Abundance of Lithium, Beryllium, and Boron in the Primary Cosmic Radiation*

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The flux of nuclei of charge greater than two of the primary cosmic radiation has been measured at 41° and 55° geomagnetic latitudes with photographic emulsions flown in "Sky Hook" balloons. The technique used at the lower latitude is similar in principle to that employed originally by Bradt and Peters, while that used at the higher latitude is the method of Dainton, Fowler, and Kent. The different experimental methods are discussed and the latter is found more satisfactory for the light-element problem. Primary flux values are reported for the medium nuclei ($6\leqslant Z\leqslant 10$) and the heavy nuclei ($Z>10$) at the two latitudes. It is concluded that there exists a finite primary flux of the light nuclei ($3\leqslant Z\leqslant 5$) and the most reliable value from these experiments of the ratio of the primary light-nuclei flux N_L^0 to the primary medium-nuclei flux N_M^0 at the top of the atmosphere is found to be 0.46 ± 0.15.

INTRODUCTION

ONE of the important problems in the study of the cosmic radiation today is that of determining the charge and energy spectrum of the primary beam. After the existence of multiply charged nuclei in the primary radiation was established,[1] the results of many different laboratories on experiments carried out at varying geomagnetic latitudes were in essential agreement on the magnitude of the incoming flux of nuclei with $Z\geqslant 6$, and established in first order the shape of their energy spectrum.[2] Because of the lack of agreement of subsequent experiments[3,4] designed to investigate in greater detail the chemical composition of the nuclei with $Z\geqslant 3$, and since a detailed knowledge of the chemical composition, especially the existence or non-existence of the light nuclei, is of great importance in assessing the role of collisions of the heavy nuclear component with interstellar matter and its subsequent implications with respect to theories of the origin of cosmic radiation,[3] we have undertaken to repeat and evaluate the two experimental methods[3,4] which gave such markedly different results. To accomplish this purpose, two separate experiments, employing a different technique in each case have been carried out. The first experiment[5] was done with an emulsion stack flown at high altitude at 41° geomagnetic latitude and employed a technique similar to that used by Bradt and Peters.[3] The second was carried out with a stripped emulsion stack flown at 55° geomagnetic latitude and used the technique of Dainton, Fowler, and Kent.[4] We shall consider in order the two different experiments after a short discussion on the general problems involved in measurements on heavy nuclei in photographic emulsion.

DETECTION OF HEAVY NUCLEI IN EMULSION

In any experiment in photographic emulsion in which a systematic selection of a certain type of event is undertaken two general features always present themselves. The first involves the scanning of the emulsion and requires the fixing of some set of criteria so that the experimenter is assured that the particular class of events one is looking for is a subclass of that fixed by the scanning criteria; this is merely a reflection of setting the criteria loosely enough so that there exists a very high efficiency (which we will call scanning efficiency) for the inclusion of all events of the type sought. The second general feature that presents itself is that of selecting from all the events found in the scan those of the particular type sought; we shall call the efficiency with which this is done the decision efficiency.

The most general basis for selecting heavy nuclei in emulsion is that in which some measure of ionization is used, since for any given nuclear charge Z, the ionization at any arbitrary velocity less than c is greater than that at velocity c. Thus if it is desired to select all nuclei of $Z\geqslant 3$, which would be characterized by having $I/I_{\min}\geqslant 9$, one need only set the scanning criteria at some value sufficiently less than 9 so that a very high efficiency for the selection of all tracks having $I/I_{\min}\geqslant 9$ is realized. This scanning basis (along with some others) is the one adopted in the following experiments and a very high scanning efficiency is attained. It is in realization of the second feature (selection of class of events sought from those obtained in the scan) that the two experiments to be described here differ and indeed it is this feature which seems to be the root of discrepancies.

The necessity of setting the scanning criteria for ionization low enough so that a high scanning efficiency is attained has the consequence of introducing a large background of undesired events into the experiment

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[1] P. Freier *et al.*, Phys. Rev. **74**, 213 (1948).
[2] For a review of the situation as of 1951 see the article by B. Peters in *Progress in Cosmic Ray Physics* (North-Holland Publishing Company, Amsterdam, 1952), Vol. I. A survey covering the results as of the Fall of 1953 is given by E. P. Ney in the Report of the Duke Conference on Cosmic Radiation (unpublished).
[3] H. L. Bradt and B. Peters, Phys. Rev. **80**, 943 (1950). They find $N_L^0/N_M^0<0.1$ at $\lambda=30°$.
[4] Dainton, Fowler, and Kent, Phil. Mag. **43**, 729 (1952). They find $N_L^0/N_M^0\approx 1$ at $\lambda=55°$.
[5] First reported by Racette, Kaplon, and Ritson, and Kaplon, Racette, and Ritson, Phys. Rev. **93**, 914(A) (1954).

and the decision efficiency attained while working in this background is quite crucial to the success of the experiment. Since it is desired to select nuclei of charge $Z \geqslant 3$ this requires the measurement of some property of the track that is a function of the mass of the particle giving rise to it, since the measurement of ionization for a given charge is a measure only of velocity. There are two readily measurable properties in emulsion which serve this purpose; the first is the range which is a function of the mass, charge, and velocity, and the second is multiple Coulomb scattering which is a different function of the same parameters. The combination of either of these two measurements with ionization will serve to select multiply charged particles from the background of slow singly charged particles observed in the scan.

In the first experiment to be described nuclei of charge greater than two are selected by the combined measurements of ionization and range; this method is in principle simple to implement and results from the fact that for a particle with an ionization $\geqslant 9I_{\min}$ to be at least triply charged it must have a certain minimum range in which the ionization remains constant. In the second experiment the nuclei are selected by combining the measurements of ionization and multiple Coulomb scattering. While in principle each of these techniques is straightforward it will be seen that there is basis for criticism of the results obtained in employing them.

