Time and Directional Study of Primary Heavy Nuclei*†

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The "plate mover" technique has been used in two emulsion studies of the time dependence of the flux of primary heavy nuclei ($Z \geq 10$). No evidence for the previously reported "day-night" effect was found. The angular distribution was studied on an oriented flight, and some statistically significant azimuthal asymmetries were noted, but these showed no obvious trend in time. The absorption mean free path was found to be 19 g/cm², independent of depth in the atmosphere for depths ≥ 18.5 g/cm².

I. INTRODUCTION

Decisive checks on some theories of the origin of cosmic rays would be furnished by measurements of the intensity of the primary radiation as a function of time and direction of incidence. Such measurements have been attempted often in the past,[1] but until recently, they were made only at great depths in the atmosphere where the behavior of the primary rays is obscured by that of the secondaries. The development of high-altitude, constant-level balloons has lately made it convenient to study the primary beam directly for long periods of time, so that a new approach to the time and directional measurements is possible.

The heavy-nucleus component of the primary radiation has some properties which made it especially well suited for these measurements. In the first place, the heavy nuclei observed are known either to be primary or to be fragments of heavier primary nuclei, so that at reasonably high altitudes and with sufficiently heavy nuclei one deals directly with primary particles only, while ambiguities arising from multiplication and albedo are absent from heavy nucleus measurements. Second, the lower charge-to-mass ratio for heavy nuclei allows them to pass through the earth's magnetic field at energies below the cutoff for protons, extending the range of energies over which the time and directional measurements can be made. Third, heavy nuclei can be efficiently detected with nuclear emulsions, so that the well known advantages for balloon work of this modern tool can be utilized. Special techniques for time measurements using emulsions have been developed, and are described briefly below and in more detail elsewhere.[2]

For the study of directional effects, emulsions continue to be highly effective, accepting particles from all directions at once and permitting the direction of incidence of any particular particle to be measured with great accuracy. As with any detector, however, it is necessary to know the attitude of the plates with respect to the earth in order to reduce the observed directions to geomagnetic directions.

On the other hand, by selecting heavy nuclei instead of protons for study, one sacrifices statistical accuracy in the observations, since protons are roughly 500 times more abundant in the primary flux than are heavy nuclei with charges $Z \geq 10$. In the present experiments, the counting rate was of the order of 50 particles per hour, but could have been increased simply by exposing more area of emulsion and by devoting more scanner time to the analysis.

II. EARLIER WORK

Earlier emulsion measurements of time fluctuations in the flux of primary heavy nuclei have been quite conflicting. In 1949, the Minnesota group[3] first reported evidence for a night-time decrease in the flux of nuclei with $Z \geq 10$. The flux was found to be lower than previously measured daytime values by a factor of two to three, but the results were considered to be tentative because of the poor altitude record of the balloon. Also in 1949, Lord and Schein[4] reported similar results based on two night flights at depths in the atmosphere of 47 and 87 g/cm². They performed a more thorough experiment in 1950,[5] exposing two stacks of plates during the night, dropping one of them by parachute about sunrise, and allowing the other to remain with the balloon through the rest of the morning. By a subtraction technique they found the night and day fluxes separately, and concluded that the flux at night was lower than during the morning by a factor of 2.5 ± 0.26.

The Minnesota group studied the results from another night flight in 1950, and found that the flux was consistent with their daytime fluxes. In 1951 this group published a survey[6] of flux values from seven day flights and the two night flights, and concluded that the spread of the values was such that the low measurement

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[1] H. Elliot, *Progress in Cosmic Ray Physics* (North Holland Publishing Company, Amsterdam, 1952), Chapter VIII.

[2] Anderson, Ney, and Thorness, Rev. Sci. Instr. **24**, 997 (1953).

[3] Freier, Ney, Naugle, and Anderson, Phys. Rev. **79**, 206 (1950).

[4] J. J. Lord and M. Schein, Phys. Rev. **78**, 484 (1950).

[5] J. J. Lord and M. Schein, Phys. Rev. **80**, 304 (1950).

