experimental errors. However, any additional states contributing to the scattering would add to the total cross section. The angular distributions are qualitatively different from a pure $P_{\frac{3}{2}}$ state $(1+3\cos^2\theta)$. In fact, if one assumes α_{33} near 90°, then, independent of any normalization, the angular distribution at 188 Mev would imply an even-wave contribution of at least 40 mb.[28] Thus the total cross section would have to be larger than 240 mb. No such argument may be made against a possible α_{31} resonance. The experimental momentum dependence of the α_{33} phase shift suggests a leveling-off although an extrapolation to 90° at about 230 Mev is possible.

[28] This is obtained by forming the ratio $[\sigma(0°)+\sigma(180°)]/2[\sigma(90°)]$ as $\alpha_{33}\to 90°$. For the 188-Mev case, this is 2.1 ± 1.0 and implies $\sin^2\alpha_3>0.5$ or $\sigma_T>2.5(4\pi\lambda\!\!\!^{-2})$.

TABLE V. Phase-shift solutions.

Lab. energy Mev	Phase shifts	M
151	$\alpha_3=-30°$, $\alpha_{31}=8°$, $\alpha_{33}=45°$	12
188	$\alpha_3=-35°$, $\alpha_{31}=+0°$, $\alpha_{33}=55°$	15
Combined $\bar{E}=168$	$\alpha_3=-40°$, $\alpha_{31}=12°$, $\alpha_{33}=40°$	10
$\bar{E}=168$ and D waves	$\alpha_3=-23°$, $\alpha_{31}=-8°$, $\alpha_{33}=50°$ $d_{53}=-5.4°$	4.5

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Neutron Production by Cosmic Rays*

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An experimental study has been made of the production of neutrons in the nuclear interactions of cosmic rays. An apparatus selected events in which a nuclear interaction occurred in or near a liquid scintillation counter, with the production not only of ionizing particles but also of neutrons of a few Mev energy which were slowed to thermal energy in a paraffin moderator and detected by BF_3-filled proportional counters. Such coincidences are termed (s,n), $(s,2n)$, and so on, according to the number of *detected* neutrons. The average number, $\bar{\nu}$, of neutrons *produced* per disintegration was calculated from the observed relative numbers of (s,n) and $(s,2n)$ coincidences.

These data were obtained at Climax, Colorado, at an altitude of 11 200 ft. Analysis shows that events of the type selected in this experiment account for the production of 3×10^{-4} neutrons g^{-1} sec^{-1}, a figure which is close to the total neutron-production rate in carbon as previously measured at the same location. In these events, it is concluded that $\bar{\nu}=1.3\pm0.2$. Combination of this result with previously determined relative multiplicities yields the values $\bar{\nu}=2.2$ for production in aluminum and $\bar{\nu}=6$ for production in lead.

I. INTRODUCTION

EVIDENCE that neutrons are produced by cosmic rays in their interactions with matter was sought and found soon after the discovery of the neutron.[1] It is believed that the predominant neutron-production process must be the type of high-energy nuclear disintegration observed as a "star" in nuclear emulsion. The ionizing particles produced in stars are accessible to study since they leave tracks, or "prongs," in emulsion. It has been established[2] that in emulsion exposed at mountain altitude the mean number of prongs per star of one or more prongs is 2.2 and that many prongs represent protons of energy near 10 Mev. It is reasonable that neutrons of comparable energy and number should also be produced. Direct measurement of these neutrons is severely restricted by the low efficiency of all available neutron detectors, and the mean number, or "multiplicity," of neutrons produced in one act has remained quite uncertain.

A number of comparisons of the over-all rates of neutron and star production have been made. All these involve two extrapolations. First, some adjustment must be made to allow for the difference in the materials for which the neutron and star rates have been measured. Second, the star rate must be corrected for the disintegrations involving 2, 1, and 0 ionizing secondaries, which are events difficult or impossible to observe

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† U. S. Atomic Energy Commission Predoctoral Fellow.

[1] G. L. Locher, Phys. Rev. **44**, 779 (1933) and J. Franklin Inst. **224**, 555 (1937); L. H. Rumbaugh and G. L. Locher, Phys. Rev. **49**, 855 (1936); E. Schopper, Naturwiss. **25**, 557 (1937); E. M. Schopper and E. Schopper, Physik. Z. **40**, 22 (1939); E. Fünfer, Naturwiss. **25**, 235 (1937) and Z. Physik **111**, 351 (1938).

