Primary Heavy Nuclei*

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Primary cosmic-ray nuclei of $z\geq 2$ were observed in a balloon-borne cloud chamber. The chamber was triggered by events with ionization loss ≥ 6 minimum in each of three proportional counters, arranged in a telescope. Proportional counter pulse amplitudes were recorded by a neon bulb system.

Two Skyhook daytime balloon flights at geomagnetic latitude 41° maintained average altitudes of 17.6 and 14.3 g/cm². In the 0.77 hour *sensitive* time, in two flights, there were observed in the cloud chamber (charge determined from *both* cloud chamber and proportional counter data) 3–5 Li, 1 Be, 0 B, and 21 $z\geq 6$ nuclei. A primary flux of $10.2_{-3.4}^{+4.5}$ particles per m² sec sterad is found for the $z\geq 6$ nuclei. An unusually large fraction of this group is indicated to be heavier than oxygen. The primary flux of Li, Be, and B nuclei is found to be 5_{-5}^{+32} percent of the primary flux of $z\geq 6$ nuclei, from which we conclude that heavy nuclei have traversed less than 7 g/cm² interstellar hydrogen [$=(4/n)\times 10^6$ light years, where n = number of H atoms per cm³].

The proportional counter data *alone* showed a 14±16 percent decrease in intensity of particles of $z>8$ from morning to afternoon.

I. INTRODUCTION

THE discovery of heavy primaries among cosmic rays[1] brought about important modifications of thought concerning the origin of cosmic radiation. Because these nuclei of helium through iron are stripped (or mostly stripped), their charge to mass ratio is almost independent of charge, and differs by only a factor of two from that of the protons. If then the protons sweep out orbits in extraterrestrial magnetic fields, the heavies should sweep out roughly similar orbits. Following along the proton paths, the heavies serve as sensitive probes to matter encountered on the way since they are irreversibly destroyed by collision.

Comparison of the number of heavy nuclei coming into the earth's atmosphere with the number of protons and alpha particles can lead to an upper limit on the amount of interstellar matter traversed by the heavy nuclei. For example, in the present experiment, at 41° north geomagnetic latitude, a vertical flux of 10 particles per m² sec sterad was found for nuclei of $z\geq 6$. The total number of vertically incident cosmic ray particles (mostly protons) with energies above 1.65 Bev per nucleon (cutoff energy at 41° for stripped heavy nuclei) is around 1700 per m² sec sterad.[2] Consider the extreme case: that only nuclei of $z\geq 6$ are originally accelerated. The 1700 protons then are the fragments of about 100 original heavy nuclei. If 110 heavies had been present at the start, the fluxes observed at the earth imply that 10 remained intact. The attenuation of 11 to 1 implies 2.4 "annihilation" lengths, or perhaps 4.8 mean free paths for collision with interstellar matter. The geometric mean free path for a nitrogen nucleus in hydrogen (the main constituent of matter in space) is 4.3 g/cm². The maximum amount of traversed interstellar hydrogen is thus about 20 g/cm². The interstellar proton density is, within a factor of 10, about 1 per cm³.[3] For a density of n protons per cm³ in interstellar space, one can state equivalently that the heavy nuclei cannot have traveled more than $13/n$ million light years between the time of their acceleration and their observation at the earth.

The foregoing estimate used the protons and alpha particles as indicators of interstellar fragmentation of heavier nuclei. A more sensitive measure of such fragmentation was discovered by Bradt and Peters.[4] The elements of lithium, beryllium, and boron which are very rare in the universe,[5] may nevertheless appear in the cosmic radiation as breakup fragments of $z\geq 6$ nuclei which have collided with interstellar hydrogen. In fact, Hodgson[6] found, in agreement with Bradt and Peters' surmise, that the probability that a CNO nucleus would produce a Li, Be, or B fragment on collision with a proton was 0.22±0.06.[7] From a measurement of the amount of Li, Be, and B occurring in the primary cosmic-ray flux, one can set an upper limit to the amount of traversed interstellar hydrogen.

The results of different measurements of the primary Li, Be, and B flux have been severely contradictory,[8–10] and are summarized in Table I. The last column of Table I estimates, on the basis of Eq. (12), the amount of traversed interstellar hydrogen. The last line of

* The principal results presented here were reported at the 1953 American Physical Society Washington Meeting: T. H. Stix, Phys. Rev. **91**, 431 (1953). The work was supported in part by the U. S. Office of Naval Research, and was submitted by the author to the Graduate School of Princeton University in partial fulfillment of the requirements for the Ph.D. degree.
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[1] Freier, Lofgren, Ney, Oppenheimer, Bradt, and Peters, Phys. Rev. **74**, 213 (1948).
[2] Winckler, Stix, Dwight, and Sabin, Phys. Rev. **79**, 656 (1950).
[3] B. Stromgren, Astrophys. J. **108**, 242 (1948).
[4] H. L. Bradt and B. Peters, Phys. Rev. **80**, 943 (1950).
[5] L. Spitzer, Jr., Astrophys. J. **109**, 548 (1949); J. L. Greenstein and E. Tandberg-Hanssen, Astrophys. J. **119**, 113 (1954).
[6] P. E. Hodgson, Phil. Mag. **42**, 955 (1951).
[7] Noon, Kaplon, and Ritson, Phys. Rev. **92**, 1585 (1953), quote a value of 0.83±0.5 for this probability.
[8] Dainton, Fowler, and Kent, Phil. Mag. **43**, 729 (1952).
[9] Kaplon, Peters, Reynolds, and Ritson, Phys. Rev. **85**, 295 (1952).
[10] Kaplon, Racette, and Ritson, Phys. Rev. **93**, 914 (1954).

TABLE I. Primary cosmic-ray flux of Li, Be, B nuclei.

Group	Technique	Geomagnetic latitude	Results: estimated primary fluxes	Implication: based on Eq. (12) using $\gamma=0.22$
Bradt and Peters,[a] 1950	Nuclear emulsions	30°	$\frac{\text{Li, Be, B}}{\text{C, N, O, F}}<0.1$	$z\geq 6$ nuclei have traversed <1.5 g/cm^2 interstellar hydrogen.
Dainton, Fowler, and Kent,[b] 1952	Nuclear emulsions	55°	$\frac{\text{Li, Be, B}}{\text{C, N, O, F}}\sim 1$	$z\geq 6$ nuclei have traversed >15 g/cm^2 interstellar hydrogen, or Li, Be, B nuclei are abundant in source region.
Kaplon, Peters, Reynolds, and Ritson,[c] 1952	Nuclear emulsions	42°	Be and B rare or absent	Same as first reference.
Kaplon, Racette, and Ritson,[d] 1953	Nuclear emulsions	41°	$0.1\leq\frac{\text{Li, Be, B}}{\text{C, N, O, F, Ne}}\leq 0.5$	$z\geq 6$ nuclei have traversed between 1.5 and 8 g/cm^2 interstellar hydrogen, or Li, Be, B are abundant in source region.
Stix, 1953	Cloud chamber proportional counter telescope	41°	$\frac{\text{Li, Be, B}}{z\geq 6}<0.37$	$z\geq 6$ nuclei have traversed <7 g/cm^2 interstellar hydrogen.

[a] See reference 4. [b] See reference 8. [c] See reference 9. [d] See reference 10.

Table I gives the results from the present experiment. These are statistically compatible with all but the Bristol measurements.

