THE FLUX OF PRIMARY COSMIC RAY NUCLEI OF ATOMIC NUMBER $Z \geqslant 2$ AT GEOMAGNETIC LATITUDE 30°

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ABSTRACT

The method of determining the primary flux of nuclei with atomic number $Z \geqslant 3$ developed by Bradt and Peters, has been extended to include all nuclei of charge $Z \geqslant 2$. It is shown that the method permits the identification of primary helium nuclei with an efficiency $\eta \geqslant 90\%$. The primary α-particle flux obtained in this way is in very good agreement with that obtained by other methods and the relative flux values for nuclei of atomic number $3 \leqslant Z \leqslant 5$ and $6 \leqslant Z \leqslant 9$ agree with previous determinations.

I. INTRODUCTION

AN analysis of the relative intensity of light nuclei in the primary cosmic radiation was carried out by Bradt and Peters (1950)* with stacks of glass backed photographic emulsions exposed in balloon flights at geomagnetic latitude 30°. The experiment showed that under 20 g./cm.^{2} of residual atmosphere the relative intensity of the flux of nuclei with atomic number $3 \leqslant Z \leqslant 5$, $6 \leqslant Z \leqslant 8$ and $Z \geqslant 9$ is in the ratio of about 1 : 5 : 2.

Taking account of fragmentation processes in the upper atmosphere, Bradt and Peters concluded that the primary radiation contains few, if any, Li, Be, B nuclei near the top of the atmosphere.

This conclusion has been confirmed by Stix (1954), but has been challenged by other experimenters [Dainton, Fowler and Kent (1951, 1952), Gottstein (1953, 1954), Kaplon, Noon and Racette (1954)]. It seems, therefore, necessary to re-examine the validity of the various interpretations.

In this paper which forms part of a series dealing with this subject we shall investigate only one of the relevant questions:

What is the relative efficiency of detecting particles of various charges in the experiment of Bradt and Peters, and is it possible that the low

* This paper will be referred to as reference I.

relative intensity of Li, Be, B nuclei found by them is due to a low efficiency of detection for light nuclei compared to heavier ones ?

The most direct method of answering this question consists in using the same plates and exactly the same procedure as that used in reference I, but to extend the measurements to particles of still lower ionizing power. This was done by changing the selection criteria to include primary α-particles, and determining their flux and the efficiency of their detection and identification.

Since the α-particle flux at various latitudes is known from measurements in which quite different techniques are used, the efficiency of the method can also be determined by comparison. If the method turns out to be close to 100% efficient for detecting α-particles it is safe to conclude that it has a still higher efficiency for the more than twice as heavily ionizing Lithium nuclei and the still heavier components.

The measurements described here had actually been completed in 1951, but were not analysed and published before.

II. Experimental Procedure

(*a*) *The Apparatus.*—The apparatus was the same as that used by Bradt and Peters. It consisted of a stack of 24 glass backed Kodak NTB 3 emulsions of overall dimensions 3″×10″. The plates were exposed inside a thin metal container and inserted into groves which had been machined on a milling machine. This insured that the plate spacing (d) was exactly 3 mm. Between any pair of NTB 3 emulsions was inserted a glass plate coated with less sensitive NTA emulsions. Between corresponding points on neighbouring NTB 3 emulsions there were 0·55 g./cm.^{2} of absorber (consisting mainly of glass), distributed over a distance of 3 mm.

The stack was exposed for 6 hours at geomagnetic latitude $\lambda = 30°$ under 20 g./cm.^{2} of residual atmosphere.

The emulsion thickness at the time of exposure was measured in the following way:

Tracks of heavy primary nuclei were traced through neighbouring plates. If l is their track length in one plate and L the distance between corresponding entrance points in adjacent emulsions, then the emulsion thickness at the time of exposure "a" is given by:

$$a = \frac{l}{L} d.$$

The average value of " a " was found to be 69 μ† and its variation from the average less than 7% as estimated from the straggling of individual thickness determinations and from thickness variations measured in the processed emulsion layers.

(*b*) *Selection Criteria.*—Fig. 1 shows the position of the three plates involved in this study. The surveyed area lies in the centre of the solidly drawn portion of Plate B 445, and was 3 cm. high, and 6 cm. wide. In this area of 18 cm.^{2} all tracks were selected provided their projected length in the emulsion exceeded 400 μ and their grain density exceeded 35 grains per 75 μ. (In the experiment reference I, the corresponding value was 60 grains/75 μ.)

Plateau grain density in this emulsion was found to be 16 grains/75 μ, so that the grain density of an α-particle must be much greater than 35 grains/75 μ. The survey included, therefore, slow singly charged particles ($v/c \leqslant 0 \cdot 55$) and all multiply charged particles, whatever their energy, provided their trajectories were sufficiently parallel to the emulsion to produce the required minimum track length.

It is the purpose of this paper to show, that by a simple range criterion and without any reference to their ionizing power, relativistic α-particles (and other relativistic multiply charge nuclei) can be separated from the remaining tracks with high efficiency.

In order to show that the efficiency is high we must, however, make use of the length distribution and the grain density distribution of these tracks.

