Flux of Cosmic-Ray Particles with $Z \geq 2$ over Texas*

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(Received May 15, 1958)

The fluxes of multiply charged cosmic-ray particles have been measured with nuclear emulsions in a high altitude balloon flight. The identification of α-particles was based on "blob-gap" measurements; that of elements with $Z \geqslant 3$, on δ-ray densities. The charge resolution obtained was satisfactory. To calculate the fluxes at the top of the atmosphere an extrapolation procedure, previously introduced in this laboratory, was employed. Two sets of parameters which account for the interactions in the residual atmosphere, differing considerably as far as their influence on the fluxes of light elements is concerned, were used. The results (in particles/m² sec sterad) are as follows:

	Set I	Set II
$Z=2$	90.9 ±8.0	89.2 ±8.0
$3 \leqslant Z \leqslant 5$	1.68±0.32	0.45±0.36
$6 \leqslant Z \leqslant 9$	5.60±0.58	6.05±0.56
$Z \geqslant 10$	2.19±0.38	2.19±0.38

INTRODUCTION

THE question of the relative fluxes of the different components of the primary cosmic radiation has been a subject of intensive study since 1948.[1–12] One of the most important and difficult problems is the determination of the abundance (or absence) of the light elements Li, Be, and B, from which it is believed that the mean life of cosmic rays in intergalactic space and the distribution of the sources could be estimated.

Most of the work has been done with nuclear emulsions and only very recently have counter techniques[13] become refined enough to permit reliable charge discrimination. The early experiments, performed with glass-backed emulsions, were subject to several uncertainties, and the results obtained by various authors differed widely as far as the relative abundance of elements in the stack and especially the ratio of light/medium elements was concerned.[2,3,5] Only very recently have large stacks of stripped emulsions, exposed at high altitude and at latitudes with a relativistic cutoff energy, been used for the study of the primary charge spectrum; consequently some of the principal sources of error inherent in the original experiments were minimized. Another uncertainty, especially in the determination of the light-element flux at the top of the atmosphere, is due to the extrapolation procedures involved. A separate paper by the authors of this work is devoted to a critical discussion of the extrapolation procedures.[14]

DETAILS OF STACK AND EXPOSURE

A stack of 60 Ilford G-5 stripped emulsions, 6 in. ×4 in.×400μ, was exposed with the 6-in. side vertical on February 6, 1956 to the cosmic radiation in a balloon flight over Texas. The flight duration at level altitude was about 6 hours, between 5.7 and 7.3 g/cm² vertical residual atmosphere. An additional 2 g/cm² were taken into account in the final calculations to allow for the packing material. The balloon proceeded in a nearly straight line from San Angelo, Texas, to Kirbyville, Texas. The flight curve is shown in Fig. 1.

A reference grid was printed on the emulsions to allow accurate tracing of tracks from one emulsion to the other. The processing was done by the usual temperature method.

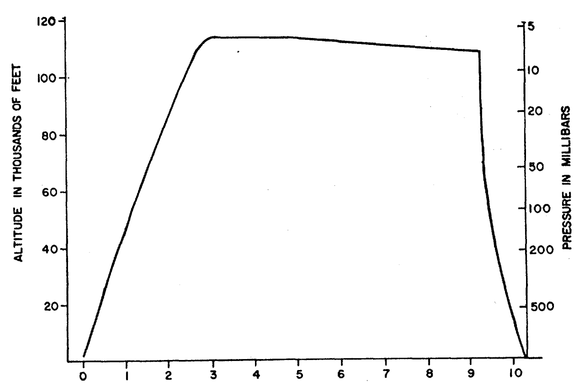

FIG. 1. The flight curve.

* This research was supported in part by the U. S. Air Force through the Office of Scientific Research, Air Research and Development Command.

[1] P. Freier *et al.*, Phys. Rev. **74**, 213 (1948).
[2] H. L. Bradt and B. Peters, Phys. Rev. **80**, 943 (1950).
[3] Dainton, Fowler, and Kent, Phil. Mag. **43**, 729 (1952).
[4] K. Gottstein, Phil. Mag. **45**, 347 (1954).
[5] Kaplon, Noon, and Racette, Phys. Rev. **96**, 1408 (1954).
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[7] H. Fay, Z. Naturforsch. **10a**, 572 (1955).
[8] T. H. Stix, Phys. Rev. **95**, 782 (1954).
[9] C. J. Waddington, Phil. Mag. **2**, 1059 (1957).
[10] Noon, Herz, and O'Brien, Nuovo cimento **5**, 854 (1957).
[11] Cester, Debenedetti, Garelli, Quassiati, Tallone, and Vigone, Nuovo cimento **7**, 371 (1958).
[12] Koshiba, Schultz, and Schein, Nuovo cimento **9**, 1 (1958).
[13] W. R. Webber, Nuovo cimento **4**, 1285 (1956).
[14] Engler, Kaplon, and Klarmann (to be published).

SCANNING CRITERIA AND DETECTION EFFICIENCY

The search for particles in the emulsion was done by the "area scan" method. To allow for sufficient path length in the stack for positive identification of tracks, the scan area in each plate started $1\frac{1}{2}$ in. from the top edge and ended $1\frac{1}{2}$ in. from the bottom edge. At the sides the scan area ended 1 cm from the true edge to avoid regions of anomalous development. Before starting the systematic scan, the grain count corresponding to minimum ionization and to relativistic α-particle tracks was determined in each scan plate on tracks identifiable by suitable interactions. It was found that variations in development did not change the grain count by more than 10% from one plate to another and even less in different regions of the same plate.

In the first part of the experiment, devoted principally to an α-flux determination, tracks were accepted in the scan if they (a) had an ionization by grain count of more than 3.3×minimum, (b) had a projected length of more than 1.42 mm in the scan plate, and (c) did not interact in the scan plate. The tracks satisfying these criteria were then traced back to their entrance at the top of the stack and down to their exit or to an interaction. Tracks which were obviously secondaries of interactions or were nonrelativistic by visual observation of a change in ionization were then discarded. From an original sample of 817 tracks satisfying the scanning criteria, 208 remained after tracing, of which only 11 were due to nuclei of $Z \geqslant 3$.