A strong diurnal variation for heavy nuclei would suggest a solar origin for these particles, but observations on this effect have been contradictory. Dwight's[11] calculations point out that charged particles coming directly from the sun can only enter into the earth's atmosphere from certain directions, at certain latitudes and times. For example, particles over a wide range of energies emitted in straight lines from the sun can arrive at the latitude of 41° only in the vertical direction in the middle of the winter, and only between 4 and 8 o'clock in the morning. The calculations thus imply that the heavy nuclei that passed through our vertical telescope in this experiment cannot have come directly from the sun.

Time variation measurements of the heavy nucleus flux are summarized in Table II.[12–18] The present experiment is consistent with a constant isotropic flux.

The present experiment introduces a new technique—the cloud chamber-proportional counter telescope combination—for observation of heavy cosmic-ray primary particles. Skyhook balloons carried 220-lb gondolas above 90 000 ft in two flights at 41° geomagnetic latitude. A gondola contained a cloud chamber which was triggered by a vertical telescope of three proportional counters (Fig. 1). An ionization larger than six times minimum was required in *each* of the three proportional counters in order to trip the discriminator-coincidence circuit. This selection scheme accepts all particles of $z>2$.

At the latitude and altitude of operation, vertically

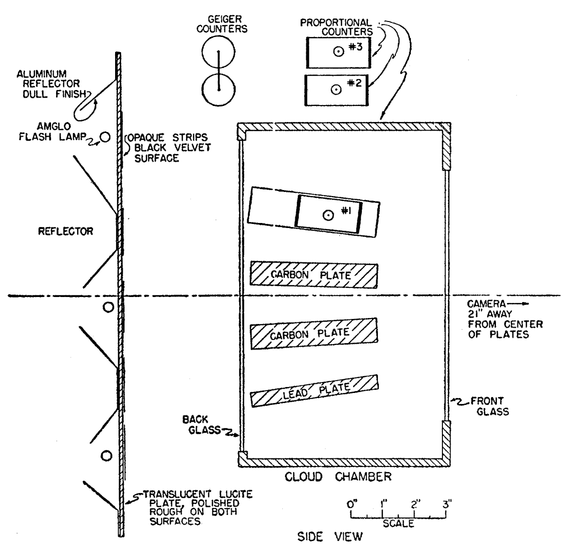

FIG. 1. Schematic drawing of balloon-borne cloud chamber and proportional counter telescope. Bottom counter of telescope is inside cloud chamber. Neon bulbs recorded pulse amplitudes from each proportional counter as variable length streaks above the cloud chamber photograph on the continuously moving 35-mm film. An additional neon bulb indicated events where one or both of the out-of-line Geiger tubes discharged in coincidence with the proportional counter telescope. Also indicated on the drawing is the compact cloud chamber rear illumination scheme.

[11] K. Dwight, Phys. Rev. **78**, 40 (1950).
[12] J. J. Lord and M. Schein, Phys. Rev. **78**, 484 (1950); Phys. Rev. **80**, 304 (1950).
[13] Freier, Ney, Naugle, and Anderson, Phys. Rev. **79**, 206 (1950).
[14] E. P. Ney and D. M. Thon, Phys. Rev. **81**, 1069 (1951).
[15] Freier, Anderson, Naugle, and Ney, Phys. Rev. **84**, 322 (1951).
[16] G. W. McClure and M. A. Pomerantz, Phys. Rev. **84**, 1252 (1951).
[17] Anderson, Freier, and Naugle, Phys. Rev. **91**, 431 (1953).
[18] V. H. Yngve, Phys. Rev. **92**, 428 (1953).

TABLE II. Time variations in the heavy nuclei flux.

Group	Technique	Geomagnetic latitude	Date of flight launching	Altitude in g/cm²	Results
Lord and Schein,[a] 1950	Nuclear emulsions	55°	Oct. 31, 1949	45	$\frac{\text{Night flux}}{\text{Day flux}}=0.48\pm0.14$
		55°	Nov. 30, 1949	87	$\frac{\text{Night flux}}{\text{Day flux}}=0.33\pm0.12$
		55°	May 22, 1950	15	$\frac{\text{Night flux}}{\text{Day flux}}=0.39\pm0.04$
Freier, Ney, Naugle, and Anderson,[b] 1950	Nuclear emulsions	55°	Oct. 26, 1949	23–35	$\frac{\text{Night flux}}{\text{Day flux}}=0.3$ to 0.5
Ney and Thon,[c] 1951	Scintillation counter	55°	Oct. 4, 1950	10	$\frac{\text{Afternoon flux}}{\text{Morning flux}}=1.44\pm0.18$
Freier, Anderson, Naugle, and Ney,[d] 1951	Nuclear emulsions	55°	April 13, 1950	14	Night flux = day flux
McClure and Pomerantz,[e] 1951	Ionization chamber	55°	Aug. 17, 1951	29	Night flux = day flux $\pm13\%$
Anderson, Freier, and Naugle,[f] 1953	Nuclear emulsions	55°	July 31, 1952	18.5	Constant flux $\pm20\%$ over 20-hr period
		55°	Aug. 28, 1952	30	
Yngve,[g] 1953	Nuclear emulsions	55°	June 4, 1952	17	Flux at 1 P.M. = $125\pm9\%$ of average of 10:30 A.M. and 3:30 P.M. fluxes
Stix	Cloud chamber-proportional counter telescope	41°	April 26, 1952	17.6	$\frac{\text{Afternoon flux}}{\text{Morning flux}}=0.86\pm0.16$
			May 8, 1952	14.3	

[a] See reference 12.
[b] See reference 13.
[c] See reference 14.
[d] See reference 15.
[e] See reference 16.
[f] See reference 17.
[g] See reference 18.

incident particles have velocities corresponding to minimum ionization for their charge. A measurement of the ionization loss can lead to a unique value of the charge of the particle. Consequently, the pulse height from each of the three proportional counters was recorded.

Previous work has shown a great need for accurate measurement of altitude. A drop in altitude causes a decrease in high-z particles and an increase in Li, Be, and B nuclei. An incorrect flux value or an apparent diurnal variation can thus appear. For this crucial reason the amount of residual atmosphere was measured by mercury manometer, photographed every two minutes.

The proportional counter telescope would be suited to survey measurements. In designing the present experiment, one had in mind that the counter telescope, without the cloud chamber but with additional shower protection from Geiger tubes, could at some time be used in a series of heavy-nuclei observations at different latitudes.

II. INTERPRETATION OF DATA FROM A PROPORTIONAL COUNTER TELESCOPE

In this experiment, heavy nuclei pass through the cloud chamber and their charge can be estimated. For events thus known from their cloud-chamber pictures to be heavy nuclei, the nuclear charge is measured quantitatively by the three proportional counters in the proportional counter telescope. The geomagnetic cutoff at this latitude (41°) for stripped vertically incident nuclei with equal numbers of protons and neutrons is 1.65 Bev per nucleon.[19] Allowed particles are still at minimum ionization at the balloon altitude ($\sim$15 g/cm²), consequently a proportional counter measurement of ionization loss can lead to a unique value for the nuclear charge.