(*c*) *Range Criteria.*—A particle passing through the surveyed area of Plate B 445 may be incident from the upper hemisphere in such a direction as to traverse the stack without passing through either of the neighbouring plates (*see* Fig. 1). Particle tracks which have this position and direction, irrespective of whether they enter from the outside or originate in the stack, are put into Class O, meaning that they are not traceable into adjacent plates either into the upper or into the lower hemisphere.

A particle may be incident from the upper hemisphere in such a direction that in traversing the stack it passes through a neighbouring plate:

† This value differs from the approximate average thickness of 80 μ given in reference I. The flux values in reference I should, therefore, be increased slightly but the relative strength of various components is not affected by this correction, because its measurement does not depend on emulsion thickness.

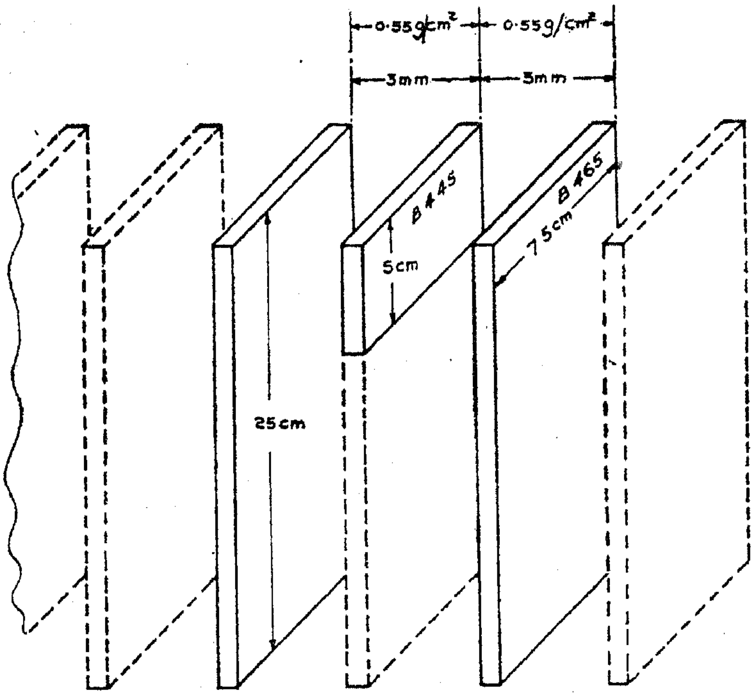

FIG. 1

(i) *before* reaching the surveyed area of Plate B 445,

(ii) *after* reaching the surveyed plate, or

(iii) *before and after* reaching the surveyed plate.

Particle tracks with the corresponding positions and directions, irrespective of whether they enter from the outside or originate inside the stack, are put into Classes U, L and UL, respectively, meaning that the tracks are traceable into the upper, the lower or the upper and the lower hemispheres.

We have tried to find the continuation in the appropriate adjacent plate or plates of all tracks which satisfied the selection criteria in Plate B 445, and which because of their geometric location fell into Classes U, L or UL. For this purpose we calculated the probable location of the track in the neighbouring plate from its direction and projected length in the surveyed area and from the known plate separation. We then surveyed an area of 6 mm.^{2} surrounding the predicted location.

A track is said to have been "followed successfully", if in the region surrounding the predicted location, a track was found whose grain density exceeded 35 grains/75 μ, and whose track length did not differ by more than 20%, either in its horizontal or vertical components, from the corresponding lengths in the surveyed area.

"Successful tracing" means, therefore, one of three things:

(i) The track is due to a fast particle of charge $Z \geqslant 2$ which did not suffer a destructive nuclear collision in the intervening glass plate.

or (ii) The track is due to a proton, deuteron or triton. If a proton, its energy must exceed 60 MeV, since a track whose length in the emulsion exceeds 400 μ, must traverse at least 3·2 g./cm.^{2} of glass to reach the neighbouring emulsion; on the other hand the energy must not exceed 200 MeV so that its grain density lies above 35 grains/75 μ.

or (iii) The tracks in the two neighbouring plates are due to two different particles and their relative position and orientation happens to satisfy our tracing criteria.

We shall show that in our comparatively light exposure (6 hours at low latitude in the stratosphere) "successful tracing" alone separates almost quantitatively the heavy primary and particularly the α-particle component from all other particles.

III. Experimental Results

(*a*) *The Efficiency of Surveying and Tracing.*—470 tracks satisfying the selection criteria were found in the 18 cm.^{2} surveyed in Plate B 445. Of these, 9 belonged to heavy primaries of atomic number $Z < 2$; their charge distribution is given in Section III (*d*).

Four tracks, due to relativistic α-particles, are strictly parallel and very closely bunched; they can be shown to arise as fragments in the collision of a heavy primary particle in the glass backing of Plate B 445, a collision of the type discussed earlier (Bradt and Peters, 1949). These four tracks are omitted from the discussion which follows.

The remaining 457 tracks are classified as to whether they are followable into the upper, or lower hemisphere, or both, as discussed above:

Class UL (followable in both hemispheres)	165 tracks
Class U (followable into upper hemispheres only) ..	54 tracks
Class L (followable into lower hemispheres only) ..	175 tracks
Class O (not followable)	63 tracks
Total ..	457 tracks

We first carry out some tests to determine η_s the efficiency of the survey (selection efficiency) and to obtain at least an approximate value for η_t the efficiency with which the continuation of a track traversing two adjacent plates, could be located (tracing efficiency).

