for scattering through an angle greater than 15° is $\sim 3\times 10^{-28}$ cm^2 per *nucleon.*

It is not very meaningful to compare the observed scattering cross section with the cross sections calculated from various meson theories, since the energies of the particles are not known and the calculated values are quite energy dependent. It seems, however, that most meson theories, coupled with reasonable estimates of the energies, give scattering cross sections which are an order of magnitude or more greater than the observed cross section.

Experiments by Piccioni[13] indicate that the particles produced in penetrating showers are mostly π-mesons. We are thus confronted with too few scatterings, according to present theories, by a factor of ten or so. It may be that when these particles scatter they nearly always produce a nuclear disruption, and thus count, not as an anomalous scattering, but as a nuclear event. Most of the nuclear events were high energy, however, and the question of the low cross section for scattering remains unresolved.

[13] O. Piccioni, Phys. Rev. **75**, 1281 (1949).

A final remark should be made concerning the comparisons which have been made between the observed data and the various meson theories. Because of the uncertainties in the meson coupling constants, none of the numerical comparisons can be considered as rigorous. In addition to this uncertainty, it is often necessary to jump from one meson theory to another in order to get any kind of agreement at all between theory and experiment. Thus, any numerical comparisons which have been made in this paper have been for illustrative purposes only, and cannot be considered as proof that any particular theory is correct.

ACKNOWLEDGMENTS

We are indebted to Mr. Carl P. Russell, Superintendent, Yosemite National Park, and to the National Park Service men who were so helpful to us during the summer at Tioga Pass, and without whose cooperation our work would have been impossible. Professor R. B. Brode's continuing interest and support, and the help of John Ise, Jr., and Andrew Yeiser in taking the pictures, are also gratefully acknowledged.

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On the Mechanism of Production of the Neutron Component of the Cosmic Radiation

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Experiments have been performed on the neutron component of the cosmic radiation, with a system of BF_3 proportional counters embedded in paraffin, capable of recording neutrons in the energy range between $\sim$2 and $\sim$15 Mev. The neutron rate recorded with such a detector is due to both neutrons locally produced inside the detector and neutrons produced outside the detector, i.e., in the surroundings and in the atmosphere.

The local neutron production is due to a radiation which in the great majority does not consist either of photons or μ-mesons.

The intensity of such a radiation increases with altitude with a mean free path in air of 120–130 g/cm^2, which is confirmed by the fact that it shows a barometric coefficient ≈ -11 percent per cm Hg. At mountain elevation (4000 m) the intensity of this radiation is close to that of the total ionizing cosmic radiation. This suggests that it consists principally of fast neutrons.

The locally produced neutrons are mostly produced in multiples, with multiplitics depending upon the material. In lead the average multiplicity observed was close to 8, in carbon smaller than 2.

The rates of neutron production in different materials are satisfactorily described by a cross section proportional to the $\frac{2}{3}$ power of the mass number of the material.

The results indicate that the main source of all the neutrons present in the cosmic radiation are "stars," though high energy processes like penetrating and extensive showers do contribute to neutron production.

I. INTRODUCTION

FOR more than ten years neutrons have been known to exist in the atmosphere as a component of the cosmic radiation and many experiments have been performed to study their properties.

In the last few years the importance of the strongly interacting radiations (neutrons, protons, heavy mesons) for the general understanding and interpretation of the cosmic-ray phenomena has been steadily growing. Recently the phenomena concerning the neutron component have been framed in a picture in which stars, penetrating showers, bursts and extensive showers also find their places.

According to this picture, the presence of neutrons in the atmosphere can be justified somewhat as follows. As neutrons have a finite lifetime, they cannot be primaries, hence they must originate within the atmosphere. The primary radiation (say protons and heavy ions), when it collides with air nuclei, produces fast neutrons in association with fast protons, heavy mesons and photons. High energy processes of this kind can be thought of as the origin of extensive showers, bursts and penetrating showers. The fast neutrons and

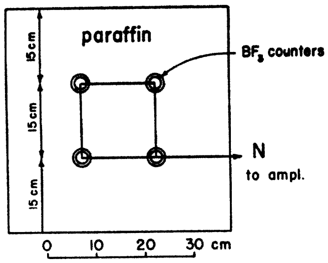

FIG. 1. Construction of the neutron detector. The paraffin block is 45×50×45 cm^3. Four BF_3 proportional counters (2.5×45 cm^2) connected in parallel are embedded in it. The paraffin block is completely covered with aluminum foil to provide electrical shield to the counters.

protons produced in these phenomena are eventually capable of giving rise to further nuclear disintegrations, as a result of which more neutrons are produced, either through one of the processes listed above or through the occurrence of stars. Nuclear evaporations with consequent emission of neutrons can be produced also by both π- and μ-mesons undergoing capture and, finally, neutrons can be ejected from a nucleus through photonuclear processes ((γ,qn) reactions) induced by the photons of the soft component.

Whatever is the nature of the nuclear process occurring, a neutron has a small probability of being emitted from a nucleus with kinetic energy lower than about 1 Mev. The great majority of the neutrons are likely produced with energies of several Mev. In the following we shall call "moderate energy neutrons" the particles, whose energies lie between 0.5 and 50 Mev and "fast neutrons" those with energies higher than 50 Mev.

The neutrons produced are then slowed down in the atmosphere by inelastic and elastic collisions with nuclei in the air and eventually undergo capture mostly by nitrogen nuclei through (n,p) processes. The average energy at which the capture occurs is about 0.07 ev and the root mean square distance traveled by neutrons with energies of the order of 10 Mev from their point of origin to the capture point is of the order of 100 g/cm^2.[1] Hence, as a result of this diffusion process, an equilibrium energy distribution is reached, in which slow neutrons predominate, though neutrons at thermal energies represent (in the free atmosphere) only ~15 percent of the neutron component.

This picture is based on many pieces of information collected from experiments on neutrons, stars, etc.[2] The most significant result is that the altitude variations of penetrating showers, extensive showers, stars and neutrons seem to be all described by an exponential law, $e^{-x/\lambda}$, with roughly the same mean free path λ.

