Abundance of Lithium, Beryllium, Boron, and Other Light Nuclei in the Primary Cosmic Radiation and the Problem of Cosmic-Ray Origin*

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A combination of sensitive and insensitive photographic emulsions is used to improve the accuracy of measurement of the specific energy loss of relativistic nuclei. The method is applied to the determination of the charge spectrum of the primary cosmic radiation at geomagnetic latitude $\lambda=30°$ and results in nearly complete resolution between neighboring elements up to $Z\sim 14$. It is shown that lithium, beryllium, and boron nuclei are almost or entirely absent in the primary cosmic ray beam. Since nuclear disintegrations of energetic heavy ions frequently lead to fragments of $3\leqslant Z\leqslant 5$ it is concluded that most heavy primary nuclei do not suffer nuclear collisions between the time of acceleration and arrival and that this time must be less than $10^6/\rho$ years, where ρ is the density of atoms along the trajectory.

This result seems to be in disagreement with several recent theories on the origin of cosmic rays and raises some general difficulties for theories assuming galactic origin.

I. INTRODUCTION

In recent years various new theories of the origin, of cosmic rays have been proposed.[1–6] These theories may be classified according to the proposed mechanism for acceleration of the nuclei of the primary cosmic radiation (electromagnetic acceleration, radiation pressure, etc.) or according to the assumptions made concerning the source region. The question of whether cosmic rays are of solar, galactic, or extragalactic origin may ultimately find a conclusive answer on the basis of observations on the dependence of cosmic-ray intensity on sidereal or solar time.[7–9] Another classification, which is independent of the assumed specific mechanism of acceleration and not necessarily uniquely correlated with the problem of the source region may be based on the answer to the following question: What happens to the nuclei of the cosmic radiation after they have been accelerated but before they hit the earth's atmosphere? In particular, have the cosmic-ray nuclei, on their voyage through space, traversed an amount of interstellar matter sufficient to establish equilibrium with their collision products? A theory based on the assumption of magnetic fields sufficiently strong to retain the particles in a closed region (containing the source and the earth) until they collide with interstellar matter, in gaseous or dust form, would imply a positive answer. A negative answer would, for instance, result from a theory which assumes that the majority of the primary nuclei, after being accelerated in a given region, either escape from that region, or are adiabatically decelerated or collide with bodies sufficiently large to absorb both the primaries and their break-up products and that these processes take place in a time short compared with the time between collisions with atoms in interstellar space. A negative answer would also result from a non-equilibrium theory like that proposed by Lemaître.[10] It is the purpose of this paper to show how an empirical answer to the question formulated above can be obtained and to present the results of an investigation which provides a partial answer.

The absence in the incident radiation of the lighter particles (mesons, electrons, and photons), which must be produced in collisions of cosmic ray nuclei with matter gives us no obvious clue as to the importance of collisions in interstellar space, since the mesons decay spontaneously, the photons would not be retained by assumed magnetic fields and electrons will in general be emitted with momenta much lower than that of heavier collision fragments and may in addition lose their energy by absorption processes which are much less effective for protons and heavier nuclei.[11]

If a nucleus with relativistic energy per nucleon ϵ collides with a proton and produces a radioactive fragment the decay electron will on the average obtain an energy $\epsilon'=\epsilon(\epsilon_0/Mc^2)$, where ϵ_0 is the total energy of the electron in the rest system of the nucleus and M is the nucleon mass.

If the electron is produced by the decay of a charged meson it will still receive a relatively low energy. Assuming that the mesons in the center of mass system are on the average created with a kinetic energy comparable to their rest energy and that the average energy of a decay electron is 40 Mev we get

$$\epsilon'\approx\epsilon/10.$$

Thus the magnetic rigidity of electrons produced in interstellar collisions is greatly reduced as compared with that of the primary nucleonic component and the large majority of such electrons would be excluded by the earth's magnetic field. Electrons produced by γ-rays resulting from neutral meson decay do not have to be considered since the γ-rays will not have a chance to be converted in traversing the solar system or the galaxy.

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† On May 24, 1950 Helmut L. Bradt died unexpectedly, as this work, to which he devoted the last months of his life, was nearing completion.

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In order to study the importance of collisions with interstellar matter we may then turn our attention to the relative abundance of the various elements that are found to be present in the incident radiation. The most abundant elements in the primary cosmic radiation are hydrogen, helium, carbon, oxygen, nitrogen, magnesium, silicon, etc.,[12] which are also the most abundant elements in the known universe.[13] The elements between helium and carbon in the periodic system, lithium, beryllium, and boron, are elements of very low abundance, as compared with the neighboring elements. In meteorites (Goldschmidt) and in the solar atmosphere (Russell) their abundance is some 100,000 times smaller than the abundance of oxygen.[13] In interstellar space, according to Spitzer[13] the abundance of Li is at least 10^{-1} and the abundance of Be $\sim 10^{-4}$ times smaller than the abundance of Na, the cosmic abundance of which is 500 times smaller than that of oxygen. If the parallelism between the abundances in the primary cosmic radiation and the cosmic abundances still holds even approximately for these light elements, we may expect Li, Be, and B to be practically absent from the primary cosmic radiation *near their source region*. But this will no longer be true for the *incident* radiation, if nuclear collisions are important. As is known from recent emulsion work,[14] Li, Be, and B are quite frequently produced as "splinters" in collisions of fast nucleons with heavy nuclei, such as Ag and Br. High energy collisions between protons and the more abundant heavy cosmic-ray nuclei such as carbon and oxygen are also expected to result frequently not in complete dissociation of these nuclei into nucleons and alpha-particles, but to leave behind a residual fragment of charge $Z=3$, 4, or 5. We shall show below that on the assumption of equilibrium between the acceleration of cosmic ray nuclei of charge $Z\geqslant 6$ and their destruction in collisions with interstellar hydrogen we must expect that Li, Be, and B nuclei, produced in these collisions as fragments, must have an abundance comparable to that of all the heavier nuclei together.

If the abundances of Li, Be, and B nuclei in the incident radiation should turn out to be much greater than the lower limit given by the production of these nuclei in interstellar collisions, one would have to conclude that these nuclei are abundant in the source region and thus constitute an important fraction of the true primary radiation. On the other hand, the absence of Li, Be, and B among the incident nuclei would be incompatible with the assumption of an equilibrium between the production of the heavy nuclei of the primary cosmic radiation and their destruction in collisions with interstellar atoms.

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II. THE CHARGE SPECTRUM OF NUCLEI WITH $2<Z\leq 14$ at $\lambda_{\text{geom}}=30°$ BELOW 20 G/CM² OF AIR

(1) Charge Determination

In a previous paper[12] we have shown that at least up to charge $Z=14$ primary nuclei are completely stripped of electrons before they enter the earth's magnetic field and therefore arrive at a geomagnetic latitude $\lambda=30°$ with a kinetic energy of at least 3.5 Bev/nucleon. The energy loss which these particles suffer by ionization in the first 20 g/cm² of atmosphere is only a small fraction of this minimum energy. They will therefore enter a stack of photographic plates exposed at $\sim$90,000 ft. with relativistic velocities. Neglecting the relativistic increase of ionization, their specific energy loss in the photographic emulsions is therefore a function of their charge only and is proportional to Z^2.

The specific energy loss in emulsions is measured in this work by the grain density along the track. By comparing the grain density along tracks of electron-positron pairs produced with widely differing angular divergence it has been shown that the relativistic increase of grain density for electrons in the energy range between 10 mc² and 10⁴ mc² is less than seven percent. A study of the relativistic increase of grain density for multiply charged particles has not yet been completed. There is an indication for such an effect but its magnitude is less than 20 percent.

