Neutrons Produced in the Atmosphere by the Cosmic Radiations*

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The distribution of disintegration product neutrons in the atmosphere has been measured from the geomagnetic equator to 65°N and up to ~220 g-cm^{-2} air. The measured exponential absorption of the neutron producing radiations in the equilibrium portion of the atmosphere is: $L(0°)=212$, $L(19°)=206$, $L(40°)=181$, $L(53°)=157$, $L(65°)=157$ g-cm^{-2}. It is shown that the neutron component has the largest latitude effect of any known secondary component in the cosmic rays and that the neutrons are part of a low energy nucleonic component in the atmosphere. The yield of neutrons per incident primary particle in an air column one cm^2 area extending through the atmosphere has been calculated at various latitudes. The yield increases by 400 percent between 0° and 55°N. The slow neutron absorption in air at the geomagnetic equator under 312 g-cm^{-2} air was measured. It is concluded that nucleon collision chains in the atmosphere are the principal process by which a low energy nucleonic and neutron component is produced. Measurements at high latitudes over a period of two years have shown that fluctuations and large changes of intensity of the neutron component may occur during solar and terrestrial disturbed days.

I. INTRODUCTION

RECENT measurements[1] indicate that the neutron half-life is approximately 15 minutes so that only a small portion of the primary cosmic radiations is expected to consist of free neutrons. However, neutrons of all energies, up to and including primary particle energies, are produced abundantly in the atmosphere by primary and secondary cosmic-ray particles interacting with oxygen and nitrogen nuclei. The energy ranges of these neutrons may be somewhat arbitrarily defined in this paper according to the kind of nuclear interaction by which they are produced. *High energy neutrons* are defined as being produced by nucleon-nucleon or exchange interactions and may have initial energies extending from primary particle energies down to the order of 40 Mev. Processes in which a portion of the nucleus or the entire nucleus is excited to high temperatures produce evaporation or disintegration products including neutrons, protons, and alpha-particles with initial energies of the order 2–30 Mev; these processes include nucleon-nucleus collisions and photon or π- or μ-meson nuclear capture. These disintegration product neutrons are defined as the *fast neutrons* in this paper. Since these disintegration product neutrons, in general, have insufficient energy to produce further nuclear disintegrations, they are slowed in the atmosphere by elastic and inelastic collisions.[2] Hence, neutrons slowed to less than ~1 ev are defined as *slow neutrons*.

The objectives of this study were (a) to determine the principal nuclear processes which contribute to the production of fast or disintegration product neutrons in the atmosphere, and (b) to determine the relationship of the fast neutron production to primary particle energy and primary particle intensity. Fast and slow neutron intensities in the free atmosphere were obtained as a function of atmospheric depth (Sec. III and Appendix I) and as a function of geomagnetic latitude and longitude (Sec. IV). The measurements were restricted to regions below the air transition maximum for the primary radiations so the fast neutrons would be in equilibrium with their producing radiations. The experiments covered the period of December, 1947 through November, 1949 and were performed in aircraft. Preliminary accounts have been given of some of the measurements.[3]

Prior to these measurements, neutron measurements by several observers had been obtained at high latitudes, indicating satisfactory agreement on the exponential form of the increase of intensity with altitude.[2,4,5] More recently, Yuan[6] has shown the existence of a maximum in the slow neutron intensity curve at high altitudes expected on the basis of the secondary origin of the slow neutrons.

A preliminary account of the time dependent changes of neutron intensity observed at the high latitudes is presented in Sec. VI.

II. APPARATUS AND METHODS OF MEASUREMENT

All neutron measurements were obtained in B-29 type aircraft with boron trifluoride proportional counters enriched in the B-10 isotope. Neutrons are isotropically incident on the detector. Since the most probable processes for fast neutron production emit neutrons isotropically,[7] the orientation of the detectors was not critical. In the equilibrium region of the atmosphere it may be shown[2] that the mean distance from the point of origin of a free fast neutron to the point of detection

* Assisted by the joint program of the ONR and AEC.
[1] A. H. Snell and L. C. Miller, Phys. Rev. **74**, 1217 (1948). J. M. Robson, Phys. Rev. **77**, 747 (1950).
[2] Bethe, Korff, and Placzek, Phys. Rev. **57**, 573 (1940) and references therein.
[3] J. A. Simpson, Jr., Phys. Rev. **73**, 1389 (1948); Phys. Rev. **74**, 1214 (1948). See also references 8 and 11.
[4] S. A. Korff and E. T. Clarke, Phys. Rev. **61**, 422 (1942) and references therein.
[5] Agnew, Bright, and Froman, Phys. Rev. **72**, 203 (1947).
[6] L. C. L. Yuan, Phys. Rev. **74**, 504 (1948).
[7] G. Cocconi and V. Tongiorgi, Phys. Rev. **76**, 318 (1949). J. A. Simpson, Jr. and R. B. Uretz, Phys. Rev. **76**, 569 (1949).

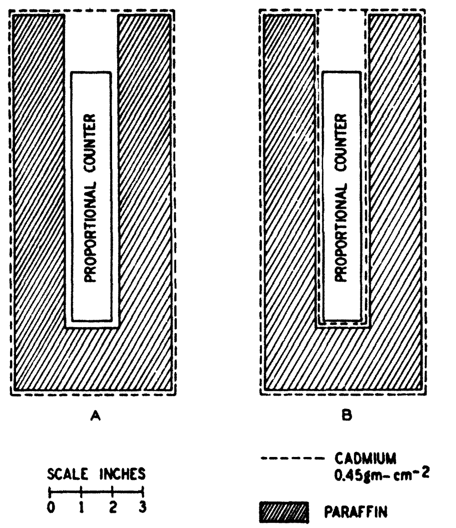

FIG. 1. Cross sections of BF_3 proportional counter geometries used to measure neutron intensity. By inserting the cadmium thimble around the counter as shown in 1(B) the counter background may be measured.

is sufficiently short to assume that the density of neutrons measured at a point in the atmosphere is proportional to the rate of production of neutrons at that point. Thus, a measurement of the rate of production or absorption of neutrons with altitude in the atmosphere is a close approximation of the absorption of the neutron producing radiations by air nuclei. Unless otherwise noted, the Gross transformation has not been used.

The fast neutron measurements are relative, and must be normalized to one absolute measurement in space. Measurements have been reported showing that the energy spectrum of atmospheric neutrons in the range of fast to slow neutrons below the air transition maximum does not appear to change with altitude[5] or latitude.[8] This is in agreement with theory, since this energy distribution arises from the slowing down processes of neutrons in nitrogen and oxygen, and the capture of neutrons by nitrogen and oxygen, and does not depend strongly on the initial kinetic energy of the nuclear disintegration product neutrons. Therefore, in the equilibrium region of the atmosphere at atmospheric depths >200 g-cm^{-2} the relative intensity distribution of fast neutron intensities in the atmosphere is the

TABLE I. The exponential absorption L of the neutron producing radiation in the atmosphere at geomagnetic latitude λ.

λ	L (g-cm^{-2})	b (absorption coefficient)
0°	212±4	0.064
19°	206±4	0.067
40°	181±3	0.076
53°	157±2	0.086_5
65°	157±3	0.086

[8] Simpson, Baldwin, and Uretz, Phys. Rev. **76**, 165 (1949).

same as the relative intensity distribution of slow neutron intensities in the atmosphere. Thus, by measuring the absolute intensity of slow neutrons at one point in the atmosphere, the relative fast neutron distribution will give the absolute distribution of slow neutron intensities. It will be shown that there are large changes of neutron intensity with time at high latitudes and altitudes which make it difficult to attempt absolute measurements above approximately 40° geomagnetic latitude. Therefore, slow neutron absorption measurements were obtained at the equator so that all the relative fast neutron data could be normalized at one point, showing negligible time or seasonal dependence.

The slow neutron measurements were made inside a thin aluminum skin in the tail of the aircraft, using pressurized high voltage circuits. The method was similar to that used by Agnew *et al.*[5] in their measurements. One counter was covered with 0.030-in. cadmium; the other counter was covered with brass. These measurements are discussed in Appendix I.

The fast neutron detector was composed of a BF_3 proportional counter surrounded by paraffin inside a cadmium shield as shown in Fig. 1(A). Such a detector is insensitive to neutrons below 0.4 ev and does not depend critically on energy up to the order of 2–5 Mev.[9] Two detectors were operated in parallel to increase the measured counting rate. By locating their cylindrical axes in a vertical plane and approximately 45 cm apart, large and small shower effects were negligible. A second pair of detectors, identical with the exception that they contained non-enriched boron at the same pressure, were used in the early measurements to confirm the negligible contribution of shower effects, star production, and recoils. Cadmium thimbles could be placed around the counters as shown in Fig. 1(B) to measure background from star production in the counter wall and recoil processes. The contribution of these processes is discussed in Sec. III(c).

The vertical meson intensity for mesons of momenta $>4\times10^8$ ev/c and the total vertical charged particle intensity were measured as a function of latitude along with the early neutron measurements in order to confirm the independence of the neutron production processes and the classical charged particle components. Since these latter measurements are incidental to the neutron measurements, they are discussed in Appendix II.