For this purpose we surveyed with identical selection criteria an additional area of 21·5 cm.^{2} in Plate B 465, which is one of the two plates adjacent to B 445. Of the tracks found in this survey we selected those which were so oriented that they could have a continuation in the originally surveyed area of Plate B 445. There were 218 such tracks. We tried to locate their continuation in B 445 and were successful in 38 cases. We now selected among the tracks of the first survey (B 445) those which had been traced successfully into the area of the second survey (B 465) and found 34 such tracks.

33 of the tracks found and traced successfully were common to both experiments.

1 track found and traced successfully in the first survey was missed (not found) in the second survey.

5 tracks which were found and traced successfully in the second survey, were found also in the first survey, but not successfully traced.

From this we obtain an estimate for the survey efficiency η_s' and the tracing efficiency η_t' for particles with ionization *equal to or larger* than that of relativistic α-particles. If we designate by the letter n the total number of tracks which actually have segments in both the surveyed areas we get:

$$n\, \eta_s'^2\, \eta_t'^2 = 33$$

$$2n\, \eta_s' (1 - \eta_s')\, \eta_t = 1$$

$$2n\, \eta_s'^2\, \eta_t' (1 - \eta_t') = 5.$$

These equations yield:

$$n = 39$$

$$\eta_s' = 98{\cdot}5\%$$

$$\eta_t' = 93\%$$

If we exclude the tracks of 5 primaries heavier than helium which are included among the 33 particles common to both investigations, we obtain the corresponding efficiencies for tracks whose ionization *equals* that of relativistic α-particles:

$$\eta_s = 98 \cdot 5\%$$

$$\eta_t = 92\%$$

We confirm the high *survey* efficiency by plotting the length distribution of the 175 tracks from the original survey whose grain density is consistent with their being tracks of relativistic α-particles. In Fig. 2, the number of

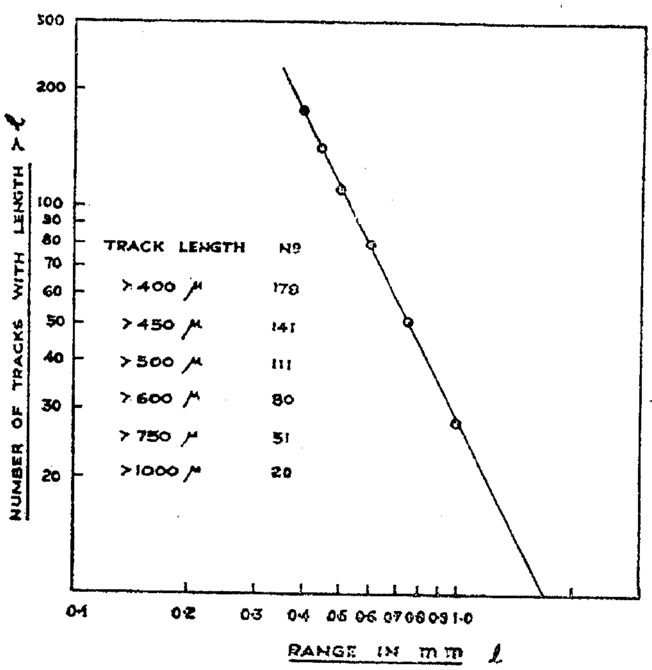

FIG. 2.

tracks whose projected length exceeds l is plotted against l. The solid line represents the relation:

$$N_{>l} \approx \frac{1}{l^2}$$

which is the expected length distribution for purely geometric reasons. Any departure of survey efficiency from 100% must primarily effect the short tracks whose length is close to the limit of 400 μ, set by the selection criteria. The fact that the experimental points at small ranges do not fall below the theoretical curve, confirms the high survey efficiency η_s deduced above.

In order to obtain independent corroboration for the high *tracing* efficiency indicated above, a more detailed analysis of the tracks is needed. We proceeded to measure the grain density of all 457 tracks in Plate 445. We also determined separately the grain density of secondary but relativistic α-particles choosing jets of parallel tracks which originated in the break up of heavy primary nuclei in other parts of the stack. We find for relativistic α-particles a mean grain density of $51 \cdot 8$ grains/75 μ. In no case did their grain density fall below 45 or exceed 57 grains/75 μ in any one emulsion traversed. In the histograms (Fig. 3) where the number of particles in various