Heretofore charge determinations were mostly carried out using the method of δ-ray counting. The accuracy of this method has been discussed[12] previously and permits the determination of charges $Z\geqslant 6$ with an error of approximately 10 percent. For particles lighter than carbon the number of δ-rays approaches the random background of slow electrons, and charge determination by this method becomes very inaccurate except for tracks of exceptional length.

For the purposes of this investigation we must not only extend the charge determination to the lighter elements, but must also improve the accuracy to the point where one element can be distinguished from its immediate neighbors in the periodic system.

The method of counting the number of developed silver grains along the track of a particle gives more accurate values for the specific energy loss, but in an emulsion of given sensitivity discrimination between tracks is feasible only if their specific ionization does not differ by more than a factor of about 15. If a given particle makes a track which can just be perceived against the random background, another particle of 15 times this ionizing power will leave a track so dense that clogging of grains makes grain counting difficult. In order to extend the range of applicability of the grain counting method we have exposed a closely packed stack of plates in which highly sensitive emulsions alternate with emulsions of very low sensitivity. The ionization loss of a particle which traverses the stack can therefore be studied in both types of emulsion.

The sensitive plates consisted of Eastman *NTB*3 emulsions developed by the standard temperature method first suggested by Dilworth and Occhialini and

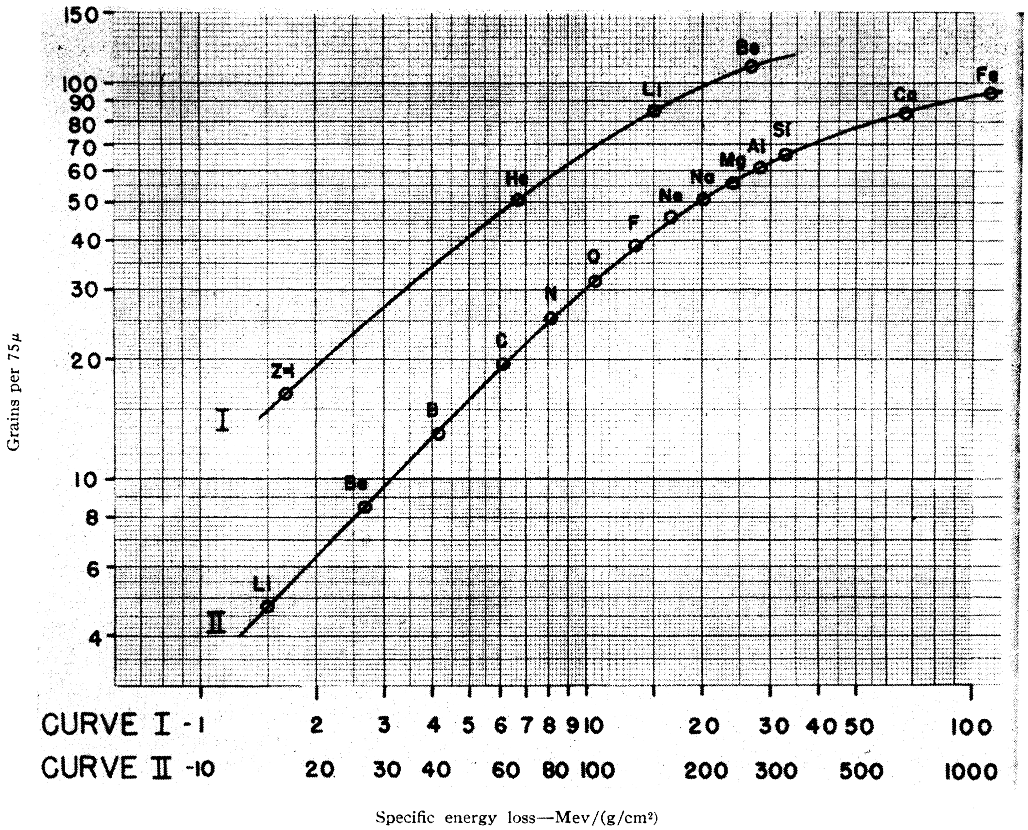

FIG. 1. Grain density *versus* specific energy loss. Curve I refers to NTB3 emulsion. Curve II refers to strongly underdeveloped *NTA* emulsions. The expected grain density of tracks due to various relativistic nuclei is indicated on the diagram.

Payne.[15] The insensitive plates consisted of Eastman *NTA* emulsions developed by the same method but using 20 parts of water to one part of *D*-19 developer. This development procedure was chosen such as to make the heaviest countable tracks in the *NTB*3 emulsions just barely detectable in the *NTA* emulsion.[16] In Fig. 1 the grain density for both emulsions is plotted against the specific energy loss of the particle.

Curve I refers to the electron sensitive emulsion. Shower particles and high energy electron-positron pairs created by γ-rays in the emulsion were used to establish the grain density corresponding to a relativistic singly charged particle. This point is marked $Z=1$ on the curve. The points marked He, Li, Be giving the grain density corresponding to 4, 9, and 16 times minimum ionization were determined from the particle tracks shown in Fig. 2. Here a nitrogen nucleus after traversing several plates in the stack breaks up into a nucleus of lithium and a nucleus of beryllium, the latter in turn breaks up, after traversing several additional plates, into two α-particles. The small angle between the collision fragments and in particular the small divergence between the two α-particles from the disintegration of beryllium makes it certain that all the particles have relativistic energies. The grain density curve obtained in this way was checked by grain counting other relativistic α-particles and singly charged particles of long range.

Curve II refers to the emulsions which were strongly underdeveloped. Here the point marked Be was calibrated by using the relativistic beryllium nucleus previously identified and several other such nuclei found in the course of this investigation. The points marked O and Mg were fixed by grain counting tracks which in the neighboring sensitive emulsion were identified by δ-ray count as due to relativistic oxygen and magnesium nuclei. The calibration curve was then drawn through these three points and the grain density corresponding to relativistic nuclei of other charges was obtained from this curve by assuming a specific energy loss proportional to Z^2. A relativistic carbon nucleus is then expected to give a grain count of 20 grains/75μ. Since previous work has established the existence of a strong carbon peak in the primary radiation, the appearance of such a peak in the charge spectrum (Fig. 3) at the predicted value of grain density establishes the correctness of the calibration curve used for the underdeveloped emulsions. The uniformity of development

[15] Dilworth, Occhialini, and Payne, Nature **162**, 102 (1948).
[16] We are indebted to Mr. T. Putnam for carrying out the necessary development tests.

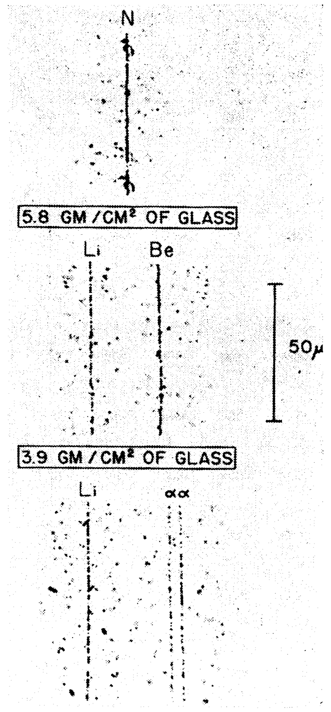

FIG. 2. A relativistic nitrogen nucleus is destroyed in two successive collisions as it traverses a stack of plates. The collisions occur in the glass between emulsions. Sections of the track are shown before and after the collisions. The nitrogen nucleus first disintegrates into a nucleus of lithium and a nucleus of beryllium, the latter then disintegrates into two α-particles.

of successive *NTA* plates may be judged from the grain densities in several plates of five long tracks listed in Table I. The over-all resolution is not as good as is suggested by these examples, since most of the tracks have shorter paths in the stack. Figure 4 shows the appearance of tracks of different particles in both types of emulsion.