It was important to show that all measurements in aircrafts correspond to free atmosphere measurements. The possibilities of systematic errors and spurious effects are investigated and discussed in Sec. III(b). Local production in materials of high atomic weight and slowing down of neutrons in large amounts of hydrogenous materials were the principal sources of difficulty. Preliminary measurements of the local production of neutrons in materials as a function of atomic

[9] For example, B. Rossi and H. Staub, *Ionization Chambers and Counters* (McGraw-Hill Book Company, Inc., New York, 1949), p. 192.

weight A have been reported at these altitudes.[10] Detectors were located so as to avoid appreciable local production in materials of atomic weight higher than aluminum. No measurements were taken in or near dense cloud formations where the measured intensity is known to be anomalous.[5]

Errors in the determination of the free atmospheric air pressure from a moving aircraft may be appreciable and may lead to serious errors in the determination of the absorption of radiation with atmospheric depth. Some of these errors depend on the location of the measuring system with respect to the slip stream of the aircraft, the gross weight, the speed and yaw of the aircraft, and are independent of the precision of manometers or altimeters. Calibrated and temperature corrected sensitive Kollsman 0–50,000 ft pressure—altitude altimeters were used with provision for eliminating hysteresis caused by friction in the moving parts. All pressure altitudes and pressures are related to the N.A.C.A. "standard" atmosphere and then corrected.

All measurements with BF_3 proportional counters employed negative feedback wide-band amplifiers, pulse size discriminators, and scaling circuits. Both photographic and manual recording of the events, time, and air pressure were provided on most of the flights to assure independent checks on the counting rates. All high potential circuits were regulated, pressurized, and treated for high humidity conditions in the tropics.

It was found that fast neutron measurements at low latitudes could be repeated easily within ± 2 percent, and that all instrument errors were maintained below ± 1 percent.

III. ALTITUDE DEPENDENCE OF DISINTEGRATION PRODUCT NEUTRONS

(a) The Altitude Dependence as a Function of Latitude

The altitude dependence of fast neutrons was measured using detectors of the type shown in Fig. 1(a) at the geomagnetic latitudes λ of 0°, 19°, 40°, 54°, and 65°N and at atmospheric depths 217 g-cm^{-2} to 600 g-cm^{-2}. Series of flights were made in December, 1947–February, 1948, May–June, 1948, April–May, 1949 and August–October, 1949. Since independent sets of detectors were used in the various flight series, their relative efficiencies were measured in the laboratory and at $\lambda=0°$ at an atmospheric depth of 312 g-cm^{-2} (30,000 ft pressure altitude). In this way a normalization factor for each series of flights was determined. The experimental data are given in Fig. 2. The bands of curves at 40° and higher latitudes indicate the changes in intensity observed in these flights except for the data given in Sec. VI. For example, the altitude curves for both 55° and 65° obtained in April, 1949 lie along the upper edge of the 53°–65° band. The lower edge of each band represents the undisturbed day

[10] Simpson, Baldwin, and Molner, Phys. Rev. **77**, 751 (1950).

TABLE II.

Status of aircraft	Altitude in feet—pressure altitude	Counting rate events per minute
Full tanks on way up	27,050	508± 7
Full tanks on way up	33,150	823±10
Low tanks on way down (later)	33,000	809±10
Low tanks on way down (later)	27,050	499± 7

neutron intensity. The longitude and latitude dependence of neutron intensity will be discussed in Sec. IV. It should be noted that the absorption mean-free paths as obtained from the combined data of all the flight series changes slightly the preliminary data of December, 1947–February, 1948.[3] Below approximately one m.f.p. from the top of the atmosphere, these curves are fitted by an expression of the form $D=D_0e^{-h/L}=D_0e^{-bp}$, where D is the neutron density in events per minute, h is the atmospheric depth in g-cm^{-2}, b is the absorption coefficient in cm^{-1}, and p is in cm Hg air pressure. Although it is not expected that the altitude curves at all latitudes are true exponentials, this exponential function is the simplest expression which provides a good fit with the data below 15 cm Hg atmospheric pressure. It is clear from Fig. 2 that at $\geq 52°$N the neutron altitude curve deviates appreciably from a simple exponential below 55–60 cm Hg.

The values for the exponential absorption length for the neutron producing radiation are obtained from Fig. 2 and are tabulated in Table I. Since there is a large latitude dependence, the aircraft was either flown in a circle over a fixed land mark or along a short segment of a constant geomagnetic line. Experienced navigators were used on all flights where space position was important. It may be shown easily that a 0.5° error in position for any λ between 20° and 45°N would produce a marked error in measuring L. For example, the change in neutron intensity at $\lambda=40°$ at 30,000 ft is $[\delta D/\delta\lambda]_{\lambda=40°}=25$ counts per minute per degree.

Fluctuations in pressure altitudes at 15,000 ft were ± 50 ft; at 30,000 ft were ± 100 ft, and at 36,000 ft or higher were ± 150 ft. Frequent checks on pressure during each measurement reduced the average value of these fluctuations.

(b) Local Neutron Production

The local production and slowing down of neutrons by the aircraft gasoline was checked by measurements at increasing altitudes and then, as the fuel supply became low, at decreasing altitudes so as to repeat the

TABLE III. Local production of neutrons in paraffin as a function of latitude at 312 g-cm^{-2}.

λ	Local production in paraffin; counts per minute	Fast neutron detector; counts per minute
0°	298	202
55°	975	665
Ratio: λ_{55}/λ_0	3.27±0.03	3.31±0.03

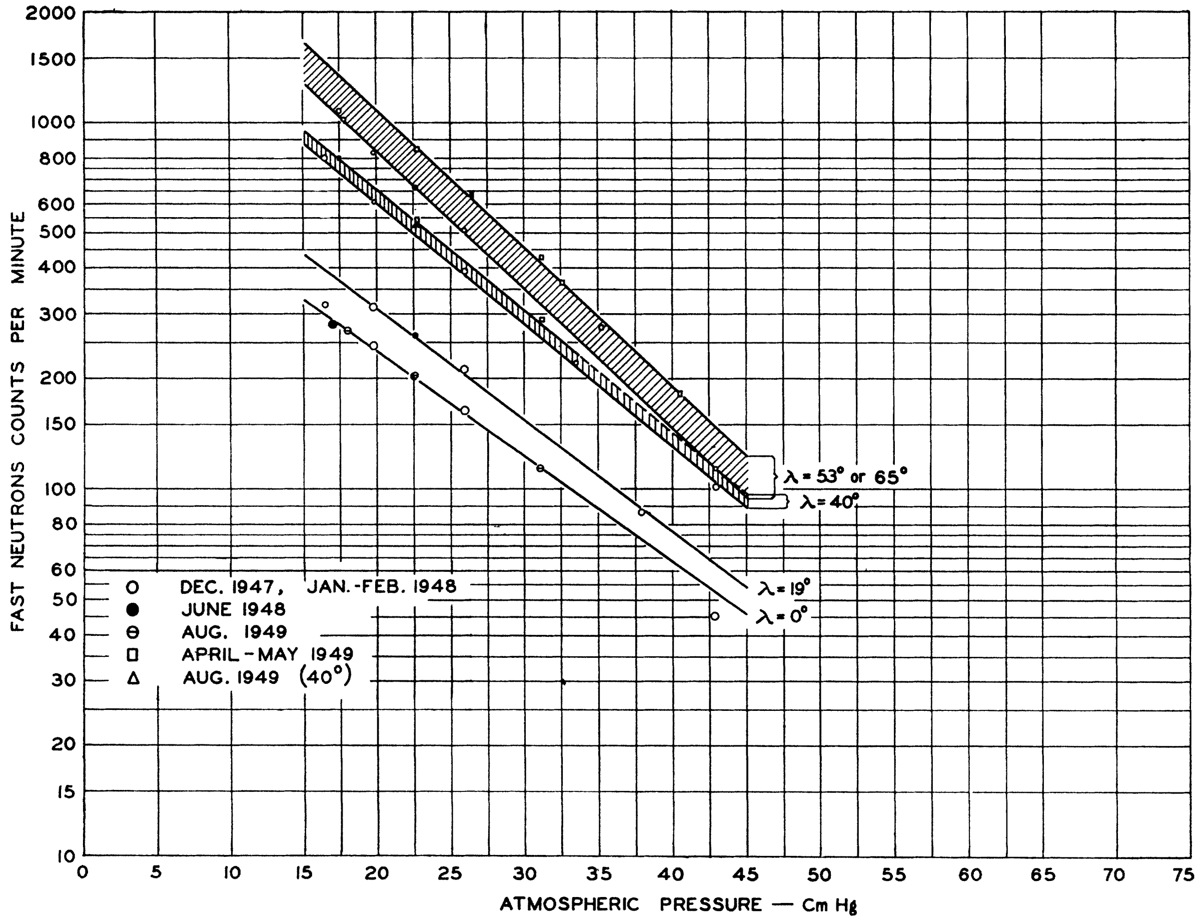

FIG. 2. The measurement of the exponential absorption of the neutron producing radiations or altitude dependence of neutrons. The quiet day curve is shown as the bottom curve of the $\lambda=53°$ or $65°$ band, while the top curve corresponds to measurements on a solar disturbed day (see Fig. 5). The data for $\lambda=40°$ is at 108–112°W longitude.

measurements for comparison. Measurements for $\lambda=53°$, for example, are shown in Table II. These measurements lie within statistical fluctuations.