In order to select nuclei of $Z \geqslant 3$ more rapidly, a new area scan was then introduced in which criterion (a) was changed to accept only tracks of ionization greater than 5×minimum, (b) and (c) remaining the same. To guard against systematic errors in the grain count, the scanners frequently recounted the grain density of a standard track.

Tracks whose grain densities and lengths are close to the acceptance criteria may easily be lost by a scanner due to individual fluctuations in measurement conventions. To eliminate detection inefficiency due to this cause, only tracks well inside the acceptance criteria were accepted in the final analysis. Thus the minimum acceptable grain count was set well below the expected grain count of a relativistic α-particle or Li nucleus, respectively, and in the final analysis only tracks longer than 1.50 mm (projected length) in the scan plate were accepted. (The error in the length measurement as done by the scanners is less than 20μ.) Random losses of tracks because of "the human element" cannot be guarded against and have to be estimated. Table I lists the number of tracks accepted in the final analysis found by each scanner. It is seen that with one exception the yield of each scanner is in agreement with the average yield, indicating a uniform detection efficiency. In the scan for heavy nuclei the anomalously high yield of medium nuclei of observer B can be explained in terms of a statistical fluctuation, as is seen when the results of two plates scanned by observer B are displayed separately in Table I. It is therefore assumed that the detection efficiency is close to 100%.

A separate check on the detection efficiency is possible for the nuclei of $Z \geqslant 3$. A large fraction of the tracks passed through two or more "scan areas" in different emulsions. If we denote by R the ratio of the number of tracks of a given charge group found in all "scan areas" to the number of independent tracks in the same charge group, i.e., the average number of times a track of a given charge group was found in the scan, the result is

Charge group		R
Heavy, H	$(Z \geqslant 10)$	1.4
Medium, M	$(6 \leqslant Z \leqslant 9)$	1.4
Light, L	$(3 \leqslant Z \leqslant 5)$	1.6

Since our stack was rather small, the differences to be expected in R due to the variation in interaction mean free path between different charge groups is small. Assuming the detection efficiency for H nuclei to be close to 100%, the fact that R is essentially constant for all charge groups gives additional support to the view that even for light elements (where scanning losses are *a priori* most critical) the detection efficiency was high.

IDENTIFICATION OF ALPHA PARTICLES

In the first part of the scan, 197 tracks were found which satisfied the scanning criteria, were not discarded in tracing, and were not due to nuclei of $Z \geqslant 3$. Ionization measurements by the "blob-gap" method[15] were made at two points at least 4 cm apart on those of the above tracks which had a projected length of more than 1.5 mm in the scan plate. At each point 400 blobs and 50 gaps were counted in the middle of the emulsion, the resulting statistical error in the ionization determination being $\sim 5\%$. Calibration measurements were performed on the tracks of relativistic α-particles which

TABLE I. Scanning results. (The numbers quoted are particles found per cm².)

	(a) Alpha particles			
	Observer A		25.4±2.2	
	Observer B		27.1±5.3	
	Average		25.7±2.1	
	(b) Heavy primaries			
	L $3 \leqslant Z \leqslant 5$	M $6 \leqslant Z \leqslant 9$	H $Z \geq 10$	Total
Observer A	0.48±0.06	1.11±0.16	0.27±0.08	1.92±0.21
Observer B	0.63±0.11	1.60±0.18	0.31±0.08	2.54±0.22
Observer C	0.54±0.10	1.07±0.15	0.32±0.08	1.92±0.20
Observer D	0.67±0.16	1.10±0.21	0.32±0.11	2.09±0.29
Average	0.57±0.06	1.26±0.09	0.31±0.04	2.14±0.11
	Breakdown of scanning results of Observer B			
Plate I	0.59±0.15	1.30±0.19	0.36±0.12	2.26±0.30
Plate II	0.66±0.16	1.90±0.27	0.27±0.10	2.83±0.33

[15] P. H. Fowler and D. H. Perkins, Phil. Mag. **46**, 587 (1955).

produced high-energy disintegrations. The over-all accuracy of the ionization measurement on one point of a track including calibration but excluding systematic variations was of the order of 7%.

The purpose of these measurements was to discriminate between tracks of relativistic α-particles and those produced by slow protons, deuterons, and tritons. A proton track having an ionization of $3.5\times$minimum (given by g, the coefficient of the exponent of the gap length distribution) will stop inside the emulsion after $\sim$4 cm, while a deuteron of the same ionization will show a change of about 40% in g and a triton a change of 20% over the same distance. In order to check whether an observed difference between the values of g obtained at two points of the same track was the result of a statistical fluctuation or an actual change in ionization, the results were compared with the known variation of ionization with range of singly charged particles. In no case was there any ambiguity as to the nature of the particle producing the track.

In some cases a shorter length of track than 4 cm was available since the particle either interacted or emerged from an interaction. The identification in these cases was unambiguous, however, since in addition to ionization measurements the direction and collimation of shower tracks gave additional evidence for the nature of the particle.

Out of a total of 197 tracks on which measurements were made, 156 were identified as α-particles. A histogram of the measured values of g^* (normalized to the minimum ionization of a relativistic α-particle) is given in Fig. 2. As can be seen, the distribution is roughly normal, though perhaps slightly more peaked than expected.

Since all the tracks of α-particles were followed from the point of detection until they left the stack, the interaction mean free path in emulsion could be determined. In a total track length of 704.8 cm, 43 interactions were found, yielding a value

$$\lambda_\alpha = 16.4 \pm 2.5 \text{ cm}.$$

The above value of the interaction mean free path was not corrected for the finite size of the stack (the correction would increase λ_α by $\sim$5%); it is in agreement with the value 20.5 ± 2.2 cm quoted by Waddington[16] for α-particles in a comparable energy range.