(2) The Survey for Tracks of Primary Particles of Charge $Z>2$

The stack was arranged in such a way that successive sensitive plates (separated by insensitive plates) were exactly 3 mm apart. The thickness of the emulsions was $d=80\mu$. From the position, length, and inclination of a track observed in one sensitive plate one could determine its position accurately in the next sensitive plate provided the particle penetrated the intervening glass without appreciable scattering. A sensitive plate was surveyed for all tracks traversing the emulsion, having a projected track length $l>300\mu$ and a grain density larger than that corresponding to five times the ionization of a relativistic singly charged particle. Most of the tracks so selected were of course not due to relativistic particles of charge $Z>2$ but to singly charged particles with velocity $v/c<0.37$ or doubly charged particles with velocity $v/c<0.78$. The positions of all tracks in the next sensitive plate were then calculated and this second plate was surveyed using the same criteria as before. In this way it was established which of the particles observed in the first plate penetrated $0.3l/d>1.12$ cm of glass or 2.75 g/cm^2 and reached the second plate without changing their direction by more than about 5°. For those tracks where grain counting was possible (grain density less than 16 times minimum) the additional restriction was imposed that the grain density had to remain constant within 10 percent. By this selection we eliminate the tracks of all singly charged particles and of all α-particles of energy less than 260 Mev. We retain all particles of charge $Z>2$ and range larger than 2.75 g/cm^2 which do not undergo a nuclear collision between the plates. (Since heavy ions of such ranges have never been observed to be produced in nuclear collisions except by incident nuclei of still larger charge, these nuclei must be considered to be part of the primary radiation.[12]) The tracks which appeared in both sensitive plates were then followed through all the plates of the stack.

It was found that (a) all of them had an ionization density larger than or equal to nine times minimum ionization. Combined with a minimum range of 2.75 g/cm^2 this proves that all singly charged particles were eliminated and all α-particles of energy higher than 700 Mev.

(b) all particle tracks could be followed into the upper hemisphere to the point where the track entered the stack indicating that none of these particles were produced in the stack by other than heavily ionizing particles.

(c) the minimum range of any of these tracks to the point of exit or to the point where the particle suffered a nuclear collision was 5.8 g/cm^2. Combining this fact with the absence of an appreciable increase of ionization

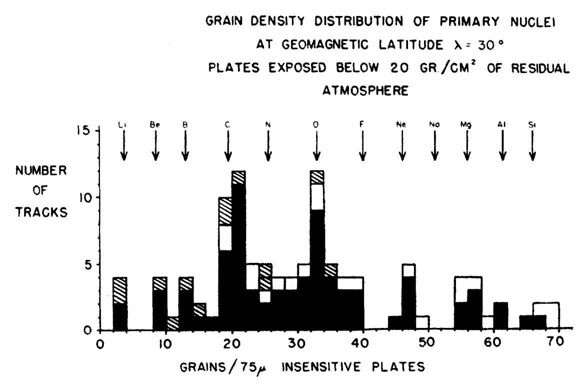

FIG. 3. Histogram of 111 tracks *vs.* grain density in underdeveloped *NTA* emulsions. The solid squares represent a systematic survey. The open squares represent tracks obtained in a less systematic manner in the course of this work. Shaded squares represent relativistic fragments produced by heavier primary nuclei in collisions in the stack. The expected grain densities from different nuclei obtained from Fig. 1 are indicated by arrows. Lithium tracks as explained in the text are included in the diagram although they were identified in neighboring emulsions of higher sensitivity.

within this distance all α-particles are also excluded whatever their energy.

The tracks have therefore to be ascribed to fast particles of charge $Z>2$ entering from the outside. On the basis of arguments previously presented[12] we conclude that they are primary cosmic-ray particles. The only primaries of $Z>2$ which could have been missed in such a survey are those which suffered nuclear collisions in the glass between the two plates which were surveyed. This correction is small and it is negligible as far as the ratio of particles of different charges are concerned.

In order to make sure that no particles were missed by this method the results were checked by surveying in two adjacent sensitive plates for all tracks longer than 400μ and a grain density corresponding to more than *three* times minimum ionization. The tracks in both plates were then matched and followed through the rest of the stack. The results were identical with those obtained by the first method.

(3) The Charge Spectrum of Primary Nuclei at $\lambda=30°$

The tracks obtained in the surveys were grain counted in the underdeveloped (*NTA*) emulsions. Four tracks which in the sensitive emulsion indicated an ionization loss equal to 9 times minimum ionization and are therefore ascribed to Lithium nuclei did not leave a visible track in the *NTA* plates. For completeness sake they have been included, however, in the histogram Fig. 3 at their calculated (but unobservable) grain density of 4.8 grains/75μ. The grain density of all other tracks as determined in the *NTA* plates is shown in Fig. 3. The charge values corresponding to these grain densities were obtained from Curve II, Fig. 1 as explained above.

The solid squares in the histogram of Fig. 3 refer to tracks obtained in a systematic survey. The open squares represent additional tracks obtained in a less systematic manner. The shaded squares represent relativistic fragments of heavier nuclei which suffered collisions in the glass.

Figure 3 confirms our previous result that among the nuclei with charge $Z>2$ carbon and oxygen are the most abundant. They are responsible for the two most

TABLE I. Grain counts for successive 1000-micron intervals for five tracks traced through several insensitive plates.

Track no. Element	B 403 Carbon	568 Nitrogen	B 12 Oxygen	B 416 Neon	408 Magnesium
	265	391	403	555	726
	266	359	390	553	722
	283	307	394	572	737
	251	353	465		
	257	347	385		
	275	348	393		
		350	394		
		351			
Average grains/1000μ	266	351	404	560	728

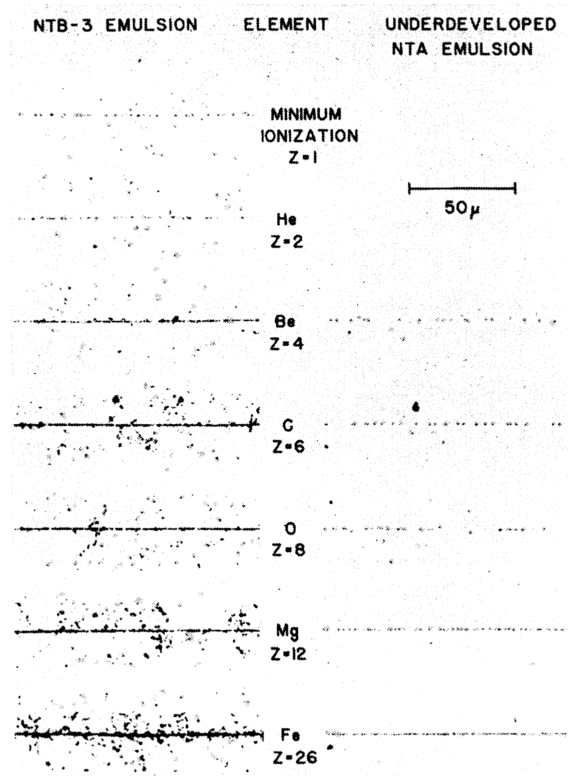

FIG. 4. Tracks of relativistic nuclei of different charge as they appear in electron sensitive *NTB* emulsions and in underdeveloped *NTA* emulsions.

prominent peaks of about equal intensities. Though nitrogen nuclei have been identified (Table I), their number seems to be at least three times smaller than the number of either C or O nuclei and the nitrogen peak disappears in the high grain density "tail" of carbon. The "tail" of the oxygen peak makes it difficult to judge whether or not there is a significant number of fluorine nuclei. Between $Z=8$ and $Z=12$ we have a group corresponding to the charge $Z=10$ (neon). Next comes the Mg, Al, Si-group: these three elements are only poorly resolved, since the grain-density *vs.* energy-loss curve (Fig. 1) flattens already considerably in this region.

