must await further theoretical attention before a valid comparison with theory can be made.

3. Energy Distribution of the Low Energy Negative Electron

It appears from the measurements of the low energy negative electron of the triplet that the main part of this process is connected with small momentum transfer to the recoil electron. This is in agreement with predictions of Bethe,[18] Votruba, and Nemirovsky.

ACKNOWLEDGMENTS

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[18] H. A. Bethe, Proc. Camb. Phil. Soc. 30, 524 (1934).

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Neutron Production at Mountain Altitudes*

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The rate of production of neutrons by cosmic rays was measured at 3510 meters elevation in lead, aluminum, and paraffin, and in paraffin at 1640 meters elevation by means of an ionization chamber filled with boron trifluoride. The variation with elevation for production in paraffin differs slightly from that in the heavier elements, but agrees well with observations by other observers of the production in air at higher altitudes and with the variation of extensive showers. The neutrons are produced with a larger multiplicity in lead than in paraffin. Comparison with measurements of star production in photographic plates results in the value of 3 to 6 neutrons per star. Bursts of ionization resulting from other cosmic-ray phenomena were also observed.

INTRODUCTION AND APPARATUS

During the spring of 1948 measurements were made[1] of the rate of production of cosmic-ray neutrons in several materials at sea level. The experiment was so designed that absolute rates of neutron production could be accurately calculated from known nuclear cross sections, both total and capture, for the elements used. The detector consisted of a cylindrical ionization chamber filled to atmospheric pressure with boron trifluoride gas of standard isotopic composition. Bursts of ionization in the chamber were caused by α-particles produced in the reaction $B^{10}+n=Li^7+\alpha$. The chamber was placed at the center of a pile of material consisting of approximately equal amounts by weight of paraffin and of the element to be investigated, distributed homogeneously. Enough paraffin was used so that only neutrons formed within the pile were able to reach the ionization chamber and be detected. The ionization chamber was furnished with "guard rings" constructed of borax and other chambers filled with boron trifluoride, so that the calculation of the number of neutrons diffusing into the chamber and being captured was reduced to a one-dimensional problem with axial symmetry which could be solved rigorously. The ionization chamber was connected to an electrometer tube with a balanced amplifier. The output voltage was applied to a galvanometer which produced a trace on moving photographic paper. Thus the size of the ionization pulse in the chamber could be measured. The background was determined by surrounding the chamber with a layer of borax within the pile of paraffin. For further details of the experimental arrangement, reference should be made to the thesis mentioned. Since the rates to be reported here depend on the nuclear cross sections chosen, these values are reproduced in Table I.

OBSERVATIONS

During the summer of 1948 the sea level observations were extended by others taken in Colorado at Denver, 1640 meters elevation, atmospheric depth 865 g/cm^2, magnetic latitude 48.5°N and at Climax, 3510 meters elevation, atmospheric depth 675 g/cm^2, magnetic latitude 48.1°N. The experiments were performed in a truck with a light roof of approximately 1.3 g/cm^2 thickness in open areas.

The direct result of the observations is a set of curves giving the rate of occurrence of pulses of a given size in the ionization chamber. Figure 1 shows three such curves taken at Climax. The abscissas are given in arbitrary units (a deflection of $\frac{1}{32}$ inch on the photographic paper) and the ordinates are rates per hour of occurrence of pulses per unit interval of size. The highest curve shows the observations obtained when the pile contained 517

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[1] A. R. Tobey, Ph.D. thesis, Yale University (1948); Phys. Rev. 75, 894 (1948).

lb. of lead and 770 lb. of paraffin, the middle curve for the paraffin alone and the lowest curve shows the background and was obtained with the chamber surrounded by borax which in turn was surrounded by the paraffin. The peaks resulting from the disintegration alpha-particles are well marked. The neutron production in any case is proportional to the area between the background curve and a higher one.

The counting rates at high altitude were so large that a correction had to be applied for the resolving time of the apparatus. The galvanometer used had a period of 1.1 sec. and it was estimated that if two neutrons were captured in the chamber within an interval of less than 0.36 sec. $=10^{-4}$ hr., the resultant pulse would be classed as a single pulse but of larger size. The occurrence of a subsidiary peak at twice the abscissa of the main peak is evident in Fig. 1. The true counting rate N is related to the observed rate N_0 by the equation

$$N_0 = Ne^{-\sigma N},$$

where σ is the resolving time. From the corrected counting rates the rates of neutron production were calculated and the results obtained are given in Table II. For convenience the sea level values are included also.