[2] P. E. Hodgson, Phil. Mag. **42**, 82 (1951); N. C. Barford and G. Davis, Proc. Roy. Soc. (London) **A214**, 225 (1952).

in emulsion. Montgomery and Tobey[3] made one of the best comparisons of this sort. They measured the neutron-production rate in several materials, deriving an empirical interpolation formula from which to estimate the production rate in emulsion. Two sets of star data were available to them for comparison. For each of these, they extrapolated the observed prong-number distributions to include zero-prong events and concluded that the neutron multiplicity in emulsion was 2.6 or 4.6. Recent star observations favor the smaller figure. Another figure has been published by Puppi and Dallaporta,[4] based on Yuan's[5] measurements of the neutron-production rate in the atmosphere. They estimate that the neutron multiplicity for production in air is 3.5.

A more direct measurement of the neutron multiplicity may be made by observing coincidences between a detector of neutrons and a detector of neutron-producing events. The present experiment is of this type. Several previous coincidence experiments have been reported in which boron detectors in a paraffin moderator have been used to detect neutrons. In all of these, however, arrays of Geiger counters have been used to select neutron-producing events. The efforts of the Washington University group[6] have been concentrated on neutron production by μ mesons. The Cornell group has studied neutron production in extensive air showers[7] and in events in which penetrating ionizing particles are produced.[8] Examination of the counting rates of all of these experiments indicates that the events selected were very infrequent compared to those selected in the present experiment so that the measured multiplicities are not characteristic of the most common neutron-producing processes. The Cornell experiments were designed to select quite high-energy events, and it was judged that the observed neutrons were in general the products of several simultaneous disintegrations; thus the multiplicity per disintegration was not determined.

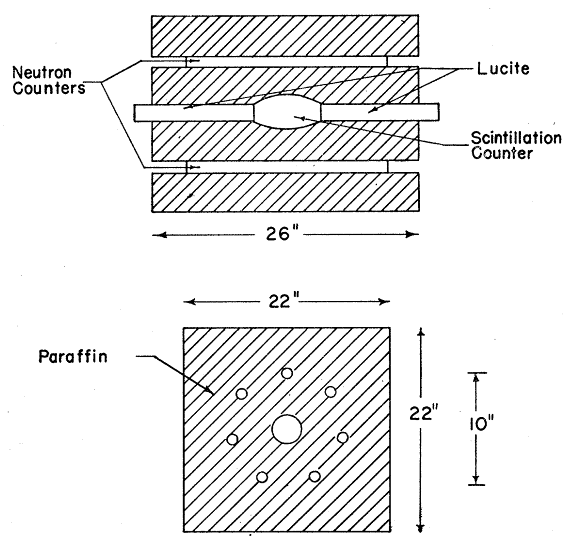

Fig. 1. Sketch of the apparatus.

The present experiment differs from previous coincidence experiments in that the most common neutron-producing events are selected, and the location of these events is specified well enough to permit knowledge of the efficiency of neutron detection. The apparatus is shown in Fig. 1. BF_3-filled proportional counters were used as neutron detectors. They were embedded in a paraffin moderator in which the neutrons would slow down from their initial energies of a few Mev to thermal energies, the range where the counters are most sensitive. A scintillation counter, consisting of 210 g of an organic liquid, was placed in the center of the moderator. A nuclear disintegration in or near this counter was detected by it if among the disintegration products there was a particle whose loss of energy by ionization in the counter exceeded 13 Mev.

Those scintillations accompanied by one or more neutron counts were selected. These coincidences will be referred to as (s,jn) events, with j standing for the number of detected neutrons. Coincidences may be attributed primarily to nuclear disintegrations in or near the scintillator. The efficiency ϵ, for detecting a neutron originating in this region, was measured with a calibrated neutron source. The multiplicity of neutron production could then be derived from the rates of (s,n) and $(s,2n)$ events.

Tongiorgi *et al.*[7] established that the extensive air showers contain neutrons and neutron-producing particles. A Geiger counter tray of sensitive area 560 cm^2 was employed to reject such showers. Since the scintillator's area was 58 cm^2, a shower of sufficient density to be detected by the scintillator would almost certainly produce a Geiger pulse. The neutron multiplicity was derived from the Geiger anticoincidence rates $(s,n,\bar{g})$ and $(s,2n,\bar{g})$.

Whenever a coincidence occurred, the scintillation pulse height and the delay time between the scintillation and the first neutron pulse were recorded. The electronic recording circuits have, for the most part, been described previously.[9] Additional circuits of conventional design were employed to note the occurrence of a second or third neutron pulse or of a Geiger pulse in prompt coincidence with a scintillation.