The relation between most probable ionization loss and incident particle charge is found using an extension of the theoretical work of Landau[20] and Symon.[21] The

[19] M. S. Vallarta, Phys. Rev. **74**, 1837 (1948).
[20] L. Landau, J. Phys. (U.S.S.R.) **4**, 201 (1944).
[21] K. R. Symon, Harvard Ph.D. thesis, 1948 (unpublished). I am grateful to Dr. Symon for verifying the validity of this extension.

ionization loss fluctuation treatment developed by both of these authors becomes valid for incident particles of charge ze (rather than charge e) when the energy ξ defined by Landau is simply replaced by the new energy $\xi''=z^2\xi$. For Landau's work, we then have

$$\xi''=1.54\times10^5\mu z^2\frac{\Sigma Z}{\Sigma A}\frac{1}{(v/c)^2}\text{ electron volts,}\qquad(1)$$

and the most probable energy loss is now given by Δ_0 as

$$\Delta_0=\xi''\left[\log\left\{\frac{4.62\times10^8\mu z^2\Sigma Z/\Sigma A}{Z^2[1-(v^2/c^2)]}\right\}+1-\frac{v^2}{c^2}\right]\text{ electron volts,}\qquad(2)$$

where μ is the thickness of matter traversed in g/cm^2, ΣZ is the molecular charge, ΣA is the molecular weight of the traversed matter, and v is the velocity of the incident particle.

In particular, for minimum ionizing particles passing through one of the proportional counters (4.0 mg/cm^2 of argon), the most probable ionization loss is found to vary approximately as

$$\Delta_0\sim z^{2.16},\qquad(3)$$

in contrast to the z^2 variation for *average* ionization loss.

For a single particle, the proportional counter telescope gives three ionization loss measurements, Δ_1, Δ_2, Δ_3. It is necessary to determine from the three measurements a single equivalent ionization loss, Δ_E. Because the ionization loss distribution has a high positive skew, cosmic-ray workers by rule of thumb choose the smallest of the three measurements to be the equivalent ionization loss. In an effort to improve on this rule of thumb, the following data fitting scheme was used: For the ith counter, we denote the probability that a particle with most probable ionization loss Δ_0 will give rise to an ionization loss Δ_i in the range $d\Delta_i$ by $L(\Delta_i;\Delta_0)d\Delta_i$. By using the method of maximum likelihood, Δ_E for the group is then that value of Δ_0 for which the likelihood

$$L(\Delta_1;\Delta_0)L(\Delta_2;\Delta_0)L(\Delta_3;\Delta_0)\qquad(4)$$

is a maximum.[22]

The ionization loss distribution, $L(\Delta_i;\Delta_\mu)$ was determined experimentally at sea level for fast mu mesons passing through one of the proportional counters (Fig. 2). A twofold Geiger tube telescope collimated the beam, and only those events were recorded where the mesons penetrated 4 in. of lead after passing through the proportional counter. The median energy for these mesons is 18 times their rest mass[23] corresponding to a most probable ionization, (Δ_μ), according to the Landau formula of 1.19 times that for a minimum ionizing particle. To maximize the expression in (4), one has to know $L(\Delta_i;\Delta_0)$ for all values of Δ_0. In the absence of direct experimental knowledge, we used the scaling relation

$$L(\Delta_i;\Delta_0)=(\Delta_\mu/\Delta_0)L(\Delta_\mu\Delta_i/\Delta_0;\Delta_\mu)\qquad(5)$$

to obtain an ionization loss distribution for particles of all values of Δ_0 (thus all values of z) from the experimental mu meson distribution. Equation (5) is an approximation to the Landau formula when ionization is considered a function only of the charge of the incident particle.

By using (5), the condition that (4) be a maximum is found by solving the equation

$$M(\Delta_1/\Delta_0)+M(\Delta_2/\Delta_0)+M(\Delta_3/\Delta_0)=-3\qquad(6)$$

for Δ_0. Here we have defined

$$M\left(\frac{\Delta_i}{\Delta_0}\right)=\frac{\Delta_i}{L(\Delta_i;\Delta_0)}\frac{\partial L(\Delta_i;\Delta_0)}{\partial\Delta_i}.\qquad(7)$$

M is the slope of the ionization loss distribution when the latter is plotted on log log paper. A graph of M is shown in Fig. 3.

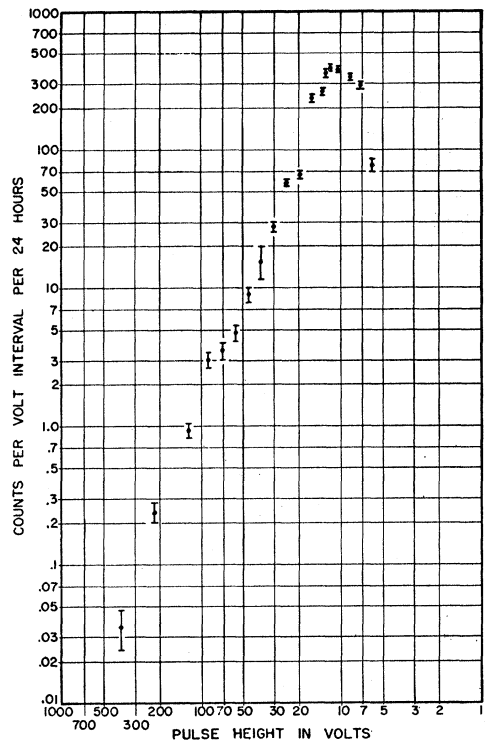

FIG. 2. Ionization loss distribution for fast mu mesons passing through a single proportional counter. Beam was collimated by twofold Geiger tube telescope, and only those events recorded where the mesons penetrated 4 in. of lead after passing through the proportional counter. Pulse-height distribution obtained at sea level using laboratory (not flight) electronics.

[22] The method of maximum likelihood assumes a flat *a priori* spectrum. The analysis was also carried through using a $1/\Delta_0$ *a priori* spectrum, but the change in results was completely negligible.

[23] B. Rossi, Revs. Modern Phys. **20**, 537 (1948).

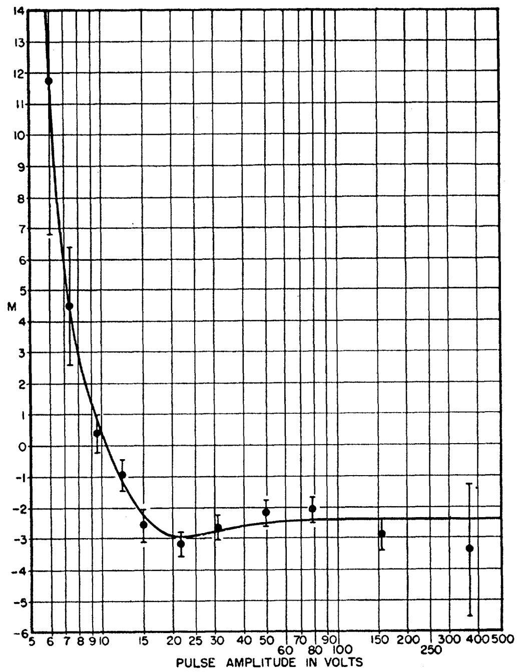

FIG. 3. $M(\Delta_i/\Delta_\mu)$ *versus* ionization loss (Δ_i) for a most probable ionization loss for μ mesons (Δ_μ) of $\Delta_\mu = 10.5$ volts. [See Eq. (7).] Values of M were calculated from the data in Fig. 2.