EXPERIMENT I

Experimental Arrangement

In this experiment twenty-four 4 in.$\times$6 in.$\times 250\mu$ Ilford emulsions mounted on 1.4-mm glass were arranged in 8 triads of G-5, C-2, and D-1, emulsions, each plate separated from its neighbor by thin paper. The stack was flown with the 6 in.$\times 250\mu$ emulsion edge vertical for approximately 8 hours at White Sands, New Mexico (41° geomagnetic latitude); the flight curve is shown in Fig. 1 (an additional 4 g/cm^2 of effective residual atmosphere must be added to account for the packing and the stack material above the survey plate). The emulsions were processed by the usual methods of temperature development and after completion each plate was cut into four 2-in.$\times$3-in. sections for microscopic observation. The relative alignment of the cut plates was determined by using very heavy nuclei ($Z>10$) as markers and a coordinate transformation scheme was derived to facilitate the tracing of tracks from plate to plate. The thickness of the emulsion at the time of exposure was determined by measurements on heavy nuclei which traversed the entire stack.

Scanning Criteria and Charge Calibration

The scanning for heavy nuclei was carried out under low magnification (diameter of field of view$=720\mu$) on the top sections of the 5th and 7th G-5 emulsions. Only those tracks were selected which had a projected length $L_p \geqslant 720\mu$ and a grain density $g>100/75\mu$. The length criterion was adopted to reduce background and ensure more efficient tracing; the ionization criterion insured the inclusion of all nuclei with $Z \geqslant 3$, while excluding fast α particles since this grain density corresponded to $I/I_{\min}>5.1$.

Charge calibration was obtained in the following way. The value of minimum ionization for singly charged particles is easily obtained from observations on the decay electrons from μ mesons, and, from this, the value for fast α particles is predicted. From observations on the breakup of fast heavy nuclei fast α particles are selected and from these we determine in G-5 emulsion the values of grain density per $75\mu(g)$, δ-ray density per $100\mu(n_\delta)$, and the gap density (G) and the corresponding values in C-2 emulsion for grain density (g') and gap density (G'), thus establishing the values of these quantities for $I/I_{\min}=4$.

To extend the calibration, gap-density measurements were made on stopping μ mesons in the G-5 emulsion, and it was found that μ mesons of residual range $R=1900\mu$ had the same ionization as the fast α particles; in addition the gap-density of μ mesons of 290μ residual range was the same as that of particles tentatively identified as fast Li nuclei (on the basis of δ-ray and grain density) in the collision fragments of heavy nuclei. Since the ratio of specific ionization for a μ meson of 290μ residual range to that of one with 1900μ residual range is $\approx 2.2=9/4$, the identification of fast Li nuclei ($I/I_{\min}=9$) is established. The grain and gap density of these particles was then determined in the C-2 emulsion.

Since the δ-ray density for fast α particles and Li nuclei was known, the δ-ray density for fast particles of arbitrary Z could be predicted. From $n_\delta(2)$ and $n_\delta(3)$ we obtain $n_\delta'(1)$, the true δ-ray density for a fast singly charged particle and the background contribution b by using the relation $n_\delta(Z)=Z^2 n_\delta'(1)+b$. For these emulsions and our counting criterion (4 grain convention) we determined $n_\delta'(1)=0.09$ per 100μ and $b=0.24$ per

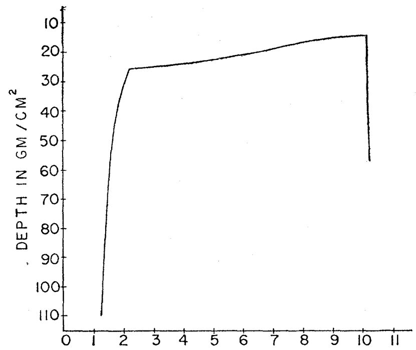

FIG. 1. Flight curve of balloon carrying plates used in experiment I.

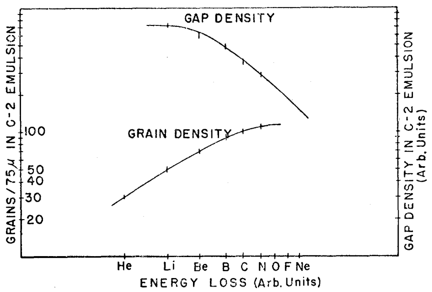

FIG. 2. Grain-density and gap-density calibration curves for C-2 emulsions of experiment I.

100μ. This calibration was further checked by studying an interaction in emulsion which could be interpreted only as the breakup of a fast N nucleus. (Two doubly charged and one triply charged particles emitted.) The observed $n_\delta(7)$ agreed very well with the predicted value; the grain density in C-2 emulsion for this particle was then determined enabling a calibration curve for this emulsion extending from $I/I_{\min}=4$ to 49 to be constructed (Fig. 2). Since the high sensitivity of our C-2 emulsion, compared to that of normal C-2 emulsion, did not allow accurate charge resolution for fast nuclei of $Z>7$[6] (but did allow excellent discrimination between B and C) the gap density of identified nuclei with $Z\leqslant 7$ was determined in C-2 emulsion to establish a calibration curve which was extrapolated to higher Z (Fig. 2).

Scanning and Decision Efficiency-Observed Fluxes

The minimum grain density $g>100$ used in the selection of tracks in the scan corresponded to $I/I_{\min}>5.1$. Since this ionization acceptance is quite conservative it ensures the inclusion of all nuclei of $Z\geqslant 3$ (as will be demonstrated shortly) in the scan. To establish which of the tracks accepted in the scan were indeed heavy nuclei of $Z\geqslant 3$, it was necessary to establish a minimum range. At the geomagnetic latitude of this flight the cut-off kinetic energy per nucleon $\epsilon=1.58$ Bev. At this energy all nuclei with $3\leqslant Z\leqslant 10$ are sufficiently relativistic at flight altitude so that their ionization (n_δ, g or G) is a direct measure of their charge; the distinction is not valid for the heavier nuclei but is such that there is no lack of resolution between the medium and heavy group. Thus if a minimum range could be established for a given track its charge is established as being $\geqslant 3$, and its ionization is then a direct measure of its charge. In order to establish the minimum range an attempt was made to trace through the stack all the tracks obtained in the scan. Only those tracks were accepted as heavy nuclei ($Z\geqslant 3$) which could be traced either to a point of entrance at the top of the stack or to an interaction above the survey plate, and which in addition had traversed sufficient material in the stack to ensure that they were not slow α particles. Since an α particle of the same ionization as a fast Be nucleus has a range <7.2 g/cm^2 this discrimination could be made positively for all nuclei with $Z\geqslant 4$; an α particle of the same ionization as a fast Li nucleus has a residual range of 36 g/cm^2 so that a track must be traced for at least 12 g/cm^2 with no change in ionization (an α particle would change its ionization by more than 15 percent) to be accepted as Li. In two cases (due to geometrical restrictions) it was not possible to distinguish with certainty between a slow α and a Li nucleus; these two cases are accepted in the analysis as Li nuclei.