[6] Freier, Anderson, Naugle, and Ney, Phys. Rev. **84**, 322 (1951).

TABLE I. Previous emulsion work on day-night effect in heavy nucleus flux.

Date	Observer	Av. pressure (g/cm²)	Method	Day flux / Night flux
Oct. 26–27, 1949	Minn.[a,b]	25	Night flight	2–3 (?)
Oct. 31–Nov. 1, 1949	Chicago[c]	45	Night flight	2.1 ±0.6
Nov. 30–Dec. 1, 1949	Chicago[c]	87	Night flight	3.0 ±1.1
April 13–14, 1950	Minn.[b]	14	Night flight	1.0 ±0.2
May 22–23, 1950	Chicago[a]	15	Drop load	2.55±0.26

[a] See reference 3.
[b] See reference 6.
[c] See reference 4.

on the first night flight could have been a fluctuation consistent with fluctuations in the daytime measurements. These fluctuations could reasonably be attributed to various experimental and statistical uncertainties.

Table I summarizes the data from these emulsion experiments.

Although it did not deal with the day-night effect discussed above, the experiment of Ney and Thon[7] is relevant to the later discussion. In 1950, they employed a scintillation counter telescope to measure the flux and charge spectrum for $Z \geq 1$ at 10 g/cm². It was found that the frequency of pulses of magnitude greater than 16 times the average proton pulse increased by 35 percent between the morning (10:30 A.M.–12:20 P.M.) and the afternoon (1:20 to 3:30 P.M.) while the frequency of proton pulses remained constant within 3 percent.

III. THE PRESENT EXPERIMENT

In view of the importance of this problem to theories of the origin of cosmic rays and of the conflicting results reviewed above, it was apparent that a more direct and more detailed measurement of the flux as a function of time was needed. The two experiments described here were designed for this purpose. The balloon flights for these experiments took place on July 31-August 1, 1952, and August 28–29, 1952. They will be referred to as the A experiment and the B experiment, respectively. Both of these experiments, as well as all others discussed in this paper, were performed at geomagneitc latitudes between 54° and 56° north.

An effect worthy of further investigation noted on both of the Minnesota night flights listed in Table I, but not found on a similar day flight, was an asymmetry in the azimuthal distribution of the heavy nucleus flux.[6] However, the evidence for this asymmetry was considered to be preliminary, since the record of the orientation on both flights was incomplete. Furthermore, on the first night flight the sphere was known to have been tilted, but an exact record of the positioning was not made during either flight. After making the most plausible corrections, it was found that on October 26, 1949, the flux as a function of azimuth varied roughly sinusoidally about the mean with an amplitude of about 50 percent of the mean and with the maximum near the west. On April 13, 1950, the asymmetry was about 10 percent with the maximum 20° west of south. Since time variations in the flux, at least any due to the rotation of the earth, would probably have such asymmetries associated with them, a further study of the azimuthal dependence of the flux was made an additional objective of experiment A.

IV. APPARATUS

To obtain the heavy-nucleus flux as a function of time, a device called a "plate mover" was used. The principle of the method was first suggested by Lord and Schein,[5] while Yngve and Schein[8] have used the idea in a measurement of time variations during the daytime. The idea is simply to move one plate slowly across another during the high altitude exposure, so that the relative separation of the two segments of the track of any particle which penetrates both plates indicates the time of incidence of the particle. Details of the plate mover built for use at Minnesota are described elsewhere.[2]

In order to study directional effects, it is necessary to hold the plates in a fixed orientation with respect to the earth. The device designed for this purpose used a magnetic compass for the sensing element and coupled it to the orienting motor through a light beam and photocell system. Four plate movers arranged around the sides of a square were kept oriented to within ±10° by this system on the A flight, but no attempt was made to orient the B flight.