We denote by α the ratio $\Delta_E/\Delta_{\text{smallest}}$. The approximate solution of Eq. (6), α = constant, would correspond to the rule of thumb mentioned earlier. If one uses the *theoretical* Landau ionization loss distribution in 4.0-mg/cm^2 argon for $L(\Delta_i; \Delta_0)$, one finds that α always lies between 0.97 and 1.10. By using the *experimental* ionization loss distribution found for fast mu mesons for $L(\Delta_i; \Delta_0)$, the values of α are found to lie between 0.88 and 1.33. While these last values of α were the ones used in the analysis of the experimental data, it is worth noting that the rule of thumb ($\alpha = 1.11$ for all values of Δ_1, Δ_2, Δ_3) would never give values for Δ_E which differed by more than 26 percent from the values of Δ_E arrived at on the basis of the above detailed method. A difference of 26 percent in ionization loss corresponds to a difference of only 12 percent in charge.

In the analysis of the experimental data, one assigns a value Δ_E to the group Δ_1, Δ_2, Δ_3 for each heavy nucleus. The nuclear charge that is assigned to this event is that value, z_E, for which Δ_E is the most probable ionization loss. We use the relation

$$\Delta_E \sim z_E^{2.16}. \tag{8}$$

The calibration technique will be outlined in the next section.

III. THE FLIGHT APPARATUS

The flight apparatus contains a rear-illuminated cloud chamber which is triggered by a threefold proportional counter telescope (Fig. 1). The cloud chambers in this experiment had been used previously for balloon flight work.[24] The distance between the centers of the top and bottom counters of the telescope is $5\frac{1}{8}$ in. The area integral of the telescope solid-angle is 14.0 cm^2 sterad. With an isotropic flux, the average deviation from the vertical for particles traversing the telescope is 17°.

The rectangular proportional counters have a sensitive volume $4\frac{1}{2}$ in. long, $\frac{7}{8}$ in. high, $1\frac{7}{8}$ in. wide. Top and bottom counter walls are $\frac{1}{32}$-in. bronze, the side walls $\frac{1}{16}$-in. bronze. The counters are filled with 769 mm Hg of tank argon, are operated with approximately 1200 volts on the 0.00135-in.-diameter tungsten center wire, producing a gas amplification of about 200. A field tube termination for the center wire shown in Fig. 4 is used to reduce end effect.[25] Experiments made in the laboratory with collimated polonium alpha particles and collimated gamma rays indicated that the rms fluctuation in a random ionization measurement, due to gas attachment, recombination, and variation of gas amplification in the counter would be about 15 percent. The ionization loss distribution for fast mu mesons (Fig. 2) shows a half-width at half-maximum of about 50 percent. This is in excellent agreement with D. West[26] who beamed relativistic electrons through the central portion of a proportional counter filled with a similar amount of argon, and found a half-width at half-maximum of about 45 percent.

A block diagram of the electronics is given in Fig. 5. Separate channels amplify and record pulses from each of the three proportional counters. At the output of the gate circuits, the durations of the amplified pulses are 50 to 400 μsec and roughly proportional to the logarithms of the original amplitudes, owing to their exponential decay in the early stages of amplification. The linear pulse lengthener (Fig. 6) stretches these pulses to durations between $\frac{1}{4}$ and 2 sec. Neon recording lights

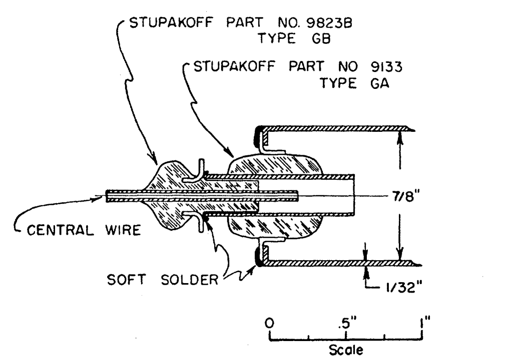

FIG. 4. Wire termination on proportional counters. Co-axially mounted Stupakoff seals provide simple field tube geometry. End of 0.00135 in. tungsten center wire is run through $1\frac{1}{4}$ in. long 0.045 in. o.d. nickel tube (not shown), which is clamped shut with spot-welder and soft-soldered in place inside innermost Stupakoff tube.

[24] R. R. Rau, Rev. Sci. Instr. **23**, 443 (1952).
[25] A. L. Cockcroft and S. C. Curran, Rev. Sci. Instr. **22**, 37 (1951).
[26] D. West, Proc. Phys. Soc. (London) **A66**, 306 (1953).

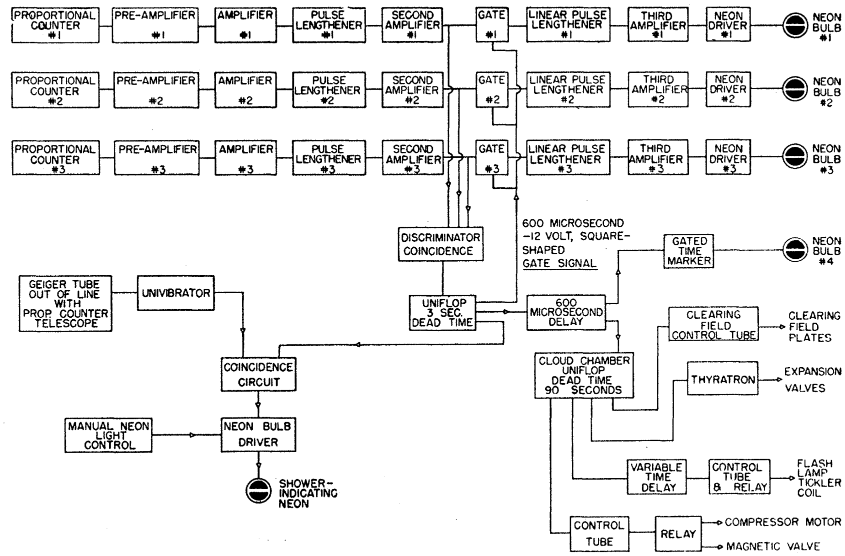

FIG. 5. Block diagram of electronics for balloon-borne cloud chamber and proportional counter telescope. Discriminator-coincidence circuit is triggered when event produces ionization loss greater than 6 times minimum in each proportional counter, and in turn triggers uniflop, which then cannot be retriggered for 3 sec. Gates open for 600 μsec, allowing signals to reach neons. Neon recording lights are energized for lengths of time between $\frac{1}{4}$ and 2 sec roughly proportional to logarithms of corresponding proportional counter pulse heights. Neon bulb No. 4 oscillates for 3 sec, 10 times per sec, providing time base on film record. Dead time for recording circuit is 3 sec, for cloud chamber, 90 sec.

are energized for these times producing streaks near the edge of the continuously moving 35-mm camera film—the same film used for the cloud-chamber photographs.

The triggering of the cloud chamber is delayed by 600 μsec so that the firing of the expansion valve thyratron and the removal of the cloud chamber clearing field voltage will occur *after* the gates are closed. Pickup from these cloud-chamber operations then can *not* produce spurious contributions to the proportional counter pulse-height record. A uniflop circuit inhibits the triggering of the cloud chamber if less than 90 sec have elapsed since the previous expansion.