[6] Though it was originally hoped to use the D-1 emulsions to obtain a higher degree of charge resolution for the heavier nuclei this was not possible due to the existence of a high fog background in these emulsions.

The observed charge spectrum on the survey plates resulting from the decisions made in the tracing (this is the weighted result as determined by δ-ray, grain, and gap density) is shown in Fig. 3 and corresponds to:

$$L \text{ nuclei } (3\leqslant Z\leqslant 5):\ 20/15.6\text{ cm}^2;$$
$$M \text{ nuclei } (6\leqslant Z\leqslant 10):\ 31/15.6\text{ cm}^2;$$
$$H \text{ nuclei } (Z>10):\ 8/15.6\text{ cm}^2.$$

The plates were scanned and the tracks followed by two independent observers. Their results are given in Table I. In addition 0.8 cm^2 of the same emulsion was scanned by both observers. In this scan, observer A found 6 tracks missed by B; of these, 3 had g so close to 100 as to represent fluctuations in grain counting, and the other three had $g\leqslant 110$ corresponding to $I/I_{\min}\leqslant 6$. It thus seems highly probable that the scanning efficiency for tracks with $I/I_{\min}\geqslant 9$ is 100 percent. In tracing, observer A traced one track not successfully traced by B due to an error in sign in determining the coordinate transformation; however in this aspect of tracing the sign convention was always independently checked so this could not be a contribution to decision inefficiency. Two other tracks were traced by both observers, but the remainder of the tracks found in this area could not be traced by either observer.

In an experiment of the type under discussion here it is quite important to realize 100 percent decision efficiency; since the observed signal-to-noise ratio (see Table I) is ≈ 0.05, it is seen that a decision inefficiency of only 2 percent would imply that $\sim$1.6 tracks/cm^2 were not traced and included as heavy nuclei when they should have been, and this would correspond to

TABLE I. Results obtained in scanning and tracing in Experiment I.

Observer	A	B
Total area scanned	10.03 cm^2	5.57 cm^2
Tracks/cm^2 with $g>100$	73.5 ± 8.6	89.6 ± 9.5
Tracks traced/cm^2 (total)	4.1 ± 0.64	3.24 ± 0.76
$Z>10$	0.5 ± 0.22	0.54 ± 0.32
$6\leqslant Z\leqslant 10$	2.2 ± 0.46[a]	1.62 ± 0.54[a]
$3\leqslant Z\leqslant 5$	1.4 ± 0.37[a]	1.08 ± 0.45[a]

[a] One of the total number traced of these particles was found to arise from an interaction above the survey plate.

losing approximately $\frac{1}{3}$ to $\frac{1}{2}$ of the signal. It is quite difficult to estimate in a reliable way the decision efficiency attained, but one estimate can be made as follows. Because of the stack arrangement each track selected in the scan in the G-5 emulsion had to pass through a C-2 emulsion before passing through another G-5 emulsion, so that in tracing an attempt was first made to locate a track in the nearest C-2 emulsion (since the distance involved was least). In a separate survey covering 4.25 cm^2 on plate 14 (a C-2 emulsion) which accepted tracks with $L_p \geqslant 432\mu$ and $g' \geqslant 45$, 7 tracks were found which were followed to the survey area of plate 13 (a G-5 emulsion) and which met the acceptance criteria for that plate; all of these had been previously found and successfully traced from the G-5 plate. We find then from the scan and tracing from the C-2 emulsion the selection of $7/4.25 = 1.65 \pm 0.6$ tracks per cm^2 as nuclei with $Z \geqslant 3$. This figure is the order of $\frac{1}{2}$ the number of tracks selected per cm^2 from the G-5 emulsion as being L nuclei or heavier and indicates certainly that the product of scanning efficiency and decision inefficiency in the insensitive emulsion is about twice that in the G-5; in addition, it certainly seems reasonable and is borne out by subsequent observations that the L nuclei are the ones most strongly affected. This feature (lack of 100 percent efficiency for detecting a particle known to be in the insensitive emulsion) was recognized in the course of the experiment and to remedy this the tracing was attempted directly to the nearest G-5 emulsion if a null result was obtained on the tracing attempt to the nearest C-2 emulsion. This increase of distance over which the tracing must be done, especially for the light nuclei, would tend to reduce the decision efficiency for this class. A crude estimate of the decision inefficiency may be obtained by saying that it is equal to 100η (tracks traced/cm^2 from G-5 − tracks traced/cm^2 from C-2)/(tracks accepted/cm^2 in G-5), where $0 \leqslant \eta \leqslant 1$; for $\eta \sim \frac{1}{2}$ the decision inefficiency is $\sim$1.4 percent.