Among the auxiliary data recorded on both flights were the residual pressure, the history of movement of the plate movers, the levelness of the plates, and

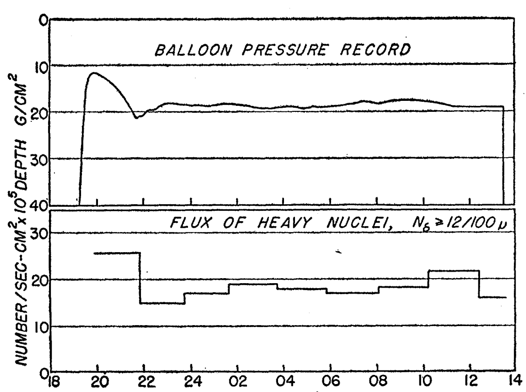

FIG. 1. The residual atmospheric pressure and heavy nuclei flux as a function of time for the July 31, 1952 flight.

[7] E. P. Ney and D. M. Thon, Phys. Rev. **81**, 1068 (1951).

[8] V. H. Yngve and M. Schein, Phys. Rev. **92**, 428 (1953).

direction of facing of the plates. Accuracy and reliability in the pressure measurements are especially important in heavy nucleus studies, because of the rapid rate of decrease of the flux with increasing atmospheric depth. Wallace and Tiernan aneroid gauges reading directly in mm Hg absolute pressure were used on both flights and were calibrated both before and after the flights by laboratory standards. Standard errors of 0.2-mm Hg for both flights were assigned to the pressure data. In addition, the pressure readings were verified by secondary instruments, a General Mills barograph on July 31 and a telemetered aneroid gauge on August 28.

A check on the levelness of the plates during exposure has been made standard practice in the Minnesota laboratory since the discovery that on two occassions the plates were tilted during the flight in spite of preflight precautions. One of these occasions was the A flight described herein. The recording level showed that the apparatus was tilted a constant 9 degrees from the vertical throughout the flight, in a known but varying direction with respect to the plates, the plates themselves being kept oriented in azimuth. It was estimated that owing to the rapid decrease of the heavy nucleus flux with zenith angle, a spurious azimuthal asymmetry of as much as 34 percent could have appeared in the data if the tilt had not been detected or had remained uncorrected. From the attitude of the plates as a function of time, however, the corrections were made, with the result that the directional data are believed to be free of large systematic errors arising from the tilt, but are somewhat less accurate because of the introduction of experimental errors in measurement of the parameters of the tilt. The time-variation data are negligibly affected by the tilt, since the plates were arranged symmetrically around the sides of a square, and equal areas were scanned on each plate. The recording level on the August 28 flight showed that the plates were vertical within one degree.

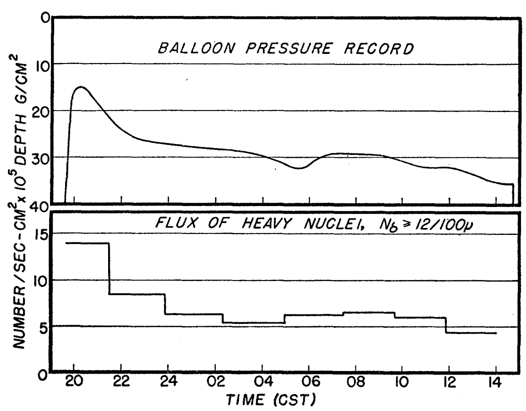

Fig. 2. The residual atmospheric pressure and heavy nuclei flux as a function of time for the August 28, 1952 flight.

Table II. Relative flux of heavy nuclei as a function of time.

Flight	Period	Time start CST	N	$dN/dtdA$ (corr.) percent of average
A				
(July 31)	2	1956	158	106±9
	3	2151	92	86±9
	4	2346	105	96±10
	5	0142	127	109±10
	6	0347	121	104±9
	7	0554	117	94±9
	8	0803	127	98±9
	9	1013	148	120±10
	10	1223	59	92±11
B				
(Aug. 28)	3–4	1929	151	101±8
	5–6	2126	118	101±9
	7–8	2354	91	91±10
	9–10	0226	79	87±10
	11–12	0502	88	112±12
	13–14	0730	83	108±12
	15–16	0943	74	114±13
	17–18	1153	53	92±13

V. TIME VARIATION MEASUREMENTS

Ilford G-5 plates of 400-micron thickness were used in both experiments, and were processed by the temperature cycle method. The plates were scanned for tracks having at least 12 delta rays per 100 microns, which corresponds to accepting only those heavy nuclei having an atomic number of at least 10.[6] A total area of 179.4 cm^2 was searched on the A-flight plates, and 213.2 cm^2 on the B-flight plates. The total numbers of $Z\geq 10$ tracks analyzed were 1110 and 773, respectively, for the two flights.

