Cosmic-Ray Neutrons in Water at an Altitude of 10 600 Feet*†

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The neutron component of the cosmic radiation in the first 50-cm layer of water adjacent to the surface of a mountain lake, located at an altitude of 10 600 feet, was studied with the aid of a tray of ten enriched boron trifluoride filled counters connected in parallel. A measure of the thermal neutron intensity was obtained by alternately shielding the tray of counters with tin and cadmium of equal g cm^{-2}. A transition region was found to exist between the surface and the 30-cm level wherein the thermal neutron intensity decreased rapidly with depth. Below the 30-cm level, the thermal neutron intensity was found to be almost constant over an interval of 20 cm. The neutron production rate and thermal neutron flux, just below the transition region, were found to be 4.6×10^{-5} neutrons g^{-1} sec^{-1} and about 4.3×10^{-4} thermal neutrons cm^{-2} sec^{-1}, respectively.

I. INTRODUCTION

A LITTLE over a decade ago Bethe, Korff, and Placzek[1] considered the effect of the surface of the earth on the energy and spatial distributions of cosmic-ray neutrons on theoretical grounds. To show how large the influence of the ground can be, they chose an extended water surface as a special case since the known chemical composition of air and water permitted numerical calculations to be made on the basis of neutron slowing-down theory. The results of the calculations indicate that the influence of the water surface should be felt up to a height equivalent to 1 meter of water in air and only over an interval of about 30 cm of water below the surface.

This paper is only concerned with the distribution of cosmic-ray neutrons below the surface of an extended body of water. The surface of the water, according to Bethe *et al.*, has a marked influence on the spatial distribution of thermal neutrons in the 30-cm layer of water adjacent to the surface. At the 1.5-cm level, the thermal neutron intensity is predicted to be a maximum while in the interval 3 to about 20 cm below the surface the thermal neutron intensity is predicted to decrease rapidly. Below the 30-cm level, however, the thermal neutron intensity is predicted to remain almost constant over an interval of at least 20 cm.

Bethe *et al.* attribute the form of the thermal neutron distribution in the first 30 cm of water to neutrons which are produced in air and enter the water while their energies are between 4 Mev and 0.06 ev. These neutrons, on colliding with hydrogen nuclei, are rapidly slowed down to thermal energies. Since the diffusion length of thermal neutrons in water is about 2 to 3 cm, some of the thermal neutrons within 2 cm of the surface diffuse back into the air where they are captured by nitrogen nuclei. As there are more neutrons available to be slowed down near the surface than at greater depths a greater intensity of thermal neutrons should exist near the surface. At depths greater than 30 cm the thermal neutron distribution should be due only to neutrons produced in water since neutrons produced in air cannot penetrate there.

During the summer of 1950, an experiment was carried out to study the neutron component of the cosmic radiation below the surface of Echo Lake, located at an altitude of 10 600 feet in Colorado. The objectives of the experiment were to determine the form of the thermal neutron intensity variation over the first 50 cm of water from the surface and to obtain quantitative measurements of the production rate and flux of neutrons in water at mountain altitudes. All measurements were made at the center of the lake where the neutron distribution near the surface is least influenced by the surrounding ground.

II. APPARATUS

A block diagram of the experimental setup is shown in Fig. 1. The neutron detector was composed of a tray of ten identical neutron counters positioned side by side in a horizontal plane. The counters were connected in parallel to the input of a cathode follower preamplifier. The counters were filled to a pressure of 25 cm of Hg with enriched BF_3 (96 percent B^{10}). Each counter had a 50 cm long copper cathode of

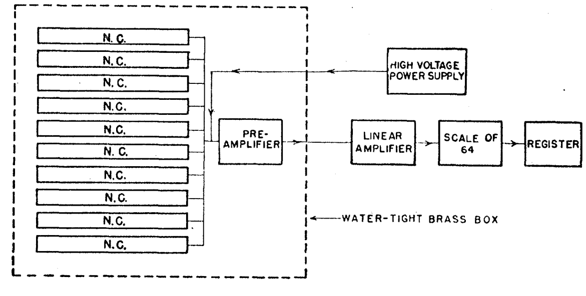

FIG. 1. Block diagram of experimental setup.