An additional check on the decision efficiency is obtained by an examination of the interactions undergone in glass by those nuclei successfully traced below the survey plate. We find for the interaction mean free paths in g/cm^2 of glass the values $\lambda_H = 19.4 \pm 9$, $\lambda_M = 38.5 \pm 12$, and $\lambda_L = 26 \pm 12$. The values obtained for the heavy and medium nuclei are in excellent agreement with those expected[7] (and support the contention that the decision and tracing efficiency for these nuclei is 100 percent), but the value for the eight nuclei is considerably less than the expected value of 42 g/cm^2. Since a particle is said to have interacted if (*a*) interaction products can be seen or (*b*) if it cannot be traced further, a possible contribution to the measurement of a too short mean free path could be due to a tracing inefficiency giving rise to pseudointeractions. If the discrepancy in the measured value of λ_L is ascribed to

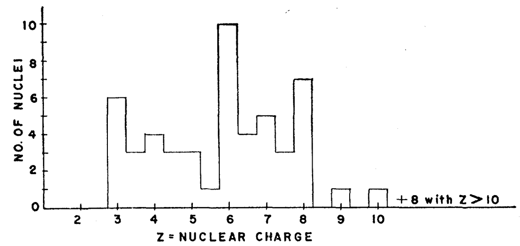

FIG. 3. Charge spectrum observed at flight altitude in Experiment I.

tracing inefficiency we find this implies that an additional 10 L nuclei which should have been detected and successfully traced from the scanning area were missed. This leads to an estimate of decision inefficiency of 100 (true tracks not traced from survey area/cm^2)/(tracks accepted/cm^2) $\approx$ 0.8 percent. The approximate agreement between these two different estimates of the decision inefficiency suggests that there exists a systematic error arising from this which affects the L nuclei predominantly; the magnitude of this effect being a loss of $\sim$0.65 to 1.2 L nuclei per cm^2. It is thus possible that if the above estimates are meaningful that at least 10 to 18 L nuclei which existed in the area scanned on the survey plates were not properly classified due to a small departure from 100 percent decision efficiency so that the true light nucleus flux per 15.6 cm^2 could be as high as 30 to 38.

Primary Flux Values

In order to obtain the true flux values of the various components of the heavy nuclei at the top of the atmosphere it is necessary to extrapolate the values observed at flight altitude back through the residual atmosphere to the top. Since it is known that in the interactions of these nuclei, nuclei of lower Z are emitted as fragmentation products with appreciable probabilities (especially the light nuclei),[8] a straight exponential type of extrapolation is not appropriate and one should consider the diffusion equations for the heavy nuclei. With the neglect of ionization loss and the assumption of energy independence for the parameters λ_I, $P_{I'I}$ (defined below) these are

$$dN_I(x)/dx = -N_I(x)/\lambda_I + \sum_{I' \geq I} P_{I'I} N_{I'}(x)/\lambda_{I'} \qquad I = H, M, L \qquad H > M > L,$$

where λ_I is the mean free path in g/cm^2 of atmosphere for the Ith component of the heavy element flux, $P_{I'I}$ is the probability that in an interaction of a nucleus of type I' a nucleus of type I (of assumed comparable momentum per nucleon) is emitted, $x = h/\cos\theta$ is the amount of atmosphere traversed, h the vertical depth below the top of the atmosphere and θ the zenith angle;

[7] M. F. Kaplon *et al.*, Phys. Rev. 85, 295 (1952).

[8] J. H. Noon and M. F. Kaplon (to be published).

in addition the nuclei are classed into three charge groups: L nuclei ($3\leqslant Z\leqslant 5$) with mean $Z=4$; M nuclei ($6\leqslant Z\leqslant 10$) with mean $Z=7$; and H nuclei ($Z>10$) with mean $Z=15$. These equations are subject to the initial condition $N_I(0)=N_I^0=$ the primary flux of nuclei of type I incident on the top of the atmosphere (assumed isotropic).

The solutions are:

$$N_H(x)=N_H^0\exp(-x/\lambda_H'),$$
$$N_M(x)=N_M^0\exp(-x/\lambda_M')+(\alpha_{HM}P_{HM}/\lambda_H)\times[N_H^0\exp(-x/\lambda_M')-N_H(x)],$$
$$N_L(x)=N_L^0\exp(-x/\lambda_L')+(\alpha_{ML}P_{ML}/\lambda_M)\times[N_M^0\exp(-x/\lambda_L')-N_M(x)]+(\alpha_{HL}/\lambda_H)(P_{HL}+P_{HM}P_{ML}\alpha_{ML}/\lambda_M)\times[N_H^0\exp(-x/\lambda_L')-N_H(x)],$$

where $\lambda_I'=\lambda_I/(1-P_{II})$, $\alpha_{IJ}=\lambda_J'\lambda_J'/(\lambda_J'-\lambda_I')>0$; $\lambda_J'>\lambda_I'$. In the above the first term on the right-hand side represents the absorption of the incident flux of type I, and the other terms represent contributions to this flux at depth x due to interactions of heavier nuclei.

For this experiment the detection efficiency of the plates for their geometry at exposure (a function of zenith angle θ) and the time variation of the flight curve must be taken into account. The detection efficiency factor $F(\theta)$ for vertically oriented plates is given in Sec. IV of a paper by Bradt and Peters.[9] In this experiment the altitude variation can be well represented by $h(t)=h_0-(\Delta h)t$. The solutions of the equations given above are then multiplied by $F(\theta)d\theta dt$ and integrated. The following values of the parameters were used:[8] $\lambda_L=31.5$ g/cm², $\lambda_M=26.5$ g/cm², $\lambda_H=18$ g/cm², $P_{LL}=P_{MM}=0.13$, $P_{HH}=0.25$, $P_{HM}=0.27$, $P_{ML}=0.42$, and $P_{HL}=0.48$. The results obtained are given below where $N_I(F)$ means the number of nuclei of type I observed at flight altitude

$$N_H^0=2.6\pm0.9 \text{ particles/meter}^2\text{ sec steradian.}$$
$$N_M^0=7.1\pm1.3 \text{ particles/meter}^2\text{ sec steradian.}$$
$$N_L(F)=0.76N_M(F)+(N_L^0/N_M^0)(32.3\pm6).$$

The flux values obtained for the medium and heavy nuclei agree with values previously reported.[7] Due to fragmentation into L nuclei of M and H nuclei in the residual atmosphere we see that 23.5 ± 4.3 of the L nuclei observed must be due to these processes and are not of a primary nature. Thus we find that $N_L^0/N_M^0=0$, if no correction for decision efficiency is made in obtaining the light element flux at flight altitude. On the other hand, since the estimate of decision efficiency would predict a value of $N_L(F)$ as high as 38, an upper limit can be set at $N_L^0/N_M^0\leqslant 0.55$. It is thus readily apparent that the value of the light element flux at the top of the atmosphere is extremely sensitive to the decision efficiency attained in this type of experiment.