Measurements[11] to be reported in a later paper show that the local production in carbon and aluminum is proportional to the production in atmospheric nitrogen and oxygen at all measured altitudes and latitudes. For example, a 9×10^4 g mass of paraffin containing BF_3 proportional counters was arranged so that the detected neutrons came from neutron production in paraffin. Measurements at the equator and above $\lambda=55°$ showed that the ratio of production rates in carbon and nitrogen-oxygen are the same, as shown in Table III, for an altitude of 30,000 ft. Therefore, the local production in the paraffin cylinders of the fast neutron detectors contributes a background counting rate proportional to the fast neutron production in the atmosphere. Using the absolute measurement of slow neutron absorption, this background was calculated at 30,000 ft and at $\lambda=55°$. Each cylinder produces approximately 25 counts per minute. Thus, the contribution of local production in the paraffin to the total counting rate is 7–8 percent, which is not important for the relative measurements of the fast neutron intensity. However, the movement of materials of high atomic weight in close proximity to a single detector introduces serious errors. For example, fast neutron measurements made with and without 21 kg of lead or 8.5 kg of aluminum adjoining the paraffin cylinder at 37,000 ft gave the counting rates shown in Table IV.

Thus, the importance of not placing materials of high atomic weight in the vicinity of the detectors or not moving materials during the measurements is evident.

(c) Counter Background

The contribution to the observed neutron counting rates of star production in the walls of the counters, recoils in the BF_3 gas, and electronic showers was investigated. Since these background effects are independent of the boron-10 enrichment factor two pairs of detectors described in Fig. 1 were used, one set being the enriched counters used for the data in Fig. 2, and

[11] J. A. Simpson, Proc. Echo Lake Cosmic-Ray Symposium 252 (1949).

the other set being normal BF_3 counters but otherwise identical.[5] Owing to the large decrease in neutron intensity with decreasing λ, any evidence of showers and recoils should be most pronounced at the geomagnetic equator. The observed data are shown in Table V.

Since the enrichment ratios have been determined only to within ± 3.5 percent it is clear that there are no significant indications of showers or recoils.

By inserting a cadmium thimble around the counter inside the paraffin cylinder as shown in Fig. 1(B), the background caused by star production, recoils, showers, and fast neutron capture may be estimated. These data are summarized for the enriched BF_3 detectors in Table VI.

Thus, the total background from these processes is approximately 2 percent and not greater than 3 percent of the observed detector counting rate. Since this background is approximately proportional to the neutron intensity at all latitudes and altitudes it is assumed that this represents the contribution of stars[7] produced principally in the counter walls.

To show that the contribution of electronic showers was negligible lead (21 kg) was placed beside a single fast neutron detector. The counting rate was determined with and without the inner cadmium shield around the proportional counter. Typical measurements are given in Table VII. It is seen from these measurements that there is a negligible contribution of local showers to the detector counting rate. Also, it is evident that the increase in detector counting rate with the lead present arises from neutron production in the lead and moderator and not additional star production in the counter wall.

IV. THE LATITUDE AND LONGITUDE DEPENDENCE OF NEUTRONS

It is clear from Fig. 2 that a large latitude effect exists for the production of neutrons. This latitude dependence of the neutron intensity demonstrates that the neutrons are produced by primary charged particles. This was observed in detail by flying aircraft at constant air pressures from the geomagnetic equator to 65°N geomagnetic latitude. The time intervals for the individual measurements were approximately 15 to 30 minutes and represented a compromise between statistics and latitude change since the aircraft traversed approximately four degrees per hour. An experienced navigator used two or three independent methods for checking aircraft positions, and positions were established at the beginning and end of each measurement. Some of the flights were along the 80th meridian which closely corresponds to a constant geomagnetic longitude. All flights below 20°N geomagnetic were along 80°±1°W longitude. Flights at the higher latitudes extended as far as 122°W longitude. Thus, between 20° and 48°N geomagnetic latitude the shape of the latitude curve is dependent on the longitude effect. Figures 3, 4, and 5 show the results obtained with the fast neutron detectors. Recently Yuan[12] has confirmed this effect for slow neutrons in flights down to $\lambda = 20°$.

TABLE IV.

	c/min without	c/min with lead	c/min with aluminum
$\lambda = 0°$	157	176	—
$\lambda = 53°$	539	606	545
rate at $\lambda = 53°$ / rate at $\lambda = 0°$	3.4	3.4	—

The selection of the appropriate geomagnetic coordinates for these data is a serious problem. Neither centered dipole nor eccentric dipole[13] field distributions fit all of the data. However, since most cosmic-ray data to date have been fitted to the centered dipole distribution, it is this distribution which was used in Figs. 3, 4, and 5. The coordinates used for the intersection of the dipole axis with the surface of the northern hemisphere are: 78° 32′ N latitude; 69° 8′ W longitude.

Changes in cosmic-ray intensity with longitude are expected to occur[14] since the magnetic center of the earth is approximately 300 km from the center of the earth along a line passing through 10°N geomagnetic latitude and 160°E longitude. The magnetic field distribution of the earth is represented by an equivalent dipole located at this point. Thus, at a given latitude, λ, the distance r from the magnetic center to the given atmospheric depth of the observer will change with longitude. According to the theory of Vallarta and Lemaître[15] the solid angles of the allowed cones for any given primary particle energies will change with this distance. It should be noted that this longitude effect should decrease with increasing magnetic latitude for two reasons. First, owing to the eccentricity, the percentage change in this distance r diminishes with increasing geomagnetic latitude λ. Second, the solid angles of the allowed cones are increasing with λ. However, because of the momentum distribution of the primary particles, the change $\delta I/\delta\lambda$ of neutron intensity I with latitude is greatest in the region of 20°

TABLE V. Neutron measurements using normal and enriched B-10 counters to determine shower backgrounds.

$\lambda = 0°$	15,000 ft	27,000 ft	33,200 ft
Enriched BF_3	45 ±1	154 ±3	243 ±4
Normal BF_3	10.3±0.5	39.9±0.9	57.4±1.4
Enrichment ratio	4.4	4.1	4.3
$\lambda = 53°$	15,000 ft	27,000 ft	33,150 ft
Enriched BF_3	109	507	823
Normal BF_3	26	115	185
Enrichment ratio	4.2	4.4	4.4

[12] L. C. L. Yuan, Phys. Rev. **76**, 1267 (1949).
[13] J. Bartels, Terr. Mag. **41**, 225 (1936).
[14] T. Johnson, Revs. Modern Phys. **10**, 193 (1938).
[15] M. S. Vallarta, Phys. Rev. **47** (1935). G. Lemaître and M. S. Vallarta, Phys. Rev. **50**, 493 (1936).

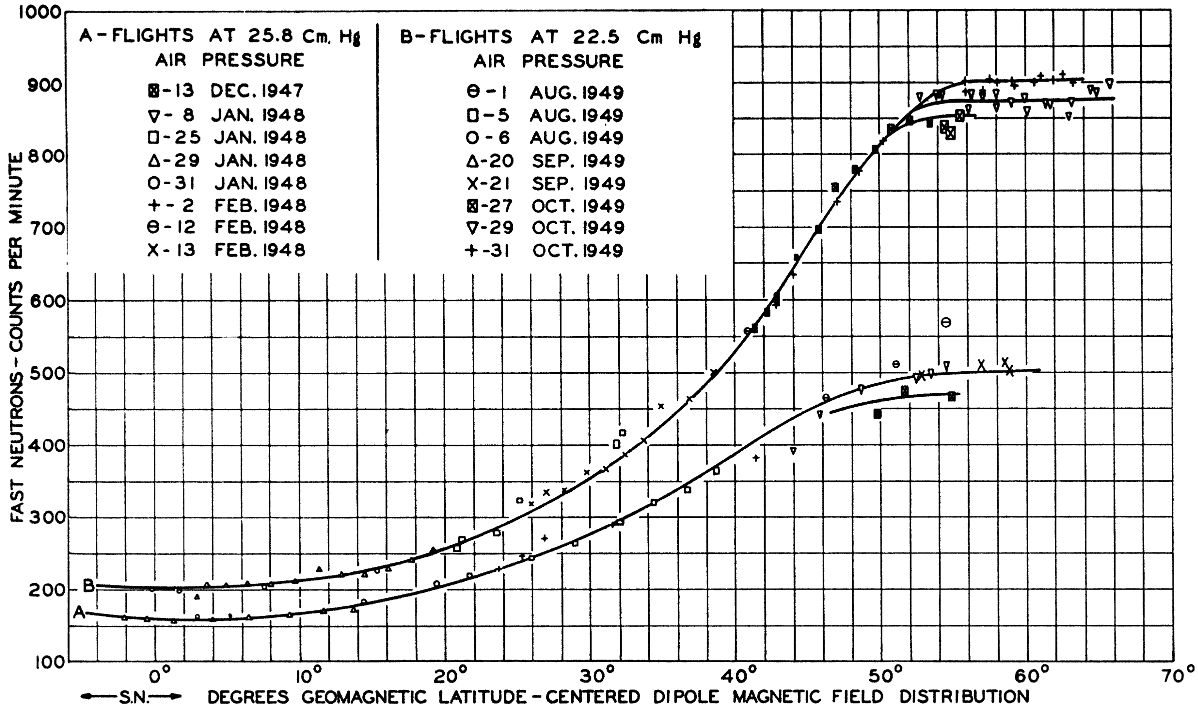

FIG. 3. Latitude dependence of fast neutrons at (A) 27,000 ft and (B) 30,000 ft. Several points lie off the curve between 20° and 40° owing to errors in navigation. The family of curves at high latitude for B show the change of intensity between October 27 and 31, 1949.

to 50°N. Below approximately $\lambda=10°$, $\delta I/\delta\lambda$ is small; above $\lambda=50°$ at atmospheric depths ~ 200 g-cm^{-2} or more, $\delta I/\delta\lambda \rightarrow 0$. Since at any λ a change in geomagnetic longitude φ may be represented by a change in latitude, it is seen that the region of 20°–50° latitude is most sensitive to the longitudinal position of measurements. Thus, the shape of the latitude curve in Fig. 3 between 20°–50° is determined by the longitude of the measurements.