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† This report is an abridgement of a dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at New York University, 1951.
‡ Now at the Anton Electronic Laboratories, Inc., Brooklyn, New York.
[1] Bethe, Korff, and Placzek, Phys. Rev. 57, 573 (1940).

2-cm i.d. and 0.2-cm wall thickness. Three-mil tungsten wire served as counter anodes.

The neutron detector and a cathode follower preamplifier were enclosed in a thin-wall, water-tight brass box. The box was equipped with a pair of lever arms that were fastened to the legs of a small wooden platform which had been erected at the center of the lake. The lever arms served to hold the tray of counters parallel to the surface at all depths within the first 50 cm of water from the surface.

The linear amplifier, scaling circuit, and high voltage supply were kept on the small wooden platform. The circuitry was kept in an insulated box to protect them from the elements. Power for the equipment was brought to the platform by means of heavy duty cable that was connected to a transformer on shore.

III. THERMAL NEUTRON DETECTION

To determine the thermal neutron counting rates, a 1-mm thick cadmium shield and a tin shield of equal g cm^{-2} were used in conjunction with the neutron detector. When the detector is shielded with cadmium, the counting rate is due to neutrons having energies greater than 0.4 ev, the cadmium cutoff, to ionizing events produced by cosmic and counter background radiations, and to some star fragments produced in the cadmium shield. When the detector is shielded with tin, the counting rate is due to neutrons having all energies, to cosmic and counter background radiations, and to star fragments produced in the tin shield. The difference between the tin and cadmium counting rates gives an accurate measure of the thermal neutron counting rate. The counting rates due to the cosmic and counter background radiations and to the star fragments produced in the shields cancel out since they are the same for the tin- and cadmium-shielded detector.

The tin shield is primarily used to compensate for the star fragments that are produced in the cadmium shield, which at the 10 600 foot elevation may be a few percent of the thermal neutron counting rate. As remarked by Yuan,[2] the production rate of stars in the tin and cadmium shields of equal g cm^{-2} should be about equal since the atomic numbers of tin ($Z=50$) and cadmium ($Z=48$) are almost the same.

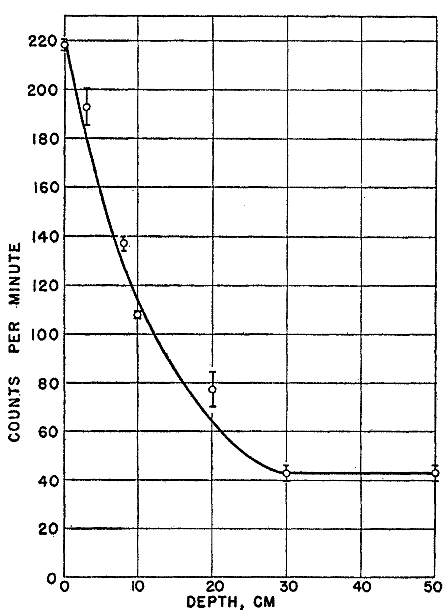

FIG. 2. Variation of the thermal neutron counting rate with depth below the surface of an extended body ofw ater at an altitude of 10 600 feet.

IV. EXPERIMENTAL PROCEDURE

Measurements of the thermal neutron intensity were made at the surface, and at the 3-cm, 8-cm, 10-cm, 20-cm, 30-cm, and 50-cm depths. At each of these depths the following procedure was followed. First the tin shield was placed over the box containing the detector and the counting rate was determined at 50-volt intervals between 1800 volts and 2550 volts. The tin shield was then replaced by the cadmium shield and the counting rate was once more determined as a function of voltage at the same 50-volt intervals. The time of each run at a particular voltage setting varied between one-half hour and three hours, depending on the counting rate. To check the consistency of the measurements, they were repeated at different depths during the five weeks the experiment was carried out.

There were two reasons for making the tin and cadmium counting rate determinations as a function of voltage instead of at one fixed voltage midway along the neutron detector plateau. The first was that these measurements permitted a continuous check on the operation of the detector. In the event the plateau shifted or changed its length or slope it would be an indication that one or more counters were not operating properly. This situation could then be corrected. If, on the other hand, the detector was operated at one fixed voltage, a change in its operating characteristics would yield ambiguous counting rates. The second reason was that on taking the tin-cadmium difference counting rate a thermal neutron counting rate plateau would be found where the average of the counting rates on the plateau could be taken as the thermal neutron counting rate at the depths investigated.

