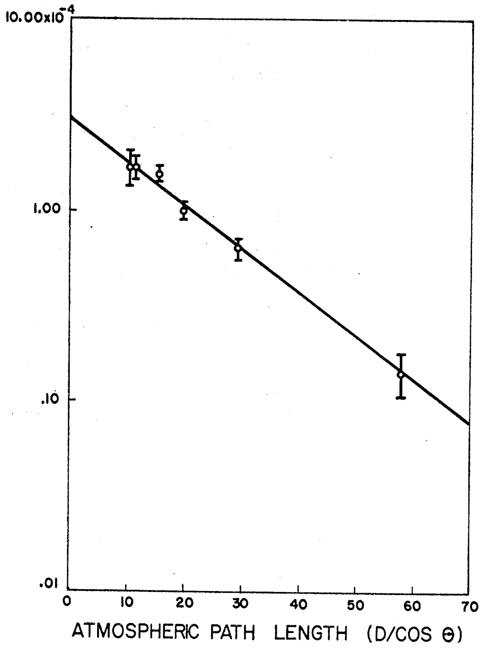

FIG. 4. Flux of $Z \geq 10$ on plate HHN11.

for each group is:

$$\text{Group I} = 28.5 \pm 2.8 \text{ g/cm}^2,$$
$$\text{Group II} = 26.7 \pm 2.9 \text{ g/cm}^2,$$
$$\text{Group III} = 23.6 \pm 3.7 \text{ g/cm}^2.$$

These results agree well with those of other workers. It can be seen that the order of the MFP's is in the order predicted by theory in that the MFP varies inversely with Z.

Mean Free Path on Plate HHN11

An unusually low MFP was found on plate HHN11 for the $Z \geq 10$ group (19.0). Therefore, it was not included in the MFP calculation by group as only plates of similar characteristics were used. On the basis of one section of this plate (176 tracks), it was found that the values of the MFP for the CNOF group and $Z \geq 10$ were

$$Z \geq 10 \text{ group} = 19.0 \pm 0.7 \text{ g/cm}^2,$$
$$\text{CNOF group} = 16.1 \pm 0.64 \text{ g/cm}^2.$$

Not only are these values unusually low, but the order is reversed. Apparently the mean free paths are energy-dependent. The velocity change was probably due to modulation by changed magnetic fields of the earth and sun.

Flux

The flux at the top of the atmosphere was computed by using the equation

$$I(\theta) = I_0 \exp[(-d/\lambda) \cos\theta],$$

which applied directly after λ had been found as previously described. The angular distributions of the particles were measured and a separate calculation was made for each interval of ten degrees. The number of particles in each interval was determined by use of Eq. (2) under "Method of Mean Free Path Calculation" in this paper. The total flux was the sum of the values obtained for the ten-degree intervals.

The flux at the top of the atmosphere of all nuclei with $Z \geq 10$ for the 749 tracks on the plate HHN11 was found to be 2.66±0.3 particles/m^2 sec sterad which is in close agreement with a value of 2.64±0.3 particles/m^2 sec sterad found for the four plates with a total of 906 tracks used in the MFP calculation by groups. Hence on a bais of 1655 tracks the flux has been found in this paper to be 2.65±0.3 particles/m^2 sec sterad.

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