[9] H. L. Bradt and B. Peters, Phys. Rev. **77**, 54 (1949).

EXPERIMENT II

Experimental Arrangement

A stack of twenty-four 4-in.×6-in.×400μ G-5 stripped emulsions (in direct contact with each other) was flown with vertical geometry for 8.2 hours at 102 000 ft at 55° geomagnetic latitude; the flight curve is given[10] in Fig. 4 (an additional 2 g/cm² must be added to account for the packing material). The stripped emulsions were mounted on glass before development and then processed by the usual temperature methods. After completion of the processing each plate was cut into four 3-in.×2-in. sections which were then mounted and consecutively aligned on Lucite frames using very heavy nuclei as markers.[11] The degree of alignment attained was such that minimum ionizing tracks could be unambiguously traced through the stack. The emulsion thickness at the time of exposure was determined by measurements on long tracks traversing the stack.

Scanning Criteria and Charge Calibration

The survey plates were scanned for tracks satisfying the following four criteria: (1) projected length in emulsion $L_p>3$ mm; (2) zenith angle $\theta<45°$; (3) so located geometrically that each track had a possible range in the stack $R\geqslant 20$ g/cm² of emulsion; (4) $I/I_{\min}\geqslant 6.2$ on the basis of grain density. Criteria (1) and (3) were adopted to ensure sufficient track length so that scattering and δ-ray measurements could be done with sufficient statistical accuracy; criterion (2) was adopted in order to reduce the uncertainties involved in the extrapolation of the observed fluxes to the top of the atmosphere (all particles accepted in the scan had traversed <25.4 g/cm² of atmosphere, including the atmospheric equivalent of the packing material); and criterion (4) was adopted to ensure the inclusion in the scan of all tracks with $I/I_{\min}\geqslant 9$.

The basic charge calibration for fast nuclei was established in the G-5 emulsion used in this experiment in an identical manner to that described in Experiment I. For these emulsions, using a 4 grain convention in δ-ray counting, we obtained $n_\delta'(1)=0.097$ and a background contribution $b=0.1$. The grain density g corresponding to the acceptance criterion (4) was $g=125$. In addition to the measurements made above to establish the calibration for fast nuclei, an extensive check was possible in this experiment by studying a number of interactions in emulsion of fast heavy nuclei (a measure of the energy per nucleon can be obtained from the degree of collimation of the fragments) in which charge balance between the incoming nucleus and its fragmentation products was obtained;[8] the results obtained in this study were in excellent agree-

[10] We are indebted to Professor E. P. Ney for a discussion of the characteristics of this balloon flight and its latitude trajectory. He informs us that a more realistic figure for the ceiling attained is 92 000 ft instead of the 102 000 ft shown in the curve of Fig. 4.

[11] J. Crussard *et al.*, Phys. Rev. **93**, 253 (1954).

ment with those obtained by the method of Experiment I.

In an experiment of this type charge identification is made by the simultaneous measurement of momentum (by multiple Coulomb scattering) and velocity (by δ-ray density). This requires knowledge of the dependence of δ-ray density on velocity. No systematic attempt was made in this experiment to verify the relationship between velocity and δ-ray density obtained by the Bristol group.[4] Verification of their relation on both a theoretical and experimental basis has recently been obtained by Tidman, George, and Herz.[12] The results obtained in this experiment in the low momentum region[13] also support the validity of that relationship. Measurements on several stopping nuclei supply an independent verification of this relationship; the observed variation of δ-ray density with range for these nuclei is in agreement with that derived from the Bristol results giving the velocity dependence of δ-ray density. We have adopted this calibration for charge identification of non-relativistic nuclei.

Scanning and Decision Efficiency-Observed Fluxes

The scanning was done on the top sections of 7 emulsions using the criteria given previously. A total area of 210 cm² was scanned by two observers independently, and an area of 30 cm² included in the above was scanned by a third. In the total area observer A found 680 tracks satisfying the scanning criteria, B found 708, and no additional tracks were found by observer C in scanning the area of 30 cm². The over-all scanning efficiency is thus ∼96 percent for the inclusion of tracks with $I/I_{\min}>6.2$. In the tracks selected in the scan there is a considerable background of slow singly charged particles as well as nonrelativistic α particles. The slow singly charged particles are easily discriminated against in tracing through the stripped emulsion since they have a residual range <7.2 g/cm² (1.8 cm) and exhibit a striking change in grain density over this region. By this procedure most singly charged particles were rejected leaving a total of 136 (by observer A) and 142 (by observer B) tracks retained for measurement of δ-ray density and multiple scattering. The results of these measurements showed that the 6 additional tracks found by B were α particles; since the ionization criterion was set sufficiently low we believe that no tracks with $I/I_{\min}>7.5$ were missed in the scan, and thus a scanning efficiency of 100 percent was attained for the inclusion of nuclei with $Z\geqslant 3$. Since the tracing in the stripped emulsion serves to eliminate the background of singly charged particles and some few doubly charged particles and the charge of the remaining tracks are all determined by the same method of scattering and δ-ray density, then, with the assumption that this method is not subject to systematic errors the decision efficiency for nuclei with $Z\geqslant 3$ is 100 percent.

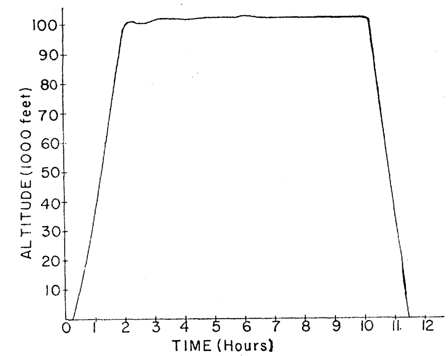

FIG. 4. Flight curve of balloon carrying emulsions used in Experiment II. (See reference 10.)