Some evidence for the magnitude of the change in neutron intensity with longitude has been obtained in the region of $\lambda=41°$ and $\varphi=95°$–110°W geographic longitude. In Fig. 6 it is seen that $[\delta I/\delta\varphi]_\lambda=-1.5$ percent at 312 g-cm^{-2} and -1 percent at 448 g-cm^{-2}. From Fig. 3 $[\delta I/\delta\lambda]_\varphi=4.6$ percent at 312 g-cm^{-2}; thus, approximately,

$$\left[\frac{\delta I}{\delta\varphi}\Big/\frac{\delta I}{\delta\lambda}\right]_{\lambda=40°}=0.33.$$

TABLE VI.

$\lambda=0°$	37,000′	27,000′	36,200′	30,000′
c/min with Cd thimble	5.5±0.5		9.5±0.4	
c/min without thimble	315±4		300	
$\lambda=55°$				
c/min with Cd thimble	22.5	12±1		19±1.0
c/min without thimble	1072	507		662

These data may be compared with the longitude effect of charged particles as determined by Biehl and Neher[16] using an ionization chamber on the same flight at 312 g-cm^{-2} air. For the ionization chamber at $\lambda=41°$, $\delta I/\delta\varphi=-0.24$ percent and $\delta I/\delta\lambda\approx 0.8$ percent. Thus, for charged particles

$$\left[\frac{\delta I}{\delta\varphi}\Big/\frac{\delta I}{\delta\lambda}\right]_{\lambda=40°}=0.3.$$

It has been shown that these results are in fair agreement with theory.[16]

The sea level latitude dependence was measured for neutron energies above 0.4 ev during the June, 1948 series of flights. Local neutron production in the earth's

TABLE VII. Measurements to estimate the contribution of local showers to the neutron counting rate—see Fig. 1(B).

Time sequence of measurement	$\lambda=54°$N (27,000 ft)	Events per minute
1	detector without lead	252±3
2	detector with 2 kg lead	341±2
3	detector with 2 kg lead plus cadmium thimble surrounding proportional counter	12±1.5
4	detector with cadmium thimble but without lead	12±1.5
5	detector without lead	249±3

[16] A. T. Biehl and H. V. Neher, Phys. Rev. **78**, 172 (1950).

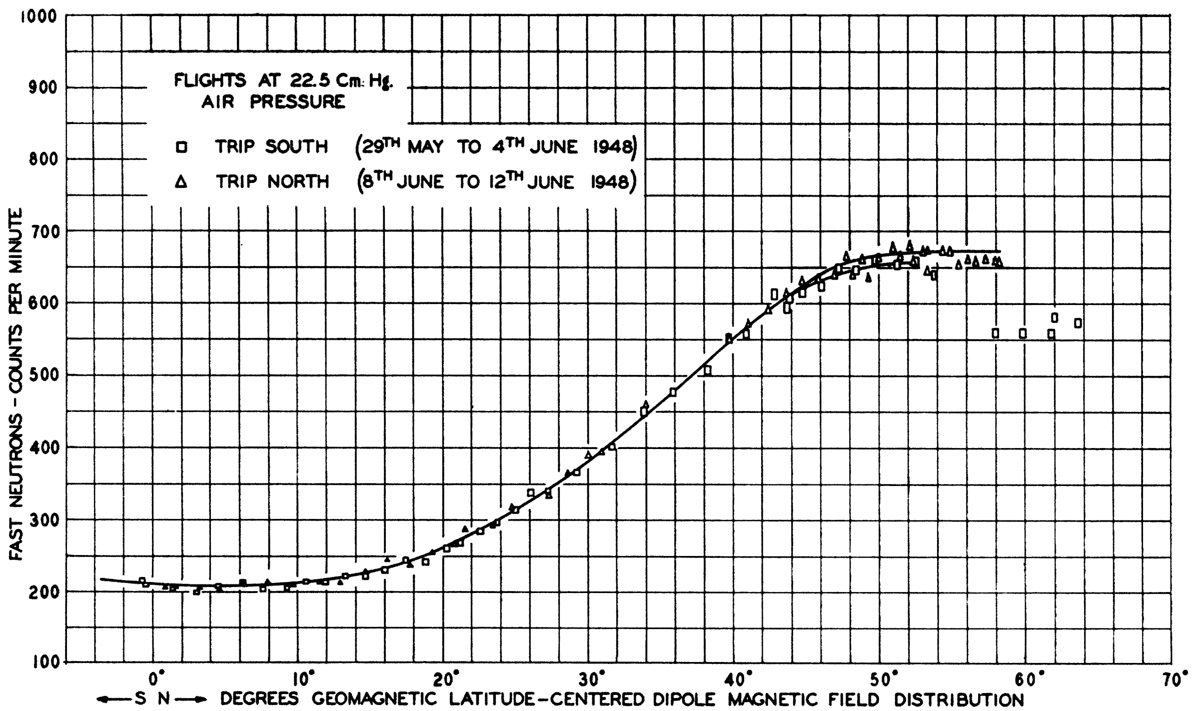

FIG. 4. Latitude dependence of fast neutrons. The time dependent change at high latitudes is shown in Fig. 10.

surface, in addition to the slowing down of neutrons in the earth, increases the neutron intensity at sea level. The results are shown in Table VIII but are difficult to interpret.

V. CONCLUSIONS REGARDING THE PRODUCTION AND DISTRIBUTION OF NEUTRONS IN THE ATMOSPHERE

(a) The Processes for Fast Neutron Production

The measurements described in the foregoing sections represent the neutron production contributions of all the nuclear processes occurring in the atmosphere. Hence, it is essential to estimate, briefly, the individual contributions of neutrons by nuclear disintegrations produced by nucleons, μ- or π-mesons, and photons before attempting to discuss neutron production as a function of primary particle energy. For example, if nonlatitude sensitive radiations contributed 10 percent of the total neutron intensity at the geomagnetic equator at 312 g-cm^{-2} atmospheric depth then the latitude factor between 0° and 55° for neutron production by the remaining kinds of neutron producing processes would be increased from the observed 3.3 to 3.5. Again, on this assumption, if a column atmosphere is defined as a vertical column of one square centimeter area extending through the entire atmosphere, the change of the latitude dependence for neutron production in a column atmosphere would be less than or more than 10 percent, depending on the altitude dependence of the assumed nonlatitude sensitive radiations.

There is evidence from independent kinds of experiments to show that most of the nuclear disintegrations or stars in the atmosphere have low energies and are produced by nucleons. Both photographic emulsion[17,18] and fast electron collection ion chamber[19] measurements at $\lambda > 50°$ show an exponential absorption of 135–150

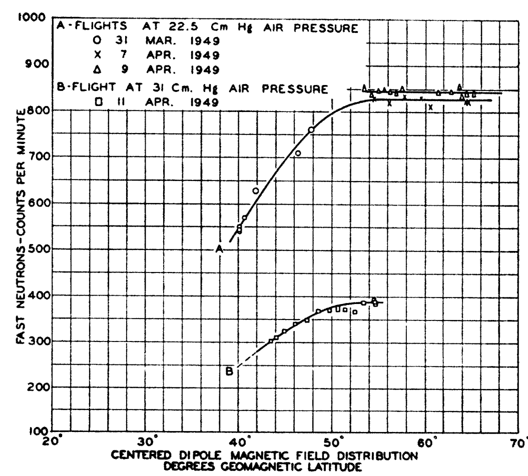

FIG. 5. Latitude dependence of fast neutrons at $\varphi = 116°$W longitude.

[17] For example, Bernardini, Cortini, and Manfredini, Phys. Rev. **76**, 1792 (1949); Phys. Rev. **79**, 768 (1950) and references therein.

[18] E. P. George and A. C. Jason, Proc. Phys. Soc. (London) **62**, 243 (1949); Lord, Schein, and Vidale, Phys. Rev. **76**, 171 (1949).

[19] Bridge, Hazen, Rossi, and Williams, Phys. Rev. **74**, 1083 (1948).

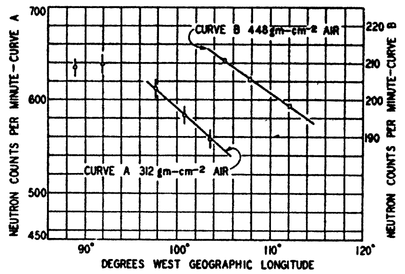

FIG. 6. The longitude dependence of fast neutrons at $\lambda=41°$ under 312 and 448 g-cm^{-2} air.

g-cm^{-2} for nuclear disintegration rates. Measurements of nuclear disintegrations using fast pulse ion chambers at $\lambda=0°$ give the same exponential absorption[20] as the fast neutron density at $\lambda=0°$, Table I. In the photographic emulsions, over 90 percent of the stars appear to be produced by nucleons at altitudes below the air transition maximum.