The number of α-particles incident on the stack was computed by using the known distance each particle traveled in emulsion above the point of detection and an interaction mean free path of 20.5 cm. The result is $N_\alpha = 3.27\times10^5$ α-particles/m² vertical area. The number of independent particles, used in evaluating the standard deviations, is 156.

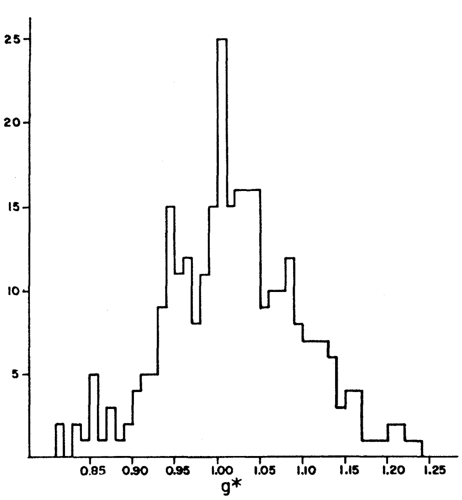

FIG. 2. g^* distribution of accepted α particles.

IDENTIFICATION OF NUCLEI OF $Z\geqslant 3$

The most commonly employed method for charge identification on tracks of relativistic multiply charged particles is the determination of δ-ray density. The difficulties and limitations of this method are well known and will not be discussed here. It is found that fairly good charge resolution can be obtained for tracks of nuclei with $Z\leqslant 9$; beyond that, other methods, such as photometric density measurements, must be used. Recently "blob-gap" measurements have also been used on very flat tracks of $Z\leqslant 9$ with good results.[9]

In the present work, δ-ray counting was employed on all tracks, while "blob-gap" measurements were made in addition only on tracks attributed to Li nuclei. On each track which satisfied the scanning criteria, 100 δ-rays (of 4 grains or more) were counted. The measurements were done by two independent observers choosing the tracks at random from the scanning results. In order to eliminate a change in the counting convention, several flat tracks were chosen as "reference tracks." Every day 100 δ-rays were counted on one of these tracks by each observer and the variation in the counting conventions were thus kept within 5%. Each observer measured about the same number of tracks and the results are shown in Fig. 3. The histograms are very similar in spite of the fact that the mean number of δ-rays/100μ for a particular charge was very different for the two observers in this experiment. For tracks of $Z\geqslant 10$, δ-ray counting is insufficient to allow reliable charge resolution and only the charge group as a whole for this class will be considered in this experiment. Moreover, for $Z\geqslant 10$, only tracks with zenith angle less than 70° were accepted for the final flux calculation.

In order to establish a charge calibration, two interactions having neither black, gray, nor minimum-ionization tracks were chosen. These interactions could be uniquely identified as corresponding to the following break-ups:

$$\text{Be}\rightarrow 2\alpha, \quad \text{O}\rightarrow 4\alpha.$$

[16] C. J. Waddington, Phil. Mag. 1, 105 (1956).

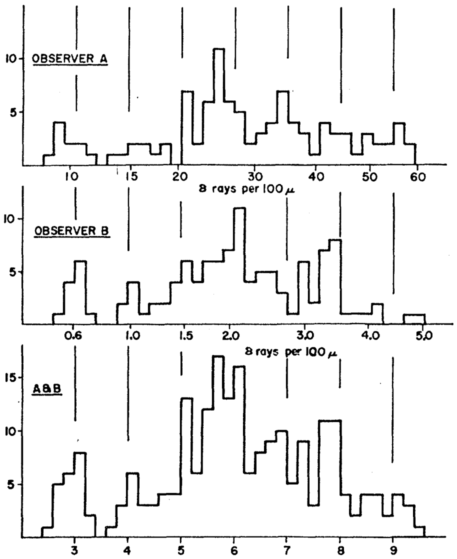

FIG. 3. Charge distribution in the emulsion.

200 δ rays were counted on each of several α-particle tracks and on the Be and O tracks leading to the above interactions. A relation of the form $N=aZ^2+b$ (where N is the number of δ-rays/100μ for a track of charge Z) was established and used in determining charges from δ-ray counts.

In addition, the quantity g (see previous paragraph) was determined by "blob-gap" measurements on all tracks which gave a value of $Z=3$ according to δ-ray counting. It turned out that $g_{\mathrm{Li}}/g_\alpha=2$ in agreement with the prediction of Fowler and Perkins.[15] Unfortunately the "blob-gap" method could not be extended reliably to higher charges, since in our work the tracks were too steep.

Additional information may be obtained from some of the fragmentations of the heavy nuclei. Table II lists all interactions with $N_h\leqslant 1$. Each disintegration is represented by the number of evaporation tracks (0 or 1), α-particle tracks, and minimum-ionization tracks associated with it. A charge can be assigned to the primary of these interactions on the basis of the number of α-particles and minimum-ionization tracks emitted in a forward cone of less than 5°. It is seen in Table II that only in one case was the assigned charge different from that found by δ-ray counting. In the one exceptional case the discrepancy may be explained by assuming both minimum tracks to be mesons. The agreement by both methods indicates that our charge calibration is essentially correct.

As in the case of the α-particles, the interaction mean free path of heavy nuclei in emulsion was determined. The results are

$$\lambda_H=10.9\pm2.9\text{ cm},\quad \lambda_M=13.2\pm1.9\text{ cm},$$
$$\lambda_L=13.3\pm2.8\text{ cm},$$

in agreement with the values

$$\lambda_H=9.1\text{ cm},\quad \lambda_M=13.0\text{ cm},\quad \lambda_L=15.7,$$

calculated on the basis of a geometrical model.[17] These latter values were used in extrapolating the flux to the top of the stack. In determining the total number of heavy nuclei incident on the stack, the distance traversed in emulsion from the point of entrance to each scan area in which a particle was found was taken into account. In the following table the number of independent particles found and the number crossing 1 meter² vertical area at flight altitude during the whole time of flight are given for each charge group.