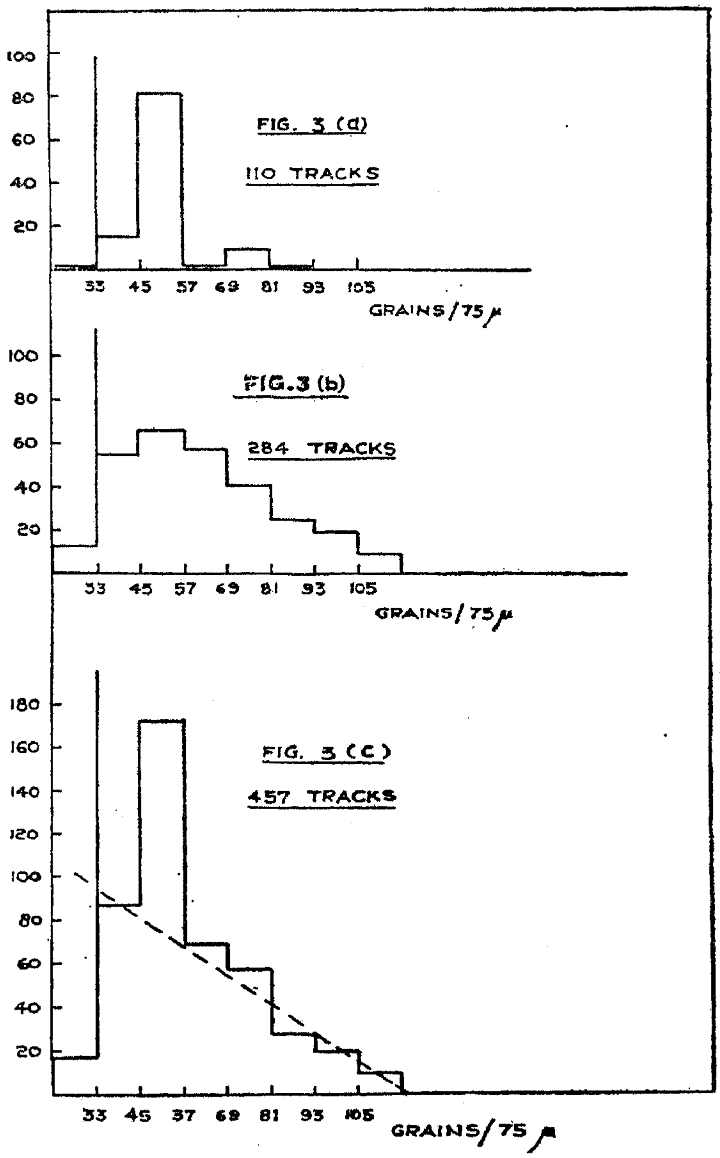

Fig. 3.

grain density intervals is shown, we have marked the abscissa in units whose width is 12 grains/75 μ, and only one of these intervals (45–57 grains/75 μ) can contain relativistic α-particles. (We are not asserting that particles in this interval of grain density are relativistic α-particles, but only that tracks which are due to relativistic α-particles must fall into this grain density interval. The arguments which follow are independent of the width of this grain density interval and depend only on the fact that it is wide enough to accommodate all relativistic α-particle tracks.)

Fig. 3 (*a*) shows the grain density distribution in the surveyed area of all those tracks which were successfully traced in at least one neighbouring plate.

Fig. 3 (*b*) shows the grain density distribution of all those tracks which, though followable (Classes U, L, UL), were not found near the predicted position.

Fig. 3 (*c*) shows the grain density distribution of all tracks irrespective of whether they were followable or not and of whether tracing was successful or not.

Let us first consider Fig. 3 (*c*). By extrapolating the background of secondary particles through the peak of the distribution along the curve shown in the diagram we can estimate the primary α-particle flux. The peak above the extrapolated background contains 96 particles. As we shall see later the corresponding flux is in good agreement with that previously obtained by Goldfarb, Bradt and Peters (1950) by a similar method; it is also in agreement with the extrapolated curve based on α-particle flux measurements at other latitudes and by other observers.‡ We can conclude then that the detection efficiencies in all the relevant experiments were approximately equal.

Next we consider Fig. 3 *b*. It represents the grain density of all those particles which were not found near the expected position in the neighbouring emulsion, either because they failed to penetrate the intervening glass absorber or because of inefficiency in tracing. In this histogram the strong peak in the grain density interval $45 < g. < 57$ grains/75 μ, has disappeared. As a whole the distribution resembles the extrapolated background curve of Fig. 3 (*c*). However, a small particle excess in the interval where relativistic α-particles must fall, indicates that some primary α-particles have stayed in this group, either because tracing was faulty or because the particles suffered a destructive collision in the intervening glass plate.

Finally we consider Fig. 3 (*a*). The histogram contains mostly particles in the grain density interval $45 < g. < 57$ grains/75 μ. Since here the background of other tracks is small, extrapolation is quite accurate and we can say that not less than 70 of the 394 particles in Classes U, L and UL are identifiable by range and ionization as relativistic particles of charge $Z = 2$.

‡ See B. Peters, *The Nature of Primary Cosmic Radiation*, Vol. I—*Progress in Cosmic Ray Physics* (J. G. Wilson ed.), North-Holland Publishing Co., 1952.

For later use we must note, however, that Fig. 3 (*a*) contains 29 tracks which because of their grain density cannot be due to relativistic particles of any charge. Thus out of approximately 300 non-relativistic particles in Figs. 3 (*b*) and 3 (*c*), 29 had a continuation in an adjacent plate either because they penetrated the intervening glass or by accidental juxtaposition of two unrelated tracks. Although we cannot give this probability a meaningful physical interpretation, we shall designate it by the symbol $\epsilon \approx 10\%$ and define it as:

> the probability that a followable track due to a non-relativistic particle which satisfies our selection criteria, is "successfully followed" in the sense previously defined.