Although the resolution by grain counting is not very good for particles of charge $Z>14$, insensitive plates will permit better charge determination than the sensitive plates for these particles also. While δ-ray tracks are not visible in the insensitive plates there are many background grains in the immediate neighborhood of heavy particle tracks which are apparently due to δ-rays ending in the emulsion. Their number is proportional to Z^2 and it is much easier to count these background grains than it is to count δ-rays on heavy tracks in electron sensitive emulsions. Charge determination by this method will be described elsewhere.

Among the 93 tracks resulting from a systematic survey shown in Fig. 3, 16 tracks belong to the Li, Be, B group. Six of those particles are fragments produced by heavier nuclei making collisions in the stack of plates.

TABLE II. Collision mean free path in glass.

Type of nuclei	Aggregate length of track observed (g/cm^2)	Number of collisions observed	Mean free path (g/cm^2)
A nuclei (Li, Be, B)	237	5	(47.4)
B nuclei (C, N, O)	2030	59	34.5 ± 4
C nuclei ($10\leq Z\leq 18$)	954	36	26.5 ± 4
($19\leq Z\leq 26$)	256	11	23.3 ± 7

This is a very large fraction, in view of the fact that few of the particles of charge $Z>5$ are fragments of still heavier nuclei produced in collisions in the stack.

The average length per track in the stack (from the point of entrance to either the point of exit or the collision) is about 15 g/cm^2, about two-thirds of the total amount of air above the balloon. The number of secondaries produced in the air overhead will therefore be somewhat larger than the number of secondaries produced in the glass and it is therefore reasonable to assume that also the remaining light nuclei (3 Be, 5 B, and 2 Li) that enter the stack from the outside are secondaries, fragments of heavier nuclei disintegrated in the air above the balloon. This indicates that at the top of the atmosphere the flux of particles of charge $3\leqslant Z\leqslant 5$ is zero or very small. A more accurate evaluation of this flux is made in the next chapter.

The flux of nuclei with $6\leqslant Z\leqslant 10$, extrapolated to the top of the atmosphere had been determined previously:[12] $I=(3.5\pm0.6)\cdot 10^{-4}$ nuclei/cm^2-sec.-sterad. for a geomagnetic latitude of 30°. The data of this flight, which was carried out near the same geomagnetic latitude, yield a flux value of $(3.3\pm0.7)\times 10^{-4}$ in good agreement with the previously determined value.

Excluding fragments produced in the glass we find in a systematic survey below 20 g/cm^2 of residual atmosphere:

	Li	Be	B	$6\leqslant Z\leqslant 8$	$Z>8$
No. of nuclei	2	3	5	51	19

At this altitude then the flux of Li, Be, and B nuclei constitutes approximately 20 percent of the flux of CNO nuclei.

III. THE PRODUCTION OF Li, Be AND B FRAGMENTS IN ENERGETIC COLLISIONS BETWEEN NUCLEI

Let us assume that Li, Be, and B nuclei are not found with any appreciable abundance among the true primaries; that is, among the nuclei originally accelerated at the source of the cosmic radiation. Li, Be, and B nuclei, observed at a certain depth h below the top of the atmosphere, may then be fragments produced in collisions of heavier cosmic-ray nuclei: (1) with air nuclei at the top of the atmosphere or (2) with interstellar matter (mostly hydrogen).

In order to estimate the contribution from these two sources we have to know the probability $p_A(Z)$ and $p_H(Z)$ that a stable fragment of Li, Be, or B will be produced in a high energy collision of a nucleus of charge Z with an air nucleus or a hydrogen nucleus respectively. For the purpose of this discussion we shall divide the heavy cosmic-ray nuclei into 3 groups:

A nuclei $(3\leqslant Z\leqslant 5)$,
B nuclei $(6\leqslant Z\leqslant 9)$,
C nuclei $(10\leqslant Z)$.

TABLE III. Stable relativistic nuclei of charges $Z>2$ resulting from collisions.

Type of primary nuclei	Fragments							Number of collisions	Number of A-nuclei produced per collision
	Li	Be	B	C	N	O	Z>8		
B nuclei	6	6	3	6	3	—	—	65	0.23
C nuclei	5	4	—	8	3	3	9	38	0.24
	11	10	3	14	6	3	9	103	0.23

Below $h=20$ g/cm^2 of residual atmosphere the relative number of these three components is approximately $N(A):N(B):N(C)=1:6:2$.

(1) Collisions in Air

(a) *The probability $p_A(Z)$ of producing an A nucleus in a collision of B or C nuclei with nuclei of the atmosphere*

The mean free path for collisions of B and C nuclei with nitrogen and oxygen nuclei of the atmosphere and the type of fragmentation occurring in such collisions may be inferred from the observed collision of such nuclei in the glass of photographic plates.

Table II gives the collision mean free path in glass for A, B, and C nuclei. The values obtained for B and C nuclei are in agreement with those reported earlier.[12] The mean free path for A nuclei (λ_A) is based on an as yet insufficient number of collisions and is only given as an indication that, as expected, it is longer than λ_B or λ_C.

Table III above shows the number of stable relativistic nuclei of charge $Z>2$ observed to result from 103 collisions of B and C nuclei in glass. Thus we get 0.23 A type nuclei (Li, Be, or B) produced per collisions of B or C type nuclei in glass. We may assume that the fragmentation of these nuclei in glass (mostly SiO_2) is very nearly identical to that occurring in air:

$$p_A(B)=p_A(C)=0.23$$

and that their collision mean free paths in air are about 10 percent less than the corresponding paths in glass.

(b) *Relativistic Li, Be, and B fragments produced in the air above the balloon*

We can now calculate the number of A nuclei which should be observed under 20 g/cm^2 of air. This number if given by:

$$N_A(\theta)=\lambda_A p_A\left\{\frac{N_B(\theta)}{\lambda_A-\lambda_B}\left[\exp\left(\frac{x}{\lambda_B}-\frac{x}{\lambda_A}\right)-1\right]+\frac{N_C(\theta)}{\lambda_A-\lambda_C}\left[\exp\left(\frac{x}{\lambda_C}-\frac{x}{\lambda_A}\right)-1\right]\right\}+RN_B(\theta)\exp\left(\frac{x}{\lambda_B}-\frac{x}{\lambda_A}\right).$$

Here $N_{A,B,C}(\theta)$ is the number of nuclei of a given type incident under an angle,
- θ with the zenith direction below h g/cm² of residual atmosphere,
- $x=h/\cos\theta$ is the path traversed in the atmosphere,
- $\lambda_{A,B,C}$ is the collision mean free paths in air (about 10 percent less than the mean free paths measured for collisions in glass),
- p_A is the probability that a collision of a B or C nucleus in air will lead to the production of a relativistic A nucleus and,
- R is the flux ratio of A and B nuclei at the top of the atmosphere.