Charge group	No. of indep. particles	No. of particles per m² vertical area
L ($3\leqslant Z\leqslant 5$)	72	0.771×10^4
M ($6\leqslant Z\leqslant 9$)	147	$1.88\ \times10^4$
H ($Z\geqslant 10$)	33	0.508×10^4

FLUXES AT THE TOP OF THE ATMOSPHERE

One of the reasons for discrepancies between the results of various authors as far as the fluxes at the top of the atmosphere are concerned is the extrapolation procedure to the top of the atmosphere. Since a separate paper[14] is devoted to a discussion of this aspect, no detail of the procedure used in the present work will be given here.

Two sets of fragmentation probabilities were used in the extrapolation to the top of the atmosphere; those given by Noon and Kaplon and those given by Rajopadhye and Waddington.[17,18] Not enough interactions were observed in the present work to allow an independent determination of these parameters, but they seem to indicate that the results of the Bristol workers are essentially correct. The values of both sets of fragmentation probabilities in air as well as the absorption mean free paths in air used are given in the Appendix.

Table III lists the fluxes derived at the top of the atmosphere. Column 1 was calculated using the Bristol fragmentation probabilities, Column 2 using the Rochester fragmentation probabilities, and Column 3 neglecting fragmentations in the atmosphere above the

TABLE II. Charge-indicating interactions.

No.	Evap. tracks	Alphas	Min tracks	Assigned charge	Charge by δ-ray count	Remarks
1	0	0	3	3	2.7	
2	0	1	2	4	4.1	
3	1	1	5	7	6.9	
4	0	1	6	8	7.9	
5	0	2	1	5	5.3	
6	0	2	2	5	5.5	1 min track at wide angle
7	0	2	4	6	5.9	2 min tracks at wide angles
8	1	2	5	8	7.7	1 min track at wide angle
9	0	2	8	7	6.8	5 min tracks at wide angles
10	0	3	2	7	5.8	1 min track at wide angle

[17] J. H. Noon and M. F. Kaplon, Phys. Rev. **97**, 769 (1955).
[18] V. Y. Rajopadhye and C. J. Waddington, Phil. Mag. **3**, 19 (1958).

TABLE III. Fluxes of this work extrapolated to the top of the atmosphere. All fluxes in particles/m² sec sterad.

Frag. prob. used	Bristol[a]	Total time Rochester[b]	None	Ceiling time Bristol[c]	Tot. time $\theta \leqslant 45°$ Bristol[c]
$N_H^0(\theta \leqslant 70°)$	2.19±0.38	2.19±0.38	2.19±0.38	2.29±0.40	1.63±0.37
N_M^0	5.60±0.58	6.05±0.56	6.70±0.55	5.89±0.61	6.18±0.70
N_L^0	1.68±0.32	0.45±0.36	2.62±0.31	1.94±0.33	1.18±0.34
$N\alpha^0$	90.9±8.0	89.2±8.0	98.5±7.9	94.5±8.3	90.3±10.1

[a] See reference 18.
[b] See reference 17.
[c] See reference 14.

stack. Column 4 was calculated using the Bristol fragmentation probabilities but assuming all the particles entered the stack while at ceiling altitude (no ascent correction); Column 5 using the Bristol fragmentation probabilities but accepting only particles with zenith angles of less than 45°. The errors quoted are standard deviations, based only on the number of independent particles observed in the stack. Wherever fragmentations were taken into account, the errors in the fluxes of higher charge groups were propagated.

A comparison of columns 1, 2, and 3 shows the dependence of the extrapolated flux on the fragmentation probabilities used. It is seen that whereas the variations due to different fragmentation corrections in the flux of M nuclei and α-particles are of the order of 10%, the differences between the extrapolated fluxes of L nuclei are very large. Although column 2 suggests that L nuclei are less abundant by a factor of 10 than M nuclei, it still indicates a finite amount of Li, Be, and B incident on the top of the atmosphere. The results of the present work are however incompatible with the view that L nuclei are as abundant as M nuclei in the cosmic radiation.[3]

Column 4 has been calculated in order to estimate the influence of the ascent time on the final flux. Waddington[19] has recently proposed a correction to fluxes calculated on the basis of ceiling altitude only in order to take into account particles entering the stack during ascent time. In the present work no correction of this kind was necessary since all of the flight curve was approximated by a series of straight lines (see reference 14). It is seen that except for L nuclei, where the ascent introduces a correction of 15%, the difference is only of the order of 4%.

Table IV lists the results obtained by other workers on the primary α-particle flux, which are intrinsically comparable with those of the present work. Thus fluxes obtained over Texas, $\lambda=41°$N, and over northern Italy, $\lambda=46°$N, are listed, the latter value being included since it has been pointed out[19,20] that the cutoff energy at both locations might be roughly the same. It is seen that most of the work was done with counter equipment. In those cases where no allowance was made for contributions from fragmentations of heavy nuclei in the atmosphere the quoted values should probably be decreased by about 10%. It is seen that all the data agree with each other to within one standard deviation.

Table V lists the relative abundance of heavy nuclei found in emulsions by several authors. The experiments listed in this table were performed over Texas or over northern Italy. Assuming the same energy cutoff at both locations, the relative abundances should be a function of altitude and zenith angle cutoff only. Since

TABLE IV. Flux determinations on primary α-particles at $\lambda=41°$N over Texas and at $\lambda=46°$N over northern Italy. All fluxes in particles/m² sec sterad.