V. EXPERIMENTAL RESULTS

Tabulated in Table I are the experimental results showing the average thermal-neutron counting rates at the depths investigated. The errors given are the probable errors of the mean. A plot of the mean thermal-neutron counting rate *versus* depth is shown in Fig. 2.

VI. DISCUSSION OF RESULTS

The form of the thermal-neutron intensity variation with depth, as shown in Fig. 2, offers direct experimental

[2] L. C. L. Yuan, Phys. Rev. 81, 175 (1951).

evidence for the existence of a surface effect on the neutron energy and spatial distributions in water. It is seen that the first 30-cm layer of water adjacent to the surface is a transition region wherein the thermal neutron intensity varies rapidly with depth. The thermal neutron intensity is found to be a maximum at the surface, and not at the 1.5-cm level as theoretically predicted. It is impossible to say, on the basis of the present experiment, whether this discrepancy is real or not. To obtain results which would clearly show the position of the maximum, measurements at 0.5-cm intervals in the first 3 cm of water would have had to be made. Such measurements could not be made with the detector used since its height of 2 cm was almost as large as the layer of water in which the maximum is located. The rapid decrease of the thermal neutron intensity between the 3-cm and 30-cm level is, however, in agreement with theory.

Below the 30-cm level, the thermal neutron intensity is found to remain almost constant over 20 cm of water. In this region there exist three conditions which make it possible to obtain a quantitative determination of the neutron production rate in water. They are (1) the accurate measure of the thermal neutron counting rate by means of the tin-cadmium difference method, (2) the fact that the intensity of the neutron-producing radiation remains almost constant over the 20-cm interval, and (3) the slowing down of about 99.3 percent of the total number of neutrons produced to thermal energies before capture.

These conditions permit the use of an expression, first given by Korff,[3] for finding the neutron production rate in terms of the thermal neutron counting rate of a BF_3 neutron detector: namely,

$$q=n(\sigma_w/\sigma_b)(2.24\times10^4/MVp),$$

where q is the neutron production rate g^{-1} sec^{-1}, n is the thermal neutron counting rate in counts sec^{-1}, M is the molecular weight of water, V is the active volume of the BF_3 detector, p is the gas pressure in atmospheres, σ_w is the capture cross section of water for thermal neutrons, and σ_b is the capture cross section of 96 percent enriched BF_3 for thermal neutrons. With $n=0.72$ neutron sec^{-1}, $M=18.00$, $V=6140$ cm^3, $p=0.33$ atmos, $\sigma_w=0.33$ barn, and $\sigma_b=3384$ barns, the production rate of neutrons just below the transition region in water at an altitude of 10 600 feet is found to be 4.2×10^{-5} neutron g^{-1} sec^{-1}.

The thermal neutron distribution below the 30-cm level also permits a quantitative determination of the thermal neutron flux in water. By flux we mean the product of the thermal neutron density ρ, and the thermal neutron velocity v, since ρv is the number of thermal neutrons incident per unit area per unit time.[4] Since v for thermal neutrons is known to be 27×10^4 cm

[3] S. A. Korff, Revs. Modern Phys. **11**, 211 (1939).

[4] J. G. Beckerley, U. S. Atomic Energy Commission Report AECD-2664, 1949 (unpublished).

TABLE I. Mean thermal-neutron counting rate *versus* depth.

Depth (cm)	Counts per minute
0	218.4±1.5
3	193.0±6.1
8	137.2±2.3
10	108.0±0.9
20	78.0±6.8
30	43.7±2.8
50	43.3±2.7

sec^{-1}, only ρ must be determined. The thermal neutron density is related to the thermal neutron counting rate, n, as follows[5]:

$$n=VLpv\sigma_b\rho,$$

where V is the sensitive volume of the detector, L is Loschmidt's number, p is the pressure in atmospheres, and σ_b is the thermal neutron capture cross section of enriched BF_3. With $n=0.72$ thermal neutrons sec^{-1}, $V=6.10\times10^3$ cm^3, $L=2.7\times10^{19}$ cm^{-3}, $\sigma_b=3.4\times10^{-21}$ cm^2, $p=0.33$ atmos, and $v=27\times10^4$ cm sec^{-1}, the thermal neutron density in water at an altitude of 10 600 feet is found to be about 1.45×10^{-8} thermal neutrons per cc. The thermal neutron flux ρv is then about 3.9×10^{-4} thermal neutron cm^{-2} sec^{-1}.