Measurements of the local neutron production and the multiplicity of neutron production in elements provides additional evidence that the neutron producing processes behave like nucleon-nucleus interactions.[21–23] Even the local production of neutrons in elements of low to intermediate atomic weight has a latitude and altitude dependence which follows closely the corresponding neutron production in the free atmosphere.[22]

Considering the results of all these experiments together, it is to be concluded that >90 percent of the neutrons in the atmosphere are the disintegration product of evaporation type stars produced by high energy nucleons of the order of 300 Mev. Additional arguments to support this conclusion will be given later in this section.

An upper limit for the remaining neutron production by other processes may be estimated from the meager experimental data available. These remaining neutron producing processes are generated by the high energy end of the primary energy spectrum, hence they make their greatest relative contribution at $\lambda=0°$, and estimates were obtained at this latitude. Nuclear disintegrations by μ- and π-mesons are considered first.

It has been pointed out by several observers that the absorption curves at $\lambda\approx 50°$ for neutrons and μ-mesons are entirely different. This was also verified for $\lambda=0°$ by measuring the vertical μ-meson absorption in the atmosphere along with the first series of neutron intensity measurements reported here. The results have been compiled in Appendix II. Both from the μ-meson intensity as a function of altitude and from the properties of the μ-meson it is seen that they contribute a negligible or vanishing proportion of the total neutron production in the atmosphere.

TABLE VIII. The sea level latitude dependence for neutrons with energies >0.4 ev.

Geomagnetic latitude λ	0°	20°	40°	52°
Neutron events per minute	2.5±0.2	2.2±0.3	2.9±0.3	3.4±0.3

Bernardini and co-workers[17] have estimated that at an altitude of 685 g-cm^{-2} the $\pi\rightarrow$star production in photographic emulsions was <5 percent for $\lambda\sim 50°$. Hence, below the transition maximum at $\lambda=0°$ it is estimated that slow and fast π-mesons produce <3 percent of the observed neutrons.

Tongiorgi[24] has shown that neutrons are associated with showers. However, from the frequency of these showers and their negligible latitude dependence it is clear that their contribution to the total neutron production is negligible.

From what little is known of the photon spectrum in the atmosphere, and from published cross sections for $\gamma-n$ and γ-star processes and resonance widths for the $\gamma-n$ process in light nuclei, it would be expected that these processes contribute <5 percent of the neutrons observed at $\lambda=0°$.

The above comments form the basis for the assumption in Sec. V(b) that the production of neutrons by nucleon-nucleus collisions accounts for >90 percent of the neutron production in a column atmosphere at the geomagnetic equator.

(b) The Dependence of the Neutron Component Intensity on Primary Cosmic-Ray Energy

In order to investigate the dependence of neutron production on primary particle energy, the neutron production arising from primary particles arriving vertically in the energy intervals corresponding to the geomagnetic cutoff for $\lambda=0°$, 20°, 40°, 53°, and 65° may be examined. Although primary alpha-particles and heavy nuclei are an important constituent of the primary radiations their role in contributing high energy nucleons in the atmosphere is complex; therefore, for the present it will be assumed that protons are the primary radiation. Geomagnetic cut-off values for *vertical* incidence as calculated from the Stöermer main plus shadow cones have been used. A method of analysis was chosen similar to that used by Bowen, Millikan, and Neher[25] (hereafter referred to as B.M.N.) in their derivation of the primary spectrum from spherical ionization chamber measurements. A comparison of the results will show the relative differences in production of the charged particle and neutron components in the atmosphere at different latitudes or primary proton energies. The B.M.N. measurements neglect a double-neutrino loss. In the B.M.N. analysis

[20] J. Simpson and E. Hungerford, Phys. Rev. **77**, 847 (1950).
[21] V. Cocconi Tongiorgi, Phys. Rev. **76**, 517 (1949).
[22] J. Simpson, Proc. Echo Lake Conf. 252 (1949); Phys. Rev. **77**, 751A (1950).
[23] C. G. Montgomery and A. R. Tobey, Phys. Rev. **76**, 1478 (1949).
[24] V. Tongiorgi, Phys. Rev. **75**, 1532 (1949).
[25] Bowen, Millikan, and Neher, Phys. Rev. **53**, 855 (1938). Millikan, Neher, and Pickering, Phys. Rev. **61**, 397 (1942).

at latitude λ the number of ion pairs measured at each altitude and integrated over the entire depth of the atmosphere is proportional to the amount of energy brought into the atmosphere by all primary protons of energies greater than the cut-off energy defined by λ. The ionization observed at any given altitude is principally caused by particles generated at a higher altitude. Similarly, the fast neutrons detected arise from nearby nuclear disintegrations which are produced by high energy nucleons generated at higher altitudes. The migration length of these disintegration product neutrons has been shown[2] to be short compared with the mean-free path of the neutron producing radiation, and, from the discussion in Sec. II, the energy distribution of disintegration product neutrons is approximately independent of altitude and latitude in the equilibrium region of the atmosphere. Therefore, the difference in areas under two altitude curves at λ_1 and λ_2 is proportional to the neutron production from primary particles which have cut-off energies between E_{λ_1} and E_{λ_2}.

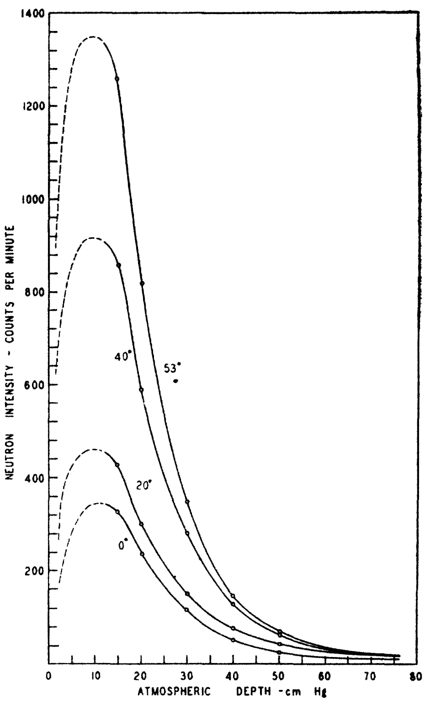

FIG. 7. The points on these curves were derived from the data in Fig. 2. The dashed parts of the curves are extrapolations based on the transition maximum found at $\lambda=54°$ by Yuan (see reference 6).

This method was followed for the interval of atmospheric depths $h=204$ to $h=610$ g-cm^{-2} in the published preliminary account[3] of the dependence of the neutron intensity on primary particle energy. More recently Yuan[6] has reported the shape of the altitude curve at $\lambda=54°$ near the top of the atmosphere. Hence, it will be assumed in the following analysis that the shape of his curve above ∼150 g-cm^{-2} is correct and represents the kind of curve to be expected at lower latitudes except that the maxima probably occur at slightly increasing atmospheric depths with decreasing λ owing to the increase in average energy of the primary radiation. With this assumption the experimental curves of Fig. 2 have been extrapolated to the top of the atmosphere. The derived curves are shown in Fig. 7. In arbitrary units the relative areas A of the atmospheric depth *vs.* intensity curves are given in Table IX.

TABLE IX. θ is a function of primary particle energy and intensity and is proportional to the number of neutrons produced in a column atmosphere per Bev energy interval of primary particle energy.

λ	Arbitrary units of areas (proportional to neutron production) A See Fig. 7	Differences in area $=\Delta A$	Vertical proton cut-off energy Bev	Energy differences in Bev $=\Delta E$	$\theta=\frac{\Delta A}{\Delta E}$
		222		21	10
0°	222		14		
		63		3.5	18
20°	285		10.5		
		309		6.2	50
40°	594		4.3		
		252		3.0	84
53°	846		1.3		
		small		0.9	—
65°	846+		0.4		

θ is a function of primary particle energy and intensity and is proportional to the number of neutrons produced in a column atmosphere per Bev energy interval of primary particle energy. The results are plotted as a dashed line histogram in Fig. 8. The results obtained by B.M.N. from their ionization chamber measurements are shown in the solid line histogram without corrections for neutrino loss. The energies given in their paper for electron primaries were changed to energies for proton primaries, and their data were fitted to the neutron data in the range of energies of

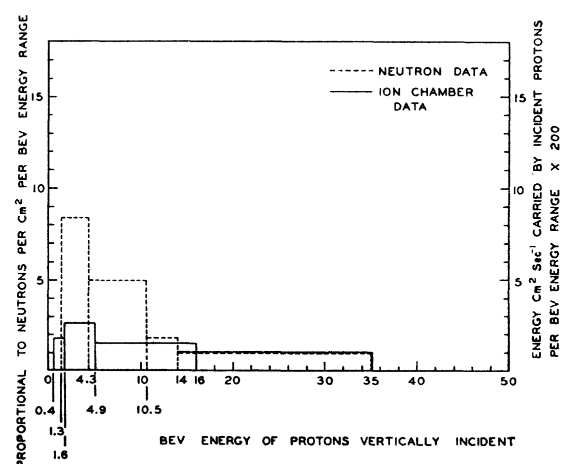

FIG. 8. A histogram of the results tabulated in Table IX. The two histograms were normalized at 16–35 Bev. The ion chamber data are the corrected results of Bowen, Millikan, and Neher (see reference 25).

TABLE X. Calculated values for the exponential absorption L of the neutron producing radiation produced by primary particles arriving between λ_2 and λ_1.