However, no *direct* experimental evidence for the picture given above is so far available, as we lack *direct* experimental information about the characteristics of the processes in which neutrons are produced, and about the behavior of the neutron producing radiation. This lack of information arises from the fact that cloud chambers and photographic plates cannot give information about neutrons, while neutron counter experiments have not been developed enough to supply consistent data. The counter experiments on thermal and slow neutrons, which are the easiest to interpret, are not probably the most suitable ones to throw light on the processes in which neutrons originate, since, as pointed out before, the great majority of neutrons are produced as either fast or moderate energy particles.

Moderate energy neutrons can be detected by the same devices capable of recording slow and thermal particles provided that a proper layer of hydrogenate material is put around them to slow the neutrons down to energies such as to make their detection probable. A system like that, however, gives results which are surely affected by scattering and local production of neutrons in the detector itself. Proper experimental arrangements must be chosen to make a sound interpretation of the results possible and still unavoidable uncertainties are left in the deductions. So far, no systematic sets of data have been taken with arrangements of this kind to study the origin of the neutrons present in the cosmic radiation.

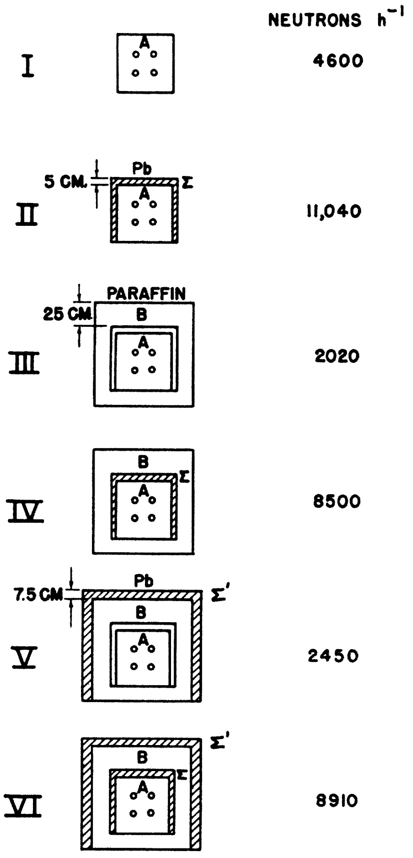

FIG. 2. Sketches of the six arrangements of paraffin and lead absorbers put around the neutron detector. Arrangement I is the naked neutron detector as drawn in Fig. 1. At the right side of the sketches are given the recorded neutron rates (h^{-1}) corrected for Cd-background.

[1] Bethe, Korff, and Placzek, Phys. Rev. **57**, 573 (1940).
[2] See e.g., B. Rossi, Rev. Mod. Phys. **20**, 537 (1948).

The aim of this paper is to present some information about the mechanism of neutron production and about the nature of the neutron producing radiation as it can be derived from experiments we have performed on neutrons of moderate energies.

II. EXPERIMENTAL ARRANGEMENT

The data we are going to report are in part the by-product of experiments performed during the spring and summer of 1948 intended to study the neutrons associated with extensive air showers, and in part the results of further experiments made during the winter of 1949 designed to complete the information acquired.

In all the experiments, the neutron detector consisted of a paraffin block ($45\times 50\times 45$ cm^3) in which four BF_3 proportional counters (2.5×45 cm^2) were embedded (see Fig. 1). Details concerning the construction of the detector and the operation of the counters have been fully given in a previous article concerning neutrons in the extensive showers,[3] that we shall quote in the following as paper I.

The neutrons that our detector is capable of recording are those whose energies lie between $\sim$2 and $\sim$15 Mev, hence the results obtained refer to moderate energy neutrons.

The over-all efficiency ϵ of the detector is given by the product of the efficiency η of the BF_3 counters to record slow neutrons (for our counters $\eta=0.3$), times the probability α that a neutron falling on the paraffin block is slowed down to detectable energies and crosses the counters. From tests with a (Ra+Be) neutron source we estimated $\alpha_4=0.1$ when the four BF_3 counters were all connected in parallel. Hence we assume $\epsilon=\eta\cdot\alpha_4=0.03$. This estimate is considered reliable within a factor 2.

The pulses of the neutron counters, amplified as described in paper I, have been recorded through a scaler circuit.

The cadmium-difference, i.e., the difference between the rates recorded without and with Cd shields (0.75 mm Cd foil) around the BF_3 counters, has been measured in all experiments and assumed as the neutron counting rate. The Cd-background was always smaller than 5 percent of the rates recorded without Cd.

All the data have been taken under roofs of a few g/cm^2 of light materials with the detector placed as far as possible from walls and other materials. In detecting moderate energy neutrons the effect of the back scattering of the ground was thought to be negligible.

As in the course of this discussion we shall often quote results given in paper I concerning neutrons coherent with extensive showers, we shall use the expression "incoherent neutrons" to identify the particles constituting the *total* neutron component of the cosmic radiation, which we are dealing with in the present paper.

[3] V. Cocconi Tongiorgi, Phys. Rev. **75**, 1532 (1949).

TABLE I. Neutron rates (h^{-1}) (corrected for Cd-background and barometric effect) recorded with the arrangement in Fig. 3 with different thicknesses t of the lead absorber.

	$t=0$ (h^{-1})	$t=\frac{1}{2}$ in. (h^{-1})	$t=1$ in. (h^{-1})	$t=3$ in. (h^{-1})	$t=6$ in. (h^{-1})
N_t	553 ± 4	596 ± 4	645 ± 5	722 ± 5	778 ± 5
N_t-N_0	0	43 ± 0.5	92 ± 1	169 ± 1.7	225 ± 2.3

III. NATURE OF THE NEUTRON PRODUCERS

Since neutrons are produced in the atmosphere, it is reasonable to expect that neutron production takes place also in condensed materials, hence experiments in which proper absorbers are put around a neutron detector can supply information about the mechanism of local production of neutrons.

With the aim of studying the origin of neutrons, a group of experiments have been performed at Echo Lake (3260-m altitude). The six arrangements of absorbers surrounding the neutron detector, drawn in Fig. 2, have been used. Arrangement I is the naked detector as it was shown in Fig. 1. The nature and the thickness of the absorbers are indicated in the drawings. The lead absorbers Σ and Σ' in arrangements II, IV, V, and VI were put on top and on four sides of the detector. The extra paraffin B in arrangements III, IV, V, and VI shielded the detector on all six sides.