[3] A. R. Tobey, thesis, Yale University, 1948 (unpublished); C. G. Montgomery and A. R. Tobey, Phys. Rev. **76**, 1478 (1949); A. R. Tobey and C. G. Montgomery, Phys. Rev. **81**, 517 (1951).
[4] G. Puppi and N. Dallaporta, *Progress in Cosmic Ray Physics*, edited by J. G. Wilson (North-Holland Publishing Company, Amsterdam, 1952), p. 378.
[5] L. C. L. Yuan, Phys. Rev. **81**, 175 (1951) and **86**, 128 (1952).
[6] R. D. Sard *et al.*, Phys. Rev. **76**, 1134 (1949); A. M. Conforto and R. D. Sard, Phys. Rev. **86**, 465 (1952).
[7] V. Tongiorgi, Nuovo cimento **5**, 101, 391 (1948); Phys. Rev. **73**, 923 (1948) and **75**, 1532 (1949).
[8] Cocconi, Tongiorgi, and Widgoff, Phys. Rev. **79**, 768 (1950).
[9] W. C. G. Ortel, Rev. Sci. Instr. (to be published).

II. APPARATUS

A. Scintillation Counter

The scintillation counter is shown in Fig. 2. The scintillating material was 210 g of a solution prepared by dissolving 1 g terphenyl and 3 mg diphenylhexatriene in $\frac{1}{3}$ l phenylcyclohexane. This liquid contains only carbon and hydrogen, being nearly identical in composition and density with paraffin. The liquid was contained in a 90 g glass cell covered with an aluminum foil reflector and a light-tight layer of tape. The photomultiplier tubes were separated from the cell by Lucite "light pipes." Since the events detected by the scintillator included disintegrations in or near it, the construction materials were chosen so that the disintegrations detected would be predominantly those of carbon nuclei. The other elements present were of quite low atomic weight and may reasonably be expected not to introduce serious error in the average neutron multiplicity.

Pulses from the two photomultipliers were added and amplified before being introduced into the coincidence circuits. For the purpose of obtaining some idea of the meaning of pulse size in terms of energy, two Geiger counters were used to select scintillations produced by ionizing particles capable of penetrating 4 in. of Pb. This amount of Pb will just be penetrated by a μ meson of energy corresponding to minimum ionization density. The arrangement of counters and the pulse-height distribution obtained are shown in Fig. 3. The pulse-height distribution expected is also shown. This was calculated with consideration of the distribution of possible path lengths through the scintillator and the distribution of possible energy losses by a minimum-ionizing particle along each path. The greater width of the observed distribution may be attributed partly to the limited energy resolution of the scintillator and partly to the possibility of spurious coincidences caused by side showers.

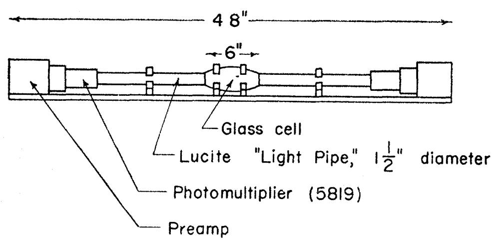

FIG. 2. Scintillator and photomultiplier assembly.

The peak of the pulse-height distribution was calculated to represent an energy loss of 8.5 Mev. All pulse-height distributions were scaled to the position of this peak. An energy value obtained in this way is not a good measure of a disintegration energy for two reasons. First, some scintillations are the result of nearby disintegrations, all of whose secondaries may not enter the counter. Second, many scintillations will be produced by heavily ionizing particles, and it is known that the light output of an organic scintillator is a function of both ionization and ionization density.

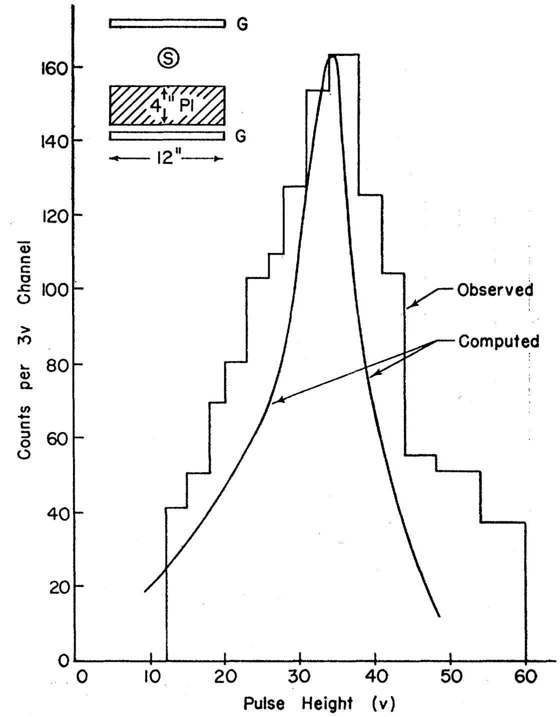

FIG. 3. Pulse-height distribution of minimum-ionizing particles.