Pressure-*versus*-time curves for the two flights are given in the upper parts of Figs. 1 and 2, while in the lower parts are plotted the numbers of particles per unit time and unit area on the plates, for qualitative comparison with the upper graphs. Since the flux data are dependent on the instantaneous atmospheric depth of the plates, it is necessary to reduce them to corresponding data at a common reference depth in order to search for time variations in the primary flux. The expected variation of the flux with depth can be deduced from the observed variation with zenith angle, described in part VIII. The desired reduction function results from integrating Eq. (8), part VIII, with the aid of the Bessel-Integral functions tabulated by Bickley and Nayler.[9]

The relative numbers of particles per unit time after correction for altitude changes are given in Table II and are plotted in Figs. 3 and 4. It may be noted on the altitude record of the A flight that except for the initial overshoot, the balloon remained at a depth between 18 and 19 g/cm^2 throughout the flight, so that the corrections for altitude changes amounted to less than four percent during this level part. In contrast, the relatively small overshoot of 3 g/cm^2 necessitated a correction of 35 percent, illustrating the importance of accurate pressure measurements on experiments dealing

[9] W. G. Bickley and J. Nayler, Phil. Mag. **20**, 343 (1935).

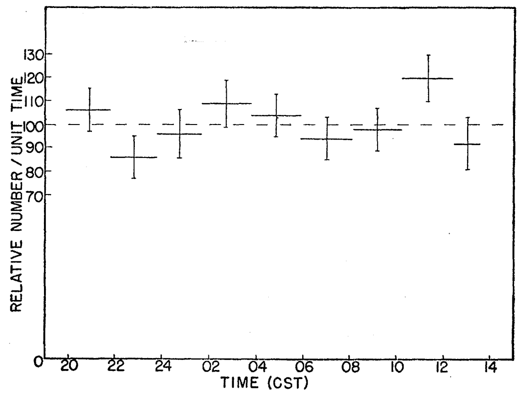

FIG. 3. The relative numbers of a heavy nuclei at 18.5 g/cm² atmospheric depth as a function of time on the July 31, 1952 flight.

with heavy nuclei. For the *B* flight, the corrections were at most 15 percent, except during the initial overshoot of the balloon.

There is clearly no evidence for a large nighttime decrease in the flux on either of the dates of these two experiments. For quantitative comparison with previous work, the "night" may be defined as the period from about midnight until about 6 A.M., and the "day" as the period from about 6 A.M. until about noon, the exact times being determined by the times at which the plate movers moved. Thus defined, the daytime flux is found to be 6 ± 8 percent higher than the nighttime flux during the July 31 flight and 15 ± 9 percent higher during the August 28 flight. The latter figure, however, is subject to experimental uncertainties of the order of 5 percent in addition to the statistical uncertainty quoted, because relatively large and somewhat approximate corrections for altitude changes were necessary. These figures may be contrasted with previous results of 100 to 200 percent cited above.

The small fluctuations about the mean of the points in Figs. 3 and 4 are possibly significant, however, and must be tested statistically. The direct test given by Jánossy[10] is applicable to the main part of the July 31 data since the corrections for altitude changes are small. From this test it is concluded that there is a probability of 71 percent that fluctuations this great or greater would be observed in a purely random flux having a constant average value.

For the *B*-flight data, it is necessary to apply the less direct χ^2 test since the atmospheric depth at the plates changed appreciably with time. Referred to a constant at the top of the atmosphere, the probability of the observed value of χ^2 is 40 percent, while a value of this probability of less than 5 percent is usually considered necessary to prove that the assumed and observed distributions are different.

These tests show, therefore, that within the statistical errors, the flux was constant in time during both flights.