The numbers given at the right side of the sketch of each arrangement are the neutron rates recorded per hour (Cd-background subtracted). The statistical errors are not given as they are smaller than 1 percent, while changes in the barometric pressure surely caused a larger uncertainty. We think that the errors that should be attributed to our data are smaller than 10 percent.

From our results the following qualitative conclusions can be derived:

(a) The large increase in the counting rates when the arrangement is varied from I to II, as well as from III to IV; hence, whenever lead is put in the vicinity of the detector, shows that a strong local production of neutrons of moderate energies occurs in lead. This means that a radiation is present capable of producing neutrons.

(b) The comparison of the difference (II–I) = 6440 with the difference (V–III) = 430 shows that the great majority of the neutrons produced in lead cannot cross 30–40 cm paraffin; hence

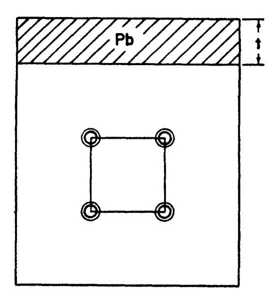

FIG. 3. Arrangement used to study the transition curve air-lead for the neutron producing radiation. The area of the lead was 45×50 cm^2. The thickness t was varied from 0 to 6 in. Pb.

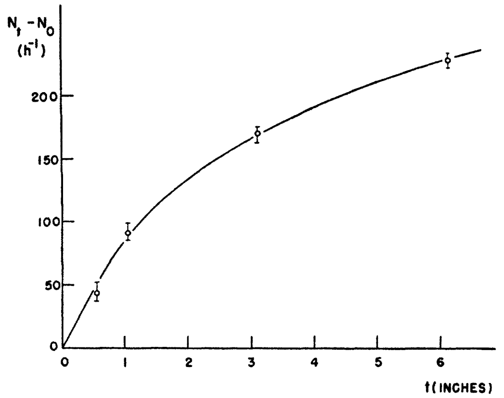

FIG. 4. Transition curve air-lead for the neutron producing radiation.

indicates that the energies of the neutrons locally produced are, on the average, smaller than 10–20 Mev.

(c) Deduction (b) implies that the mean contribution to rate VI is due to neutrons generated in the lead Σ, not in Σ'. Now, the comparison of rates IV and VI indicates that the addition of layer Σ' (7.5 cm Pb on top, 5 cm on the sides) to arrangement IV does not cause a reduction in the rates, but actually a small increase. To justify such an increase one may think that a small fraction of the neutrons produced in Σ' reaches the counters and/or that the neutron producing radiation undergoes a multiplication in lead: both effects could mask the absorption of the neutron primaries. Anyhow this result rules out the possibility that the neutron producing radiation is strongly absorbed in lead.

As pointed out in Section I, nucleonic particles, π- and μ-mesons and photons can be thought capable of producing neutrons. On the basis of the results given above we think that photons are ruled out as substantial contributors to neutron production. The layer Σ', in fact, is equivalent to $\sim$15 radiation lengths and would produce a reduction in the intensity of the photon component probably greater than 90 percent.

It is interesting to note that the same behavior observed in the series of measurements reported in Fig. 2 has been found when the same six arrangements of absorbers have been used to study the origin of neutrons coherent with extensive air showers (see paper I). In the extensive showers, electrons and photons represent more than 99 percent of the radiation present, while in the total incoherent radiation at 3260 m elevation electrons and photons are less than 70 percent of the total radiation. Furthermore, the average energy of the soft component is larger in the extensive showers than in the incoherent radiation. Then, the fact that the

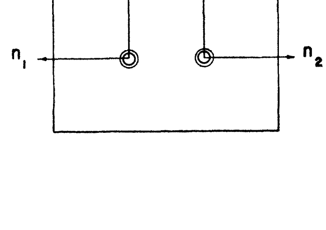

FIG. 5. Arrangement of the neutron detector used to study the multiplicity of neutron production. Pulses n_1 and n_2 were fed into two identical amplifier-discriminator channels.

same absorbers affect in the same manner neutrons both incoherent and coherent with extensive showers supports the deduction that the soft component of the cosmic radiation does not contribute substantially to neutron production. This conclusion is consistent also with the fact that stars (in which neutrons are surely emitted besides the ionizing heavy particles observed) appear to be hardly ever correlated with occurrence of a cascade shower,[4,5] as well as with the fact that neutrons are also produced in penetrating showers[6] where the originating particles are known not to be photons.

An attempt at quantitative interpretation of the data given in Fig. 2 has been made by using the method of analysis developed by Levinger.[7] The hypothesis that this procedure requires and the limitations it possesses are indicated in Levinger's paper to which we refer the reader for details.

The results obtained are the following ones:

Transmission of the neutrons through 25 cm paraffin $=0.045$,
Transmission of neutron producers through 25 cm paraffin $=1.02$,
Transmission of neutron producers through 7.5 cm Pb $=0.997$,
Counting rate due to neutrons produced in 1 cm paraffin $=45.7\ h^{-1}$,
Counting rate due to neutrons produced in 1 cm lead $=1285\ h^{-1}$,
Counting rate due to neutrons present in the atmosphere or produced in materials outside the paraffin-lead arrangement $=3229\ h^{-1}$ (with arrangement I).

These results are in agreement with the deductions derived before from the qualitative discussion of the data. The fact that the transmissions through both 25 cm paraffin and 7.5 cm Pb are close to unity for neutron producers confirms that this radiation behaves differently from electrons and photons.

The low value of the transmission of the neutrons through 25 cm paraffin confirms that the neutrons recorded are of moderate energies, roughly 3 Mev, on the average. It is interesting to note that the same transmission has been found at the same altitude for neutrons coherent with extensive showers.[7]

The analysis shows that production of moderate energy neutrons occurs not only in lead but also in paraffin. Roughly $\frac{1}{3}$ of the rate recorded with the naked detector (arrangement I) is due to neutrons locally generated in the paraffin, while about $\frac{2}{3}$ of that rate is due to neutrons entering the detector from the outside, produced in the atmosphere and in materials surrounding the detector.

In order to check and increase the information derived from the measurements taken at Echo Lake, a further experiment has been performed at Ithaca, intended to study the air-lead transition curve for the neutron producing radiation.

