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III-1-6. The Composition of Heavy Nuclei of the Primary Cosmic Radiation above the Earth's Atmosphere

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§1. Introduction

In an earlier investigation which was carried out in this laboratory[1] (hereafter referred to as I), the relative proportion L/S of the number of Li, Be, B nuclei (the L-group), to the number of nuclei with $Z\geq 6$ (the S-group) in the cosmic radiation at balloon altitude was determined as a function of the zenith angle using a stack of nuclear emulsions flown from Texas, U.S.A.; the ratio L(o)/S(o) corresponding to zero grams of overlying matter *i.e.* at the top of the atmosphere was obtained by an extrapolation procedure. An attempt was also made to extrapolate to the top of the atmosphere the ratio, M/H, of the number of M-group of nuclei (C, N, O, F nuclei) to the number of H-group of nuclei (with $Z\geq 10$). In I, L(o)/S(o) was estimated to be 0.06 ± 0.06 and M(o)/H(o) to be 3.45 ± 0.65.

Since the earlier experiment reported from here[1], a number of investigations[2)-20)] have been carried out to determine the ratios L(o)/S(o) and H(o)/M(o) at the top of the atmosphere. In the present work an attempt has been made to estimate the ratio H(o)/M(o) with an accuracy higher than any reported hitherto. In I the various ratios L/S, M/H etc. were plotted as functions of atmospheric depth x g/cm² and an extrapolation procedure employed to obtain the values at the top of the atmosphere. The statistical weights attached to the values of the ratios at depths $x>15$ g/cm² were very poor compared to those for depths $x=8-12$ g/cm², thus introducing rather large errors in the final extrapolations. In order to determine ratios at depths $x<15$ g/cm², with statistical errors comparable to those at lower atmospheric depths, we have made observations on a horizontal stack flown on the same balloon flight as that which carried the vertical stack. By combining the observations made on the vertical and the horizontal stacks, uniformly good statistical weights have been obtained throughout the range of depths investigated.

§2. Experimental Procedure

2.1 *Stacks used*

The stacks used in this experiment were flown from Texas, U.S.A. on 6th February, 1956 and were exposed at a mean altitude corresponding to 6.6 g/cm² of residual atmosphere for a period of $6^1/_4$ hours.

Two stacks were flown, one suspended vertically (as described in I) and the second suspended horizontally. The horizontal stack consisted of a celluloid sheet 3 mm. thick of size $8''\times 6''$ sandwiched between two G 5 emulsion sheets of similar area, each 400 μ thick. These and the G 5 emulsions used in the vertical stack were all from a single batch at manufacture and were processed together; this ensured that the G 5 emulsions from the two stacks had the same sensitivity characteristics as determined by ionisation measurements.

2.2 *Selection of tracks*

The central region of the top emulsion of the horizontal stack (≥ 1 cm from the processed edges) was scanned under a total magnification of $\times 150$ for tracks satisfying the following conditions:

(i) the projected length in the emulsion scanned should be $\geq 900\,\mu$; this corresponds to a zenith angle $\geq 66°$;

(ii) the grain density should be greater than that corresponding to a relativistic Be nucleus; and

(iii) the track should be straight as determined by a hairline under a total magnification $\times 375$.

For tracks identified as due to carbon or boron nuclei by δ-ray and gap length measurements the following conditions had also to be satisfied to eliminate contamination by slow singly charged particles:

(i) when it was found possible to trace

the track to the second emulsion, (and this was the case for about 90% of the tracks of boron and carbon nuclei) the ionisation measured in the two emulsions should be the same within experimental errors;

(ii) in cases where the track was not found in the second emulsion (except for those events where there was definite evidence for an interaction in the celluloid), coulomb scattering measurements were made in the first emulsion and tracks showing scattering consistent with that of slow singly charged particles were rejected; only two such tracks due to slow particles which had an ionisation corresponding to that of a relativistic carbon (within statistical fluctuations) were found in the whole area scanned.

Tracks identified by ionisation and multiple scattering measurements in the first emulsion as due to boron nuclei and which were not found in the second emulsion were not included in the analysis in view of the lack of certainty of identification by measurements in one emulsion alone.