B. Neutron Counters

The neutron counters[10] were of 1.5-in. outer diameter and 22-in. active length, with center wires of 0.002-in. diameter. They were filled to a pressure of 45 cm Hg with BF_3 enriched to 96 percent in B^{10}.[11] All counters together had a 150-v plateau starting at 2200 v when all pulses greater than 0.003 v were recorded.

The counting rate averaged 144 min^{-1} over background. The background, measured with no paraffin present but with each counter surrounded by at least 1 in. of borax, was 16 min^{-1} and may probably be attributed to radioactive contamination of the counter walls and to cosmic-ray bursts.

The efficiency of the moderator and neutron counters for detecting neutrons from a point source was measured directly. The efficiency of the apparatus is somewhat energy dependent; however, it has been shown previously[7] that the energy of neutrons produced by cosmic rays is about the same as the average energy of those from a Ra-Be source. A 5-mC source of this type was supplied by the Canadian Radium and Uranium Corporation, who state that the rate of neutron emission is

[10] The neutron counters were made and filled by the N. Wood Counter Laboratory, Chicago, Illinois.

[11] The BF_3 was furnished by the Isotopes Division, U. S. Atomic Energy Commission, Oak Ridge, Tennessee.

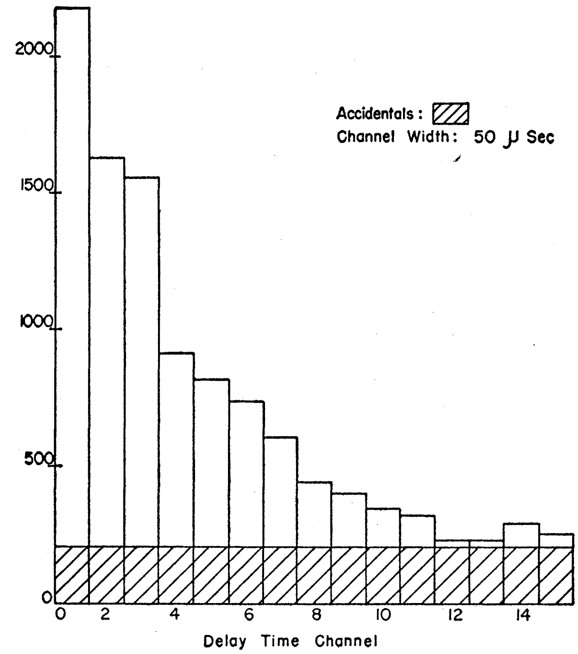

FIG. 4. Distribution of delay times for (s,n) coincidences. The channel width is 50 microseconds.

5.2×10^4 sec^{-1}, with an estimated error of ± 10 percent. This figure was checked by comparing this source with two others, one calibrated by the Bureau of Standards and one by the Argonne National Laboratory. The measured efficiency for neutrons originating in the center of the scintillator was 0.050. The location of the detected disintegrations may be estimated from the previously observed range distribution of the protons from emulsion stars. Such an estimate, based on the data of Lattimore,[12] indicated that 45 percent of the detected disintegrations are within the scintillator and 90 percent are no more than 11 g cm^{-2} distant. Investigation showed that ϵ is very nearly constant over this region.

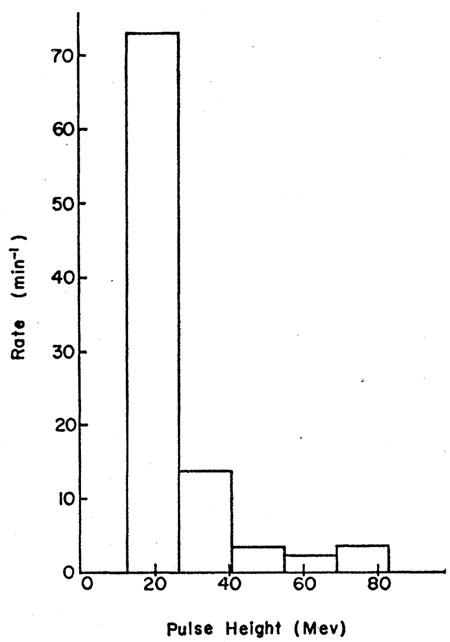

FIG. 5. Scintillation pulse-height distribution.