The scattering measurements were made using the coordinate method.[14] In this method the scattering in degrees/100μ is given by

$$\bar{\alpha}_{100}=KZ/(Ap\beta c)=0.573\bar{D}_t/(t/100)^{\frac{3}{2}},$$

where K is a constant slightly dependent on the cell size t used.[15] A is the mass number of the nucleus with charge Z, βc its velocity, p the momentum per nucleon, and $\bar{D}_t$ is the average of the absolute value of the second differences obtained by the coordinate method. In the measurement of $p\beta c$ by multiple scattering any sources of error are usually of such a nature as to increase the measured scattering angle and therefore lead to an underestimate of the true momentum. The systematic errors inherent in the measurement of scattering are of two different types: (1) statistical and (2) nonstatistical. Errors of the first type arise from uncertainties involved in setting the hairline due to finite track thickness and also from the pseudoscattering arising from stage noise; the setting error is relatively unimportant except for the very thickest tracks. With the assumption that these errors are independent of cell size and are distributed Gaussianly we may consider them together as a statistical noise. It is then possible to correct for these errors in the measurement by the method of noise elimination between different cell sizes[16] or by the use of the third differences obtained in the coordinate method.[17] The most important error of a nonstatistical nature arises from emulsion distortion. If the emulsion distortion is of the normal C-shaped type it may be corrected for by subtracting from each second difference the average of the

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

[13] It is in the low momentum region that the greatest deviation of the Bristol results from that of the so-called Rutherford formula for δ-ray density occurs. The verification obtained from our results is most reliable in this region since any systematic sources of error, such as stage noise or emulsion distortion, will have the least effect for particles of low momentum.

[14] P. H. Fowler, Phil. Mag. **41**, 169 (1950).

[15] L. Voyvodic and E. Pickup, Phys. Rev. **85**, 91 (1952).

[16] M. G. K. Menon *et al.*, Phil. Mag. **42**, 932 (1951).

[17] J. E. Moyal, Phil. Mag. **41**, 1058 (1950).

algebraic value of the second differences. Any other type of emulsion distortion is more difficult to correct for; where extreme local distortions exist, these are usually detectable visually and that region of the emulsion is not used for measurement.

The scattering microscopes used in this experiment had noise levels corresponding to $\bar{\alpha}_{100}\sim 0.01$ for 500μ cell lengths and ~ 0.02 for 250μ cell sizes corresponding to $p\beta c\sim 1.3$ Bev and ~ 0.65 Bev, respectively. The tracks were scattered using either 500μ or 250μ cells depending on the momentum. Since the true scattering for low momentum is much greater than that due to noise, noise elimination was performed only on the faster tracks. In addition the correction referred to in the previous paragraph for distortion was applied to all measurements.

The results obtained by the measurement of multiple scattering and δ-ray density are shown in Fig. 5 (the crosses refer to stopping tracks). We have plotted δ-day density normalized to that of a fast α particle *versus* the scattering angle $\bar{\alpha}_{100}$. The solid curves drawn represent lines of constant charge derived from the Bristol calibration. The charge spectrum at flight altitude derived from this figure is given in Fig. 6 and corresponds to 30 light, 28 medium, and 5 heavy nuclei.

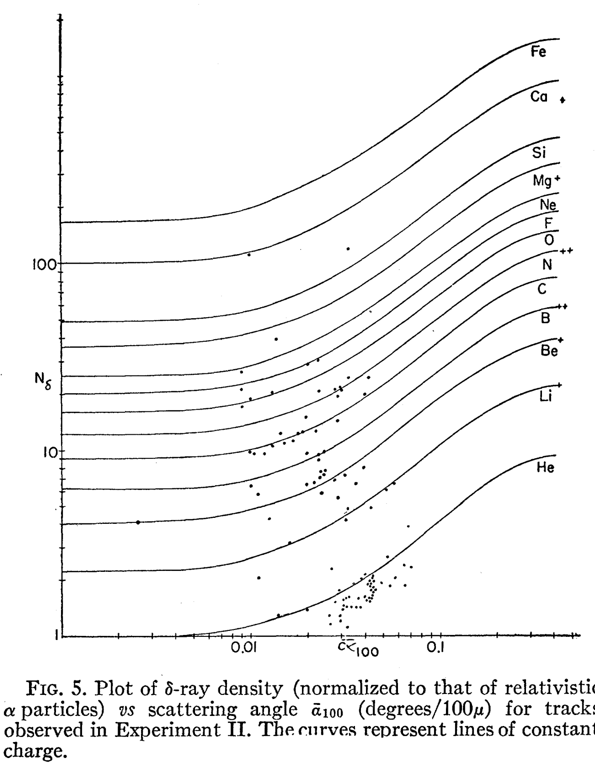

FIG. 5. Plot of δ-ray density (normalized to that of relativistic α particles) *vs* scattering angle $\bar{\alpha}_{100}$ (degrees/100μ) for tracks observed in Experiment II. The curves represent lines of constant charge.

Discussion of Data

An inspection of Fig. 5 shows that there are only 8 nuclei with $Z\geqslant 3$ having a kinetic energy per nucleon $\epsilon>850$ Mev, corresponding to $\epsilon>1$ Bev at the top of the atmosphere. An integral energy spectrum of the form[7] $1/(1+\epsilon)^{1.35\pm 0.1}$ would predict that the ratio of the number of nuclei with $\epsilon>1$ Bev to those with $\epsilon<1$ Bev at this latitude should be ~ 0.9 in contrast to the observed ratio of ~ 0.15 (the observed ratio for those nuclei with $Z\geqslant 6$ is ~ 0.22). It is difficult to see how the predictions of the above spectrum could be in serious error for these energy ranges since it is derived from the results of flux measurements of heavy nuclei at different latitudes. (This spectrum is consistent with the flux values observed at the two different latitudes reported in this paper.) This discrepancy strongly suggests the existence of a systematic error in the estimation of the momentum by the scattering method, resulting in an underestimation of the true momentum. This does not affect charge determination for $\bar{\alpha}_{100}\leqslant 0.01\,(p\beta c\geqslant 1.3$ Bev) because the δ-ray density for a given nucleus of $\beta=1$ differs from that of a nucleus of this momentum by less than 10 percent. However for $\bar{\alpha}_{100}\gtrsim 0.01$ this error can result in underestimation of charge by one unit and a resultant distortion of the charge spectrum for this momentum region.