λ	$\lambda_2-\lambda_1$	L_λ g-cm^{-2}	Derived values for $L_{\lambda_2-\lambda_1}$ g-cm^{-2}
0°		212	212
	(20°–0°)		187
20°		206	
	(40°–20°)		162
40°		182	
	(50°–40°)		123
55°		157	

vertically incident protons of $E>16$ Bev. The more recent measurements of Biehl, Neher, and Roesch[26] were not used to change the ionization chamber measurements of B.M.N.

Before discussing these graphs, the following terms are defined: J_λ = integrated primary cosmic-ray nucleon intensity over the entire solid angle at the top of the atmosphere at magnetic latitude λ. Q_λ = total neutron capture cm^{-2}-sec^{-1} in a column atmosphere at magnetic latitude λ. $Y_\lambda(\bar{E})$ = yield of disintegration product neutrons in a column atmosphere per incident primary particle of average energy $\bar{E}$.

It is seen that

$$Q_\lambda \sim J_\lambda Y_\lambda(\bar{E}),$$

and that between two latitudes λ_1 and λ_2 with average vertical primary cut-off energies E_{λ_1} and E_{λ_2},

$$Q_{\lambda_2-\lambda_1}K = J_{\lambda_2-\lambda_1}Y_{\lambda_2-\lambda_1},$$

where $Q_{\lambda_2-\lambda_1}$ is proportional to the differences in areas, in Table IX.

Thus:

$$\frac{Q_{\lambda_2-\lambda_1}}{E_{\lambda_1}-E_{\lambda_2}} \rightarrow \frac{\delta Q}{\delta E_\lambda} = K_2\theta_{\lambda_2-\lambda_1}.$$

The change in θ_λ from $\lambda=0°$ to the interval $\lambda_{53}-\lambda_{40}$ is,

$$\frac{\theta_{53-40}}{\theta_0} = \frac{\delta[J_{53-40}Y_{53-40}(E)]}{\delta[J_0Y_0(E)]} = 8.4$$

from Fig. 8.

The exponential absorption for the neutron producing radiation derived from primary particles admitted between λ_2 and λ_1 may be estimated in the equilibrium region of the atmosphere by the crude assumption that the secondary particles which are generated in the interval between λ_2 and λ_1 have an exponential absorption, and that,

$$I_0^{\lambda_2-\lambda_1}\exp[-h/L_{\lambda_2-\lambda_1}] = I_0^{\lambda_2}\exp[-h/L_{\lambda_2}] - I_0^{\lambda_1}\exp[-h/L_{\lambda_1}]$$

The calculated values for $L_{\lambda_2-\lambda_1}$ are given in Table X.

Since $L_0 > L_{55-40}$ then $Y_{53-40}/Y_0 < 1$ and $J_{53-40}/J_0 > 8.4$.

[26] Biehl, Neher, and Roesch, Phys. Rev. **76**, 914 (1949).

The primary energy dependence of Y may be investigated by assuming a knowledge of the integral number spectrum. The best values for J_{55}/J_0 range from 5 to 6 on the basis of recent work by Biehl[26] and Winckler and co-workers.[27] Hence, since $(Q_{55}/Q_0) = (Y_{55}/Y_0) \times (J_{55}/J_0) \approx 4$ then $Y_{55}/Y_0 = 0.5$ to 0.7. It is seen, therefore, that Y is a slowly varying function of the primary particle energy.

It is evident from Figs. 3 and 8 that with decreasing primary particle energy the ratio of the production of nucleons to the production of high energy charged mesons increases rapidly, especially above $\lambda=40°$. For example, from Fig. 2 at 312 g-cm^{-2} air the fast neutron production increases by ~ 1.5 between 40° and 50°. This large latitude effect is a unique characteristic of the low energy nucleonic component.[28]

C. The Formation of Nuclear Collision Chains in the Atmosphere

The evidence in the foregoing sections provides the basis for a crude description of the production of neutrons in a column atmosphere initiated by an incident primary particle. Using the curves in Fig. 7, the slow plus fast neutron capture in air per second, Q, in a column atmosphere may be determined from Appendix I. Hence, at $\lambda=55°$ the total neutron production, Q, is $Q=8$. With $J_{55}=0.95$ the yield is $Y_{55}=8.4$. This high yield of neutrons in a column atmosphere must come from a multiplicative process by which the neutron producing radiations are absorbed in the atmosphere. It will be assumed that fast nucleons excite air nuclei by collision processes, and, hence, that $L_{\text{collision}} \leqslant L_{\text{absorption}}$.

In particular, the first interaction of a primary particle with a nucleus may produce several nucleons and π-mesons. These nucleons and π-mesons, along with the primary particle of reduced energy, may produce further inelastic collisions in the atmosphere with the excited nuclei returning to stable states by emission of fast neutrons, protons, and alpha-particles. Each primary particle thus produces several secondary nucleons which, together with the primary, may each produce a few excited nuclei in subsequent collisions at greater atmospheric depths. This crude picture requires the assignment of the following energy dependent multiplicities for measurements at λ: ν_1 = average multiplicity of high energy nucleon production by a primary particle; ν_2 = average multiplicity of nuclear disintegrations per high energy nucleon; and ν_3 = average multiplicity of fast neutrons from a nuclear disintegration.

Values for ν_3 in carbon and aluminum near $\lambda=55°$ and $\lambda=40°$ have been measured[29] with $\nu_3 \sim 2$. Also,

[27] Winckler, Stix, Dwight, and Sabin, Phys. Rev. **79**, 656 (1950).

[28] Recently a comparable latitude effect for charged particles, probably protons of momenta >1 Bev, has been found by M. Conversi, Phys. Rev. **76**, 444 (1949).

[29] V. Tongiorgi, Phys. Rev. **76**, 569 (1949). J. Simpson, Proc. Echo Lake Conf. 252 (1949); Phys. Rev. **77**, 751(A) (1950). C. G. Montgomery and A. R. Tobey, Phys. Rev. **76**, 1478 (1949). A. R. Tobey and C. G. Montgomery, Phys. Rev. **81**, 517 (1951).

$\nu_1\nu_2$ may be estimated from the absolute nuclear disintegration rates observed in photographic emulsions.[17,30] One and two prong stars and disintegrations emitting only neutrons are not counted in the emulsions, and they must be estimated. By including these latter events it is estimated that 3–4 events per second which emit neutrons occur in a column atmosphere at $\lambda \approx 50°$; then $\nu_1\nu_2 \approx 4$. Hence, it appears that a low multiplicity ν_1 of secondary high energy nucleons, each making a few inelastic collisions, may account for the entire neutron production in a column atmosphere.

As the average energy of the primary particles is increased, the average energy as well as the multiplicity ν_1 of secondary nucleons increases. In this way collision chain processes extend to greater atmospheric depths with increasing primary particle energy, and the multiplicity ν_2 of star production per high energy nucleon increases. This accounts for the change of exponential absorption L of the neutron producing radiations from $L_{55°} = 157$ g-cm^{-2} to $L_{0°} = 212$ g-cm^{-2}.

It should be emphasized that this is only a qualitative discussion. J_λ, Q, and the star production in a column atmosphere are not known precisely. In several respects the above remarks are consistent with models proposed by Thomson,[31] Rossi,[32] and Bernardini[17] to describe the behavior of the low energy star producing radiations. Recently Cocconi and co-workers have proposed a model which appears to fit the experimental data at high nucleon energies.[33]

VI. TIME DEPENDENT CHANGES OF THE NEUTRON INTENSITY

On the basis of the measurements described in the preceding sections there do not appear to be significant differences in neutron intensity between winter and summer. Although the optimum times for the measurements would be close to March and September, only measurements in December, 1947–January, 1948 (Fig. 2) and May–June, 1948 (Fig. 4) have been made at both $\lambda = 0°$ and $\lambda = 54°$. The winter and summer measurements are the same within the experimental error of ± 5 percent. These measurements were made during periods in which no significant geomagnetic or solar disturbances were reported. Also, with a larger experimental error, the slow neutrons measured in January and August, 1949 at $\lambda = 0°$ (Table XI) show no significant change between winter and summer (see Appendix I). Neutron intensities on these quiet days have, therefore, been selected as a measure of the quiet day intensity of neutrons from the low energy nucleonic component.

It is evident from a close examination of the statistical fluctuations of the experimental points along a latitude curve that, aside from occasional position errors, the fluctuations of neutron intensity are greater for $\lambda > 50°$ than for $\lambda \to 0°$. In fact, the intensity as a function of time at high latitudes shows periods of relatively large fluctuations. For example, in Fig. 9 two flights are represented which occurred on disturbed days.

In order to investigate time dependent changes, two series of flights were made in 1949 at 30,000 ft pressure altitude. Both series will be described before discussing their interpretation. The first set included March 31, April 7 and 9, 1949, as shown in Fig. 5(A). Considerable solar activity was reported during the period April 5–9. Many stations reported[34] magnetic storms on April 7. The principal increase of neutron intensity above $\lambda = 50°$ was ~ 25 percent higher than the quiet day intensity, with this increase apparently occurring before the April 7 flight. Aircraft difficulties prevented flights at 30,000 ft on April 11, but data at 23,000 ft were recorded. Using $L = 157$ g-cm^{-2} the extrapolated intensity at 23,000 ft on April 9 would have been 450 events per minute. However, by April 11 the observed intensity was 390 events per minute. This indicates that there was a decrease of neutron intensity toward normal occurring between April 9 and 11.