2.3 *Charge Identification*

Three methods of charge determination have been employed in this investigation:

(i) Gap length measurements were used for tracks of particles with $Z \leq 6.5$ as determined by ordinary δ-ray measurements.

(ii) Ordinary δ-ray measurements were employed for tracks of particles with $Z \leq 12$; δ-rays with four or more grains were counted in this method.

(iii) For tracks of particles with $Z \geq 8.5$, as determined from ordinary δ-ray measurements, a "long δ-ray method" was employed. In this a graticule with three parallel hairlines each spaced from the next by 2.5 μ was used. Under a total magnification $\times 1500$ the track was set along the central hairline, and long δ-rays that were associated with the track, which reached beyond the outside lines of the graticule were counted. A total of ≥ 80 long δ-rays were counted on each track.

2.4 *Classification of the heavy nuclei*

The following observations can be made regarding the H-nuclei: (i) from our investigation, as also from those of others[5,7,16,18], it is found that nuclei with $Z=16-19$ are very rare at the top of the atmosphere; (ii) From a study of the change of the flux of nuclei with $Z=10-15$, $Z=16-19$ and ≥ 20 as a function of x it is found that these three groups of nuclei have quite different growth curves. For these reasons we thought it

Table I. Corrected charge spectrum as a function of atmospheric depth

Atmospheric depth	Description	B	C	NOF	H_3	H_2	H_1
17.4 -20.0 g/cm²	Observed Number	18.5	53.5	74.5	39.5	11	8
	Scanning Efficiency %	95	95	98.8	100	100	100
	Loss due to Nuclear Interaction %	6.8	0.8	0.8	1.0	1.1	1.3
	Corrected Number of Particles entering the stack	19.8	56.8	76.0	39.9	11.1	8.1
20.1 -25.0 g/cm²	Observed Number	32.5	41.5	74.5	36.5	8	4
	Scanning Efficiency %	96	99.5	100	100	100	100
	Loss due to Nuclear Interaction %	8.1	0.9	1.0	1.2	1.3	1.5
	Corrected Number of particle entering the stack	36.9	42.1	75.3	37.0	8.1	4.1
25.1 -40.0 g/cm²	Observed Number	21.5	30.5	58.0	30.0	10	5
	Scanning Efficiency %	97	100	100	100	100	100
	Loss due to Nuclear Interaction %	11.2	1.3	1.4	1.6	1.9	2.1
	Corrected Number of particles entering the stack	25.0	30.9	58.8	30.5	10.2	5.1

desirable to classify the H-group of nuclei into three sub groups H_1, H_2 and H_3 comprising of nuclei with charge values 20–28, 16–19 and 10–15 respectively.

2.5 *Corrections*

Corrections were made for scanning loss and loss by interaction. These are given in Tabl I.

2.6 *Results*

A total area of 135.1 cm^2 was scanned in the horizontal stack and 589 tracks due to particles with charge $Z \geq 5$ were obtained. The corrected numbers of nuclei falling into the various groups are given in Table I as a function of zenith angle. We also included in the ensuing analysis 613 tracks due to particles of charge $Z \geq 3$, obtained from an area of 170.0 cm^2 in the vertical stack. The charge spectra obtained by measurement on the total of 1202 tracks are shown in Fig. 1 as a function of atmospheric depth. These histograms clearly demonstrate the transformation in the charge spectrum which occurs as the radiation passes through the atmosphere.

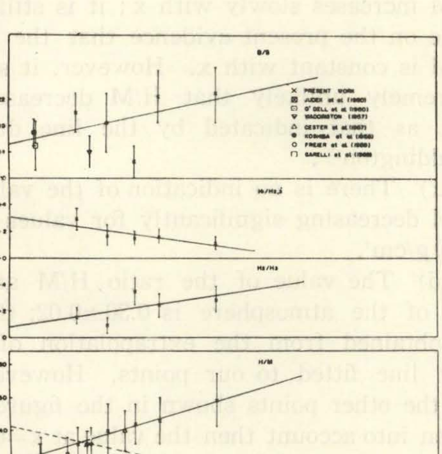

Fig. 1. The observed charge spectrum of 1202 particles with $Z \geqq 3$ as a function of atmospheric depth.