An inspection of Fig. 5 shows that with the exception of one nucleus at $\bar{\alpha}_{100}=0.0025$ (which value was derived by using the relative scattering method[18] and for which a value of ~ 0.01 was obtained using the conventional method), that the maximum detectable value of $p\beta c$ in this experiment is ~ 1.3 Bev. The discrepancy previously mentioned may therefore be due to limitations imposed by instrumental or emulsion characteristics. The minimum value of the scattering detected in this experiment implies the existence of some systematic error of $\sim 0.01°$ in the scattering measurements which may exist for all the tracks. This error may be of a statistical nature arising from microscope noise which was not constant with cell size or it may be of a nonstatistical nature, possibly due to some anomalous emulsion distortion, in which case it would contribute arithmetically. If it is of a statistical nature (assumed Gaussian for purposes of estimation) it will appreciably affect only those values of $\bar{\alpha}_{100}\lesssim 0.02$. A correction of this nature does not alter the charge spectrum but does have the consequence of making the ratio of nuclei with $\epsilon>1$ Bev to those with $\epsilon<1$ Bev of the order of 0.5. An error of a nonstatistical nature which would contribute arithmetically to the observed scattering would affect those values of $\bar{\alpha}_{100}\lesssim 0.06$. This results in a considerable distortion of the charge spectrum but only a minor change in the total number of nuclei in the light and medium groups; we obtain a reclassification corresponding to 27 light nuclei, 32 medium nuclei and 5 heavy nuclei as contrasted with 30, 28, and 5 respectively (this involves the reclassification of one α-particle); the breakdown into component elements corresponds to 10 Li, 7 Be, 10 B, 10 C, 12 N, 5 O, 2 F, and 3 Ne as contrasted with 10 Li, 13 Be, 7 B, 12 C, 9 N,

[18] Noon, Kaplon, and Crussard, Phys. Rev. **95**, 1103 (1954).

3 O, 3 F, and 1 Ne in the uncorrected charge distribution shown in Fig. 6. The ratio of nuclei above and below $\epsilon=1$ Bev now becomes ~ 0.71. Since an arithmetical correction is the most extreme method of correcting a scattering measurement the results given above represent the maximum of charge spectrum distortion in this experiment.

Due to the uncertainties involved in the correction of the charge spectrum we adopt the following median values of the two limiting spectra at flight altitude for the analysis; 28.5 light nuclei, 30 medium nuclei, and 5 heavy nuclei.

Primary Flux Values

The tracks selected in this experiment have all traversed between 18 and 25.4 g/cm^2 of atmosphere (including packing material)[10] before reaching our emulsion stack. For the track length criterion adopted in this experiment the geometrical detection factor becomes independent of zenith angle, and at the depth of this exposure it is sufficiently accurate to consider all these nuclei as having traversed this depth at a mean zenith angle of 30° corresponding to a mean path in atmosphere of 20.7 g/cm^2.

TABLE II. Extrapolated primary flux values observed at 41° and 55° geomagnetic latitudes.

Primary flux values (particles/meter^2 sec steradian)			
Geomagnetic latitude	$M(6\leqslant Z\leqslant 10)$	$H(Z>10)$	$N_L^0/N_M^0(3\leqslant Z\leqslant 5)$
41°	7.1±1.3	2.6±0.9	$\leqslant 0.55$
55°	11.5±1.7	3.0±1.2	0.46±0.15

The observed fluxes at flight altitude are then extrapolated to the top of the atmosphere by means of the diffusion equations whose solutions were given previously under Experiment I; the same values of the parameters are used here. The following flux values were obtained after making a correction for ionization loss in the residual atmosphere.

$$N_H^0=3.0\pm 1.2 \text{ particles/meter}^2 \text{ sec steradian,}$$
$$N_M^0=11.5\pm 1.7 \text{ particles/meter}^2 \text{ sec steradian,}$$
$$N_L^0/N_M^0=0.40\pm 0.12.$$

The values for the medium and heavy nuclei fluxes are in substantial agreement with those obtained elsewhere.[2,4] If the flight did indeed obtain the altitude of 102 000 ft we find then $N_L^0/N_M^0=0.52\pm 0.15$ for the same ratio of light to medium nuclei at flight depth. The extreme limits for this ratio taking into account the uncertainty in depth and the effect of charge distortion are 0.35 and 0.65. We feel the most reliable value is 0.46±0.15.

An independent estimate of the contribution of interactions to the observed flux of light nuclei at flight altitude is obtained by an examination of those light nuclei whose measured energy when extrapolated to the top of the atmosphere is below the geomagnetic cut-off value for the latitude of the flight; four of the light nuclei are in this category and certainly must come from interactions of slow heavier nuclei. The maximum energy of heavy nuclei at the top of the atmosphere which could produce these secondaries is ~ 0.56 Bev/nucleon (we assume the velocity per nucleon is invariant in these interactions). If we assume energy independence for the production probabilities we then calculate, using the energy spectrum of Kaplon *et al.*[7] that the number of light secondaries produced by heavier nuclei with $\epsilon\geqslant 0.56$ Bev is $\geqslant 11$. This corresponds to a secondary light nuclei flux of $\geqslant 15$ in approximate agreement with the predictions obtained using the diffusion equations.