Author	Method	Frag prob used	Month and year of flight	$N\alpha^0$	Location
Perlow *et al.*[a]	Proportional counters	None	2–50	110±20	Texas
Bohl[b]	Double scintillator	None	?	88±10	Texas
Horowitz[c]	Čerenkov counter	None	2–54	99±16	Texas
Webber and McDonald[d]	Čerenkov counter	None	2–54	82±9	Texas
Linsley[e]	Čerenkov ctr.+cloud chmbr.	None	2–54	88±8	Texas
McDonald[f]	Čerenkov ctr.+scintillator	Rochester[j]	1–55	87±9	Texas
Webber[g]	Čerenkov ctr.	Rochester[j]	1–55	74±5	Texas
O'Brien and Noon[h]	Emulsions	Rochester[j]	2–56	102±15	Texas
Present work	Emulsions	Rochester[j]	2–56	89±8	Texas
		Bristol[k]		91±8	
Fowler and Waddington[i]	Emulsions	Bristol[k]	9–54	93±8	N. Italy

[a] G. J. Perlow *et al.*, Phys. Rev. **88**, 321 (1952).
[b] L. Bohl, Ph.D. thesis, University of Minnesota, 1954 (unpublished).
[c] N. Horowitz, Phys. Rev. **98**, 165 (1955).
[d] W. R. Webber and F. B. McDonald, Phys. Rev. **100**, 1460 (1955).
[e] J. Linsley, Phys. Rev. **101**, 826 (1956).
[f] F. B. McDonald, Phys. Rev. **104**, 1723 (1956).
[g] See reference 13.
[h] B. J. O'Brien and J. H. Noon, Nuovo cimento **4**, 1285 (1956).
[i] P. H. Fowler and C. J. Waddington, Phil. Mag. **1**, 637 (1956).
[j] See reference 9.
[k] See reference 14.

[19] C. J. Waddington, Nuovo cimento **6**, 748 (1957).
[20] Simpson, Fenton, Katzman, and Rose, Phys. Rev. **102**, 1648 (1956).

TABLE V. Relative number of particles with $Z>3$ found in emulsions at $\lambda=41°N$ over Texas and at $\lambda=46°N$ over northern Italy. (The numbers are quoted in percentages of the total number of particles found with $Z>3$.)

Author[a]	Depth in g/cm²	Zenith cutoff	Be	B	C	
R	8.5	90°	7.0±1.8	14.8±2.7	27.0±3.9	
B	12	60°	7.1±1.7	11.8±2.3	25.1±3.5	
C	9	30°	8.7±1.7	10.9±2.0	25.0±3.2	
T	17	90°	10.0±1.7	14.1±2.1	29.8±3.2	
S	8.5	45°	9.3±3.1	27.8±5.7	25.9±5.5	
Author[a]	Depth in g/cm²	Zenith cutoff	N	O	F	$Z\geqslant10$
R	8.5	90°	16.5±2.9	13.5±2.6	7.0±1.8	14.4±2.7
B	12	60°	16.1±2.7	13.8±3.0	3.5±1.2	17.7±2.9
C	9	30°	16.7±2.5	15.4±2.4	2.2±0.8	21.2±2.9
T	17	90°	11.6±1.9	9.5±1.7	5.1±1.2	20.0±2.5
S	8.5	45°	3.7±1.9	7.4±2.7	3.7±1.9	22.2±5.0
Author[a]	Depth in g/cm²	Zenith cutoff	Be+B	C	N+O+F	$Z\geqslant10$
R	8.5	90°	21.8±3.4	27.0±3.9	37.0±4.7	14.4±2.7
B	12	60°	18.8±3.0	25.1±3.5	38.4±4.6	17.7±2.9
C	9	30°	19.6±2.7	25.0±3.2	34.3±3.8	21.2±2.9
T	17	90°	24.0±2.8	29.8±3.2	26.2±2.9	20.0±2.5
S	8.5	45°	37.0±6.9	25.9±5.5	14.8±4.0	22.2±5.0

[a] *R* = Rochester, present work; *B* = Bristol (reference 9); *C* = Chicago (reference 12); *T* = Torino (reference 11); *S* = Sydney (reference 10).

most observers admit low detection efficiency for Li, the numbers quoted are percentages of all particles with $Z\geqslant4$. The errors quoted are standard deviations. Although different methods of charge determination were used in the different experiment, the agreement on the relative abundance of elements in the emulsions is seen to be excellent with the exception of the results of the Sydney group. (Since the stack used by the Sydney group was exposed on the same flight with the stack used in the present work, the difference in the results is rather hard to understand.) The relatively high abundance of *L* nuclei found by the Torino group seems to reflect the increase in flux of these elements with decreasing altitude. The general agreement on the relative abundances is especially striking since previous experiments did not show any agreement whatever, and shows the vast improvement of charge determination techniques in recent years.

Table VI lists the extrapolated fluxes at the top of the atmosphere at both locations and by authors using stripped emulsions. Earlier work has not been included because of the much higher tracing efficiencies available in stripped emulsions. It is seen that all recent flux determinations are in agreement, with the exception of the Sydney results.†

TABLE VI. Fluxes at the top of the atmosphere (particles/m² sec sterad).

Author[a]	Frag. prob. used	N_L^0	N_M^0	N_H^0
B	Bristol[b]	2.3±0.4	6.1±0.6	2.5±0.3
R	Rochester[c]	0.5±0.4	6.1±0.6	2.2±0.4
	Bristol[b]	1.7±0.3	5.6±0.6	2.2±0.4
S	Rochester[c]	3.5±0.5	5.5±0.8	2.6±0.6
T	Torino[d]	1.7±0.4	5.5±0.4	2.8±0.4

[a] *B* = Bristol (reference 9); *R* = Rochester, present work; *S* = Sydney (reference 10); *T* = Torino (reference 11).
[b] See reference 18.
[c] See reference 17.
[d] See reference 11.

REMARKS ON GEOMAGNETIC THEORY

The observation of equal fluxes at geomagnetic latitude 41°N over Texas and at geomagnetic latitude 46°N over northern Italy indicates that the magnetic field as seen by the cosmic radiation cannot be given by the usual fixed centered dipole field as observed on the earth's surface. Several other experiments both at sea level and at high altitude support this view.[20–24] Thus the energy spectrum of the primary cosmic radiation cannot be reliably deduced from a comparison of fluxes measured at different, theoretical, geomagnetic cutoff energies.