III. EXPERIMENTAL DATA

The equipment was operated at the Yale Cosmic Ray Laboratory at Climax, Colorado, during the autumn of 1952. The laboratory is located at 11 200-ft altitude, 51-cm Hg atmospheric pressure, magnetic latitude 48.1°N. The neutron production rate was measured there by Montgomery and Tobey[3] and found to be 13 times as great as at sea level.

TABLE I. Coincidence rates.

Pulse height (Mev)	$r(s,n)$ (min^{-1}) Observed	Observed less accidental
13–27	0.321 ±0.005	0.173 ±0.008
27–41	0.142 ±0.003	0.114 ±0.004
41–55	0.067 ±0.002	0.060 ±0.003
55–69	0.062 ±0.002	0.057 ±0.003
>69	0.100 ±0.003	0.093 ±0.004
>13	0.692 ±0.006	0.496 ±0.010
Pulse height (Mev)	**$r(s,2n)$ (min^{-1}) Observed**	**Observed less accidental**
13–27	0.0063±0.0006	0.0047±0.0007
27–41	0.0029±0.0004	0.0022±0.0005
41–55	0.0019±0.0004	0.0016±0.0005
55–69	0.0018±0.0003	0.0014±0.0004
>69	0.0046±0.0006	0.0041±0.0007
>13	0.0175±0.0011	0.0140±0.0015
Pulse height (Mev)	**$r(s)$ (min^{-1})**	
13–27	73 ±2	
27–41	13.8 ±0.3	
41–55	3.53±0.06	
55–69	2.11±0.05	
>69	3.37±0.06	
>13	96 ±3	

Figure 4 shows the delay time distribution of all (s,n) coincidences. If the accidentals are subtracted, the distribution is exponential. From this distribution, the mean life of neutrons in the moderator was found to be 175 μsec, a reasonable value.

The coincidence rates (s,n) and $(s,2n)$ and the scintillation rates not selected by any coincidence requirement are given in Table I. The pulse-height distributions of these events were measured in 40 channels, and the channels were grouped into five ranges of equal voltage width. It should be recalled from the discussion of Sec. IIA that the energy values given

[12] S. Lattimore, Phil. Mag. 40, 394 (1949) and 41, 819 (1950).

for the boundaries of these pulse-height ranges are derived from a calibration in terms of the energy loss of minimum-ionizing particles and are probably underestimates by a factor of two or more for pulses due to heavily ionizing particles. The accidental (s,n) coincidence rate is distributed according to the pulse-height distribution of the total, unselected scintillations. The accidental $(s,2n)$ coincidence rate is distributed according to the distribution of (s,n) coincidences. The number of accidental $(s,2n)$ events was calculated from a measurement which indicated that there is a probability of 0.0050 ± 0.0003 that any neutron pulse will be closely followed by another. These "neutron showers" were about twice as frequent as would be expected on a random basis. The pulse-height distributions in Table I are presented graphically in Figs. 5, 6, and 7.

The Geiger tray was placed near the moderator, 4 ft center-to-center from the scintillator. The coincidence

TABLE II. True coincidence and anticoincidence rates with the Geiger counters.

Pulse height (Mev)	$r(s,n,g)$ (min^{-1})	$r(s,n,\bar{g})$ (min^{-1})
13–27	0.0044 ± 0.0006	0.168 ± 0.008
27–41	0.0046 ± 0.0006	0.109 ± 0.004
41–55	0.0023 ± 0.0004	0.057 ± 0.003
55–69	0.0037 ± 0.0005	0.053 ± 0.003
>69	0.0113 ± 0.0012	0.082 ± 0.005
>13	0.0264 ± 0.0013	0.470 ± 0.011
Pulse height (Mev)	**$r(s,2n,g)$ (min^{-1})**	**$r(s,2n,\bar{g})$ (min^{-1})**
13–27	—	0.0047 ± 0.0007
27–41	—	0.0022 ± 0.0005
41–55	—	0.0016 ± 0.0005
55–69	—	0.0014 ± 0.0004
>69	0.0020 ± 0.0003	0.0021 ± 0.0006
>13	0.0024 ± 0.0003	0.0115 ± 0.0009

rates, corrected for accidentals, are given in Table II. These data are included in Figs. 5, 6, and 7. The (s,g) coincidence rate of 33 ± 2 hr^{-1} agrees with the expected rate of air showers to which the present arrangement of counters is sensitive. The (s,n,g) rate of 0.026 ± 0.002 min^{-1} is small compared with the (s,n) rate of 0.496 ±0.006 min^{-1}, indicating, as expected, that only a few percent of the neutrons produced by cosmic rays are produced in air showers.