The over-all gain of the amplifier up to the discriminator stage is around 3000, and the rise time is 40 μsec, although the rise time of the preamplifier is 6 μsec. The noise level is below 1 percent of the smallest signal that the discriminator will accept. Cross-talk can introduce spurious signals in adjacent channels no larger than 0.005 of the original signal. The ratio between maximum and minimum readable pulses is around 300 to 1, although readability becomes poorer for large pulses. The over-all resolution of the pulse height recording system was approximately 10 percent for the small pulses, 20 percent for the very large pulses.

The equipment was calibrated before flight by applying standard pulses of different amplitudes to the three preamplifiers. The neon bulb output was recorded on the camera film, as in flight. For the second flight, a post-flight calibration was also made. The two calibration curves were constant within a *full width* of 20 to 30 percent at the beginning and the end of the 22-hr period. From this and from similar curves made in the laboratory, we conclude that over the 8-hr period at altitude, the over-all drift in amplification was less than 20 percent in full width, or 10 percent from an average value. For the purpose of this experiment, this drift is small.

By an indirect method, a reference point was established correlating recorded proportional counter pulse output with ionization loss inside the counter. The response of the counters to an external radium source was used as a link. From the fast mu meson curve (Fig. 2), the pulse height P_0 was determined, which corresponded to six times the most probable ionization loss for minimum ionization-singly charged particles. Then, using the same equipment, with a 100 microcurie radium source placed exactly 1 meter away from the counter it was found that 320 pulses per min occurred with amplitude larger than P_0. The final step was to adjust the flight apparatus, before flight, so that with the same radium source at 1 m, 320 pulses per min arrived in each proportional counter channel with an amplitude larger than the discrimination level of the electronic circuitry. The "cutoff" point for small pulses is thus set in each channel at "6 minimum." The requirement that the ionization loss in each of three counters be larger than 6 minimum was approximately equivalent to an equivalent ionization loss, Δ_E, larger than 6.7 times minimum. In Sec. IV, we shall see that the alpha-particle data provides an independent verification of this reference "cutoff" point at 6.7 minimum.

Two units were flown at Pyote, Texas. A General Mills type 871 balloon was used for Flight I, on April 26, 1952, and reached 90 500 ft (17.1 g/cm^2) at 0830 CST. In the first 7 hr at altitude, the balloon dropped only 500 ft. In the eighth hour, the balloon lost 2000 ft more. The load was released at 1630 CST from 88 000 ft (19.2 g/cm^2). With a General Mills type 1101 balloon, Flight II, on May 8, 1952, reached 98 000 ft (12.0 g/cm^2) at 0915 CST, held full altitude $1\frac{1}{2}$ hr, then in $5\frac{1}{2}$ hr gradually lost 7500 ft. The load was released at 1620 CST from 90 500 ft (17.1 g/cm^2).

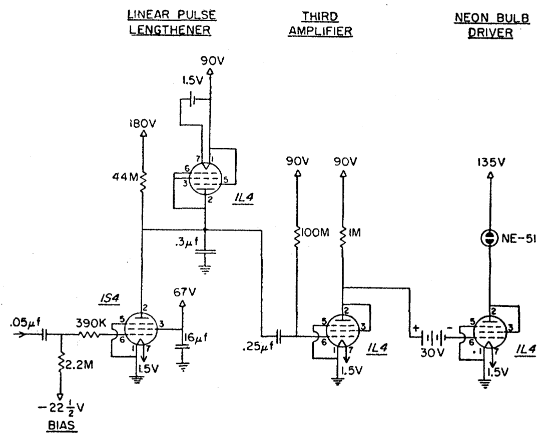

FIG. 6. Neon-bulb pulse recorder. Positive input pulses, which are 35 volts high, approximately square, and of 50 to 400 μsec duration, are stretched in time by a factor of about 5000, amplified, and used to drive Ne51 recording light. Under no-signal condition, diode-connected 1L4 holds plate of 1S4 at 90 v. The 0.3 mfd condenser discharges linearly when signal is applied and 1S4 pentode conducts, and charges linearly afterwards through 44 megohm resistor, as though charging to 180 v. When potential approaches 90 v, current flows in grid circuit of next stage and in 1L4 diode, returning voltages quickly to equilibrium. Amplifier stage is dc coupled to neon driver to accommodate repeated signals.

IV. THE FLIGHT DATA

In the course of the two balloon flights, about 7000 events triggering the proportional counter telescope were recorded. Cloud-chamber pictures accompanied approximately 10 percent of these events and 423 readable cloud-chamber pictures were obtained over a 10-hr period corresponding to 0.77 hr sensitive time. The photographs were classified: 68 nuclei of $z \geq 2$, 5 heavy nuclei which broke up before they reached the cloud chamber; 5 heavy nuclei which came very close to the wall of the top or bottom proportional counter and gave misleading proportional counter pulses; 3 heavy nuclei which broke up in the chamber, sending fragments back up through the telescope to trigger it; 57 slow protons stopping in an absorber in the cloud chamber; 76 showers; 63 bursts; and 146 cases identified simply as not due to a heavy nucleus.

Heavy nuclei were identified from the cloud-chamber data alone by the density of ionization along the track, estimated by visual examination, by their ability to penetrate the 4.1-g/cm^2 brass-jacketed carbon absorbers without an observed change in ionization, by the presence of delta rays, and occasionally by the appearance of an energetic nuclear interaction. With these criteria, it was possible to differentiate slow proton tracks (about 10 percent of the incident protons with energies in the range 50–100 Mev would produce ionizations in the three proportional counters sufficient to trigger the discrimination circuit) from tracks of relativistic particles of $z \geq 2$. Fast nuclei seen in the cloud chamber were classified as $z = 1$, 2, 3, or ≥ 4. For $z \geq 4$, the average ionization is greater than 16 minimum and the cloud-chamber track is opaque. One estimates that the error in charge classification for fast particles ($z = 1$, 2, 3, or ≥ 4) is one unit.

The histograms in Fig. 7 show the number of cloud-chamber pictures of different types, plotted against the proportional counter telescope charge measurement. For a single traversal, the fractional rms deviation from the mean in the three proportional counter pulse heights is σ/Δ_0:

$$\frac{\sigma}{\Delta_0} = \frac{1}{\Delta_0} \left\{ \frac{(\Delta_1 - \Delta_{Av})^2 + (\Delta_2 - \Delta_{Av})^2 + (\Delta_3 - \Delta_{Av})^2}{3} \right\}^{\frac{1}{2}}. \quad (9)$$

(Quantities defined in Sec. II, and denoting $\Delta_{Av} = \frac{1}{3}[\Delta_1 + \Delta_2 + \Delta_3]$.) In Fig. 7, narrow histogram bars indicate those events for which $\sigma/\Delta_0 \geq 100$ percent. For three counters, an *average* dispersion σ/Δ_0 indicates a dispersion in equivalent pulse heights, Δ_E, of $\sigma/\sqrt{3}\Delta_0$ and a dispersion in the resultant charge measurements, z, of $\sigma/2.16\sqrt{3}\Delta_0$. [See Eq. (8).] In Fig. 7, $\sigma/\Delta_0 \geq 100$ percent for only 3 of the 34 alpha particles and for none of the 21 $z \geq 6$ events. Thus, in more than 90 percent of the cases, the indicated deviation from the