[10] L. Jánossy, *Cosmic Rays* (Oxford University Press, London, 1948), p. 377.

Special attention may be directed to the anomalous flux observed at about noon on August 1 (Fig. 3), since the Chicago group has recently reported a similar deviation also at about noon.[8] The probability of occurrence of a deviation at least this great (two standard deviations) sometime during the *A* flight is 30 percent. This figure is large enough that it is not possible to assert firmly that the deviation is due to a real physical process. Furthermore, comparison of Figs. 3 and 4 shows that there is no trend to the fluctuations which is common to the data of both our *A* and *B* flights. If we consider the Chicago and Minnesota results together, however, and in addition consider the results of Ney and Thon[7] cited above, it appears that further measurements of time variations with greater statistical accuracy and with attention centered on the period about noon would be worthwhile.

Simpson[11] has reported that no special activity was recorded by his neutron monitoring network on either of the dates of these experiments. The neutron flux on July 31-August 1 was reported to be higher than average, however, since these dates occurred a few days after a 27-day maximum in the neutron intensity.

Since no evidence for the "day-night" effect was found in these experiments, it may be supposed that the effect is a sporadic one, due, say, to some sporadic solar phenomenon. However, as shown above, without plate movers or without accurate and reliable pressure information, the measurement is quite liable to error. Perhaps, therefore, the hypothesis of large sporadic day-night effects should be withheld until further evidence for them is found by the new techniques.

VI. AZIMUTHAL ASYMMETRY MEASUREMENTS

As noted before, a search for azimuthal effects could not be undertaken until corrections were made for the effects of the tilted sphere. The result of the corrections was to define a new zenith and azimuth angle for each track, these new angles being on the average closer to

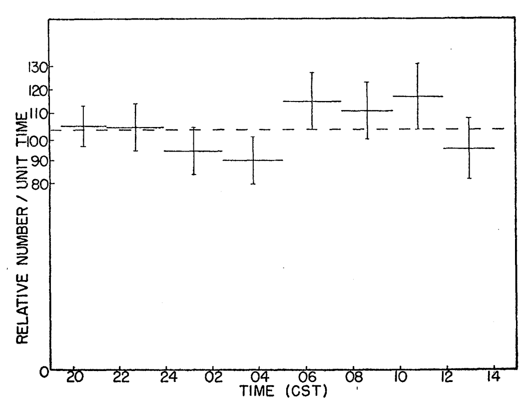

FIG. 4. The relative numbers of heavy nuclei at 30 g/cm² atmospheric depth as a function of time on the August 28, 1952 flight.

[11] Dr. J. A. Simpson (private communication).

the correct angles in an untilted system. Each track was then assigned a weighting factor $L=R/t$, where R is the range of the track in the emulsion and t is the thickness of the emulsion. It may easily be seen that L is inversely proportional to the effective area of the plate as seen by the incoming particle, so that the tilt-corrected, weighted data are no longer dependent on the attitude of the plates. In order to reduce the number of unduly large fluctuations due to single large weights, it was desirable to assign to each track an additional weight of $\sin\theta$, where θ is the particle's zenith angle of incidence. This may be regarded as the projection of each track onto a horizontal plane on which azimuthal effects can be studied in two dimensions.

In brief, the angles measured with respect to the plates have been replaced by angles measured with respect to the earth, and the plain numbers of particles have been replaced by sums of $L'\equiv L\sin\theta$.

Geomagnetic azimuth angles ϕ are defined from 0–360° in the N-E-S-W sense. The azimuthal asymmetry is defined as follows:

$$\mathbf{A}=2(\Sigma\mathbf{L}'/\Sigma L'), \tag{1}$$

where $\mathbf{L}'$ is a vector denoting a track of weight L' and direction of incidence ϕ. The physical significance of this definition is that $A(=|\mathbf{A}|)$ is the ratio of the amplitude of the first Fourier component of the flux, when analyzed by azimuth angle, to the average flux per unit angle of azimuth. That is, if

$$dN/d\phi=a+b\cos(\phi-\phi_0), \tag{2}$$

then

$$a=\Sigma L'/2\pi,\quad b=|\Sigma\mathbf{L}'|/\pi, \tag{3a}$$

and

$$A=b/a. \tag{3b}$$

The direction of $\mathbf{A}$ is denoted by ϕ_0.