The probable errors that are indicated in Table II are those arising from the statistics of counting only. The rates are uncertain also because of uncertainties in the values of the nuclear constants assumed. Since no tests of the purity of the substances used were made, no estimate of the inaccuracy arising from this source is possible. Small amounts of boron will, of course, make large changes in the neutron rates. Probably no contamination resulted from the use of borax to determine the background of the chamber since the values determined from two different amounts of lead agree well. The values listed for carbon are based on the assumption that the hydrogen in the paraffin does not contribute and that the composition of the paraffin could be represented by C_nH_{2n}. Neutron production in the chamber walls, which were thin, was neglected.

VARIATION WITH ELEVATION

The observed variation with elevation of the rates of neutron production is illustrated in Fig. 2 where the ratio to the sea level value is plotted on a logarithmic scale against the atmospheric depth. It is seen that the variation is approximately exponential but that the neutron production in paraffin increases more rapidly than that in lead or aluminum. Measurements at higher elevations of the neutron production in air have been reported by Agnew, Bright, and Froman,[2] by Simpson,[3] and by Yuan.[4] All these observers agree that an exponential absorption occurs with a mean free path of approximately 160 g/cm² of air. For comparison with these observations the dashed line in Fig. 2 is drawn

[2] Agnew, Bright, and Froman, Phys. Rev. **72**, 203 (1947).
[3] J. A. Simpson, Jr., Phys. Rev. **73**, 1389 (1948).
[4] L. C. L. Yuan, Phys. Rev. **74**, 504 (1948).

TABLE I. Nuclear cross sections used for calculations.

Substance	Total cross section	Capture cross section
H	41.0×10^{-24} cm²	0.29×10^{-24} cm²
B	830.0	830.0
C	4.6	0.0045
Al	1.6	0.23
Pb	11.0	0.17
CH_2	86.4	0.59

which has a slope corresponding to this value of the mean free path.

It is of interest to compare the neutron rates with some observations of the counting rate of a set of Geiger counters arranged to record extensive showers. These observations[5] were made at the same locations and simultaneously with the neutron observations. They are represented by the circles in Fig. 2. It is apparent that the agreement with the paraffin observations is very close.

The variation with elevation can be used to correct the neutron-production rates given in Table II for the absorption of neutron-producing rays within the pile. The detecting chamber was covered with a layer of 30 g/cm² of paraffin and consequently the neutron production in the vicinity of the chamber corresponds to a primary intensity at a somewhat lower elevation than that at which the observations were made. A similar correction can be applied for the case in which lead is present in the pile. However, when the total quantity of lead in the pile was reduced by a factor of nearly 2, the rate of production of neutrons per gram remained unaltered to within the accuracy of the counting as shown in Table II. Hence we conclude that the absorption in the lead is negligible.

This conclusion is strengthened by a separate experiment in which the pile of paraffin was shielded on the top

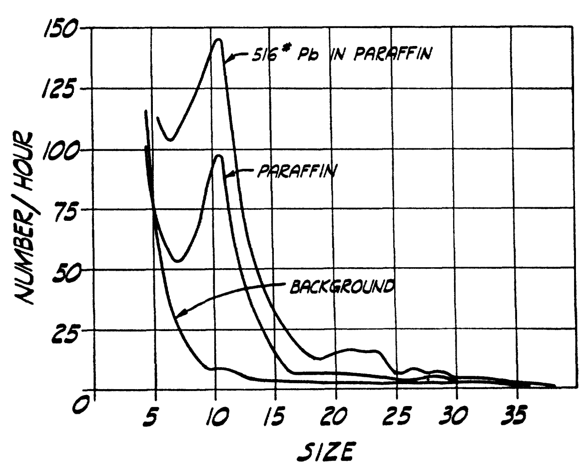

FIG. 1. Neutron distribution at Climax: (a) for 517 pounds of lead and 770 pounds of paraffin. (b) for paraffin alone. (c) for chamber surrounded by borax and paraffin (background).

[5] J. Wei and C. G. Montgomery, Phys. Rev. **76**, 1488 (1949).

TABLE II. Observed rates of neutron production. Values are in units of 10^{-5} g^{-1} sec.$^{-1}$.