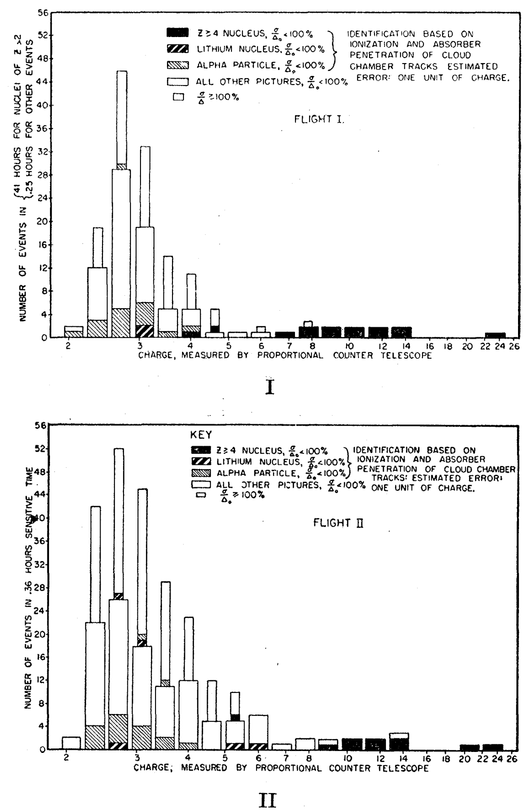

FIG. 7. Charge spectrum for events seen in cloud chamber, Flights I and II. Charge estimated visually from density of ionization along track and absorber penetration (indicated by shading) and measured by proportional counter telescope (abscissa). For each event, σ/Δ_0 denotes the fractional rms deviation from the mean of the three proportional counter ionization loss amplitudes.

mean measured value of z was less than $100/2.16\sqrt{3}=27$ percent. Similarly, the *median* value of the dispersion, σ/Δ_0, for the alpha and $z\geq 6$ events was 31 percent, indicating a median deviation from the mean measured value of z of less than 9 percent.

A comment can be made on skewness. The three pulse heights show a positive skew if the average pulse height is larger than the middle pulse height. Twenty-five of the 34 alpha particles and 16 of the 21 $z\geq 6$ events showed such a positive skew. A positive skew is predicted both by the theoretical Landau ionization loss distribution and by the experimental fast mu meson ionization loss distribution (Fig. 2). The observation of positive skew in the flight data provides a qualitative justification for the use of a data fitting scheme (Sec. II) which assigns to an ionization loss group Δ_1, Δ_2, Δ_3 an equivalent ionization loss, Δ_E, smaller than the average ionization loss, $\Delta_{Av}=\frac{1}{3}(\Delta_1+\Delta_2+\Delta_3)$.

The counter telescope and discrimination circuit were adjusted to reject all events with equivalent ionization loss smaller than 6.7 minimum (Sec. III). This cutoff at 6.7 minimum provided the reference point for calibrating the charge measurement scale. An independent check on the accuracy of this scale calibration comes from the alpha-particle data. A fraction of the incident alphas gave ionization losses in each of the three proportional counters sufficiently larger than the most probable loss (4.5 minimum) to trigger the telescope. Knowing the dispersion in the ionization loss and the fraction of alphas that triggered the telescope, we can make an independent estimate of the equivalent ionization loss at the cutoff point.

Based on a primary alpha flux at 41° of 140 particles per m^2 sec sterad and an absorption length in the atmosphere of 60 g/cm^2,[9] the flux of alphas expected to reach the cloud chamber is 103 particles per m^2 sec sterad. The 34 observed alpha particles correspond to an incident flux of 11.0 particles per m^2 sec sterad *triggering* the telescope, or 11 percent of the incident alphas. The area under a *Gaussian* curve to the right of center by 1.23 standard deviations (1.23σ) is 11 percent of the total. The median value of the dispersion σ/Δ_0 for the observed alphas was 35 percent, indicating a dispersion in Δ_E of 20 percent. The cutoff point then occurs at an ionization loss of $4.5(1+1.23\times 0.20)=5.6$ minimum. The possible error introduced by calling this point 6.7 minimum, as we do in this experiment, is 20 percent in ionization or 9 percent in charge. However, since the ionization loss distribution is not Gaussian, but skewed positive, the above error is smaller and could be zero.

In summing up, single nuclei are classified from their cloud-chamber photographs into $z=1$, 2, 3, or ≥ 4 with an error estimated to be one unit of charge. For the proportional counter telescope, the dispersion data leads us to expect that in 90 percent of the cases the fractional deviation from the mean measured value of z will be less than 27 percent, and in 50 percent of the cases, less than 9 percent. Furthermore, the alpha-particle data indicate that the calibration accuracy of the charge scale is better than 9 percent for low values of z. These estimates of the accuracy of the charge determination provide useful criteria in the identification of nuclei of Li, Be, and B.

Two events in Flight I gave the appearance of lithium nuclei (Fig. 7). For both events, a charge of 3 was estimated from the cloud chamber picture and measured by the proportional counter telescope.

Five events were identified as $z=3$ from their cloud chamber pictures in Flight II (Fig. 7). However, for two of them, the charges measured by the proportional counter telescope were 5 and 6. Such errors are out of the question for the proportional counters, and similarly, the cloud chamber pictures are completely inconsistent with labeling these particles boron or carbon nuclei. We interpret these two cases as unusual bursts or heavy nucleus fragmentations, and discard them from consideration as valid examples of Li nuclei. For two more of the $z=3$ events in Flight II, dispersions σ/Δ_0 of 162 percent and 175 percent were recorded. The smaller of these dispersions is 5.2 times as large as the median dispersion found for alpha and $z\geq 6$ particles. It is thus probable that these two events also are not valid Li nuclei, but, to be conservative, we do not discard them. The number of Li nuclei observed is then 2 Li in Flight I in 0.41 hr sensitive time, and 1–3 Li in Flight II in 0.36 hr sensitive time.

For Flight I, Fig. 7 shows one beryllium nucleus and one event halfway between beryllium and boron. Figure 7 shows an apparent boron nucleus in Flight II. However, these last two events both showed dispersions σ/Δ_0 larger than 100 percent (3.2 times as large as the median dispersion for alphas and $z\geq 6$ nuclei). More important, the three pulses for both these events showed a large negative skew (one small pulse and two large pulses) which is highly unusual (see above). The small pulse came in both cases from the counter inside the cloud chamber, and the stereographic cloud-chamber photographs show that in each case the particle passed *very* close to the front wall of this proportional counter. This close passage could account for the small pulse. In both events, the density of ionization of the cloud-chamber track, and the pulse amplitudes from the top two proportional counters are consistent with particles of $z\geq 6$. We conclude that these events are $z\geq 6$ nuclei which passed outside the proper solid angle of the proportional counter telescope, and on this basis, we discard them from consideration. The only valid observation is then the first: 1 beryllium and 0 boron nuclei in Flights I and II in 0.77 hr sensitive time.

For all of the $z\geq 6$ nuclei, the dispersions σ/Δ_0 were <100 percent. From Fig. 7, we have 12 nuclei of $z\geq 6$ in Flight I in 0.41 hr sensitive time, and 9 nuclei of $z\geq 6$ in Flight II in 0.36 hr sensitive time.

V. EXPERIMENTAL RESULTS

In this section we present the significant experimental results and interpretations bearing on (a) the mean free path for heavy nuclei in carbon and lead, (b) the time variation in the primary flux of heavy nuclei, (c) the primary flux and relative abundances of nuclei of $z \geq 6$, and (d) the primary flux of nuclei of $z=3$, 4, and 5.