Some statistical characteristics needed in the analysis are found as follows. If the angles ϕ for N particles having *unit* weight are randomly distributed, the distribution for A is given by[12]

$$P(A<A')=1-\exp[-NA'^2/4], \tag{4}$$

where $P(A<A')$ is the probability that A is less than a given A'. The differential distribution is

$$dP/dA=\tfrac{1}{2}NA\exp[-NA^2/4]. \tag{5}$$

From this, the expected value of A is found to be

$$A_{\text{exp}}=(\pi/N)^{\frac{1}{2}}. \tag{6}$$

The statistical limits corresponding to standard errors are found from

$$\begin{aligned} P(A<A_L)&=0.16,\quad A_L=0.84/N^{\frac{1}{2}},\\ P(A<A_U)&=0.84,\quad A_U=2.70/N^{\frac{1}{2}}. \end{aligned} \tag{7}$$

[12] J. V. Uspensky, *Introduction to Mathematical Probability* (McGraw-Hill Book Company, Inc., New York, 1937), pp. 314 ff.

TABLE III. Analysis of azimuthal data, July 31–August 1, 1952.

Period	Time, CST	N	A_{exp} (%)	A_L (%)	A_U (%)	A_{observed} (%)	ϕ_0
4	Start 2346	97	22	11	32	34	290
5	Start 0142	116	20	10	30	7	330
6	Start 0347	116	20	10	30	21	320
7	Start 0554	109	21	10	31	46	115
8	Start 0803	121	20	10	31	9	315
9	Start 1013	140	18	9	28	32	010
10	Start 1223 End 1333	57	28	13	42	34	220
4–10	2346–1333	756	8	4	14	7	345

The data used to find the observed A are not of unit weight, as assumed in the above analysis. A more detailed calculation taking into account the weights shows that the above distribution should be broadened by the factor $(0.53+0.20\ln N)^{\frac{1}{2}}$, so that A_L, A_{exp} and A_U as given above are increased somewhat, e.g., by a factor of 1.20 when $N=100$.

Table III gives the results of the azimuthal analysis for each plate mover period during the level part of the flight, as well as for all of these periods considered together.

The observed asymmetries are seen to vary considerably, including values both larger and smaller than the statistical limits calculated for a symmetrical random process. The smaller values are clearly statistical fluctuations, since no easily imagined physical process would produce a flux of particles coherently symmetrical in their directions of incidence. In periods 4, 7, and 9, the asymmetries observed are larger than those expected in a random process, and may represent real physical effects. However, there is no obvious trend from period to period in either the magnitude or the direction of the effect. This fact prevents explaining the effect by the simplest type of mechanism for producing asymmetries, namely, an anisotropic flux which appears on earth to change direction because of the earth's rotation. The observed asymmetry for the combined periods agrees with the value predicted on the basis of a symmetrical random flux.

It should be noted that under the conditions of this experiment, it would be impossible to detect asymmetries due to geomagnetic effects. At 55° geomagnetic latitude the energy cutoffs for a zenith angle of 60° for the eastern and western directions are, respectively, 0.33 and 0.25 Bev/nucleon, which means for $Z\geq 10$, ionization range cutoffs of 12.8 and 8 g/cm². Therefore, none of the particles in this geomagnetic-sensitive energy region would reach the plates at a depth of 18.5 g/cm².

VII. ABSOLUTE FLUX

The heavy nucleus flux in absolute units as determined by these experiments is shown in Fig. 5 along with the daytime flux previously measured in this laboratory.