Before we can derive the tracing efficiency η_t more accurately, we still have to determine one other quantity, namely the collision probability σ. It is defined as the probability that a relativistic α-particle whose direction of motion satisfies our selection criteria will suffer between adjacent emulsions a collision in which it will lose at least one unit of charge, or be deflected through more than 5°. (A large angle deflection of a relativistic α-particle without loss of charge is highly improbable and has not yet been observed).

In order to determine the collision probability σ we make again use of secondary relativistic α-particles from the break up of primary heavy nuclei. Tracing their tracks through the stack yields a collision mean free path for relativistic α-particles in the material of our stack. It is true that its value will depend somewhat on our tracing efficiency, but since these α-particles occur in narrow bundles they can be traced with confidence and the disappearance of one of the members in a bunch between two emulsions can be established with certainty. We obtain the mean free path for collisions of relativistic α-particles in our stack: $\lambda = 50 \pm 10$ g./cm.^{2}

We now make use of the length distribution of tracks $N_{>l} \approx \frac{1}{l^2}$ which according to Fig. 2 holds for all tracks whose ionization is consistent with that of relativistic α-particles. The probability of destructive collision between adjacent emulsions is then given by:

$$\sigma = \int_{L_0}^{\infty} \frac{1 - e^{-L/\lambda}}{L^3} \, dL \Big/ \int_{L_0}^{\infty} \frac{dL}{L^3}$$

where L_0 is the amount of matter which the steepest of the acceptable particles has to traverse in going from one emulsion to the next. Using $L_0 = 3 \cdot 2$ g./cm.^{2}

as calculated before and $\lambda = 50$ g./cm.^{2} the probability of collision between emulsions becomes:

$$\sigma = 12\%$$

(*b*) *Detailed Determination of the Tracing Efficiency* η_t.—We divide the 457 tracks into 9 Groups by asking four questions:

Question 1.—Is the track traceable into the next emulsion in the direction of the upper hemisphere, yes or no?

Question 2.—Was the track "successfully traced" into the upper hemisphere, yes or no?

Question 3.—Is the track traceable into the next emulsion in the direction of the lower hemisphere, yes or no?

Question 4.—Was the track "successfully traced" into the lower hemisphere, yes or no?

Since a "no" answer to questions one and three implies automatically "no" for questions two and four respectively, we obtain 9 Groups of tracks. We designate yes by (+) and no by (—) and list below the number of tracks in each Group.

TABLE I

Class	Group	Symbol	No. of tracks found	
UL	1	+ + + +	25	
	2	+ + + −	18	
	3	+ − + +	17	
	4	+ − + −	105	165 tracks
U	5	+ + − −	5	
	6	+ − − −	49	54 tracks
L	7	− − + +	45	
	8	− − + −	130	175 tracks
O	9	− − − −	63	63 tracks
				457 tracks

The classification of tracks into different Classes is purely geometric, while the classification into Groups depends on the penetrating power of the particle involved.

It is important to realize the expected difference in composition in Groups like, for instance, Group 6 (+ − − −) and Group 8 (− − + −). Since all primaries enter from the upper hemisphere, Group 6 in which the particles were predicted in the upper hemisphere, but not found, cannot contain primaries unless the tracing was inefficient. Group 8, on the other hand, which contains particles predicted in the lower hemisphere, but not found, will contain some primaries which collided between plates *after* going through the surveyed area.

We can now calculate and compare with experiment the expected number of relativistic α-particles (α) and secondaries (S) in each Group in terms of three previously defined quantities, namely:

η_t, the efficiency of tracing relativistic α-particles.

$\sigma = 12\%$, the probability for a relativistic α-particle to disappear between adjacent emulsions because of collision in the glass.

$\epsilon = 10\%$, the probability for a non-relativistic particle track to have an acceptable continuation in the adjacent emulsion.

One gets:

Class UL

$$\alpha_1 = \eta_t^2 (1 - \sigma)\, \alpha_{UL} \quad (1, a)$$

$$\alpha_2 = [\eta_t (1 - \eta_t)(1 - \sigma) + \eta_t \sigma]\, \alpha_{UL} \quad (1, b)$$

$$\alpha_3 = \eta_t (1 - \eta_t)(1 - \sigma)\, \alpha_{UL} \quad (1, c)$$

$$\alpha_4 = [(1 - \eta_t)^2 (1 - \sigma) + (1 - \eta_t)\sigma]\, \alpha_{UL} \quad (1, d)$$

$$S_1 = \epsilon^2 S_{UL} = 0{\cdot}01\, S_{UL} \quad (2, a)$$

$$S_2 = \epsilon (1 - \epsilon) S_{UL} = 0{\cdot}09\, S_{UL} \quad (2, b)$$

$$S_3 = \epsilon (1 - \epsilon) S_{UL} = 0{\cdot}09\, S_{UL} \quad (2, c)$$

$$S_4 = (1 - \epsilon)^2 S_{UL} = 0{\cdot}81\, S_{UL} \quad (2, d)$$

Class U

$$\alpha_5 = \eta_t\, \alpha_U \quad (1, e)$$

$$\alpha_6 = (1 - \eta_t)\, \alpha_U \quad (1, f)$$

$$S_5 = \epsilon S_U = 0{\cdot}1\, S_U \quad (2, e)$$

$$S_6 = (1 - \epsilon) S_U = 0{\cdot}9\, S_U \quad (2, f)$$

Class L $\alpha_7 = \eta t\,(1 - \sigma)\,\alpha_L$ (1, *g*)

$\alpha_8 = [(1 - \eta t)\,(1 - \sigma) + \sigma]\,\alpha_L$ (1, *h*)

$S_7 = \epsilon S_L = 0{\cdot}1\ S_L$ (2, *g*)

$S_8 = (1 - \epsilon)\,S_L = 0{\cdot}9\ S_L$ (2, *h*)

Class O $\alpha_9 = \alpha_0$ (1, *i*)

$S_9 = S_0$ (2, *i*)

These formulas permit us to predict (in terms of the tracing efficiency ηt) the relative strength and composition of each Group belonging to a given geometric Class.