The influence of the earth's shadow in geomagnetic theory can also be tested with the help of flux measurements. Figure 4 shows the variation of the flux $I(\theta)$ with zenith angle θ; here $I(\theta)$ is the number of particles

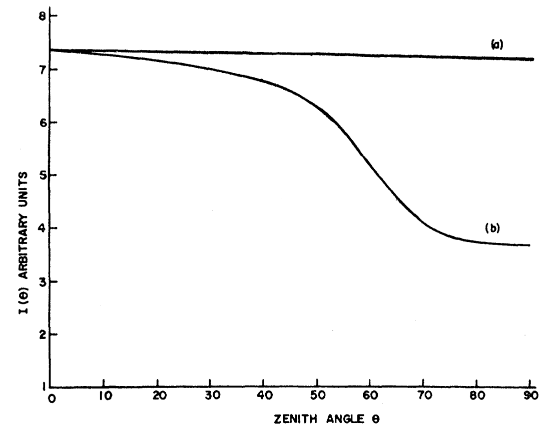

FIG. 4. Variation of the flux with zenith angle (*a*) using Störmer theory only; (*b*) including the earth's shadow effect.[25]

having a zenith angle θ crossing unit area normal to the direction of motion per second per steradian, averaged over all azimuth angles. $I(\theta)$ was calculated assuming an integral energy spectrum of the form $E^{-1.6}$ (E is the total energy per nucleon of the incoming particles) and the cutoff predictions of (a) Störmer theory only (b) Störmer theory plus earth's shadow cone at geomagnetic latitude of 40°, as given by Alpher.[25] It is seen that the shadow effect is rather small for zenith angles below 45°, but that it increases sharply at higher zenith

† *Note added in proof.*—Appa Rao, Biswas, Daniel, Neelakantan, and Peters [Phys. Rev. **110**, 751 (1958)] find essentially no light elements in an emulsion stack flown on the same flight as the present work. They use a quite different extrapolation procedure and obtain a medium flux about 25% higher than that reported here.

[21] C. J. Waddington, Nuovo cimento **3**, 930 (1956).
[22] P. H. Fowler and C. J. Waddington, Phil. Mag. **1**, 637 (1956).
[23] Danielson, Freier, Naugle, and Ney, Phys. Rev. **103**, 1075 (1956).
[24] R. E. Danielson and P. S. Freier, Phys. Rev. **109**, 151 (1958).
[25] R. A. Alpher, J. Geophys. Research **55**, 437 (1950).

angles. Using the curves of Fig. 4, one expects a difference in the extrapolated fluxes depending on whether only particles of zenith angle less than 45° are included or all particles are taken. The expected difference is

$$\frac{N_I(\theta_{\max}=45°)-N_I(\theta_{\max}=90°)}{N_I(\theta_{\max}=45°)+N_I(\theta_{\max}=90°)}=0.13.$$

By comparison of columns 1 and 5 in Table II it is seen that no such effect was observed in the present work. The weighted average of the experimentally determined differences is

$$\frac{N_{Z\geq2}(\theta_{\max}=45°)-N_{Z\geq2}(\theta_{\max}=90°)}{N_{Z\geq2}(\theta_{\max}=45°)+N_{Z\geq2}(\theta_{\max}=90°)}=0.02\pm0.015.$$

Although the errors in the above numbers may be slightly underestimated, the result is definitely in disagreement with the predictions of the earth's shadow effect. These predictions are also in disagreement with observations of the azimuthal asymmetries of cosmic ray fluxes.[24] Recent calculations by Schwartz[26] indicate that the original calculations of the earth's shadow effect were in error.

REMARKS ON THE ORIGIN OF THE COSMIC RADIATION

In the extrapolation of the fluxes observed at the top of the atmosphere to the origin, it is assumed that the origin of at least the greater part of the cosmic rays observed in the present work is located near the center of the galaxy. It has been shown by Ginzburg[27] that an assumption of a uniform distribution of sources leads to a greater relative abundance of light elements than observed at the top of the atmosphere. The extrapolation procedure used in the present work is due to Ginzburg.[27]

Cosmic rays emanating from a point source are assumed to diffuse through the whole volume of the galaxy and the galactic halo. In the estimation of the diffusion constant D, it is assumed that magnetic fields are constant over a certain effective length l after which they are essentially changed. This effective length is taken to be of the order of the distance between gas clouds, 3×10^{20} cm, yielding a diffusion constant of $D=\frac{1}{3}lv=3\times10^{37}$ cm/yr. Using this constant diffusion coefficient and taking into account the fragmentations of heavy nuclei, the diffusion equations are

$$\frac{\partial N_k(r)}{\partial t}=\frac{D}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial N_k(r)}{\partial r}\right)-\frac{N_k(r)}{T_k'}+\sum_{i=1}^{k-1}\frac{P_{i,k}N_i(r)}{T_i}+Q_k\delta(r)=0,$$

where $N_k(r)$ is the number of nuclei of type k per unit volume at r; T_k is the interaction mean free time (i.e., the time needed to traverse an interaction mean free path); T_k' is the absorption mean free time; $P_{i,k}$ are the fragmentation probabilities (i.e., the average number of nuclei of type k emitted from an interaction of a nucleus of type i); and Q_k is the source strength (the number of particles of type k formed at the source per unit volume and time). The solutions to these equations are

$$N_k(r)=\frac{Q_k}{4\pi Dr}\exp\left[-\frac{r}{(DT_k')^{\frac{1}{2}}}\right]+\sum_{i=1}^{k-1}D_k^i\left[\frac{Q_i}{4\pi Dr}\exp\left(-\frac{r}{(DT_k')^{\frac{1}{2}}}\right)-N_i(r)\right],$$

where

$$D_k^i=\beta_{ik}(P_{i,k}+\sum_{j=1}^{k-i-1}P_{i,k-j}D_k^{k-j}),$$

$$\beta_{ik}=\left[T_i\left(\frac{1}{T_i'}-\frac{1}{T_k'}\right)\right]^{-1}.$$

The above equations are valid for differential energy intensities. They are valid for integral energy intensities only under the assumption that the fragmentation probabilities are energy independent.