Data have been taken with different thicknesses t of lead covering the top of the neutron detector (see

[4] W. E. Hazen, Phys. Rev. **65**, 67 (1944).
[5] W. M. Powell, Phys. Rev. **69**, 385 (1946).
[6] Cocconi, Cocconi-Tongiorgi, and Greisen, Phys. Rev. **74**, 1867 (1948).
[7] J. Levinger, Phys. Rev. **75**, 1540 (1949).

Fig. 3). The neutron rates recorded per hour, N_t, corrected both for Cd-background and for barometric effect (see Section VIII), are reported in Table I.

The differences N_t-N_0 (rate with absorber t *minus* rate with no absorber) are also given in the table and plotted in Fig. 4. Besides confirming the occurrence of neutron production in lead, the graph of Fig. 4 indicates that the mean free path in lead, λ_{Pb}, of the neutron producers must be larger than $\sim$100 g/cm^2. This experiment, however, can give only a lower limit of such a mean free path, as scattering, absorption in lead of neutrons both present in the air and locally produced, as well as variation with the thickness t of the mean distance of the point in which the neutrons originate from the detector cause an apparent decrease of λ_{Pb}. In our opinion these effects cannot change the order of magnitude of the mean free path; however, they can easily make it appear too low by a factor two or three.

The behavior of the curve in Fig. 4 is consistent with the deduction derived from the experiments made at Echo Lake, i.e., that photons do not play an important role in neutron production; in fact, the large increase in the counting rate when the lead is increased from 7.5 to 15 cm is hardly understandable if the contribution due to photo-nuclear reactions is substantial.

On the basis of the results so far reported, there is no ground for ruling out that a considerable fraction of the neutrons recorded under lead arise from processes induced by μ-mesons. However, the order of magnitude of the contribution due to capture in lead of negative μ-mesons can be estimated and put in comparison with the data plotted in Fig. 4. We shall calculate the number of neutrons expected to be produced by μ-mesons in the lead absorber when the thickness t is 1-in. Pb. Let $N_0 \cos^n\theta$ ster^{-1} sec^{-1} g^{-1} be the number of negative slow μ-mesons stopped in one gram of air at sea level per time unit, arriving in unit solid angle, with zenith angle θ. Then the number N of negative μ-mesons stopped for time unit, in the thickness t of a lead absorber whose surface is S, is:

$$N=2\pi(S\cdot t\cdot \rho/n+1)(N_0/\alpha)\ \text{sec}^{-1},$$

where ρ is the density of the lead and α is the relative stopping power of air and lead.

With $N_0=2\times10^{-6}$ g^{-1} sec^{-1} ster^{-1},[2] $n=3.3$,[8] $\alpha=1.7$,[9] $t=2.5$ cm, $S=2250$ cm^2 and $\rho=11.2$ g/cm^3, one has: $N=0.11$ sec^{-1}. If 0.03 is the over-all efficiency of the neutron detector and 0.5 the probability that a neutron produced in the lead enters the detector, one gets that the effective neutron rate to be expected is 5.8 ν neutrons/h, where ν is the average number of neutrons produced in one act by the meson. This estimate is an upper limit, as the losses of neutrons due to the geometry and to the scattering make the probability that a neutron produced in the absorber enters the detector surely smaller than 0.5.

[8] W. Kraushaar (unpublished result).
[9] G. C. Wick, Nuovo Cimento 1, 310 (1943).

TABLE II. Rates (h^{-1}) corrected for Cd-background of the neutron coincidences n_1+n_2 and average n of the rates n_1 and n_2 for arrangements III and IV.

	n (h^{-1})	n_1+n_2 (h^{-1})
Arr. III	1250	2.39
Arr. IV	5100	36.0

The figure obtained above must be compared with 92 h^{-1} neutrons actually recorded for the difference $N_{2.5}-N_0$. No satisfactory determination of ν has been made so far. The experimental evidence and the theoretical expectation, however, agree in indicating that ν is of the order of a few units. We think, therefore, that at sea level no more than 10–15 percent of the rates recorded can be accounted for by neutrons produced in capture of negative μ-mesons. If this is the case at sea level, at higher elevations the relative importance of the contribution due to μ-mesons is, of course, strongly reduced, as neutrons increase with altitude much faster than μ-mesons (see Section VII).

No appreciable contribution due to neutrons arising from μ-mesons capture has to be expected in light materials like paraffin and graphite.

IV. NEUTRON PRODUCTION IN DIFFERENT MATERIALS

The analysis of the experiments performed at Echo Lake, reported in Section III, indicates that local production of moderate energy neutrons occurs in lead as well as in paraffin.

In the course of those experiments a test measurement was made to confirm the occurrence of neutron production in materials of low atomic number.

In arrangement IV of Fig. 2 the 2-in. Pb constituting the absorber has been substituted with 2-in. graphite.

The difference between the rate recorded (corrected for Cd-background) and rate III in Fig. 2 is 430 h^{-1}. It essentially represents the neutron production in the graphite absorber. This number can be compared with the neutron production in lead, namely with the difference (IV–III) = 6400 h^{-1} (see Fig. 2), provided that a 25 percent increase is made of the production in graphite to take into account the fact that the surface of the detector covered with graphite was 25 percent smaller than that covered with lead. With this cor-

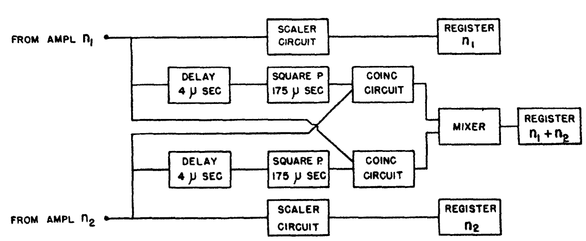

FIG. 6. Circuit used to study the multiplicity of neutron production. Pulses n_1, n_2 and coincidences n_1+n_2 were recorded.

TABLE III. Neutron rates (h^{-1}) corrected for Cd-background recorded in arrangements I, II, III and IV at Ithaca (260 m), Echo Lake (3260 m) and Mt. Evans (4300 m).