The ratios of various counting rates are given in Table III. The significance of these ratios in terms of neutron multiplicity will be discussed in Sec. IV. The ratio $r(s,n)/r(s,2n)$ is significantly greater than the ratio $r(s,n,g)/r(s,2n,g)$ and indicated that, as expected, the multiplicity of neutrons in air showers is greater than the average multiplicity. In view of the uncertainty

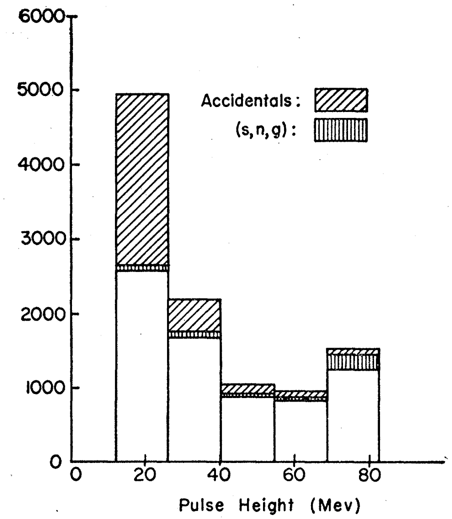

FIG. 6. Pulse-height distribution of (s,n) and (s,n,g) coincidences.

of the point of origin of the neutrons in air showers and consequent uncertainty in the efficiency of their detection, it is not considered feasible to calculate their multiplicity.

Only 23 $(s, \geqslant 3n)$ coincidences were recorded. Of these, 18 were $(s, \geqslant 3n, g)$ events. These data are not extensive enough to be of much significance. They are, however, consistent with the idea that neutrons are produced in air showers with a greater than average multiplicity.

IV. INTERPRETATION OF THE DATA IN TERMS OF MULTIPLICITY

Consider an event in which ν neutrons are produced in a disintegration near the scintillator, where the *a priori* probability of detecting a neutron is ϵ. The probability that exactly j of the neutrons will be

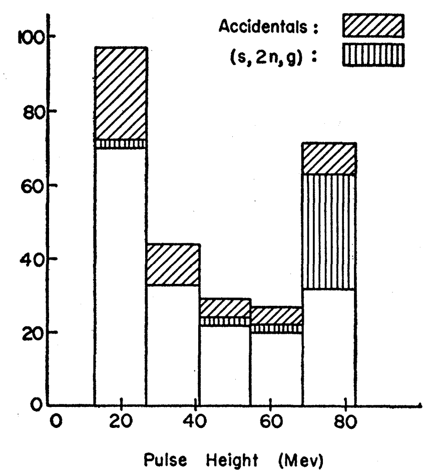

FIG. 7. Pulse-height distribution of $(s,2n)$ and $(s,2n,g)$ coincidences.

TABLE III. Ratio of rates.

Pulse height (Mev)	$\frac{r(s,\bar{g})}{r(s,n,\bar{g})}$	$\frac{r(s,n,\bar{g})}{r(s,2n,\bar{g})}$	$\frac{r(s,n,g)}{r(s,2n,g)}$
13–27	435±12	37 ±5	
27–41	127± 4	51 ±9	
41–55	62± 2	40 ±9	
55–69	39± 2	41 ±9	
>69	41± 2	39 ±7	6±1
>13	204±15	40.8±3.1	11±1

detected is given by Newton's formula:[13]

$$P_\nu(j)=\binom{\nu}{j}\epsilon^j(1-\epsilon)^{\nu-j}. \tag{1}$$

In general, all events will not have the same multiplicity, and the rate of (s,jn) coincidences may receive a contribution from any event in which j or more neutrons are produced. If the rate of those disintegrations detected by the scintillator in which ν neutrons are produced is $R(\nu)$, the rate of (s,jn) coincidences is:

$$r(s,jn)=\sum_\nu R(\nu)P_\nu(j). \tag{2}$$

The total rate, R, of detected disintegrations and the average multiplicity, $\bar{\nu}$, are

$$R=\sum_\nu R(\nu), \tag{3}$$

$$\bar{\nu}=R^{-1}\sum_\nu \nu R(\nu). \tag{4}$$

Unless the coincidence rates $r(s,jn)$ for all values of j are known, R and $\bar{\nu}$ can be computed only with some assumed form for the distribution $R(\nu)$. In the simple case that all events have the same multiplicity, ν, it may be shown that

$$\nu=1+2\left(\frac{1-\epsilon}{\epsilon}\right)\frac{r(s,2n)}{r(s,n)}. \tag{5}$$