§ 3. The absorption mean free path of heavy nuclei in air and their flux above the earth's atmosphere

The calculations of Kellogg[21] have been used to obtain the corrections for geomagnetic effects at large zenith angles. The resulting corrections to the flux amount to 17 %, 17% and 30% for the angular intervals 66°–69°, 69°–73.5° and 73.5°–80° respectively.

We have fitted straight lines to our points by the method of least squares. (Fig. 2) The values of Λ_i' obtained for the H_1, H_3, H and M-nuclei with and without the above mentioned geomagnetic corrections are given in Table II; the corresponding values of the flux at the top of the atmosphere have also been included in this table. The errors quoted correspond to standard deviations.

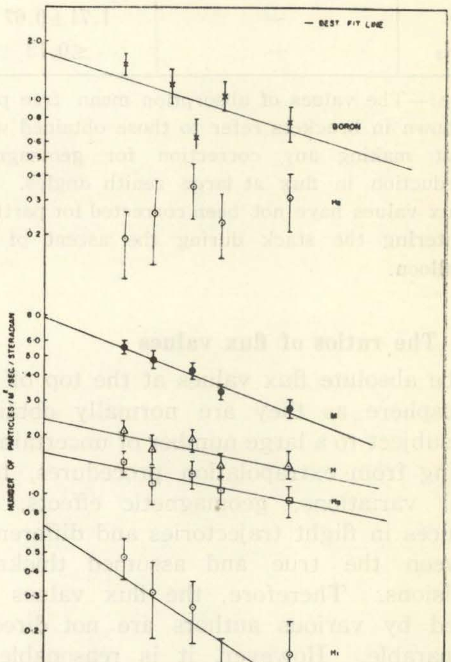

Fig. 2. The variation of the flux of H_1, H_2, H_3, H, M and boron nuclei as a function of atmospheric depth. The points at $x=18.6$, 22.2 and 30.7 g/cm^2 have been corrected for geomagnetic effects as stated in the text.

It is found that the value of Λ_M' is the most accurate one and is consistent with the values obtained by other workers. In spite of the large errors, the values of Λ_H is significantly larger than Λ_M' and is in contradiction to the ideas held by the majority of workers in this field who believe, (on the basis of fragmentation constants deduced for air from observations in, emulsion), that Λ_H is much smaller than Λ_M.

Table II. Values of absorption mean free paths (Λ_i') of H_1, H_2, H, M and Boron nuclei in air and their flux values extrapolated to the top of the atmosphere.

Nuclei	Absorption mean free path in air (g/cm²)	Flux values $J_i(0)$ particles/m²/sec/Sterad
H_1	16.7±5.9 (13.2)	0.69±0.30
H_3	53.4±16.5 (27.0)	1.67±0.19
H	51.4±18.6 (26.6)	2.40±0.32
M	28.2±1.8 (18.6)	7.80±0.50
B	—	1.71±0.67
H_2	—	≤0.13

Note:—The values of absorption mean free paths shown in brackets refer to those obtained without making any correction for geomagnetic reduction in flux at large zenith angles. The flux values have not been corrected for particles entering the stack during the ascent of the balloon.

§ 4. The ratios of flux values

The absolute flux values at the top of the atmosphere as they are normally obtained are subject to a large number of uncertainties arising from extrapolation procedures, temporal variations, geomagnetic effects, differences in flight trajectories and differences between the true and assumed thickness emulsions. Therefore, the flux values obtained by various authors are not directly comparable. However, it is reasonable to expect that for flights made from places at about the same geomagnetic latitude ($\lambda=41°$ in our case) the ratios of any two groups of nuclei at a given pressure level should be independent of the uncertainties mentioned above.

4.1 *The ratio H/M*

We have plotted in Fig. 3 the values of H/M obtained by us as a function of x and fitted a straight line to these values by the method of least squares. We have also shown in this figure the values obtained by other authors who measured this ratio at geomagnetic latitude $\lambda \approx 41°$ or close to it and whose results are based on 50 or more tracks of M+H nuclei. It is found that these values based on reasonable statistics agree extremely well with the line fitted to our points.