	I (h^{-1})	II (h^{-1})	III (h^{-1})	IV (h^{-1})	IV–III (h^{-1})
Ithaca	520	1230	285	1190	805
Echo Lake	4600	11040	2020	8500	6480
Mt. Evans	12510	25000	4780	20630	15850

rection, the rates of production in graphite and lead are respectively 108 h^{-1} cm^{-1} and 1296 h^{-1} cm^{-1}.

These figures agree very satisfactorily with the estimates made through the quantitative analysis of the data in Section III, which gave 1285 h^{-1} cm^{-1} neutrons produced in lead and 45.7 h^{-1} cm^{-1} neutrons produced in paraffin. With the assumption that the neutron production in paraffin is all due to the C-nuclei, the last figure corresponds to a neutron production in graphite$=45.7\times 1.7/0.76=102$ h^{-1} cm^{-1}. Our results indicate a ratio ~ 2 between the production per gram in lead and carbon. However, one has to keep in mind that our detector was sensitive only to neutrons in a finite energy range, hence that the comparison between production in different materials requires assumption of constant energy spectrum of the neutron produced from different nuclei.

Recently Tobey[10] reported an experiment designed to measure the absolute rates of neutron production per gram of different materials. His detector can be considered as energy independent. The rates of neutron production obtained at sea level are: 6×10^{-5} neutron sec^{-1} g^{-1} in lead and 2.3×10^{-5} neutron sec^{-1} g^{-1} in carbon. This indicates a ratio neutron production in lead/neutron production in carbon ≈ 2.6, which is in fair agreement with our result.

Our experiments were not designed to supply information about the *absolute* intensity of the neutron production. However, an order of magnitude estimate can be made from the data recorded at sea level for the transition curve given in Fig. 4, Section III. If one assumes that the neutron production is isotropic, then a recorded rate N_t-N_0 indicates a neutron production per gram of lead per sec equal to:

$$(N_t-N_0)\cdot 1/M\cdot 1/\epsilon.\ 4\pi/\omega,$$

where ω is the solid angle subtended by the paraffin at the detector, ϵ the over-all efficiency of the detector and M the mass of the lead absorber.

With $N_t-N_0=N_{2.5}-N_0=92$ neutron $h^{-1}=2.57\times 10^{-2}$ neutron sec^{-1} (see Table I), $M=2.5\times 2250\times 11.2$ g $=6.3\times 10^4$ g, $\epsilon=0.03$, $\omega/4\pi=0.3$, one finds that the neutron production in lead is 4.5×10^{-5} sec^{-1} g^{-1}. This is slightly smaller than Tobey's figure, which is to be expected owing to the finite range of neutron energies to which our detector was sensitive.

The agreement is therefore satisfactory.

[10] A. R. Tobey, Phys. Rev. **75**, 894 (1949).

V. MULTIPLICITY OF THE NEUTRON PRODUCTION

For the interpretation of the data on neutron production in different materials, it is essential to know whether neutrons are produced mostly singly or in multiples, and, in the second case, how the multiplicity of neutron production depends upon the material in which such a production takes place.

Some evidence in favor of multiple neutron production has been obtained by Korff and Hamermesh.[11] However, the geometry of their experiment is such that it does not allow quantitative interpretation of the results.

At 3260 m an experiment has been performed to get information about the multiplicity of neutron production. We shall call multiplicity, ν, the average number of neutrons simultaneously produced with energies lying in the energy range to which our detector is sensitive.

The four counters inside the detector have been connected in two groups of two counters each, as shown in Fig. 5. Their pulses, n_1 and n_2, amplified and discriminated through two identical channels, were fed into the coincidence circuit schematically drawn in Fig. 6. The delays of 4-μsec were introduced to reduce the background due to spurious phenomena. The resolving time was 175-μ sec. Coincidences n_1+n_2 as well as pulses n_1 and n_2 were recorded.

Paraffin and lead absorbers have been put around the detector as in the arrangements III and IV in Fig. 2.

The results are given in Table II. The rates n are the averages of the counts recorded for n_1 and n_2, corrected for Cd-background. Coincidences n_1+n_2 are corrected for chance events, which constitute 13 percent of the rates recorded in arrangement III and 3 percent of the rates recorded in arrangement IV. The ratio $(n_1+n_2)/n$ gives the probability that a neutron occurs within 4 and 179-μsec after the occurrence of a first neutron. With the assumption that the neutrons emitted from a nucleus are isotropically distributed, one may write:

$$(n_1+n_2)/n=1-e^{-(\nu-1)\epsilon'\cdot\omega/4\pi},$$

where ω is the solid angle subtended by the detector at the absorber. The efficiency has been estimated by assuming that the system (paraffin+2 counters) has over-all efficiency $\frac{1}{2}$ of the system (paraffin+4 counters) used in the other experiments, and that the loss of neutrons due to the delay introduced in the circuit and to the finite duration of the coincidence pulse causes a further reduction in the efficiency by a factor ≈ 0.7. Hence $\epsilon'=\frac{1}{2}\times 0.03\times 0.7\approx 0.01$.

In order to deal only with neutrons locally produced in the lead, we shall consider the differences between the rates recorded in arrangements IV and III. With

[11] S. Korff and B. Hamermesh, Phys. Rev. **70**, 429 (1946).

the assumption $\omega/4\pi=0.3$ we have:

$$83.6/3850=1-e^{-(\nu-1)\times 0.01\times 0.3}$$

and then $\nu\approx 8$. This means that, on the average, eight neutrons of energies between 2 and 15 Mev are produced simultaneously in lead by a *single* neutron producer. In fact, the possibility that two or more incoherent neutron producers fall by chance simultaneously on the lead is taken into account by the correction of the rates n_1+n_2 for chance events. The possibility that a "shower" of neutron producers falls on the detecting system is, of course, not ruled out, but it is reasonable to assume that the frequency of such an event is small enough as to make its effect negligible.

It is interesting to note that an analogous experiment on the neutrons coherent with extensive showers, performed at the same altitude, with the same apparatus (actually the two sets of data have been taken simultaneously) yielded ≈ 60 as the average multiplicity of the neutron production in lead (see paper I). A very high multiplicity in lead has been found also for neutrons produced in association with penetrating showers.[6]

The considerably smaller figure obtained for incoherent neutrons can probably be accounted for by an average energy of the neutron producers smaller in the incoherent radiation than in the showers, as well as by different relative intensities of the processes in competition in neutron production.