Material	Mass of material	Neutron production rate (10^{-5} g^{-1} sec.$^{-1}$)
Climax, 675 g/cm²		
Paraffin	770 lb.	24.7 ±0.5
Carbon calculated from paraffin		28.8 ±0.6
Aluminum	749 lb.	30.0 ±1.2
Lead	517 lb.	55.7 ±1.5
	346 lb.	54.3 ±2.1
Mean value for lead		55.0 ±1.3
Denver, 865 g/cm²		
Paraffin	770 lb.	7.98±0.18
Carbon calculated from paraffin		9.32±0.21
New Haven, 1030 g/cm²		
Paraffin	770 lb.	1.98±0.07
Carbon calculated from paraffin		2.31±0.08
Aluminum	749 lb.	3.49±0.20
Lead	517 lb.	6.47±0.24

and four sides by 1 inch of lead. Without the lead shield the neutron counting rate corrected for the background was 505±10 hr.$^{-1}$. With the shield in place 492±11 counts per hour were observed. The absorption in the lead is thus observed to be 2.6±3.0 percent or less than could be detected. This conclusion as well as the observations on the variation with elevation are in good agreement with the observations of Mrs. Cocconi.[6]

MULTIPLICITY OF NEUTRON PRODUCTION

The differences in the rates of production of neutrons in different substances are to be ascribed to two factors: the cross section σ for star production and the multiplicity, or number ν of neutrons per star. In fact the rate R of neutron production per gram is

$$R = k\sigma\nu/A,$$

where k is a constant and A the atomic weight. Now it is extremely likely that the cross section σ for star production is proportional to the total cross section σ_t for high energy bombarding particles.[7] Hence, if values are adopted for σ_t, the ratio of multiplicities can be calculated from the present observations. Choosing the total cross sections measured[8] at 90 Mev of 0.55 barn for carbon, 1.12 barns for aluminum and 4.53 barns for lead, we find at sea level

$$\nu\ (\text{lead})/\nu\ (\text{carbon}) = 6.4,$$
$$\nu\ (\text{lead})/\nu\ (\text{aluminum}) = 3.5.$$

These ratios are, of course, subject to some uncertainty on account of the variation of the transparency of nuclei as light as carbon with the energy of the fast neutrons in this energy range. These results are also in agreement with those of Mrs. Cocconi.[6]

It is possible to find the value of ν by a comparison of the neutron rates reported here with the number of stars produced in photographic plates. We assume that the neutron production R can be represented empirically as a function of the atomic weight A by the relation

$$R = CA^{\alpha},$$

where C and α are constants. With this interpolation function the rate of production of neutrons in photographic plates can be calculated. The values so calculated for Climax are given in Table III. The composition of the Ilford nuclear research plates Type C1 was taken from Gardener and Peterson.[9] The total of 157×10^{-5} neutron cm^{-3} sec.$^{-1}$ represents the rate of production under 30 g/cm² of paraffin at Climax. Correction for absorption with a mean free path of 160 g/cm² increases this value to 190×10^{-5} cm^{-3} sec.$^{-1}$.

Two sets of observations of stars in photographic plates at this elevation have been made.[10] Both can be represented by the relation

$$N = N_0 e^{-p/2.08},$$

where N is the rate of occurrence of stars having more than p prongs. This relation can be shown to be valid for $p \geqslant 3$. If it can be used also for $p < 3$, then the total number of stars is simply N_0. The observations of George and Jason give $N_0 = 41\times10^{-5}$ cm^{-3} sec.$^{-1}$ whereas those of Bernardini and collaborators give $N_0 = 73\times10^{-5}$ cm^{-3} sec.$^{-1}$. From these values, the multiplicity ν of neutron production is found to be 4.6 or 2.6 averaged

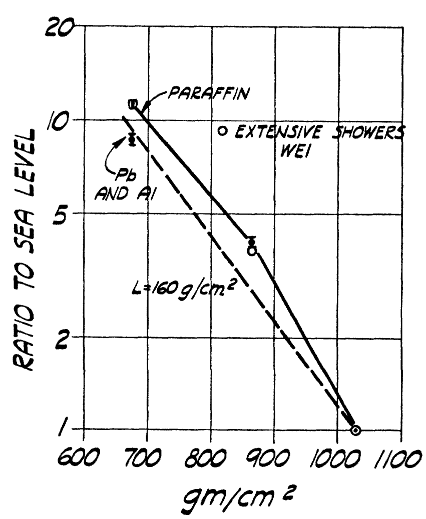

FIG. 2. Variation of production of neutrons with elevation.