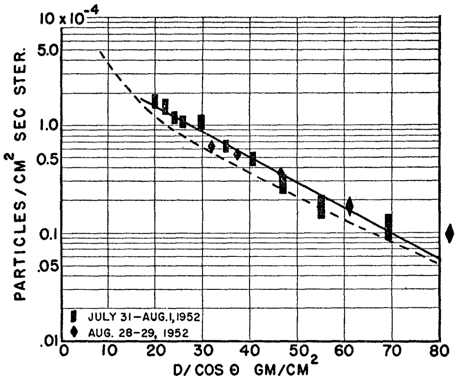

FIG. 5. The flux of $Z \geqq 10$ nuclei at geomagnetic latitude of 55°N on the July 31 and August 28 flights. The dashed curve is the average of seven other flights reported in reference 6.

Whereas the time and directional variation results of these experiments depend essentially on internal comparisons within a body of data, the absolute flux determinations requires a knowledge of several additional factors. One of these is the absolute residual atmospheric pressure; this was known with relatively good accuracy and reliability for these experiments, as discussed before. Further, the use of plate movers made it possible to eliminate from the data those tracks formed during the nonlevel parts of the flights, so that the measurements are for nearly unique altitudes.

Another factor is the time of exposure; the uncertainty in time was negligible in these experiments. Previous measurements without plate movers, however, required a somewhat ambiguous designation of the time when the balloon reached "altitude" with a consequently great uncertainty in time of exposure on short balloon flights.

The agreement between the absolute flux measurements of these experiments and the average of the other experiments shown in Fig. 5 may be considered satisfactory, in view of the spread of the previous points.[6] The agreement between the two present experiments is especially good, and it may be hoped that the spread of the flux values on future flights will be reduced through the use of plate movers to remove some of the former experimental uncertainties.

VIII. ZENITH ANGLE DISTRIBUTION

The exceptionally level balloon flight on July 31 offered a better than usual opportunity to study the zenith angle distribution of the flux. Only those tracks formed during the last 14 hours of the flight were used; during this time the plates remained at a depth of 18.5 g/cm² within 0.5 g/cm².

The amount of air traversed by a particle incident at zenith angle θ is $d\sec\theta$, where d is the vertical depth in g/cm². The number of nuclei per unit zenith angle observed in the plates would be (for untilted plates)

$$dN/d\theta = K \exp[-d(\sec\theta)/\lambda] \sin^2\theta, \qquad (8)$$

where λ is the attenuation mean free path of the flux. Although this distribution is derived by considering collision losses only, it is found to fit the experimental data satisfactorily for $d\sec\theta \geq 15$ g/cm², so that the effects of stopping by ionization appear as a constant addition to the parameter λ. In Eq. (8), one factor of $\sin\theta$ enters to convert from solid angle to angle increments, and the other to account for the effective area of the vertical plate as seen by the flux. In the case of tilted plates, the second factor becomes $\sin\theta'$, where θ' is the zenith angle with respect to the plates.

A least squares fit to the data was found by putting Eq. (8) in the form

$$\log I(d\sec\theta) = \log I_0 - (d/\lambda)\sec\theta + \epsilon\sec^2\theta, \qquad (9)$$

and determining the constant coefficients $\log I_0$, d/λ, and ϵ. $I(d\sec\theta)$ is the flux of $Z \geq 10$ particles/sec-cm²-sterad at the depth d and zenith angle θ, while I_0 is this flux at the top of the atmosphere. The value of I_0 was found experimentally to be 4.5×10^{-4}/sec-cm²-sterad, but this is of course an extrapolated value which assumes that the same absorption law holds for $d\sec\theta < 18.5$ g/cm² as does for $d\sec\theta \geq 18.5$ g/cm². There is evidence[6] that the law is in fact different at smaller depths because of ionization stopping of very low-energy particles, so that the value for I_0 obtained here will be useful for comparison with direct measurements at $d \approx 0$ to corroborate this evidence.

The attenuation mean free path λ was found to be 19 g/cm² using $d = 18.5$ g/cm². The third parameter ϵ is a measure of the departure of the attenuation law from the simple exponential law, Eq. (8). Experimentally, ϵ is found to be -0.02, which is not significantly different from zero. Within the accuracy of this experiment, therefore, the flux is found to be absorbed truly exponentially with a mean free path of 19 g/cm² at depths greater than 18.5 g/cm².

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