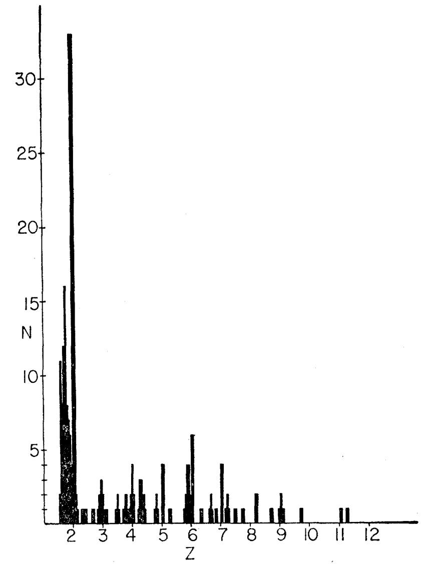

FIG. 6. Charge spectrum observed at flight altitude in Experiment II (not corrected for charge distortion).

DISCUSSION AND CONCLUSIONS

The results obtained for the primary flux values at the top of the atmosphere in this experiment are given in Table II. Within the limited statistics of these experiments, the relative fluxes for nuclei of $Z\geqslant 6$ at these two latitudes are consistent with the published spectra for heavy nuclei[7] and are in agreement with the flux values obtained at other laboratories.[1,2,4,7,19] Because of the limited statistics available it is impossible to say anything definitive about the charge spectrum for those nuclei with $Z>10$. We find the medium element group is predominantly composed of C, N, and O, the elements F and Ne comprising <10 percent of this charge group; of the elements C, N, and O we find C and N occurring in comparable amounts and the abundance of O< that of N. This result is in disagreement with that of Bradt and Peters who find that the

[19] G. D. Freier *et al.*, Phys. Rev. 84, 322 (1951).

abundance of N is distinctly less than that of either C or O and is somewhat more in agreement with the results obtained by the Minnesota and Bristol groups.

Of the two experiments described here we conclude that the second experiment is the most reliable in view of the preceding discussions and we therefore conclude that a finite flux of light nuclei exists at the top of the atmosphere, $N_L^0/N_M^0=0.46\pm0.15$. This result is in marked disagreement with that originally obtained by Bradt and Peters.[3] Their experiment, done at $\lambda=30°$, was of a similar type to our Experiment I and involved the necessity of establishing a minimum range to identify their tracks as nuclei of $Z\geqslant3$. It is possible (as in our Experiment I) that their null result is due to the existence of a finite amount of decision efficiency. The Bristol group reported $N_L^0/N_M^0\approx1.1$ at the top of the atmosphere; this result was obtained by extrapolation using the value of 0.23 for the probability of obtaining a light nucleus from either a medium or a heavy one in an interaction in atmosphere. Observationally our results at a comparable atmospheric depth are quite similar with respect to the ratio of light and medium nuclei. We have applied our extrapolation procedure to their data and find that it is consistent with a value of $N_L^0/N_M^0\approx0.6\pm0.1$. Their experiment is subject to the same criticism as that of our Experiment II. The energy spectrum derived from their data predicts a flux of medium nuclei at $\lambda=41°$ of $\frac{1}{3}$ the actual flux observed at that latitude. This suggests the existence of some systematic error in their scattering measurements such that the momentum is underestimated and could result in a distortion of their charge spectrum, the result of which would be to increase the flux of medium elements at the expense of the light-element group. Hourd, Fleming, and Lord[20] have recently reported their results of an analysis of a stack of emulsion flown at $\lambda=10°$ and obtain (using fragmentation probabilities similar to those used in the analysis here) a value of $N_L^0/N_M^0=0.33\pm0.09$. Further results on this problem have been recently obtained by the Minnesota group[21] using counter techniques in balloons flown at 41° geomagnetic latitude; they report an upper limit of $N_L^0/N_M^0\leqslant0.4$ and find that the best interpretation of their data is consistent with 0.

In view of the fact that substantial evidence has been presented for the existence of a finite ratio of light to medium nuclei at the top of the atmosphere of comparable amounts at both 10° and 55° geomagnetic latitude, the assumed validity of the null results obtained would imply the existence of an extreme time variation for this component. Since such a result would be quite difficult to understand (if at all), and in view of the fact that the experiments (at least in emulsion) giving a null result may be criticized on the basis of decision inefficiency, we conclude that the present evidence supports the existence of a finite flux of light nuclei in the primary radiation incident on the earth's atmosphere and the ratio of this flux to that of the medium-element group as obtained by different laboratories is consistent with 0.46 ± 0.15 and does not seem to be energy-dependent.

The existence of this finite flux of light nuclei in the primary radiation has important consequences for theories of the origin of cosmic radiation. If Li, Be, and B do not exist in significant amounts in the source region (or regions) of cosmic rays[22] which are retained in our galaxy by magnetic fields,[23] then an approximate value of the average lifetime of travel in interstellar matter can be set at $t\sim10^6/\rho$ years, where $\rho=$No. of H atoms/cm^3. In addition, with these assumptions, the relative magnitude of medium and heavy nuclei injected at the source cannot be significantly different from that observed in the primary radiation incident on the earth's atmosphere. In finite amounts of Li, Be, and B exist in the source region and the above assumption of galactic retention is retained, then $t<10^6/\rho$ years; if the galaxy has no retentive property and extra galactic origin is not considered, then the light elements must exist in the source region. In conclusion, we note that the lifetime $t\sim10^6$ years ($\rho\sim1$) is in agreement with that deduced by Morrison, Olbert, and Rossi[24] from considerations involving the isotropy and composition (other than Li, Be, and B) of the cosmic radiation.

We wish to thank the Aero Medical Field Laboratory of Holloman Air Force Base for supplying the balloon flight for Experiment I and the U. S. Office of Naval Research for sponsoring the balloon flight for Experiment II. We are indebted to Miss Phyllis Hull for her assistance both in scanning and in making scattering measurements and to Miss Barabara Hull for her assistance in some of the scanning.

[20] Hourd, Fleming, and Lord, Phys. Rev. **95**, 647 (1954).
[21] Leland Bohl (private communication).

[22] L. Aller, *Astrophysics*; *The Atmospheres of the Sun and Stars* (Ronald Press, New York, 1953). The astrophysical abundance of the light elements given here is $<10^{-3}$ that of the medium elements.
[23] E. Fermi, Phys. Rev. **75**, 1169 (1949).
[24] Morrison, Olbert, and Rossi, Phys. Rev. **94**, 440 (1954).