We can integrate the formula over θ, since $N_B(\theta)$ and $N_C(\theta)$ are known experimentally. Using the values: $\lambda_B=31$ g/cm²; $\lambda_C=24.5$ g/cm² and $p_A=0.23$ we obtain below 20 g/cm² of atmosphere

$$N_A=(0.28+R)N_B \text{ for } \lambda_A=31 \text{ g/cm}^2,$$
$$N_A=(0.31+1.2R)N_B \text{ for } \lambda_A=40 \text{ g/cm}^2.$$

We should therefore expect that even if no A nuclei were incident at the top of the atmosphere the number of A nuclei entering the stack of plates below 20 g/cm² of air should equal about 30 percent of the number of B nuclei.

Furthermore since the average track traverses about $L=15$ g/cm² of glass before it either leaves the stack or undergoes a collision we should expect an additional number of A nuclei to be produced in the stack given by $N_A'=p_A[N_B(1-\exp(-L/\lambda_B))+N_C(1-\exp(-L/\lambda_C))]$ leading to

$$N_A'/N_B=0.14.$$

A systematic survey of 173 cm² of emulsion yielded 51 tracks of B nuclei entering the stack from the air. Of these about 10 must be due to collisions of C nuclei in the air above the balloons. Thus 41 of the B nuclei incident at the top of the atmosphere reached the plates below 20 g/cm² of air. On the basis of our calculation we should expect in the same survey about 12 A nuclei to enter the stack from the air and 6 to be produced in the glass. We actually observed 10 A nuclei entering from the air and 6 produced in the glass. It seems therefore that we can easily account for all A nuclei observed to enter the stack by assuming that they result from disintegrations of B and C nuclei in the air above the balloons. The probability of observing 10 or less A nuclei entering the stack from the outside is

17.6 percent for $R=0$
2.5 percent for $R=0.1$
0.24 percent for $R=0.2$.

Our results therefore indicate for the flux ratios of A and B nuclei at the top of the atmosphere a value $0\leq R<0.1$.

We conclude that lithium beryllium, and boron are rare elements in the region where cosmic-ray particles are accelerated.

(2) Collisions with Interstellar Hydrogen

(a) *The probability $p_H(B)$ and $p_H(C)$ of producing A nuclei in collision between B or C nuclei and protons.*

Consider a C, N, or O nucleus at rest being struck by an incoming particle. If the incident particle is a heavy ion (say oxygen or silicon) the nuclear material of the target will disintegrate in a certain way and the probability of obtaining *from the target material* a fragment of charge $3\leqslant Z\leqslant 5$ is $p_A(B)=0.23$, the same number which was obtained in the previous sections by observing collisions in which target and projectile were interchanged. If the stationary C, N, or O nucleus is not struck by a heavy ion but by a relativistic nucleon we would obtain a star with fewer prongs (less complete disintegration) and therefore a higher probability for a fragment of charge $3\leqslant Z\leqslant 5$. This probability is the quantity $p_H(B)$ defined previously. A lower limit for $p_H(B)$ is therefore given by

$$p_H(B)>p_A(B)=0.23.$$

The same argument will apply for collisions of C nuclei ($Z\geqslant 10$) although we would expect that the probabilities depend less strongly on the weight of the nucleus with which the C nuclei collide. Therefore we have also

$$p_H(C)\geqslant p_A(C)=0.23.$$

A more accurate estimate of these probabilities can be made in the following way.

D. H. Perkins[14] has studied the production of heavy nuclear "splinters" in Ag and Br stars in nuclear emulsions exposed both at mountain altitude and in the stratosphere. He finds in all those collisions where at least half of the nuclear matter is disintegrated (number of prongs >12) about 22 percent lead to the emission of a stable Li, Be, or B nucleus of more than 30μ-range. The frequency of such fragments is found to be independent of the number of shower particles produced in the collision and therefore independent of energy at sufficiently high energies. From his data one obtains therefore $p_H(Z)\sim 0.22$ (for $Z\sim 40$).

No direct measurements of $p_H(Z)$ are available for smaller values of Z, but for $Z=6$ to 8 an estimate of this probability can be made from an analysis of stars produced in the gelatine of nuclear emulsions. Harding[17] has made such an analysis using thin gelatine layers imbedded in nuclear emulsions. (The emulsions used were not electron sensitive.)

He found (α) that the size frequency distribution of stars made in the gelatine (C, N, O nuclei) is essentially the same as that for stars of less than 6 prongs made in ordinary emulsions.

(β) That stars of more than 5 prongs are absent or very rare.

(γ) That $\sim$36 percent of stars in ordinary emulsions must be due to the disintegration of C, N, or O nuclei.

(δ) That charge conservation requires that the number of fragments of charge $Z>2$ from light nuclei is on the average about 0.7 per star.

In order to check whether the probability of producing a fragment of charge $Z>2$ in a collision between a light nucleus and a nucleon is as high as indicated by Harding's data, even if one confines one self to high energy primaries, we have made an analysis in an ordinary electron sensitive emulsion exposed at balloon altitudes of stars with less than 6 prongs produced by a singly charged relativistic primary particle. According to Salant *et al.*,[18] almost all such events represent disintegration of C, N, O nuclei contained in the gelatine of the emulsion.

Counting as prongs all tracks including recoils but excluding the incident primary we have examined 33 stars with a total of 131 prongs.

The nuclear fragments of an average star produced by a singly charged particle in the light nuclei of the emulsion must carry 7.95 units of charge, assuming a contribution from carbon, nitrogen and oxygen nuclei proportional to their geometric cross sections (water content corresponding to 50 percent humidity included). The 33 stars with a total of 131 prongs found in the survey will then emit a total of $33\times 7.95=263$ units of charge. Of the 131 prongs, 37 could be identified as due to singly charged particles, leaving 226 charges to be divided among the remaining 94 prongs. Assuming, as is indicated by the data of Perkins,[14] that stable nuclear fragments of charge 3, 4, and 5 occur with approximately equal probabilities, and making the extreme assumption that none of the unidentified prongs were due to singly charged particles, at least 19 prongs must be due to fragments of charge $Z>2$ ($Z_{\text{Av}}=4$) and the total charge is accounted for by

37 prongs caused by particles of $Z=1$	37 charges
75 prongs caused by particles of $Z=2$	150 charges
19 prongs caused by particles of $Z_{\text{Av}}=4$	76 charges
131 prongs	263

Thus at least 0.6 A nuclei are produced in an energetic collision between a proton and a B nucleus, in agreement with Harding's result. It would be desirable to measure this quantity directly by studying stars produced by single charged relativistic primaries in gelatine layers imbedded in electron sensitive emulsions. In the absence of such measurements we shall use as lower limit

$$p_H(B)=p_H(C)=0.23,$$

although present evidence indicates that this limit is considerably lower than the true value.