The second flight series at 30,000 ft was October 27, 29, and 31, 1949, shown in Fig. 3(B). Solar flares were reported of importance 1, 2, and 3 during the period October 25–31.[35] None of the flares occurred with the aircraft in the air. Some of the flares were followed by minor but distinct magnetic storms. The flight positions covered only a small range of longitudes, and corrections were made for this using the measured longitude effect at 41° in Fig. 6. The corrected curves were plotted and shown elsewhere.[36] The quiet day measurements at 40°N are shown in Fig. 2 and were obtained at 110°W longitude. A detailed discussion of these curves and their relation to changes of the primary cosmic-ray intensity has appeared elsewhere,[36] however, it is clear that:

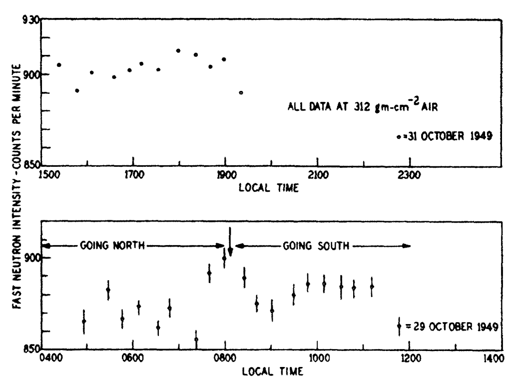

FIG. 9. The time dependent changes of neutron intensity for $\lambda > 55°$ from the latitude measurements of Fig. 3.

[30] S. Lattimore, private communication.
[31] G. P. Thompson, Phil. Mag. **40**, 589 (1949).
[32] B. Rossi, Proc. Echo Lake Conf. (1949).
[33] Cocconi, Tongiorgi, and Widgoff, Phys. Rev. **79**, 768 (1950).
[34] J. Geophys. Research **54**, 301 (1949).
[35] The data covering the solar flare observations in this period were kindly prepared by A. H. Shapley of the Central Radio Propagation Laboratory, National Bureau of Standards. (Private communication.)
[36] J. A. Simpson, Phys. Rev. **81**, 639 (1951).

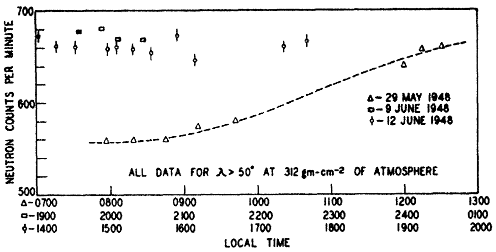

FIG. 10. The time dependence of the neutron intensity for measurements above $\lambda=50°$, as shown in Fig. 4.

1. Above $\lambda=56°$ an increase of ~ 30 percent over the quiet day neutron intensity has occurred.

2. Beginning before the measurement of October 27, additional primary particles with momenta lower than the limit on quiet days at $\lambda=50°$ arrive at the top of the atmosphere. By October 31, particles arrive with momenta as low as ~ 1 Bev/c, if singly charged, corresponding to a cutoff at $\lambda>56°$.

These neutron measurements have been compared[37] with charged particle measurements obtained in the same aircraft and at the same time; it was concluded that the observations represented a change in primary particle intensity and that the neutron intensity has an order of magnitude greater response to primary intensity change than the charged particle intensity at aircraft altitudes. Because of atmospheric absorption this increase could not have been observed at sea level.[38]

These experimental results are consistent with the conclusions derived from Sec. V B; namely, that the neutron yield as a function of primary energy decreased with increasing latitude, but that the relative cross sections for the production of the low energy nucleonic component to the cross section for the production of high energy charged mesons increased with increasing latitude.

From the measurements at high latitudes in this paper it may be concluded, tentatively, that the time dependent changes may be classified as either: (a) small fluctuations of intensity with occasional sharp increases occurring in times the order of minutes or hours, or (b) changes of intensity which persist the order of days. On the basis of approximately ten flights to high latitudes it appears that these changes occur on solar and terrestrial disturbed days.[39] An increase in star production in a photoemulsion in the stratosphere following a solar flare has recently been reported.[40] This increase may be of the same type as reported here for the neutrons.

In Fig. 4 the intensity decrease observed in the early hours of May 29, 1948 for $\lambda>58°$ is not understood. The neutron intensity as a function of time for $\lambda>50°$ has been plotted in Fig. 10. Although a change of intensity of the kind shown in Fig. 10 is not in disagreement with the phase for a diurnal effect, the observed intensity change is too large.

SUMMARY

The distribution of fast neutrons produced in the atmosphere has been measured from the geomagnetic equator to 65°N over a period of two years. It was shown that these measurements are equivalent to "free atmosphere" measurements. The results may be summarized as follows:

(a) A neutron component exists in the atmosphere which has the largest latitude dependence of any known secondary component in the cosmic radiations. This fact alone shows that the neutrons are secondary particles produced by charged primaries.

(b) The neutrons are produced as part of a low energy nucleonic component which has a latitude effect at least as great as that for the neutrons.

(c) The yield, Y, of fast neutrons in a column atmosphere from a single primary particle is only a slowly varying function of primary energy above approximately 4 Bev. There is still a large latitude effect between $\lambda=40°$ and $\lambda=50°$. These are characteristics of the neutron component.

(d) At high latitudes the ratio at the top of the atmosphere of the cross section for neutron producing radiations to the cross section for high energy meson production increases rapidly for increasing geomagnetic latitude. This is verified from the observed increases of neutron and meson production in the atmosphere at high latitudes and below ~ 200 g-cm^{-2} air following an increase in primary particle intensity.[37]

(e) Measurements of the exponential absorption of the neutron producing radiations from $\lambda=0°$ to 65°, where $L_{0°}>L_{20°}>L_{40°}>L_{53°}$, indicate that the neutrons are the disintegration products of stars and that the stars are produced in a series of collisions of a high energy nucleon. Developing at the top of the atmosphere, this process is a nucleon-nucleus collision phenomenon.

(f) From the absolute capture rate of neutrons in the atmosphere and the primary cosmic-ray flux, it has been estimated that the average multiplicities in air for high energy nucleon production, star production per high energy nucleon, and neutrons per star are low.

(g) The slow plus fast neutron capture was measured at the geomagnetic equator at 312 g-cm^{-2}. The average value was $(3.2\pm0.5)\times10^{-3}$ neutron captured in air g^{-1}-sec^{-1}. There may be large errors in this measurement because of the lack of knowledge of the neutron energy spectrum.

(h) At high latitudes and altitudes the neutron component is time dependent, with temporary increases of at least ~ 30 percent being observed at 30,000 ft and persisting for the order of days.

Although the contribution of primary alpha-particles in the primary cosmic-ray spectrum is important, it was assumed in this paper that all primary particles were protons. The effect of the alpha-particles will be discussed in a later paper.

Rossi has classed both high and low energy nucleon processes as an "N" component. It is seen in the present paper that the definition of a low energy nucleonic component is much more restricted but is

[37] J. A. Simpson, Phys. Rev. 81, 895 (1951).

[38] A recent report by M. A. Pomerantz [Phys. Rev. 81, 731 (1951)] indicates that small changes of primary radiation intensity may be detected at balloon altitudes.

[39] Staker, Pavalow, and Korff, Phys. Rev. 81, 517 (1951) have described balloon flights which show a factor of ~ 2 increase in intensity between $\sim 54°$N and 69°N at all altitudes. It is seen from Figs. 2 and 3 that their anomalous results may be explained by a change of neutron intensity in the time interval between their flights.

[40] Lord, Elston, and Schein, Phys. Rev. 79, 540 (1950).

clearly a part of the mixed "*N*" component. The neutrons are predominately produced by low energy processes, and the degradation of energy is completed with the formation of slow neutrons in the atmosphere.

The world-wide distribution of slow neutron intensity shows that the total neutron production in the atmosphere is dominated by the low latitude belt. Hence, large fluctuations of low energy primary particle intensity, such as found in the present investigation, do not change appreciably the total neutron production in the atmosphere of the earth.

On the basis of the neutron measurements and the observed time dependent changes of the nucleonic component, the neutrons appear to be the most responsive component to changes in primary particle intensity observable at low altitudes. Thus, neutron monitoring may become useful for following changes of primary particle intensity.

The author wishes to thank Messrs. H. W. Baldwin (deceased), R. B. Uretz, and E. Hungerford for assistance in collecting the data on several of the flights. The assistance of General Mills Company in launching successful "sky hook" balloon flights with photographic emulsions was greatly appreciated. The officers and men of the U. S. Air Force B-29 group at Inyokern, under the command of Major W. Gustafson, and with navigator Captain George Freyer, were both co-operative and skillful in flying the aircrafts.

APPENDIX I. MEASUREMENT OF THE NEUTRON CAPTURE ABSORPTION IN THE ATMOSPHERE

Since the slow neutrons do not attain thermal equilibrium[2] (most probable energies of ~0.02 ev) but have average energies the order of 0.2 ev, the measurement of the absolute neutron flux becomes difficult. However, as first pointed out by Montgomery and Montgomery,[41] measurement of slow neutron absorption by a detector using boron-10 is not dependent on the form of the slow neutron energy spectrum because both nitrogen and oxygen, as well as boron, have cross sections which follow the $1/v$ law. Measurements of the absolute rate of absorption of slow neutrons by the air nuclei have been described by Bethe, Korff, and Placzek[2] and more recently by Yuan.[6,12,42] (See also Staker[43] and Davis.[44])

An attempt was made to convert the relative distribution of Fig. 2 into the absolute distribution for neutron capture by cadmium difference measurements using BF_3 proportional counters in B-29 aircraft.[45] This has been shown to be equivalent to free-atmosphere measurements.[5,8,46] As indicated in Sec. VI, only measurements below approximately latitude 40° avoid the serious time dependent intensity changes found at high latitudes.