The multiplicity observed for incoherent neutrons suggests that most of these neutrons arise from stars of the same average size as observed in cloud chambers and in photographic plates.

From the data taken with arrangement III one deduces that the multiplicity of the neutron production in paraffin, and hence also in carbon, is close to unity ($\nu\approx 1.6$). The same result had been obtained from the data concerning neutrons coherent with extensive showers. These results on the multiplicity of neutron production in different materials must be considered as first approximation ones. It would be desirable to determine how the multiplicity depends upon the thickness of the absorber in which the neutron production takes place.

VI. CROSS SECTION FOR NEUTRON PRODUCTION

The estimate made in Section III of the mean free path in lead of the neutron producers, as well as the results concerning the absorption mean free path in air that will be given in Sections VII and VIII agree in indicating that the cross section for neutron production is of the order of magnitude of the geometrical cross section of nuclei. This leads to expect that the cross sections σ for neutron production is proportional to the $\frac{2}{3}$ power of the mass number A of the nuclei.

The information about the average multiplicity of the neutron production in lead and carbon obtained in Section V allows a check of whether or not such an assumption is consistent with the experimental results. In fact, if $\sigma\sim A^{\frac{2}{3}}$, the observed rate of production of neutrons under a given thickness of material, n_{obs}, must be proportional to: $(\rho/A)\cdot A^{\frac{2}{3}}\cdot\nu$ where ρ is the density of the material and ν the multiplicity of neutron production in it. Therefore, one must have

$$\frac{n_{\text{obs}}\cdot A^{\frac{1}{3}}}{\rho\nu}=K=\text{const. in different materials.}$$

With the figures obtained in Section IV for the neutron production in Pb and in C ($n_{\text{obs}}=1290\ h^{-1}\ \text{cm}^{-1}$ in Pb and $n_{\text{obs}}=105\ h^{-1}\ \text{cm}^{-1}$ in C) and in Section V for the multiplicity ($\nu=8$ in Pb and $\nu=1.6$ in C), one obtains for Pb $K=86.4$ and for C $K=88.5$. This result strongly supports the assumption that the $A^{-\frac{1}{3}}$ law holds for neutron production in different materials.

As the same law has been found to hold for production of stars,[12–14] the hypothesis that stars are the source of the great majority of the neutrons observed receives further strength.

VII. ALTITUDE VARIATION OF THE NEUTRON PRODUCERS

Measurements with the neutron detector surrounded by absorbers as in arrangements I, II, III, and IV of Fig. 2 have been taken at three different altitudes above sea level, namely at Ithaca (260 m; 1007 g/cm^2), at Echo Lake (3260 m; 708 g/cm^2) and at Mt. Evans (4300 m; 616 g/cm^2). The recorded rates (h^{-1}) corrected for Cd-background are given in Table III.

The errors in these data are smaller than 10 percent.

As shown in Section III, the rates recorded with arrangement I result from a contribution due to

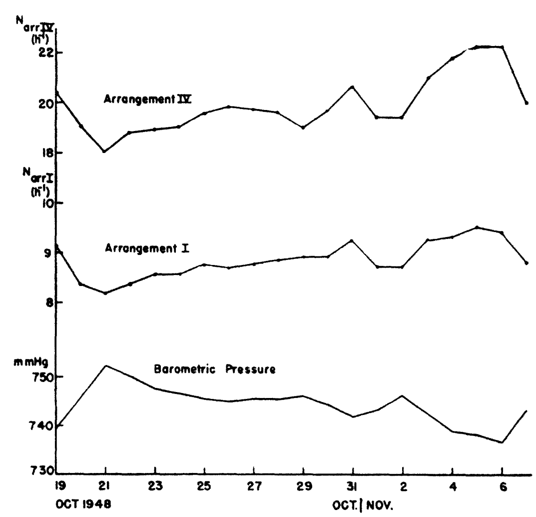

FIG. 7. Example of the correlation observed between neutron rates and barometric pressure.

[12] D. H. Perkins, Nature **160**, 707 (1947).
[13] G. Bernardini, Phys. Rev. **74**, 845 (1948).
[14] E. P. George and A. C. Jason, Proc. Phys. Soc. **A62**, 243 (1949).

neutrons produced in the paraffin and a contribution due to neutrons produced outside the detector, both in the atmosphere and in the surrounding materials. As the effect of the surroundings cannot be maintained the same in different stations we do not attribute great significance to comparison of data taken in different stations with arrangements I and II. This is not the case for arrangements III and IV in which the large thickness of paraffin made the detector practically insensitive to the effect of the surroundings. We shall consider the differences between the rates IV and III, reported in the last column of the table, which refer essentially to neutrons produced in the lead Σ. If one assumes that the efficiency for detection of neutrons is the same at all stations (which implies constant average multiplicity in the neutron production, as well as constant energy distribution of the neutrons produced), then the altitude variation of the difference IV–III is proportional to the altitude variation of the neutron producing radiation interacting with the absorber Σ. The rates (IV–III) vary by a factor 19.7 from Ithaca to Mt. Evans. If the absorption in air of the neutron producers is described by the law $I(x)=I_0e^{-x/\lambda}$, this result indicates for such a radiation an absorption mean free path $\lambda=132\pm15$ g/cm^2. This value is in good agreement with the mean free path observed for slow neutrons, stars, bursts, and penetrating showers.

This strong altitude variation of the neutron producers rules out conclusively the possibility that μ-mesons contribute substantially to the neutron production observed, which is consistent with the estimate made in Section III.

VIII. BAROMETRIC EFFECT OF NEUTRON PRODUCERS

The mean free path in air of the neutron producing radiation can be determined also by measuring its barometric effect.

The barometric effect of the rates recorded both in arrangement I and in arrangement IV has been studied at Ithaca during the winter of 1949, over a period of ten weeks.*

A very definite and strong correlation between the fluctuations in the rates recorded and the variations of the barometric pressure has been observed, as shown by the example given in Fig. 7.