(b) *Production of Relativistic Li, Be, and B Nuclei as Collision Fragments in Interstellar Space*

(α) *Effect of Radioactive Transmutations on the Expected Abundance Ratios.*—We have estimated the frequency of occurrence of Li, Be, and B fragments in collisions of heavier nuclei with hydrogen or other targets from the available data on cosmic-ray stars. Some of these fragments are certainly unstable and radioactive decay has to be considered in a discussion of the expected abundance ratios. We may, for instance, expect that some of the observed Be fragments are Be^{10} nuclei which will transform into B^{10} with a half-life of 2.5×10^6 years. Hence Be^9 and Be^7 (which is stable in the absence of an electronic shell) fragments and part of the Be^{10} fragments will contribute to the equilibrium abundance of beryllium, whereas another part of Be^{10} fragments may contribute to the equilibrium abundance of boron. This transmutation, of course, does not affect the lumped abundance of the Li$-$Be$-$B group with respect to the heavier elements. The only beta-activities that reduce this lumped abundance are those of Li^8 (beta-decay to Be^8, which dissociates into two alphas) and of B^{12} (which transforms into C^{12}); on the other hand, the lumped abundance is increased by the He^6 beta-decay into Li^6 and the decay of C^{10} and C^{11} into B^{10} and B^{11} respectively. If these processes are taken into account, only a comparatively small correction of the estimated abundance of the group may be expected. Actually, since He^6 fragments are probably more frequent than Li^8 and B^{12} fragments together, neglecting the effect of radioactive decay altogether may underestimate rather than overestimate the equilibrium abundance of Li, Be, and B nuclei.

It is not necessary to consider isotopes like Be^8 or B^9 which dissociate into fragments immediately. Their lifetimes are so short that only the dissociation fragments appear in the photographic stars; hence they are not included in the estimate number of Li, Be, and B fragments. For instance, a N^{14} nucleus disintegrating into a B^9 fragment, an alpha particle and a neutron, does not give rise to a 2-prong star but to a 4-pronged star, which is considered to correspond to complete dissociation into alphas and protons.

(β) *Comparison of the Energy Spectra of Primaries and Fragments.*—In order to correlate the expected frequency of the production of A nuclei in interstellar collisions with the corresponding abundance of these

[17] J. B. Harding, Nature **163**, 440 (1949).
[18] Salant, Hornbostel, Fisk, and Smith, Phys. Rev. **79**, 184 (1950).

nuclei in the incident radiation at a given geomagnetic latitude, we have also to consider the energy relations.

According to Perkins,[14] the velocity of the "splinters" in the rest system of the Ag or Br target nucleus rarely exceeds the value $\beta_0 = v_0/c = 0.1$. The velocity of the Li, Be, and B fragments in two- or three-pronged stars produced by fast protons in the gelatine also in general cannot exceed this value, since otherwise these fragments would give rise to easily identifiable prongs. A relativistic B or C nucleus with total energy per nucleon (ϵ) will give rise to an A nucleus with total energy per nucleon (ϵ') where ϵ'/ϵ lies within the range of values given by $(1 \pm \beta\beta_0)/(1-\beta_0^2)$ and β is the velocity of the B or C nucleus. Since at geomagnetic latitude 30° $\beta \approx 1$ and since $\beta_0 \lesssim 0.1$ we have $|\epsilon - \epsilon'|/\epsilon \lesssim 10$ percent. Thus at relativistic energies A nuclei produced in collisions in interstellar space will essentially have the same velocity spectrum as the B and C nuclei from which they derive.

(c) *The Relation between the Flux of A Nuclei and Nuclear Collisions in Interstellar Space*

Let us assume that B and C nuclei after being accelerated at the source of cosmic radiation are retained by magnetic fields in some region surrounding the source until they are destroyed by collision with interstellar hydrogen gas. On these assumptions the radiation will contain a certain fraction of A nuclei produced in collisions even if no A nuclei were originally accelerated at the source.

The relative number of A and B nuclei which we would expect to be incident at the top of the atmosphere is then

$$R = p_H(B)(\sigma_B/\sigma_A) + p_H(C)(\sigma_C/\sigma_A)(N_C/N_B).$$

Here $p_H(B)$ and $p_H(C)$ are the probabilities that the collision between a B or C nucleus with hydrogen will lead to the formation of an A nucleus. $\sigma_{A,B,C}$ are the cross sections for the disintegration of A, B, or C nuclei in collision with hydrogen and $N_C/N_B = \frac{1}{3}$ is the relative intensity of the C and B component. Assuming the cross sections to be proportional to the geometric areas of the nuclei we obtain

$$R \geqslant 0.5 \text{ if we use } p_H(B) = p_H(C) \geqslant 0.23.$$

If we use the more reasonable values discussed in Section IIa:

$$p_H(B) > 0.6, \quad p_H(C) > 0.23 \text{ we obtain } R > 1.0.$$

Thus collision equilibrium of primary particles in hydrogen gas should lead to a composition in which the number of A nuclei is at least half as great as that of B nuclei and probably considerably larger.

The ratio $R = 0.5$ is also obtained if we make the (less plausible) assumption that most of the interstellar collisions occur not with hydrogen nuclei but with dust particles (with an assumed average composition comparable to SiO_2).

Since the measurements discussed in Section III(1), give a value for R less than 0.1 we conclude that only a small fraction of the observed primary cosmic-ray particles suffer nuclear collisions between the time they are accelerated and their arrival at the top of the atmosphere.

IV. ON THE RELATION BETWEEN THE CHEMICAL COMPOSITION OF PRIMARY RADIATION AND THEORIES ON THE ORIGIN OF COSMIC RAYS

In a previous paper[12] we have shown that if the primary cosmic radiation were in equilibrium with its collision products most of its proton and helium would have to be ascribed to collision fragments from heavier nuclei. In that case in order to account for the observed chemical composition of the radiation we would have to assume that the amount of hydrogen and helium accelerated at the source is at most equal in *weight* to the amount of heavier nuclei. Therefore

(α) either the source region where cosmic-ray particles are accelerated contains a very much smaller fraction of hydrogen and helium than those regions of the universe which are accessible to spectral analysis, or

(β) the acceleration of heavy particles ($Z > 2$) is greatly favored by the accelerating mechanism compared to the acceleration of light particles ($Z \leqslant 2$). Since an electromagnetic acceleration process requires that the atom is initially ionized one might expect that elements with low ionization potential are more frequently accelerated than those with high ionization potential. Such a selective action in the accelerating process does not seem to exist. For instance Brown[13] gives the relative abundance of the elements oxygen (ioniz. pot. 13.55 ev), neon (ioniz. pot. 21.47 ev), magnesium (ioniz. pot. 7.6 ev) as 5:1:2. A comparison of these ratios with the histogram of Fig. 3 (observed ratio 22:5:5) shows that the ratios of these elements in the primary cosmic radiation do not differ significantly from the universal abundance ratios in spite of the large differences in ionization potentials. In view of this it seems difficult to think of an electromagnetic accelerating mechanism which strongly favors the acceleration of heavy elements.

These difficulties are removed if, based on the measurements described in the previous sections, we conclude that most of the cosmic-ray particles have *not* undergone nuclear collisions between their acceleration and their arrival. The chemical composition of primary particles will then reflect the composition of elements at the source; the relative number of protons and α-particles in the primary beam will not be increased compared to heavier elements by their longer mean free path for nuclear collisions or by the addition of collision fragments.

The absence or scarcity of lithium, beryllium, and boron nuclei in the primary radiation indicates therefore that as far as the distribution between light and heavy elements is concerned the chemical composition at the source is similar to the average chemical composition of the universe.

If we assume an electromagnetic accelerating process the chemical composition *within* the heavy component indicates that the source region differs from stellar atmospheres; in the source even the noble gas atoms are predominantly in an ionized state and therefore the relative abundance of ions in the source region parallels the relative abundance of elements.