The small numbers of events we have to deal with necessitate a cautious evaluation of the statistics. In assigning limits of error, we follow V. H. Regener.[27] Consider a given measured count n. It is possible to determine a value a_1 for a hypothetical average count which lies so far below n that the total probability (evaluated on the basis of a Poisson distribution) for the actual count to fall anywhere below n assumes a specific value p. Above n, another value a_2 can be determined so that the total probability for the count to fall anywhere above n assumes again the value p. In the data analysis to follow, we make the conservative choice: $p=95$ percent, noting that for a Gaussian distribution the use of limits $a_1=n-\sqrt{n}$, $a_2=n+\sqrt{n}$ corresponds to $p=84$ percent.

(a) Mean Free Paths in Carbon and Lead

By counting the number of traversals of the cloud-chamber absorbers with and without observed interaction, mean free paths can be evaluated for alphas and $z \geq 6$ nuclei. The two top absorber plates were each $\frac{3}{4}$-in. slabs of graphite jacketed with 0.020-in. brass sheeting, totaling 4.1 g/cm² apiece. The third absorber was lead, $\frac{7}{16}$ in. or 12.5 g/cm² thick. The average angular deviation from the vertical for the primary particle passing through the horizontal absorber plates was 17°. In Table III, a collision in an absorber is also counted as half a traversal.

The mean free paths listed in Table III agree within the statistics with similar measurements made in nuclear emulsions.[9,15] Later we will need to know the absorption length in air for $z \geq 6$ nuclei. On the basis of a simple geometrical model, used by Kaplon, Peters, Reynolds, and Ritson[9] to describe the cross section for collision between two heavy nuclei, the calculated mean free path expressed in g/cm² for our carbon-brass absorber is very close to that in air. Therefore we use our measured value of 29 g/cm² for an absorption length for $z \geq 6$ nuclei in air. We note also that the mean free path for the oxygen nucleus in air, calculated from the model, is also 29 g/cm².

TABLE III. Interactions seen in cloud chamber.

	Number of traversals without observed interaction	Number of observed interactions	Mean free path (95% limits) g/cm²
	Alpha particles		
78% Carbon 22% Brass	50	3	70_{-44}^{+198}
Lead	13	3	57_{-40}^{+168}
	$z \geq 6$ particles		
78% Carbon 22% Brass	27	4	29_{-18}^{+60}
Lead	9	0	>32

[27] V. H. Regener, Phys. Rev. 84, 161 (1951).

(b) Variation of Counting Rates with Time

A limited amount of information is obtainable from the proportional counter telescope data alone. The two out-of-line Geiger tubes, shown in Fig. 1, afford insufficient protection to the proportional counter telescope. Without the aid of cloud-chamber pictures, multiple particle events (showers and bursts) produce a large background against which it is not possible to detect the presence or absence of Li, Be, and B, and from which it is not possible to make a clean separation of the heavy ($z \geq 6$) nuclei. (See beginning of Sec. IV; also note white histogram bars on Fig. 7.) It was noticed, however, that multiple particle events gave rise to a pulse-height dispersion σ/Δ_0 which was on the average 4 times as large as the dispersion for single nuclei. Moreover, Fig. 7 shows that in 18 out of 20 events of $z \geq 9$ the proportional counter telescope and cloud chamber agreed. In looking for a time-intensity variation for the heavy nuclei, we choose only counter telescope events where $\sigma/\Delta_0 < 100$ percent, and for which z was measured to be ≥ 9, and which were not accompanied by a time-coincident discharge in the out-of-line Geiger tubes. We expect 90 percent of the events thus selected to be single heavy nuclei.

Figure 8 shows the counting rate, per hour, during the two flights for these events. Also shown, for comparison, is the counting rate for all events triggering the proportional counter telescope. The small steady attenuation in the observed flux during the flight period was evaluated using the method of averages. A correction was made for the small change in altitude of the balloons during flight, using an absorption length in air of 29 g/cm² for the heavy nuclei (see Sec. V-a), and of 195 g/cm² for the total counting rate (based on data taken during ascent of the balloons). Error from possible changes of electronic amplification during flight was estimated and included with the statistical counting rate error. Errors from the two sources were approximately equal.

The attenuation in intensity thus calculated was 4 ± 4 percent per 4 hr for all events triggering the proportional counter telescope, and 14 ± 16 percent per 4 hr for events where $\sigma/\Delta_0 < 100$ percent and $z \geq 9$. The measurement is compatible with no change in the intensity of the heavy nuclei during the flight period, but the observed variation is in the opposite direction from the morning-afternoon intensity variation at 55° reported by Ney and Thon[14] and fails to show the mid-day peak

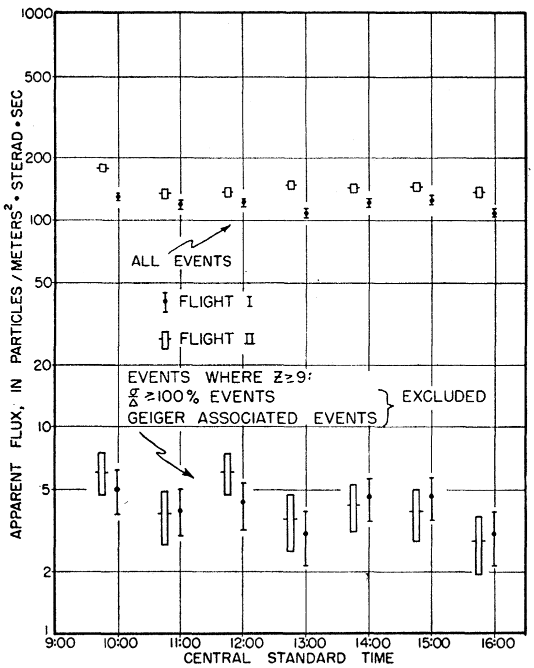

FIG. 8. Variation of event frequency with time. Events comprising upper set of points are predominantly showers and bursts. More than 90 percent of the events comprising the lower set of points are expected to be single heavy nuclei. Indicated errors are standard deviations based only on number of counts.

reported by Yngve,[18] also at 55°. However, recent measurements at 55° by Anderson, Freier, and Naugle[17] also indicated no diurnal intensity variation. Heavy nucleus intensity-time variation data is summarized in Table II.

(c) Primary Flux of Nuclei of $z \geq 6$

For the two flights, in 0.77 hr sensitive time, a total of 21 nuclei were seen in the cloud chamber for which the proportional counter telescope measured nuclear charges of $z \geq 6$. The average path length through the atmosphere and through the 2 g/cm^2 air-equivalent of material in the gondola above the cloud chamber, at 17° average deviation from the vertical, was 18.5 g/cm^2. By using an absorption length in air of 29 g/cm^2 and recalling that the solid-angle area integral of the counter telescope was 14.0 cm^2 sterad, the primary flux for $z \geq 6$ is $10.2_{-3.4}^{+4.5}$ primary nuclei per m^2 sec sterad.

The errors quoted are 95 percent limits. The upper error limit here is two standard deviations.

Van Allen[28] made rocket flights at the same latitude with a single cylindrical ionization chamber, and from his data estimated an upper limit for $z \geq 6$ of 13 nuclei per m^2 sec sterad. With nuclear emulsions also at the same latitude, Kaplon *et al.*[9] found a flux for $z \geq 6$ of 8.3±0.8 nuclei per m^2 sec sterad.