Another manageable assumption is that $R(\nu)$ has the the form of a geometric series:

$$R(\nu)=R_0e^{-\nu/\nu_0}. \tag{6}$$

This is probably a better approximation to the true distribution in the present experiment. The stars observed[2] in nuclear emulsion exhibit a prong-number distribution which is quite closely a geometric series. With this distribution the coincidence rates reduce to

$$r(s,jn)=R_0\epsilon^je^{-j/\nu_0}[1-e^{-1/\nu_0}(1-\epsilon)]^{-(j+1)}. \tag{7}$$

If the summation of Eq. 4 is performed, excluding $\nu=0$ so as to consider only neutron-producing events, the result is

$$\bar{\nu}=1+1\Bigg/\left\{\epsilon\left[\frac{r(s,n)}{r(s,2n)}-1\right]\right\}. \tag{8}$$

[13] H. Margenau and G. M. Murphey, *The Mathematics of Physics and Chemistry* (D. Van Nostrand Company, Inc., New York, 1948), p. 422.

Table IV gives the comparative results of Eqs. 5 and 8 when applied to the experimental data for all pulse sizes together after subtraction of coincidences due to air showers. These data are $r(s,n,\bar{g})/r(s,2n,\bar{g})=40.8\pm3.1$, $r(s,n,\bar{g})=0.470\pm0.006$ min^{-1}.

Comparison shows that in spite of the radical difference in the form of the assumed distributions, the calculated rate of events and the average multiplicity are not very different for the two cases.

In Table III, the ratios of various rates are given for each pulse-size group. Examination of this table leads to two conclusions. First, the neutron multiplicity of events not including air showers does not appear to be a function of pulse size. This conclusion is based on the constancy of the ratio $r(s,n,\bar{g})/r(s,2n,\bar{g})$. Second, the two ratios $r(s,n,\bar{g})/r(s,2n,\bar{g})$ and $r(s,\bar{g})/r(s,n,\bar{g})$ appear to be equal for the larger pulse sizes. This would be expected if the multiplicity distribution were a geometric series extending to zero-neutron events. If a geometric series of multiplicities is fitted to $r(s,n,\bar{g})$ and $r(s,2n,\bar{g})$ and extended to zero multiplicity, the calculated rate of disintegrations agrees with the observed rate of scintillations, for large pulses. This comparison is shown in Fig. 8. This line of argument suggests that a geometric series of multiplicities is a reasonable approximation to the true situation and that a relatively large proportion of disintegrations may have zero neutron multiplicity.

The best value of the average neutron multiplicity for neutron-producing events is judged to be $\bar{\nu}=1.5$. This value has a statistical error of ±0.05 and a further error of ±0.05 introduced by the uncertainty in ϵ.

Much recent evidence[14] favors the theory that each detected disintegration is part of a cascade of disintegrations so that the particles capable of nuclear interaction at any point are secondaries, produced in disintegrations above. Since the efficiency for neutron detection is appreciable for neutrons originating throughout a fairly large portion of the moderator, the observed events must sometimes include more than one disintegration. An estimate of the effect of cascades on the measured value of $\bar{\nu}$ was made on the basis of an oversimplified model. If a mean free path for star-producing radiation of 80 g cm^{-2} is assumed, and if it is assumed that neutrons originating within 20 g cm^{-2} of the scintillator would be detected, it may be con-

TABLE IV. Comparison of results calculated from two different assumed multiplicity distributions.

Distribution	$R(\nu\geqslant 1)$	$\bar{\nu}$
$R(\nu)=R$	5.1 min^{-1}	1.9
$R(\nu)=R_0e^{-\nu/\nu_0}$	6.6	1.5

[14] G. Thomson and P. E. Hodgson, Phil. Mag. **42**, 978 (1951); B. Rossi, *High Energy Particles* (Prentice-Hall Publishing Company, New York, 1952), p. 486.

cluded that about 25 percent of the detected events include two disintegrations. If both of these disintegrations have the same multiplicity, it may be concluded that the measured value of $\bar{\nu}$ must be corrected by the factor 0.7; thus a corrected value of $\bar{\nu}=1.1$ is obtained. This is probably an overcorrection, since, as mentioned in the previous paragraph, there is reason to believe that many disintegrations produce no neutrons, and so many cascades of more than one star will produce no more than one neutron.

It is believed that the best estimate of the corrected multiplicity is $\nu=1.3$, with an uncertainty of ± 0.2 resulting mainly from the absence of a direct experimental basis for the cascade correction.