Let us first consider the two largest Classes namely: L and UL. Table II shows the tracks in these Classes arranged according to Groups and according to their grain density.

TABLE II

Grain Density (g./75)	Class L		Class UL			
	Group 7 (− − + +)	Group 8 (− − + −)	Group 1 (+ + + +)	Group 2 (+ + + −)	Group 3 (+ − + +)	Group 4 (+ − + −)
< 33	—	4	..	..	1	5
33– 45	6	31	1	5	2	18
45– 57	35	30	24	9	10	18
57– 69	1	27	..	1	..	22
69– 81	3	18	..	3	3	15
81– 93	..	15	..	..	1	10
93–105	..	5	..	..	..	8
> 105	..	..	..	..	..	9
Total	45	130	25	18	17	105
Class Total	175		165			

The particles whose grain density lies below 45 or above 57 are secondaries. Any relativistic α-particles which may be in the Groups must be in the category 45–57 but, as explained before, this category will also contain secondary particles. For the purpose of comparing the predicted with the experimental strength within each Group we shall take as secondaries (S) the number of tracks S′ whose grain density lies below 45 or above 57 multiplied by a factor $(1 + f)$:

$$S = S'(1 + f).$$

As the number of α-particles (α) we shall take the rest, namely, the number α' of tracks in the grain densiy interval 45–57 minus the number of secondaries in that interval:

$$\alpha = \alpha' - fS'$$

In the case of Class L we have now the following relations:

$$\alpha_7 = 0{\cdot}88\,\eta_t\,\alpha_L = 35 - 10f$$

$$\alpha_8 = (1 - 0{\cdot}88\,\eta_t)\,\alpha_L = 30 - 100f$$

Eliminating α_L from these equations we get a relation between η_t and f, and can, therefore, plot the grain density distribution of the secondaries in Group 8 (S_8) for various assumptions about η_t.

In a similar way we can deal with Groups 1 and 4 in Class UL and plot the grain density distribution of secondaries in Group 4 for various values of η_t.

These histograms are shown in Figs. 4 (*a*) and 4 (*b*). Only the column in the grain density interval 45–57 is affected by the choice of η_t and its height is indicated for various assumed values. It is clear from these histograms that η_t must be very close to 100% and is unlikely to lie below 90%. In any case we can conclude frcm these histograms that $f = 0{\cdot}235$ (19% of all secondaries produce tracks in the grain density interval 45–57).

A detailed comparison of the distribution of primaries and secondaries among the Groups of a given Class has been made in Table III. In order to show how Table III was constructed we carry through a sample calculation for Groups 7 and 8 of Class L whose grain density distribution is shown in Table II.

Group 7 contains 45 tracks of which 10 fall outside the interval

$$45 - 57 \text{ g.}/75\,\mu.$$

Group 8 contains 130 tracks of which 100 fall outside the interval

$$45 - 57 \text{ g.}/75\,\mu.$$

The *calculated* values are obtained as follows:

$$S_L = S_L'(1 + f) = 110\,(1 + 0{\cdot}235) = 136$$

$$\alpha_L = N_L - S_L = 39$$

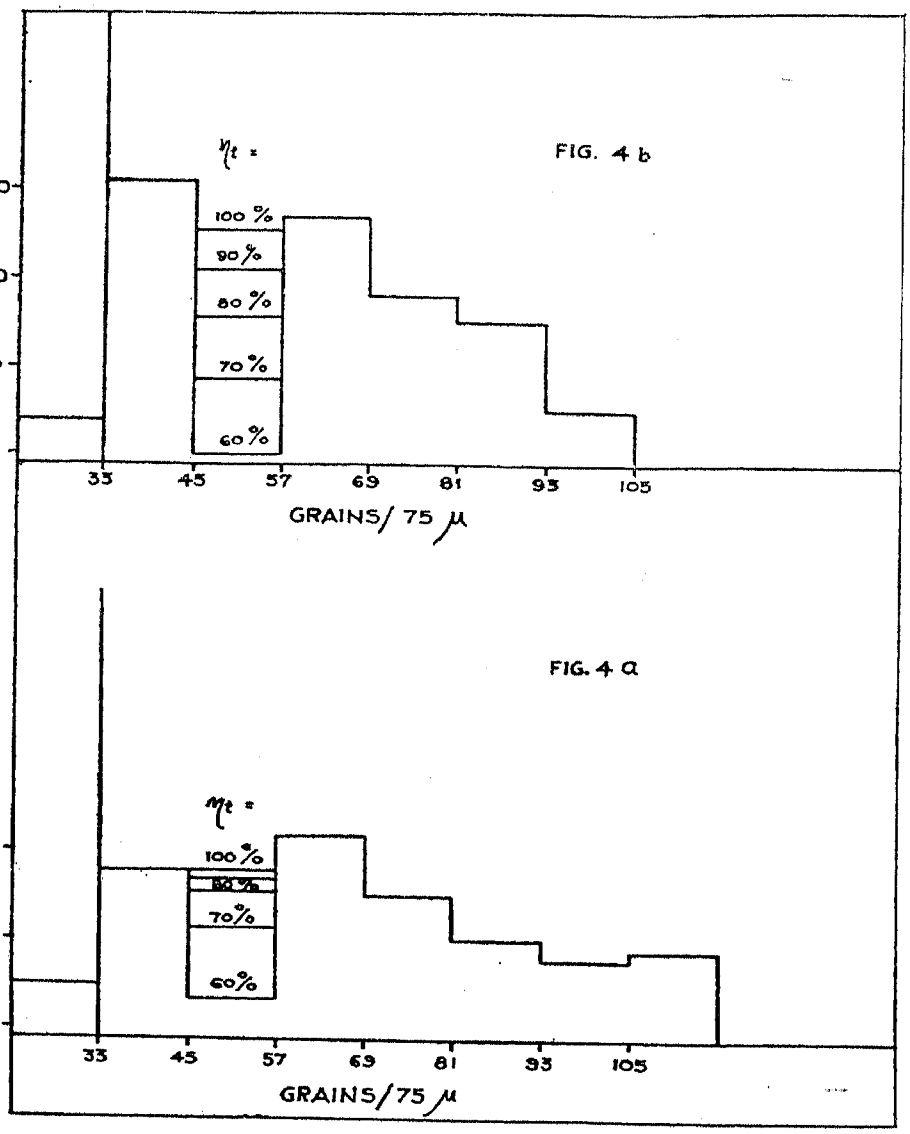

FIG. 4.

These values are inserted into eq. 1. *e*, *f*, and 2. *e*, *f*, to calculate α_7, α_8, S_7 and S_8. The calculations have been carried out for three assumed values of the scanning efficiency η_t namely, 70%, 85%, 100%, and for Classes UL, U and L. The average calculated ratio α/S for Classes UL, U and L is used to calculate α and S for Class O.

The *observed* values of α and S are obtained from the grain density distribution in each Group:

$$S_7 = S_7'(1+f) = 10\,(1+0{\cdot}235) = 12$$
$$S_8 = \quad = 100\,(1+0{\cdot}235) = 124$$
$$\alpha_7 = 45 - S_7 = 33$$
$$\alpha_8 = 130 - S_8 = 6.$$

TABLE III

Class	Group	S		α				
		Obs.	Calc.	Obs.	Calculated $n_t = 100\%$	Calculated $n_t = 85\%$	Calculated $n_t = 70\%$	Obs.
	1 (++++)	1	1	24	32	23	15	
	2 (+++−)	11	12	7	4	8	10	
	3 (+−++)	9	12	8	..	4	7	
	4 (+−+−)	105	104	..	..	1	4	
UL	165	126	129	39	36	36	36	$\alpha/S = 0{\cdot}31$
	5 (++−−)	1	4	4	14	12	10	
	6 (+−−−)	38	36	11	..	2	4	
UL	54	39	40	15	14	14	14	$\alpha/S = 0{\cdot}38$
	7 (−−++)	12	14	33	34	29	24	
	8 (−−+−)	124	122	6	5	10	15	
L	175	136	136	39	39	39	39	$\alpha/S = 0{\cdot}29$
	9 (−−−−)	48	49	15	14	14	14	
O	63	48	49	15	14	14	14	$\alpha/S = 0{\cdot}31$

The agreement between calculated and observed values in Table III is very good for $\eta_t = 100\%$ and 85% and definitely poorer for $\eta_t = 70\%$. We conclude that the efficiency for tracing relativistic α-particles $\eta_t \gtrsim 85\%$ and that out of 457 tracks in the surveyed area 108 tracks are due to relativistic α-particles.

(*c*) *The Flux of Primary Helium Under* 20 g./*cm.*^{2} *of Residual Atmosphere at Geomagnetic Latitude* $\lambda = 30°$.—In order to determine the flux of α-particles at the top of the atmosphere, the number of relativistic α-particles identified as incident on the surveyed area must be multiplied by the geometric factor appropriate to the selection criteria and by another factor to correct for the loss by nuclear collisions in the upper atmosphere and in the glass of the stack. The calculations were carried out as discussed previously (Bradt and Peters, 1950 *a*). We have used the value of 50 g./cm.^{2} for the absorption mean free path in glass and for the absorption mean free path in air, the value of 45 g./cm.^{2} The 61 α-particles in the almost pure Groups 1, 5 and 7 were used to make these corrections and the resulting flux was increased by the factor 108 ÷ 61 in order to include the primary α-particles in the remaining 6 Groups. The flux was determined separately for particles incident in the three intervals of zenith angle θ; $0 < \theta < 30°$; $30° < \theta < 60°$; $60° < \theta < 90°$ and the three values agree within statistical error. However, in order to reduce the uncertainty due to collision corrections we included in our final calculations only particles incident with a zenith angle $< 70°$.