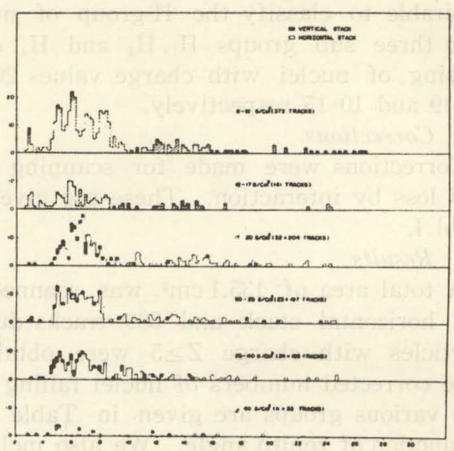

Fig. 3. The ratios of H/M, H_2/H_3, $H_1/H_{2,3}$ and B/S as a function of atmospheric depth. The solid lines are that of least equares fit for our values only. The dashed line (for H/M) is the diffusion growth curve obtained by Waddington(16).

It is now possible to draw the following conclusions from Fig. 3.

(i) There is strong evidence that the ratio H/M increases slowly with x; it is still possible on the present evidence that the ratio H/M is constant with x. However, it seems extremely unlikely that H/M decreases as fast as that indicated by the line due to Waddington[17].

(ii) There is no indication of the value of H/M decreasing significantly for values of x >20 g/cm².

(iii) The value of the ratio H/M at the top of the atmosphere is 0.30±0.02; this is as obtained from the extrapolation of the best line fitted to our points. However, if all the other points shown in the figure are taken into account then the value at x=0 gms will be smaller than 0.3.

It has been pointed out in the beginning of this paper, that any experiment done outside the earth's atmosphere or very close to the top of it (≤3 g/cm² of atmosphere), involves much less extrapolation to obtain H(o)/M(o) and thus be subject to small systematic errors. The only experiment in this category is that of Van Heerden and Judek[2], who got their emulsions exposed under 3.2 g/cm² of air at $\lambda=41°$. The value obtained by them is H(o)/M(o)=0.31±0.03 in excellent agreement with our value of 0.30±0.02.

4.2 *The ratio L/S*

In Fig. 3, we have plotted the experimentally determined ratios B(x)/S(x) as a function of x. The straight line drawn in this figure represents the best fit line obtained by the method of least squares. From this we have obtained value of B(o)/S(o)=0.14±0.05 after making an ascent correction according to the procedure described in I. We have also shown in Fig. 3 the available values of B(x)/S(x) obtained by other workers; these agree very well with the line corresponding to our observations.

In order to deduce the value of L(o)/S(o) one should know the numbers of Li and Be nuclei as compared to the B-nuclei close to the top of the atmosphere. For this purpose we made use of the recent investigations[2,3,12], made with stacks exposed at $\lambda=41°$ and very close to the top of the atmosphere and obtained the ratio (Li+Be)/B as 83/124=0.67. From this we estimated the value of L(0)/S(o) as 0.23±0.09. It, therefore, seems that our earlier value of L(o)/S(o) is rather low and that the true value lies probably between 10 and 30%: the precise value is still to be determined. It may be emphasised here that these values of L(o)/S(o) refer to $\lambda=41°$ and do not give us any information regarding their possible dependence on energy.

4.6 *The ratios H_2/H_3 and $H_1/(H_2+H_3)$*

We have also attempted to estimate the value $H_2(o)/H_3(o)$ by the method of linear extrapolation. This is not strictly correct since we know that the growth curve for H_2-nuclei deviates quite appreciably from a straight line. The value of $H_2(o)/H_3(o)$ thus obtained will, therefore, be only an upper limit.

In Fig. 3 the values of $H_2(x)/H_3(x)$ are shown as a function of x and from this we get $H(o)/H_3(o) \leq 0.08 \pm 0.08$. *This strongly indicates that nuclei with Z=16−19 are absent or almost absent in the primary cosmic radiation.*

From a similar procedure we have also obtained the extrapolated value of the ratio $H_1/(H_2+H_3)$ at the top of the atmosphere and obtain a value of 0.31±0.02. It may be stated that the value obtained by Waddington[17] for this ratio at 12 g/cm² is 0.24 in good agreement with the value of 0.23 obtained by us at a corresponding depth.

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