The results derived in the previous sections can be expressed by the statement that for most of the primary particles of charge $Z>2$ and kinetic energy per nucleon $\epsilon>3.5$ Bev, the time τ between their acceleration and their entry into the earth's atmosphere must be such that $\tau\leq10^6/\rho$ years, where ρ is the number of atoms per cc along their trajectory. This condition could be satisfied

(α) If the particles came from outside the galaxy (where $\rho<10^{-3}$) as part of primordial matter. They do not, however, show the large deficiency in protons predicted by Lemaître.[10]

(β) If they were of galactic, but relatively recent, origin and did not have time to establish equilibrium with their collision products.

This possibility cannot as yet be disregarded, but recent work by Arnold and Libby[19] on the C^{14} content of historical relics seems to prove that the intensity of cosmic radiation has undergone no appreciable change at least during the last 20,000 years.

(γ) If they were produced in the galaxy but leak out at an appreciable rate.

(δ) If they were produced in the galaxy (in the neighborhood of stars) but adiabatically decelerated in interstellar space in a time short compared to τ.

This deceleration must be much more effective than the deceleration caused by ionization losses, since the ionization loss in hydrogen in a distance corresponding to a mean free path for nuclear collision is small for all particles whatever their charge. If K is the specific ionization loss per g/cm² of a relativistic singly charged particle, the energy loss per nucleon for a heavy particle (charge Z, atomic number A) is Z^2K/A. If we assume that the mean free path for heavy nuclei is inversely proportional to their geometrical area and therefore proportional to $A^{-\frac{2}{3}}$, the specific energy loss per nucleon per mean free path increases only as $A^{\frac{1}{3}}$. Using Fermi's[1] value for the ionization loss of relativistic protons in the interstellar matter $K=4.6$ Mev/(g/cm²) we find that even for nuclei as heavy as iron the energy loss per nucleon by ionization amounts only to some 87 Mev over a distance corresponding to a mean free path for nuclear collisions in hydrogen.

(ϵ) If cosmic-ray particles were absorbed by bodies larger than bricks (such that the particle is absorbed together with its fragments) and that the mean free path for collision with these larger objects is shorter than that for collision with nuclei.

Assuming the most frequently quoted value for the average number of atoms in interstellar space ($\rho=1$), the last three conditions when applied to our galaxy have one feature in common: In order to account for the observed energy density of cosmic radiation an accelerating mechanism must be devised efficient enough to permit the transformation of approximately one percent of the entire stellar energy production into cosmic radiation. The difficulty of conceiving a high efficiency accelerating process which was pointed out by Richtmyer and Teller[2] has been increased by a substantial factor.

Apart from raising this serious difficulty about galactic origin, the apparent absence of nuclear collisions in the life history of primary particles seems to lead to difficulties with the specific theories proposed by Spitzer[4] and by Fermi.[1]

In Spitzer's theory the particles are originally accelerated as dust grains by radiation pressure in the vicinity of a supernova. Since noble gases could not be present in the dust grains in any appreciable amount, their presence in the primary cosmic ray beam and particularly the large primary helium flux[12] requires that these nuclei are fragments produced in nuclear collisions of the heavier nuclei present in dust grains. We have shown previously that the large helium flux requires complete equilibrium between heavy primary nuclei and their collision products. In view of the absence of other expected collision products in the primary beam such an explanation is no longer possible.

In the theory proposed by Fermi[1] particles are accelerated by collisions in our galaxy with inhomogeneous moving magnetic fields. Fermi points out that while protons can be accelerated and regenerated by such a process, heavy nuclei will have to be injected continuously with energies above 1 Bev per nucleon before they can gain energy by these collisions and therefore require an additional accelerating mechanism.

If one now assumes that heavy cosmic ray nuclei either leak out of the galaxy or are adiabatically decelerated or absorbed in large bodies in a time shorter than $10^6/\rho$ years one must assume similar effects for the proton component. By depriving the protons of their ability to make nuclear collisions with interstellar hydrogen one would deprive Fermi's theory of its regenerative mechanism. By reducing the lifetime of fast particles to approximately one million years as compared to the 60 million years assumed in Fermi's theory it may be more difficult to obtain agreement with the observed energy spectrum.

It seems perhaps most promising to consider the absence of nuclear collision products in the cosmic ray beam as an argument in favor of solar origin or at least in favor of a source region sufficiently close such that the chemical composition of the radiation still reflects the abundance ratios at the source.

In the theory of solar origin proposed by Richtmyer and Teller[2] and by Alfvén[3] a magnetic field is assumed to exist in the planetary system, weak enough to escape detection by direct measurements at the earth, yet strong enough to obtain isotropy and time independence especially for particles of very high energy. In its

[19] J. R. Arnold and W. F. Libby, Science **110**, 678 (1949).

present form, however, this theory allocates to the cosmic radiation a volume (radius $\sim 10^{17}$ cm) which seems to be too large to avoid nuclear collisions of primary nuclei with intraplanetary matter unless condition (ϵ) is satisfied and an appreciable fraction of the radiation is absorbed in meteoric material.

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Double Transmission and Depolarization of Neutrons

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Slow neutrons from the chain reacting pile, polarized by passage through highly magnetized iron, have been analyzed by transmission through additional iron (the "double transmission" effect). The large double transmission effects expected from the polarization cross section of iron were obtained only when the magnetic field between polarizer and analyzer was adjusted carefully to obtain non-adiabatic transitions of the neutrons relative to the field. The general methods developed have been used to measure the change in polarization of a neutron beam with passage through unmagnetized iron. The rate of depolarization is a measure of the domain size in the iron and domain sizes have been measured in this way for a number of Armco iron samples of different metallurgical treatment.

I. INTRODUCTION

NUMEROUS investigations[1–13] of the polarization of slow neutrons have been made since Bloch[14] first pointed out the possibility of producing such polarization. This phenomenon arises from the presence of an appreciable magnetic interaction between a slow neutron and a paramagnetic atom and in addition the presence of interference between the nuclear and magnetically scattered neutron waves in the case of a ferromagnetic scatterer. The scattering cross section, σ, per atom in a ferromagnet can be written in the form

$$\sigma=\sigma_0\pm p, \tag{1}$$

where p is the term arising from interference and σ_0 is the sum of the cross sections due to the nuclear interaction alone and the magnetic interaction alone. The double sign of the interference term refers to the two cases of neutron spin parallel and antiparallel to the atomic spins in the ferromagnet. In the case of transmission through a nearly saturated ferromagnet, these two neutron spin states are attenuated to a different extent, corresponding to the difference in the scattering cross sections for these states. Thus an initially unpolarized beam is changed to a polarized one in which there is an excess of neutrons with one sign of spin component, along the field direction in the ferromagnet, over those with spin component of opposite sign. If the ferromagnet is far from saturation, strong depolarizing effects are present also, which nullify the polarizing effects in the magnetic domains.