The flux of primary α-particles at geomagnetic latitude 30° is:

$$I_\alpha = 72 \pm 15 \text{ particles per m.}^2\text{, sec., steradian.}$$

This value is in good agreement with the value 80 ± 30 particles previously obtained by Goldfarb *et al.* (1950) from the grain density distribution of tracks. It also fits accurately the previously derived empirical α-particle spectrum $I_\alpha = \dfrac{400}{(1 + E)^{1.35}}$ valid in the latitude sensitive region. (I_α is the number of particles incident per m.^{2}, sec., ster., whose energy per nucleon exceeds E BeV.)

Because our efficiency in finding and identifying α-particles was slightly lower than 100%, our flux value ought to be increased by a small factor; on the other hand it must be lowered by 3–5% because at an atmospheric depth of 20 g./cm.^{2} there exist relativistic α-particle fragments from the fragmentation of heavier nuclei in the upper layers of the atmosphere. These corrections are smaller than the statistical error, and have, therefore, been omitted.

(*d*) *The Relative Abundance of Light Nuclei in the Primary Radiation Under* 20 *g./cm.*^{2} *of Atmosphere at Geomagnetic Latitude* $\lambda = 30°$.—We have already stated that in the course of the investigation described here, 9 tracks were identified as belonging to primaries heavier than helium. Their charge was determined by the method described in reference I. They were:

Element	No. of Tracks
Lithium	1
Beryllium	0
Boron	1
Carbon	4
Nitrogen	2
Oxygen	1
Total	9

Although of small statistical weight, the relative number of Lithium, Beryllium and Boron Nuclei (Li, Be, B) to those of the Carbon, Nitrogen, Oxygen nuclei (C N O Group) is the same as that obtained in reference I, and when the two results are combined one obtains at the stated atmospheric depth:

$$\frac{\text{Li, Be, B}}{\text{C N O}} = 0{\cdot}21 \pm 0{\cdot}06$$

As mentioned in the Introduction, this result disagrees with that obtained by Dainton, Fowler and Kent, by Gottstein, and with part of the experiments of Kaplen, Noon and Racette. It was the purpose of this paper to show that the discrepancy cannot be attributed to a low efficiency for identifying particles of low atomic number in the experiment of reference I. For it is clear that if an overall efficiency $\gtrsim 90\%$ is achieved for tracks made by relativistic α-particles, the efficiency for detecting heavier nuclei whose ionization is at least twice as great must be quite close to 100%. This applies particularly to the experiment of reference I, because both in the present and in the earlier experiment the greater part of scanning and tracing was carried out by the same person, Mr. R. Rickard, to whom I wish to express my gratitude at this point.

The question of efficiency in detecting and observing nuclei of various atomic numbers had been treated in great detail only in the paper of Stix (1954) but not in the other references, although it plays an important part in the interpretation. Thus, Dainton, Fowler and Kent increase the number of Lithium nuclei from the observed value of 45 to a corrected value of 130 on the basis of an argument which involves an assumed ratio between

Lithium nuclei and particles identified as Boron nuclei in various energy intervals. In Gottstein's paper (*see* his Table IV) it is assumed in the interpretation of the data that the detection efficiency for Lithium, Beryllium and Boron is five times less than for Carbon, Nitrogen and Oxygen nuclei, if the track length is less than 500 μ, and about two times less if the track length lies between 500 μ and 3,000 μ. In both these papers, therefore, the interpretation is based on an assumed overall detection and identification efficiency which for some groups of heavy primaries lies somewhere between 20% and 50%.

Although this question of efficiency contributes to the divergence of the conclusions reached by the various authors it does not represent the main cause. In the experiments of Dainton, Fowler and Kent, of Gottstein and of Kaplon, Noon and Racette (Experiment 2) the nature and energy of the particles is determined by measurements of ionization and multiple coulomb scattering of the tracks. The discrepancy in the charge spectrum as well as the very substantial disagreement in the energy spectrum (both at low and high energy) between the results obtained in these experiments and those obtained in other experiments of different type [Kaplon, Peters, Reynolds and Ritson (1952)] can, it seems, be traced to a difficulty with the technique used in measuring multiple coulomb scattering. Since this question is of great importance also for physical problems other than those discussed here it will be treated in a separate paper to be published shortly.

REFERENCES

Bradt, H. L. and Peters, B. .. *Phys. Rev.*, 1949, **75**, 1779; 1950 *a*, **77**, 54; 1950 *b*, **80**, 943.

Dainton, A. D., Fowler, P. H. and Kent, D. W. *Phil. Mag.*, 1951, **42**, 317; 1952, **43**, 729.

Goldfarb, L., Bradt, H. L. and Peters, B. *Phys. Rev.*, 1950, **77**, 751.

Gottstein, K. .. *Naturw.*, 1953, **40**, 104; *Phil. Mag.*, 1954, **45**, 347.

Kaplon, M. F., Peters, B., Reynolds, H. L. and Ritson, D. M. *Phys. Rev.*, 1952, **85**, 295.

——, Noon, J. H. and Racette, G. W. *Ibid.*, 1954, **93**, 914; *ibid.* (in Press).

Stix, T. H. *Ibid.*, 1954, **95**, 782.