By following the method indicated by Janossy and Rochester[15] we have obtained the barometric coefficients α given below, which are the averages of five partial calculations, each covering a period of two weeks:

$$\alpha_{\text{arr IV}}=-(11.2\pm0.6) \text{ percent per cm Hg},$$
$$\alpha_{\text{arr I}}=-(10.6\pm0.6) \text{ percent per cm Hg}.$$

The dependence on the barometric pressure of the Cd-background can be disregarded as the Cd-background is only 3 percent of the rates recorded without Cd.

Consider first the results obtained with arrangement IV. As indicated by the comparison between the rates III and IV in Table III, Section VII, ~75 percent of the rates recorded with arrangement IV are due to neutrons produced in the lead, while the remaining 25 percent are mostly due to neutrons generated in the paraffin. It is reasonable to expect that both the neutrons produced in lead and the neutrons produced in paraffin have the same barometric effect. This has been checked over a period of two weeks by removing the lead, hence recording the rates in arrangement III. We found $\alpha_{\text{arr III}}=\alpha_{\text{arr IV}}$ within the errors.

We are, therefore, led to conclude that the barometric coefficient obtained with arrangement IV, $\alpha_{\text{arr IV}}=-11.2$ percent per cm Hg, represents the barometric effect of the radiation that causes the local neutron production observed.

The corresponding mean free path in air is then $\lambda=13.59/11.2=121\pm7$ g/cm^2, which is in agreement with the result obtained in Section VI from the experiments at different altitudes.

We want to recall that roughly the same barometric coefficient, actually $\alpha=-(11.7\pm2.7)$ percent per cm Hg has been found by Janossy and Rochester[15] for the radiation that produces penetrating showers. This is interesting both because penetrating showers are thought to be phenomena initiated by nucleonic radiation and because penetrating showers are known to be one of the sources of moderate energy neutrons.[6]

The interpretation of the barometric coefficient obtained for neutrons recorded with arrangement I is more uncertain. As pointed out in Section III, the rates recorded with the naked detector are due both to neutrons produced locally and to neutrons produced in the atmosphere, the two contributions being of the same order of magnitude. If one assumes that the radiation which produces neutrons locally in any material has barometric coefficient $\alpha=-11.2$ percent per cm Hg, the fact that we obtained $\alpha_{\text{arr I}}=\alpha_{\text{arr IV}}$ inside the errors, leads one to think that also the neutrons present in the atmosphere have a barometric effect of the same order of magnitude. This supports the hypothesis, which is, however, quite reasonable, that neutrons in the atmosphere are produced mostly through the same processes as those that cause the local neutron production.

IX. INTENSITY OF THE NEUTRON PRODUCING RADIATION

From our data a tentative estimate can be derived of the intensity of the neutron producing radiation at different altitudes.

Consider again the arrangement drawn in Fig. 3 and the result reported in Fig. 4 for the neutron production

* We thank Mrs. Mildred Shapiro for help in performing this experiment.

[15] L. Janossy and G. D. Rochester, Proc. Roy. Soc. 183, 186 (1944).

in 1-in. Pb at 260-m elevation, namely $N_t - N_0 = 92$ neutrons h^{-1}. If N neutrons per time unit are recorded, generated with average multiplicity ν in a thickness x of an absorber in which the mean free path of the neutron producers for neutron production is λ, then the number of neutron producers falling per time unit on the surfaces S of the absorber is

$$\mathfrak{N} = N \cdot \frac{1}{(1-e^{-\nu\epsilon\cdot\omega/4\pi})} \cdot \frac{1}{(1-e^{-x/\lambda})}$$

where ω has here the same meaning as in Section V.

The information about the mean free path in lead for production of neutrons is meager. The transition curve reported in Section III sets a lower limit at $\lambda = 100$ g/cm^2 for total absorption mean free path in lead of the neutron producers. The discussion developed in Section V indicates that the cross section for neutron production in different materials is likely proportional to $A^{\frac{2}{3}}$, hence that the corresponding mean free paths obey the $A^{\frac{1}{3}}$ law. Several experiments[12–14] indicate that the mean free path of the star producing radiation is $\sim$150 g/cm^2 in air and $\sim$300 g/cm^2 in Pb, which is consistent with the $A^{\frac{1}{3}}$ law.

As a tentative assumption we shall use in our calculation $\lambda = 300$ g/cm^{-2}. This is likely correct within a factor 1.5. By substituting in the formula written above $\nu = 8$, $\epsilon = 0.03$, $\omega = 0.3$, $x = 1$-in., Pb $= 28$ g/cm^2 and $N = 92/3600$ sec^{-1}, one has $\mathfrak{N} = 4$ sec^{-1}. At the same altitude, $\sim$78 ionizing particles belonging to the total cosmic radiation fall in a second on the same surface ($S = 2250$ cm^2). This indicates, therefore, a ratio neutron producers/total ionizing cosmic radiation close to 0.05 at 260-m altitude.

By using the absorption mean free path in air of the neutron producers obtained in Section VII, $\lambda = 130$ g/cm^2, one finds that the intensity of the neutron producers falling on the same surface is

at 3260 m	$\mathfrak{N} = 40$ sec^{-1}
at 4300 m	$\mathfrak{N} = 76$ sec^{-1}.

At those altitudes the ionizing particles of the total cosmic radiation falling on the surface S are respectively 148 and 175 sec^{-1}. Then, the ratio neutron producers/total ionizing radiation is close to 0.2 at 3260 m and to 0.4 at 4300 m.

As our neutron detector is sensitive only to neutrons in a finite energy range, these figures surely err on the low side. Furthermore, because of the uncertainties involved in the calculations they can easily be wrong by a factor two in either direction.

Yet, these estimates can supply further information about the nature of the neutron producing radiation. From our previous discussion, we have reached the conclusion that both photons and μ-mesons are ruled out as substantial contributors to neutron production. This left us with σ-mesons, fast neutrons and protons.

Several estimates of the proton intensity in the cosmic radiation[2] indicate that protons at sea level are of the order of 0.1 percent of the total radiation and at altitudes of 3000–4000 m of the order of a few percent.

As for σ-mesons, only very scanty data are available, but it is believed that their intensity is negligible at sea level and at altitudes of 3000–4000 m it is still rather small compared with the total ionizing cosmic radiation. Hence, the result that the intensity of neutron producers at mountain altitudes is of the same order of magnitude as that of the total radiation, leads one to conclude that the neutron producers are predominantly fast neutrons.