The first studies of neutron polarization used a polarizer-analyzer arrangement[1–4] in which the intensity of the beam transmitted by two magnetized blocks of iron was measured before and after reversing one of the fields and these intensities compared with the intensity with the blocks unmagnetized. The dependence of the transmission of the analyzer block on its state of magnetization is empirically a measure of the polarization of the incident beam and this effect furnishes a direct way of studying neutron polarization. The intensity differences to be expected from the postulated nature of the magnetic interaction can be understood as follows. With I_+ and I_- as the intensities of neutrons in the two spin states relative to the field, the intensity I transmitted by a saturated iron slab of thickness d is given by

$$\begin{aligned} I\equiv I_+ + I_- &= \tfrac{1}{2}I_0 \exp[-Nd(\sigma_t-p)] \\ &\quad +\tfrac{1}{2}I_0 \exp[-Nd(\sigma_t+p)] \\ &= I_0 \exp(-N\sigma_t d)\cdot\cosh(Npd), \end{aligned} \tag{2}$$

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[1] Hoffmann, Livingston, and Bethe, Phys. Rev. **51**, 214 (1937).
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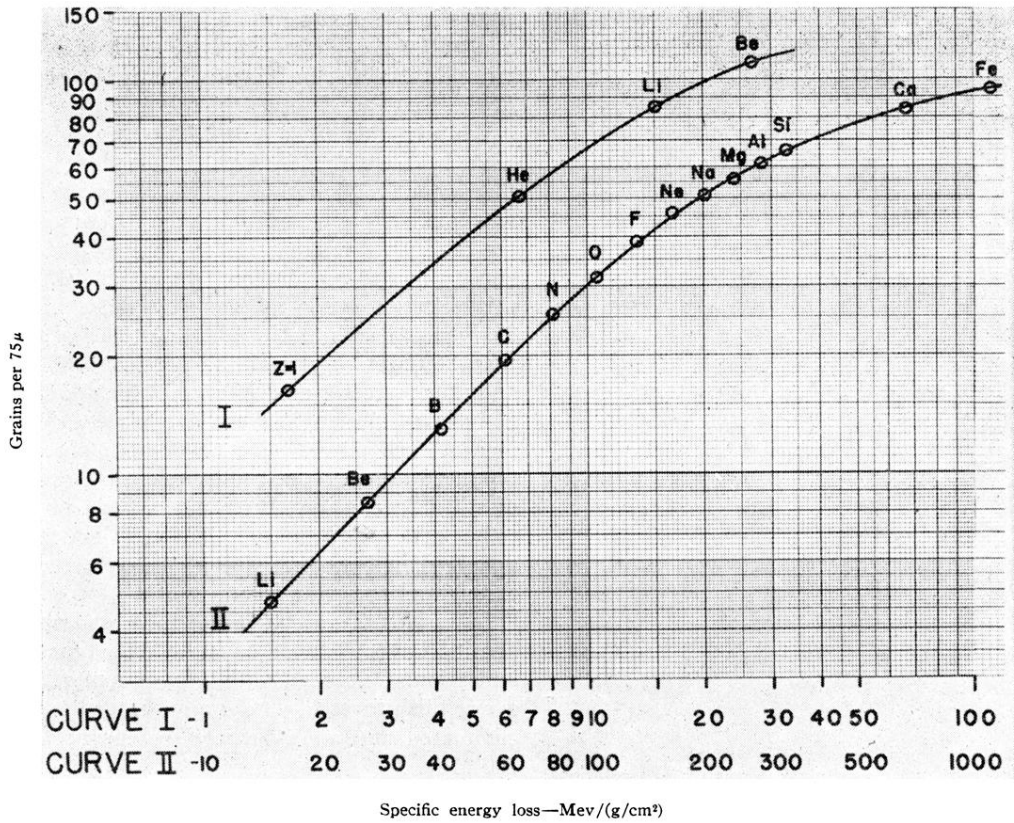

FIG. 1. Grain density *versus* specific energy loss. Curve I refers to NTB3 emulsion. Curve II refers to strongly underdeveloped *NTA* emulsions. The expected grain density of tracks due to various relativistic nuclei is indicated on the diagram.

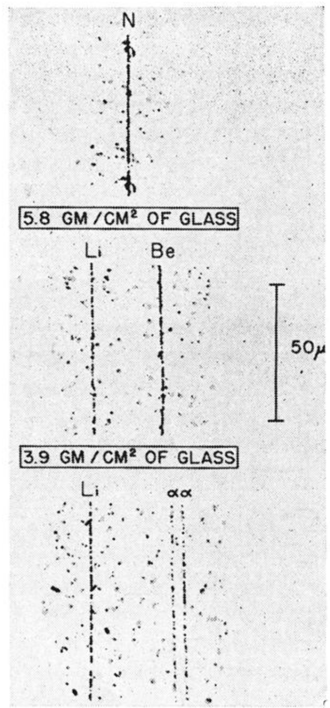

FIG. 2. A relativistic nitrogen nucleus is destroyed in two successive collisions as it traverses a stack of plates. The collisions occur in the glass between emulsions. Sections of the track are shown before and after the collisions. The nitrogen nucleus first disintegrates into a nucleus of lithium and a nucleus of beryllium, the latter then disintegrates into two α-particles.

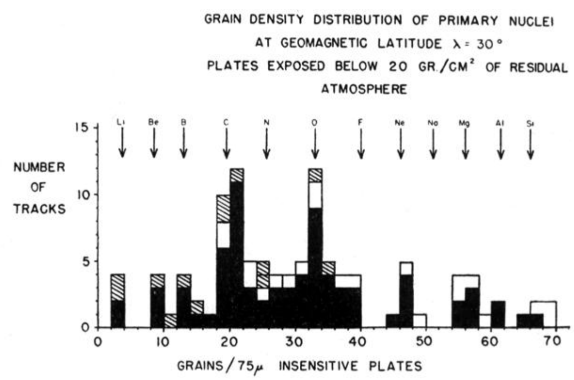

FIG. 3. Histogram of 111 tracks *vs.* grain density in underdeveloped *NTA* emulsions. The solid squares represent a systematic survey. The open squares represent tracks obtained in a less systematic manner in the course of this work. Shaded squares represent relativistic fragments produced by heavier primary nuclei in collisions in the stack. The expected grain densities from different nuclei obtained from Fig. 1 are indicated by arrows. Lithium tracks as explained in the text are included in the diagram although they were identified in neighboring emulsions of higher sensitivity.

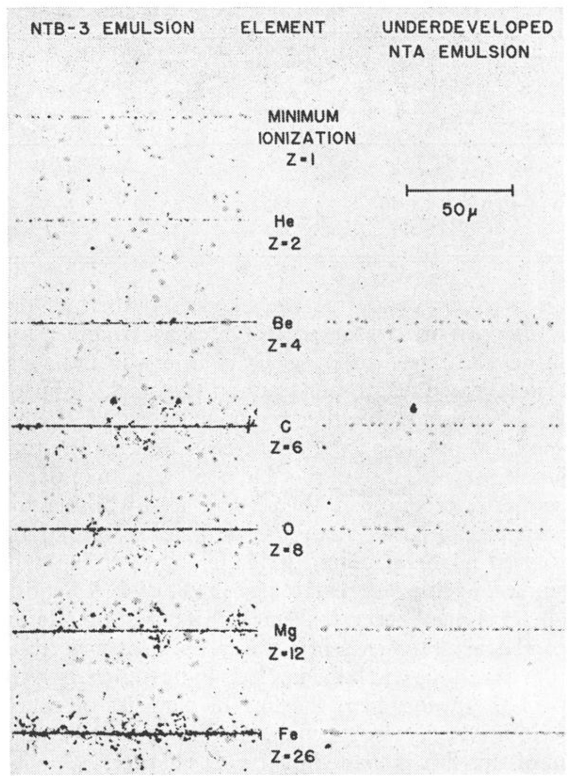

FIG. 4. Tracks of relativistic nuclei of different charge as they appear in electron sensitive *NTB* emulsions and in underdeveloped *NTA* emulsions.