In the derivation of the mean free times, experimental values for the cross section of protons on heavy nuclei quoted by Rajopadhye and Waddington[18] have been used. A density of 0.1 atom/cc has been assumed for interstellar matter (to take into account the low density in the galactic halo) and a composition of 90% H and 10% He by number was assumed for interstellar gas. Following are the mean free paths and mean free times used in the extrapolation:

	H	M	L	α
$10^{-25}\times\lambda$ (in cm)	2.08	3.88	5.78	9.85
$10^{-25}\times\lambda'$ (in cm)	2.93	4.26	6.25	10.03
$10^{-8}\times T$ (in yr)	0.22	0.41	0.61	1.04
$10^{-8}\times T'$ (in yr)	0.31	0.45	0.66	1.06

For fragmentation probabilities the following values were used:

	$P_{H,M}$	$P_{H,L}$	$P_{H,\alpha}$	$P_{M,L}$	$P_{M,\alpha}$	$P_{L,\alpha}$
A	0.36	0.64	2.28	0.49	2.08	1.97
B	0.36	0.02	0.57	0.05	1.26	0.66
C	0.36	0.27	1.79	0.34	1.60	1.50
D	0.36	0.11	1.12	0.26	1.57	1.25

The following densities were used (r_0 is the source-earth distance):

	$N_H(r_0)$	$N_M(r_0)$	$N_L(r_0)$	$N_\alpha(r_0)$
I	2.2	5.6	1.7	91
II	2.2	6.1	0.5	89

The distance of the source from the earth can be

[26] M. Schwartz (private communication).

[27] V. L. Ginzburg, *Progress in Cosmic-Ray Physics* (to be published).

TABLE VII. Source abundance ratios of primary nuclei for different assumptions concerning primary flux (I and II), source-earth distance (r_0), and fragmentation probabilities (A, B, C, D).

Flux at the top of the atmosphere used	Set of $P_{i,j}$ used	$10^{-22}\times r_0$ (in cm)	Q_H/Q_M	$Q\alpha/Q_M$	$Q\alpha/(Q_H+Q_M)$
I	*A*	1.9	0.48	13.5	9.17
I	*B*	10.9	1.8	10.6	3.77
I	*C*	3.3	0.56	12.4	7.97
II	*A*	0.55	0.57	25.5	16.2
II	*B*	3.0	0.49	11.9	7.97
II	*C*	1.0	0.40	13.4	9.58
II	*D*	1.5	0.62	21.5	13.3
Suess and Urey cosmic abundances	···	···	0.375	96.0	70.0

derived from the equations by assuming $Q_L=0$. This assumption is reasonable in view of the absence of these light elements in tables of cosmic abundances,[28] supported by theories of the formation of elements.[29] The result of the calculation is given in Table VII for various combinations of $N_I(r_0)$ and $P_{i,j}$. For each of these distances the abundance ratios of the groups at the source have been calculated and compared with the ratios derived from the cosmic abundance of elements given by Suess and Urey.[28]

An examination of the diffusion equations shows that the results are rather independent of the choice of values for the diffusion coefficient D or for the density of interstellar matter. A change by a factor of 10 in either of these parameters will change the distance r_0 by a factor of $(10)^{\frac{1}{2}}\simeq 3$, but will not affect the relative source strengths. Sets A and B of the fragmentation probabilities are upper and lower bounds of the values given by the Chicago and Bristol groups,[12,18] and most probably are exaggerated. Set C is the average of the sets given by the two groups and seems to be a reasonable approximation to the true values. Set D was used to get a reasonable upper limit on the source distance when the fluxes of set II having very little L abundance are used. Sets I and II of the fluxes seem again to be upper and lower limits on the abundance of L nuclei at the top of the atmosphere. Since reflection at the boundaries of the galaxy is not included in the diffusion equations, the calculated distances are probably slightly too large.

Since the center of the galaxy is at a distance of 2.5×10^{22} cm from the solar system, our assumption of a concentration of sources near the center seems to be justified by the results. The source strength ratios are in no case in agreement with the abundance ratios given by Suess and Urey.[28] In all cases the relative abundance of alpha particles in the cosmic-ray source is much smaller than is expected from the cosmic abundances. On the other hand, the calculated relative source strength of alpha particles is too high to allow for a source of heavy nuclei only. Investigations leading to the hypothesis of a source consisting entirely of heavy nuclei most probably did not take into account the alpha particle fluxes observed. It appears that this is a very critical aspect of the problem.

It has been customary to use a one-dimensional extrapolation rather than the radial diffusion equations given above, in extrapolations to the origin of the cosmic radiation. The main difference between the two methods is that the radial diffusion equations yield a straight-line distance between the origin and the earth, whereas the one-dimensional extrapolation yields the mean path traversed by the cosmic radiation. Using the same parameters in both equations, the latter path length is greater by a factor of 10^3 than the straight-line distance. However, the relative abundances at the origin, defined as the position at which the intensity of L nuclei vanishes, as well as the mean life-time of the cosmic radiation are the same irrespective of the way the extrapolation is done.

It is apparent from the results given in Table VII that the origin of cosmic rays cannot be explained in terms of the relative abundance of elements in stellar atmospheres. The way to a better understanding of the source of cosmic radiation most probably leads through a knowledge of the relative abundance of elements in the cosmic radiation at large distances from the earth. It seems that the frequency of occurrence of elements in the cosmic radiation (as observed at the earth) is even harder to understand in terms of the cosmic abundance of elements than is shown in the above table. Thus it appears that the ratio C:N:O is inverted in the cosmic radiation with respect to the cosmic abundance tables. Furthermore it seems that F is abundant in quantities comparable to the other medium nuclei in the cosmic radiation whereas it is essentially absent in cosmic abundance tables. These data, however, have still to be extrapolated back with the help of fragmentation probabilities for individual nuclei, before any definite statements can be made. At the present stage of our knowledge of fragmentation probabilities this cannot be done.