[6] Cocconi, Coconni Tongiorgi, and Greisen, Phys. Rev. **76**, 1020 (1949). The authors are much indebted to Mrs. Cocconi for the receipt of this manuscript before publication.

[7] See De Juren, Knable, and Moyer, Phys. Rev. **76**, 589 (1949); and Fox, Leith, McKenzie, and Wouters, Phys. Rev. **76**, 590 (1949).

[8] Cook, McMillan, Peterson, and Sewell, Phys. Rev. **75**, 7 (1949).

[9] E. Gardener and V. Peterson, Phys. Rev. **75**, 367 (1949).

[10] Reported by B. Rossi, Technical Report No. 26, Laboratory for Nuclear Science and Engineering, M.I.T. (April 4, 1949).

over all stars and over all substances in the photographic plate. A value in this range is entirely satisfactory since the average number of charged particles per star is 2.1.

THE CHAMBER BACKGROUND

It is evident from Fig. 1 that some bursts of ionization occur in the chamber even when it is surrounded by a layer of borax which excludes all thermal neutrons. The size-frequency distribution of these bursts shows no characteristic peak caused by neutrons. Moreover, it is found that these background pulses vary rapidly with elevation. The same large background is observed by other experimenters[11] and it is of some interest to ascertain its nature. The integral frequency-distribution curves observed at the three elevations are shown in Fig. 3 on a log-log plot. The increase with elevation is mostly confined to the small sizes, and the curves show a characteristic shape. This shape can be interpreted as follows.

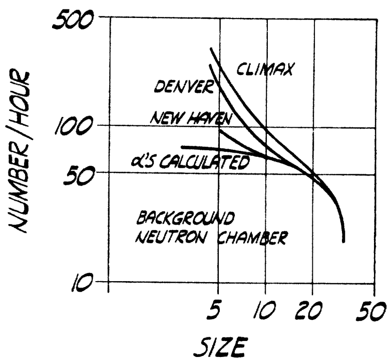

FIG. 3. Background in neutron chamber at three elevations.

At sea level alpha-particles arising from radioactive contamination in the walls of the chamber certainly contribute an appreciable portion of the bursts of ionization. Such contamination is the result of small amounts of uranium and thorium in equilibrium with their daughter substances and the shape of the integral distribution curve can be calculated easily.[12] Such a calculated curve has been drawn to fit the large bursts in Fig. 3. The total number of contamination alpha-particles so determined is of the correct order of magnitude for clean surfaces.[13]

TABLE III. Neutron production in plates—Ilford NR plates Type C1.

Substance	Density ρ	Atomic weight	R	$R\rho$
Ag	1.85 g/cm^3	108	45×10^{-5} g^{-1} sec.$^{-1}$	83.3×10^{-5} cm^{-3} sec.$^{-1}$
Br	1.34	80	41	55
I	0.052	127	47	2.4
C, H, O, N	0.661	(as paraffin)	25	16.3
S	0.010	32	31	0.3
Total	3.923			157.3

The bump in the differential distribution curve, Fig. 1, near the abscissa 30 does not vary with elevation and probably represents a surface contamination. The pulses under consideration here are the more frequent smaller ones.

The contribution of alpha-particles can then be subtracted from the curves at the three elevations to yield the burst distribution curves arising from cosmic-ray phenomena. It has been shown[14] that bursts of such a range of sizes are the result of nuclear disintegrations taking place principally in the walls of the chamber. A qualitative comparison with observations of bursts in other chambers made simultaneously at Climax[12] shows that the rate of occurrence and the frequency distribution are in approximate agreement with this explanation. Since the background measurements were taken with a complicated borax and paraffin shield it is difficult to draw further conclusions.

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[11] A good example is shown in reference 3.

[12] H. Carmichael, Phys. Rev. **74**, 1667 (1948). Also C. G. Montgomery and D. D. Montgomery, Phys. Rev. **76**, 1482 (1949).

[13] J. A. Bearden, Rev. Sci. Inst. 4, 271 (1933).

[14] C. G. Montgomery and D. D. Montgomery, Phys. Rev. **72**, 131 (1947); Bridge, Hazen, and Williams, Phys. Rev. **74**, 1689 (1948); and also reference 12.