Independent measurements in summer and winter at the geomagnetic equator under 312 g-cm^{-2} of air are given in Table XI. No significance has been attached to the difference in these two measurements.

Since each counter had the same rate of production of nuclear disintegrations and recoils, the "cadmium difference" measurements eliminated these background counting rates. An approximate upper limit for this background effect may be obtained from the data in Sec. III(c). At $\lambda=0°$ and under 312 g-cm^{-2} air the background of a single slow neutron counter is ≈6 counts per minute after correcting for the differences in geometry of the fast neutron detectors used to obtain the data in Sec. III(c) and the slow neutron detectors. This shows that an unshielded BF_3 counter cannot be used to determine the slow neutron density.

The detectors were calibrated at thermal neutron energies using a standardized neutron source and the calibrated counters used by Yuan.[47] The thermal neutron cross section of the unshielded counter was equivalent to 8.8 cm^2. At thermal energies the reported value[48] for the thermal neutron absorption cross section of a nitrogen atom is 1.7×10^{-24} cm^2. Thus, taking into account the ratio of N_2 to O_2 in air, one gram of air has an absorption of 0.055 cm^2. Hence, the unshielded counter has a thermal neutron cross section equivalent to 8.8 cm^2 and a neutron absorption equivalent to 160 g of air.

An energy distribution has been assumed for the slow neutrons, which follows the work of Bethe, Korff, and Placzek[2] but is based on more recent data and includes fast neutrons.[49] The average energy of the slow neutrons is assumed to be near 0.2–0.3 ev. This requires that for cadmium difference measurements the cadmium-covered counter response[42] must be calculated using the energy dependence of the measured cross sections for neutron capture in cadmium.[50] With these assumptions the neutron absorption for cadmium difference measurements is equivalent to the absorption of ~43 g of air.

The average value of the measurements at $\lambda=0°$ and under 312 g-cm^{-2} air using cadmium difference corrections is $(3.2\pm0.5)\times10^{-3}$ slow plus fast neutrons captured g^{-1}-sec^{-1}. Accordingly, the tentative conversion factor for the neutron intensity distributions in Fig. 2 is 1.6×10^{-5}. These measurements are in disagreement with the early measurements of Yuan[6] but are in better agreement with his recent measurements[42] at 52°, provided his data on undisturbed days are used.[51] It should be noted that absolute neutron capture rates, particularly those given in Table XI, are subject to large errors because of uncertainties in the necessary assumptions which are made when using BF_3 detectors. When new measurements of absolute neutron capture become available, the normalizing point for the fast neutron data may be changed.

TABLE XI. The measurement of slow plus fast neutron capture in the atmosphere at the geomagnetic equator and at 30,000 ft pressure altitude using BF_3 proportional counters.

Date	Counter	Events per minute	"Cadmium difference" in neutrons per minute	Cadmium ratio	Neutron capture per g and sec at $\lambda=0°$ under 312 g-cm^{-2} air
1949					
January	Cadmium covered	8.0 ± 0.2			
January	No cadmium	15.6 ± 0.4	7.6 ± 0.6	2.0 ± 0.1	2.9×10^{-3}
August	Cadmium covered	7.6 ± 0.2			
August	No cadmium	16.5 ± 0.5	8.9 ± 0.7	2.2 ± 0.1	3.4×10^{-3}

[41] C. G. Montgomery and D. D. Montgomery, Revs. Modern Phys. **11**, 266 (1939).
[42] L. C. L. Yuan, Phys. Rev. **77**, 728 (1950); Phys. Rev. **81**, 175 (1951).
[43] W. P. Staker, Phys. Rev. **80**, 52 (1950).
[44] W. O. Davis, Phys. Rev. **80**, 151 (1950).
[45] The tail gunner compartment was removed and only a thin aluminum tail piece surrounded the region of the detectors.
[46] L. C. L. Yuan, Phys. Rev. **76**, 1268 (1949).
[47] The author is indebted to Dr. Yuan for loaning his calibrated counter for comparison with the calibrated counters used in the above measurements, and to the Argonne National Laboratory for the use of the neutron source.
[48] Goldsmith, Ibser, and Feld, Revs. Modern Phys. **19**, 259 (1947).
[49] E. Melkonian, Phys. Rev. **76**, 1750 (1949).
[50] Rainwater, Havens, Wu, and Dunning, Phys. Rev. **71**, 65 (1947).
[51] L. C. L. Yuan, J. Geophys. Research **53** (1948); **54**, 661 (1949); **54**, 295 (1949).

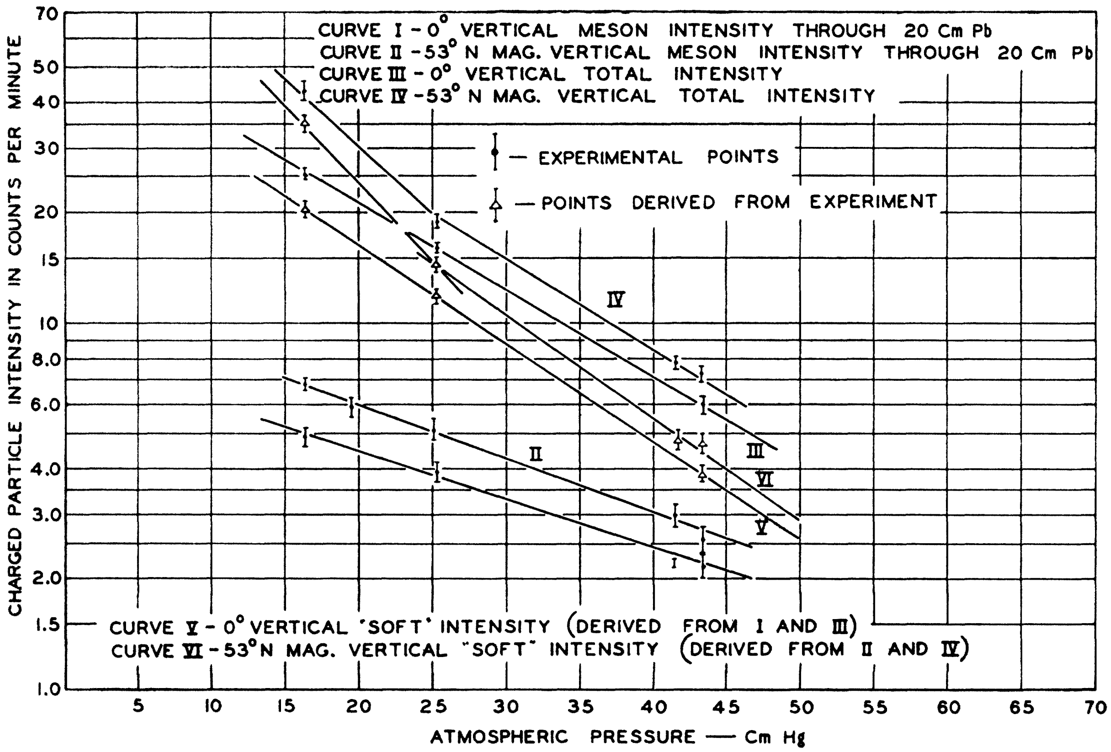

FIG. 11. The vertical charged particle intensity of the total component and mesons detected under 20 cm lead.

APPENDIX II. THE LATITUDE AND ALTITUDE DEPENDENCE OF THE PENETRATING PARTICLE AND THE TOTAL CHARGED PARTICLE INTENSITY

In order to confirm measurements of the latitude dependence of the charged particle components and to compare the cross sections for production of these components and the low energy nucleonic component, two vertical, three-fold G-M counter telescopes were carried in the aircraft in the January-February, 1948 flights. Penetrating particles, principally μ-mesons of momenta greater than 4×10^8 ev/c, were selected using a 20-cm Pb absorber. The maximum angle from the vertical with which a particle could enter either telescope was $\pm 13°$. The counters were 3.8 cm in diameter.

For the total charged particle intensity measurement the absorbing material included a plastic window above the telescope (1.0 g-cm^{-2}) plus the total mean wall mass (3.8 g-cm^{-2} of brass). The diode coincidence circuits had a resolution better than 5×10^{-6} sec. No corrections were made for side showers, since their latitude dependence is small and only relative measurements were required. Knowing the counting rates of the individual counters, corrections for accidental counts in the three-fold telescopes were applied. The data are shown in Fig. 11 with their standard deviations. The classical so-called "soft-component" was determined by subtracting the penetrating particle intensity from the total charged particle intensity. The form of the altitude curves has been represented by exponentials below 15 cm Hg. The altitude dependence of the penetrating particles at $\lambda=0°$ and $\lambda=53°$ is in agreement with the measurements of Gill, Schein, and Yngve[52] and both the penetrating and total vertical intensity altitude dependence are in fair agreement with the recent work of Biehl, Neher, and Roesch.[26]

The latitude dependence of the vertical intensity measurements at $\lambda=0°$ and $\lambda=53°$ are approximately equal below about 22 cm Hg indicating that both the penetrating and nonpenetrating charged particles have nearly the same latitude dependence. This is also the conclusion of Biehl, *et al.* from their more extensive measurements.

[52] Gill, Schein, and Yngve, Phys. Rev. **72**, 733 (1947).