V. DISCUSSION OF THE RESULTS

In addition to the neutron multiplicity, this experiment yields several secondary results. The star production rate in paraffin may be derived on the assumption that, as stated in Sec. IIB, 45 percent of the detected events are stars in the scintillator. Using the rate of neutron-producing events from Table IV, on the basis of a geometric series of multiplicities, the star production rate is 21 g^{-1} day^{-1}. For comparison, if Lattimore's star rates,[12] including the production rate of single fast protons as possible neutron-producing events, are extrapolated from emulsion to paraffin on the assumption that the cross section varies with atomic weight, A, as $A^{\frac{2}{3}}$, the result is 17 g^{-1} day^{-1}. The assumptions involved in this calculation make it difficult to estimate the errors.

The neutron production rate in paraffin may be derived from this experiment in two different ways. Using $\bar{\nu}=1.3$, the star production rate of 21 g^{-1} day^{-1} implies a neutron production rate of 3×10^{-4} g^{-1} sec^{-1}. This figure depends ultimately on the measured coincidence rates. The total neutron counting rate is also related to the neutron-production rate. A calculation identical to that of Montgomery and Tobey[3] indicates that the observed rate of 144 min^{-1} implies a neutron-production rate of 2.6×10^{-4} g^{-1} sec^{-1}. Both of these figures may be compared with the result of Montgomery and Tobey, 2.5×10^{-4} g^{-1} sec^{-1}, which was obtained at Climax. Again, it is difficult to estimate the errors. The calculation indicates, however, that the bulk of neutron production, as measured by Montgomery and Tobey, is the result of events of the type selected in the present coincidence experiment.

Relative production rates of neutrons in materials of different atomic weight have been measured by Montgomery and Tobey[3] and by Simpson.[15] As pointed out by Montgomery and Tobey, these rates are propor-

[15] J. A. Simpson, *Proceedings of the Echo Lake Cosmic Ray Symposium* (U. S. Office of Naval Research, Washington, D. C. 1949), p. 252.

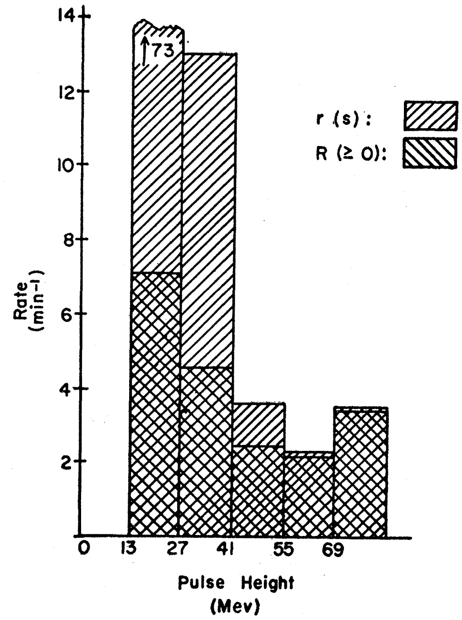

FIG. 8. Comparison of the rate of detected disintegrations, calculated from $r(s,n)$ and $r(s,2n)$, with the observed scintillation rate.

tional to $\bar{\nu}\sigma/A$, where σ is the relative cross section of the material. Relative multiplicities calculated from this expression may be reduced to absolute values by the result, $\bar{\nu}=1.3$ for C, of the present experiment. For this calculation, the production rates measured by Montgomery and Tobey were used whereas values of σ were taken to be proportional to the total cross sections measured by Fox *et al.*[16] for 300-Mev neutrons. The result is $\bar{\nu}=2.2$ for production in Al and $\bar{\nu}=6$ for production in Pb. The mean atomic weight of the elements in nuclear emulsion is about the same as the atomic weight of Al. The mean neutron multiplicity in Al is comparable to the mean prong multiplicity, 2.2, of stars observed[2] in emulsion.

This investigation was initiated following suggestions of the late Professor Carol G. Montgomery. The experiment was planned with the advice of Professor Raymond V. Adams. The experiment was performed and the data interpreted with the aid and encouragement of Professor Henry L. Kraybill, for whose constant and stimulating interest I am most grateful. The members of the Yale Cosmic Ray Group, in particular Mr. Irwin Tessman, contributed willing help to the experiment. The generous hospitality of Mr. Richard T. Hansen, Chief Observer at Climax, greatly facilitated the work there, which was carried out at the site of the High Altitude Observatory of Harvard University and the University of Colorado.

[16] R. Fox *et al.*, Phys. Rev. **80**, 23 (1950).