On the other hand, from measurements at 55° geomagnetic latitude, Dainton *et al.*[8] find the flux of particles with energies greater than 1.5 Bev per nucleon (based on measurement of multiple Coulomb scattering) and $z \geq 6$ (by grain-density and delta-ray counts) to be only 3.2±0.5 nuclei per m^2 sec sterad. The geomagnetic cutoff at 41° is 1.6 Bev per nucleon for heavy nuclei, so the flux found by the Bristol group is incompatible with both the Rochester flux measurement and our own.

Concerning relative abundances within the $z \geq 6$ classification, Bradt and Peters[29] report a primary flux for $z > 10$ particles about a third that of the $6 \leq z \leq 10$ flux, and other nuclear emulsion data[8,9,13] yield similar ratios. However, in the present experiment, for 12 of the 21 nuclei with $z \geq 6$ shown in Fig. 7, the measured charge was $z > 10$. A high proportion of very heavy nuclei is favored by the telescope's narrow angle of acceptance around the zenith and by the small amount of residual atmosphere. However, we point out that the measurement of the $6 \leq z \leq 10$ nuclei to $z > 10$ nuclei ratio requires an accurate calibration of the charge measurement scale in the neighborhood of $z = 10$. In the present experiment, we have an independent check on the calibration accuracy in the low-z region (Sec. IV) but not in the high-z region.

(d) Primary Flux of Li, Be, B

In the same interval during which 21 nuclei of $z \geq 6$ were seen in the cloud chamber, there were observed 3–5 Li nuclei, 1 Be nucleus, and 0 B nuclei (Sec. IV).

A certain number of Li, Be, and B nuclei are expected to appear in the atmosphere as breakup fragments of heavier nuclei. At the end of 18.5 g/cm^2 equivalent air path, if one observed N_H nuclei of $z \geq 6$, the expected number N_L of Li, Be, and B nuclei due to breakup is

$$N_L = \eta N_H \int_{x=0}^{x=18.5} \exp\left(\frac{18.5}{\lambda_H} - \frac{x}{\lambda_H} - \frac{18.5 - x}{\lambda_L}\right) \frac{dx}{\lambda_H}, \quad (10)$$

where η is the probability that a $z \geq 6$ nucleus, on collision with an air nucleus, will yield a fast Li, Be, or B fragment. Bradt and Peters[4] use a value of $\eta = 0.23$, while Noon, Kaplon, and Ritson[7] report a value of 0.56±0.18 for P_{ML} (Li, Be, and B fragments from $6 \leq z \leq 10$ collisions in air). In our case, $N_H = 21$, and using $\lambda_H = 29$ g/cm^2 and $\lambda_L = 37$ g/cm^2 (from an empirical formula[9] based on emulsion measurements), we get $N_L = 2.9$ and 7.0 Li, Be, and B nuclei corresponding to the values $\eta = 0.23$ and 0.56, respectively.

The observed value of N_L was 4–6 in 0.77 hr sensitive time. (The larger figure includes two doubtful events. See Sec. V.) The above calculation shows that it is possible to account for all of the observed Li, Be, and B particles on the basis of the breakup mechanism alone.

From our data, we can calculate the ratio R of the flux of Li, Be, and B to $z \geq 6$ nuclei in the primary cosmic radiation. To be conservative, we choose the smaller value of η, and attribute all Li, Be, and B

[28] J. A. Van Allen, Phys. Rev. 84, 791 (1951).

[29] H. L. Bradt and B. Peters, Phys. Rev. 77, 54 (1950).

nuclei in excess of 2.9 particles per 0.77 hr to primary cosmic radiation. To set an upper limit, we use Regener's 95 percent probability calculations[27] and again to be conservative, we include the two doubtful events in N_L observed: if the average total flux of Li, Be, and B nuclei at the end of 18.5-g/cm^2 equivalent air path were 11.84 particles per 0.77 hr, the probability would be 95 percent for *more than* 6 events to have been observed in this time. We then have

$$R=\frac{\text{Primary Li, Be, B}}{\text{Primary } z\geq 6}=\begin{Bmatrix}\text{upper limit: } (11.84-2.9)/21\\ \text{observed: } (4-2.9)/21\\ \text{lower limit: } 0\end{Bmatrix}\times\exp\left(\frac{18.5}{37}-\frac{18.5}{29}\right)=5_{-5}^{+32}\text{ percent,}$$

where the exponential factor extrapolates to the top of the atmosphere the fluxes observed at 18.5 g/cm^2 due to primary nuclei.

Table I shows the values obtained for R by different groups. Within the statistics, our finding is compatible with the various Rochester measurements, but is in disagreement with the measurements made by Bristol.

VI. CONCLUSION

Cosmic rays, between the time of their acceleration and observation at the earth, pass through interstellar space. Even if no Li, Be, B nuclei are originally accelerated, these nuclei will appear at the earth as a result of fragmentation of heavier nuclei against hydrogen nuclei, present in space. If one has an upper limit to the ratio R, one can set an upper limit to the number of g/cm^2 interstellar hydrogen traversed by the heavy nuclei.

Consider that $N_H(x)$ and $N_L(x)$ are the fluxes of heavy ($z\geq 6$) and light ($z=3$, 4, 5) nuclei as a function of x, the distance along the path from the region of origin measured in g/cm^2 of interstellar hydrogen. Assume the extreme case: $N_L(0)=0$. We can write the two equations:

$$\begin{aligned} dN_H/dx&=-N_H/\lambda_1,\\ dN_L/dx&=\gamma N_H/\lambda_2-N_L/\lambda_3, \end{aligned} \tag{11}$$

where λ_1 is the "annihilation" length for heavies, which we set equal to 2 nitrogen mean free paths (2×4.3 g/cm^2), λ_2 is the heavy nuclei mean free path for collision, and we use 4.3 g/cm^2, and λ_3 is the "annihilation" length for Li, Be, and B. The geometric mean free path for Be is 5.8 g/cm^2, and we take an "annihilation" length half again as long (8.6 g/cm^2). Annihilation lengths are chosen longer than mean free paths to provide for collisions resulting in only partial fragmentation. γ is the probability that a $z\geq 6$ nucleus will produce a Li, Be, or B fragment when struck by a proton, and was found by Hodgson[6] to be 0.22 ± 0.06 and by Noon *et al.*[7] to be 0.83 ± 0.5. The solution for the equation is, in our case

$$N_L/N_H=(\gamma/4.3)x, \tag{12}$$

and setting this ratio of N_L/N_H equal to the upper limit of R, 37 percent, we find, using $\gamma=0.22$, that $x<7$ g/cm^2 interstellar hydrogen traversed.

The interstellar proton density is, within a factor of 10, around 1 per cm^3.[3] For a density of n protons per cm^3 in interstellar space, the upper limit on x can be expressed as an upper limit on the effective mean length of path for heavy nuclei in interstellar space, L:

$$L<4\times 10^6/n \text{ light years.}$$

Such a limit on heavy nuclei interstellar path lengths may be imposed by leakage of the particles out of the volume of a containing magnetic field.[4,30] If $\gamma=0.83$ is used, the above upper limits on x and L will be proportionately reduced.

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[30] E. Fermi, Astrophys. J. **119**, 1 (1954).