ACKNOWLEDGMENTS

The authors wish to thank the Office of Naval Research and especially Commander R. C. Cochrane for sponsoring the balloon flight. It is a pleasure, too, to acknowledge the work of the Engineering and Development Department of General Mills, Inc., in connection with the flight. For their assistance in scanning, the authors are grateful to Mrs. John Allyn, Miss Elaine Beyo, Mrs. R. A. Hawrylak, Mrs. Joseph Klarmann, and Mrs. John Rutherford.

APPENDIX

The following parameters were used in the extrapolation to the top of the atmosphere.

[28] H. E. Suess and H. C. Urey, Revs. Modern Phys. **28**, 53 (1956).

[29] Burbidge, Burbidge, Fowler, and Hoyle, Revs. Modern Phys. **29**, 547 (1957).

(a) Interaction mean free paths (in air):

$\lambda_H = 18$ g/cm^2; $\lambda_M = 26.5$ g/cm^2; $\lambda_L = 31.5$ g/cm^2.

(b) Absorption mean free paths (in air):

$$\lambda_I' = \lambda_I/(1-P_{II});$$

$\lambda_H' = 24$ g/cm^2; $\lambda_M' = 30.5$ g/cm^2; $\lambda_L' = 34.0$ g/cm^2; $\lambda_\alpha' = 45.0$ g/cm^2.

(c) Fragmentation probabilities (in air):

Bristol values (B)[18]:

$$P_{HM} = 0.46;\quad P_{HL} = 0.21;\quad P_{H\alpha} = 1.23;$$
$$P_{ML} = 0.23;\quad P_{M\alpha} = 1.27;\quad P_{L\alpha} = 0.79.$$

Rochester values (R)[17]:

$$P_{HM} = 0.27;\quad P_{HL} = 0.48;\quad P_{H\alpha} = 2.07;$$
$$P_{ML} = 0.42;\quad P_{M\alpha} = 1.42.$$

PHYSICAL REVIEW VOLUME 112, NUMBER 2 OCTOBER 15, 1958

Parity Nonconservation in the Decay of Free and Bound Λ Particles

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(Received June 16, 1958)

A quantitative estimate is made of the branching ratio between two-body and more complicated mesonic decay modes for $_\Lambda He^4$ and $_\Lambda H^4$, as function of their spin J and the ratio p/s of the s- and p-channel amplitudes in free Λ decay. Comparison with the data on $_\Lambda H^4$ decay indicates that $J=1$ is rather improbable and that, with $J=0$, an upper limit on p/s is about unity, a lower limit of 0.45 being obtained from the observations on up-down asymmetry in polarized Λ decay. The theoretical and experimental values for the nonmesonic/mesonic ratio in hypernuclear decay are compared in the light of these limits on p/s. Assuming validity of the $\Delta T=\frac{1}{2}$ rule, the variations in the π^-/π^0 ratio for decays of light hypernuclei ($Z \leqslant 2$) due to the effect of the Pauli principle are also estimated. A brief discussion of $_\Lambda H^3$ decay is given in an appendix.

1. INTRODUCTION

PLANO *et al.*[1] and Crawford *et al.*[2] have recently established that the decay pions from $\Lambda \to p+\pi^-$ decay events following the $\pi^-+p \to \Lambda+K^0$ production reaction in the energy range 950 to 1100 Mev are emitted with a marked up-down asymmetry relative to the normal to the $\Lambda+K^0$ production plane. The existence of this asymmetry establishes both that this reaction produces Λ particles with a strong polarization perpendicular to their production plane, and that the $\Lambda \to p+\pi^-$ decay process does not conserve parity. In fact, as Lee and Yang[3] have pointed out, the asymmetry observed exceeds the maximum value permitted (with the angular distribution observed in the Λ rest system) for a Λ spin of $\frac{3}{2}$ or greater, being compatible only with spin $\frac{1}{2}$ for the Λ particle. Parity nonconservation in the decay of a spin-$\frac{1}{2}$ Λ particle allows the emission of both s and p waves for the outgoing pion, and the decay amplitude will have the general form

$$H(\Lambda \to p+\pi^-) = s + p\boldsymbol{\sigma}\cdot\mathbf{q}/q_\Lambda, \tag{1.1}$$

where $\mathbf{q}$ is the momentum of the decay pion in the Λ rest system (q_Λ its value for free Λ decay), $\boldsymbol{\sigma}$ denotes the baryon spin vector, and s, p denote the amplitudes for the $l_\pi=0$ and $l_\pi=1$ channels, respectively. With this expression (1.1), the angular distribution of the pions from decay of polarized Λ particles takes the form

$$(1+\alpha P_\Lambda \cos\theta), \tag{1.2}$$

where θ is the polar angle of the outgoing pion relative to the initial spin direction, P_Λ is the mean polarization of the parent Λ particles, and α denotes the combination

$$\alpha = 2\,\mathrm{Re}(s^*p)/(|s|^2+|p|^2), \tag{1.3}$$

whose value is a property of the detailed mechanism giving rise to the Λ-decay process. From the experiments mentioned above, only the combination αP_Λ can be determined. The value obtained, averaged over all production angles for the Λ particles, is given by

$$\alpha\bar{P}_\Lambda = 0.55 \pm 0.10. \tag{1.4}$$

The parameter $-\alpha$ also gives the value of the mean longitudinal polarization for the protons recoiling from Λ decay, this polarization being specified in the Λ rest system and averaged over all directions of decay. For Λ particles which decay in flight, the recoil protons observed in the laboratory system will then generally have a transverse component of polarization resulting from their longitudinal polarization in the Λ rest system and this may be measured by observations on the left-right asymmetry in their scattering from a target of known polarization properties in the standard way.

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