It is important to recall that from the analysis of stars in photographic plates and in cloud chamber pictures the conclusion has been reached that also the star primaries are mostly fast neutrons.

Estimates of the ratio star primaries/total ionizing rays can be derived from cloud-chamber and photographic plate data. The comparison with our results is of great interest.

Powell,[5] by comparing the number of stars and penetrating particles simultaneously observed in cloud-chamber pictures obtained at Mt. Evans, deduced that the star primaries are at 4300-m altitude seven times more frequent than penetrating particles, hence roughly three times more abundant than the total ionizing cosmic rays. This figure is likely too high owing to the restrictive criterion used by the author to select penetrating particles (no secondaries produced in two or more lead plates 1-cm thick).

On the other hand, in Powell's estimate a mean free path in lead for star production of $\sim$110 g/cm^2 has been used. If we introduce the same mean free path $\lambda = 300$ g/cm^2 as used in our calculations, the ratio star primaries/total radiation becomes $\sim$3 times higher.

Furthermore, in any estimate based on cloud-chamber observations, a difficulty arises from the fact that the sensitive time of the apparatus is somewhat bigger for stars than for the thin tracks of penetrating particles. In Powell's estimate the effect of sensitive time has not been taken into account. We think that a correction must be made for it, and that a reduction by a factor two or so for the ratio in question is probably reasonable. Hence, we think that Powell's data, with the assumptions and the corrections indicated, lead to a ratio star primaries/total radiation at 4300-m altitude close to two.

The cloud-chamber pictures taken by Hazen[4] at Echo Lake can be analyzed in the same way.

With the same assumptions as indicated above, one gets a ratio star primaries/total radiation at 3260 m close to $\sim$0.6. This estimate is based on the observation of 58 stars emerging from the lead plates while *two* stars originate in the gas. The uncertainty in this estimate is consequently very high. Powell's data, based on observation of 156 stars from the lead and 13 originating in the gas are statistically more significant.

TABLE IV. Ratios neutron primaries/total ionizing radiation and star primaries/total ionizing radiation as estimated by various authors at different elevations above sea level.

Neutron primaries/total radiation		Star primaries/total radiation		
260 m	0.05	sea level	0.06	(George)
3260 m	0.20	3260 m	0.60	(Hazen)
		3750 m	0.20	(George)
4300 m	0.40	4300 m	$\sim$2	(Powell)

Both these estimates refer to stars in which several ionizing particles are present. In fact, two or more prongs are observed to emerge from the lead, which corresponds to an average number of ionizing particles generated in the stars likely higher than five.

Recently George and Jason[14] have estimated that the radiation (likely fast neutrons) which produces in photographic plates stars with 3 or more prongs is about 0.20 times the total ionizing radiation at 3750-m elevation (Jungfraujoch) and about 0.06 at sea level. As the authors pointed out, this figure errs on the low side, due to stars consisting of particles with energies above the limit of detectability in the emulsion.

The estimates derived from our experiments, as well as the estimates derived from cloud-chamber and photographic plate data are summarized in Table IV. The large uncertainties involved both in the experimental data and in the calculations do not allow one to look in these estimates for more than first approximation information. It is remarkable and satisfactory indeed that these estimates based on such different kinds of experiments and methods of evaluation agree as to the order of magnitude. This gives another strong argument in favor of the conclusion that most of the neutrons of moderate energies observed to be produced in lead are originated in stars induced by fast neutrons.

Furthermore, BF_3 counters, cloud-chamber and photographic plate data agree in indicating that the intensity of the fast neutrons present at an altitude of $\sim$4000 m above sea level is of the same order of magnitude as the intensity of the total ionizing cosmic radiation.

X. CONCLUSIONS

The general picture given in Section I to justify the presence of neutrons in the cosmic radiation is consistent with all the results obtained in our experiments, hence it receives from them a direct confirmation.

On the basis of the results reported in Sections III, IV, V, VI, VII, VIII and IX the following details can be added to it:

(1) Though it is experimentally proved that high energy processes like penetrating showers do contribute to generation of moderate energy neutrons, the great majority of the neutrons of moderate energies produced in absorbers surrounding a detector are originated in less energetic phenomena (stars).

(2) The radiation that causes production of moderate energy neutrons does not consist substantially of photons or of μ-mesons; neither can σ-mesons nor protons give rise to a considerable fraction of the neutrons observed. Hence, fast neutrons are the particles that contribute mostly to the production of moderate energy neutrons.

(3) The radiation capable of producing moderate energy neutrons is, at mountain elevations, roughly as abundant as the total of ionizing particles constituting the cosmic radiation.

(4) Its altitude variation is described by an absorption mean free path in air of 120–130 g/cm^2, which is confirmed by the fact that it shows a barometric coefficient $\alpha = -11$ percent per cm Hg.

(5) In each process of neutron production in lead, on the average, roughly eight neutrons with moderate energies are simultaneously produced. In carbon the multiplicity of neutron production is close to unity. The average energy of the neutrons produced in lead is close to 3 Mev.

(6) The rates of neutron production observed in different material are satisfactorily described with the assumption that the cross section for neutron production is proportional to the $\frac{2}{3}$ power of the mass number of the material.

Note added in proof.—Recently, measurements have been performed with the equipment located at Ithaca, in a tunnel underground, at a depth equivalent to 2000 g/cm^2 water. The neutron detector was surrounded with paraffin and lead as in the arrangements III and IV of Fig. 2. The difference (III−IV) corrected for Cd-background was found to be $16.4h^{-1}$. Hence the intensity of the local production of neutrons in Pb at that depth is about 50 times smaller than that at the level of the ground (260-m elevation). With the assumption that the neutrons observed are produced only by fast nucleons, whose mean free path in the rock is 150–200 g/cm^2, one should expect that the neutron intensity is reduced by a factor larger than 10^4. Our result, therefore, shows that radiations different from nucleons, likely μ-mesons or their secondaries, contribute to neutron production. As the meson intensity at such a depth is reduced by a factor 4, one deduces that at the level of the ground the contribution to the neutron production due to μ-mesons is smaller than 10 percent of the effect observed. This is in agreement with the conclusion reached in Section III.