The values computed above for the neutron production rate and the thermal neutron flux are subject to error because of the fact that they were computed on the basis of the thermal neutron counting rate which itself is in error. This error was introduced by the walls of the brass box and the copper cathodes of the counters. Since the walls have finite slow neutron capture cross sections, they are not "thin" for slow neutrons. Absorption of slow neutrons by the walls reduces the neutron density at the detector and changes the neutron distribution near the detector.

The magnitude of the error may be computed so as to permit appropriate corrections to be made. The percentage absorption of each of the two walls may be readily calculated to be[6]:

$$H=(\sigma Adt/M)\times100,$$

where σ is the boron capture cross section for thermal neutrons, A is Avogadro's number, d is the density of the wall, t is the wall thickness in cm, and M is the mean atomic weight of the wall material. The 0.2-cm brass walls and the 0.2-cm copper walls act to absorb about 8 percent of the incident thermal neutrons. Thus, the thermal neutron density at the detector is only 92 percent of the true thermal neutron density. Applying this correction to our computed values, the true neutron production rate and thermal neutron flux are 4.6×10^{-5} neutrons g^{-1} sec^{-1} and 4.3×10^{-4} thermal neutrons cm^{-2} sec^{-1}, respectively.

[5] S. A. Korff, *Electron and Nuclear Counters* (D. Van Nostrand Company, Inc., New York, 1946), p. 53.

[6] *The Science and Engineering of Nuclear Power*, edited by C. Goodman (Addison-Wesley Press Inc., Cambridge, 1947), Vol. I, p. 15.

VII. CONCLUSIONS

The neutron component of the cosmic radiation in water at mountain altitudes has been studied. From an analysis of the experimental results it can be concluded that neutron energy and spatial distributions undergo a transition in the first 30-cm layer of water adjacent to the surface. Below the transition region the thermal neutron intensity remains almost constant over a 20-cm interval of water. The neutron production rate and the thermal neutron flux in water at an altitude of 10 600 feet are 4.6×10^{-5} neutron g^{-1} sec^{-1} and about 4.3×10^{-4} thermal neutron cm^{-2} sec^{-1}, respectively.

VIII. ACKNOWLEDGMENTS

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The author wishes to thank Professor Byron Cohn and Professor Mario Iona for their splendid cooperation during his stay at the Inter-University High Altitude Laboratory; and the Department of Mountain Parks of the City of Denver for their permission to use Echo Lake as the site for the experiment.

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High-Energy, Large-Angle Distribution of Pair Electrons Produced by Bremsstrahlung*

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The results of a calculation of the number of high-energy pair particles emitted into large angles in a pair production process initiated by bremsstrahlung are tabulated. A very approximate estimate of the effect of nuclear screening is given.

THE considerable amount of work being done at present with high-energy bremsstrahlung from electron synchrotrons and betatrons makes it useful to have some information on pair production at high energies and large angles. The computations below should have some use for estimating background and jamming levels, and may also be of interest in suggesting a test of some details of the pair production theory at high energies.

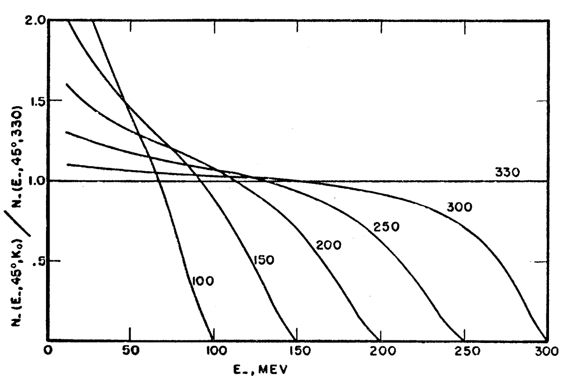

FIG. 1. Curves for extention of data in Table I to other values of k_0. Curves are labeled by k_0 in Mev. These curves were calculated for $\theta_-=45°$, but may be used for other angles between 22.5° and 90° with an accuracy of a few percent.

The expression obtained by Hough[1] for the angular distribution of high-energy electrons (or positrons) emitted into large angles in a pair production process has been integrated over the bremsstrahlung spectrum. The spectrum used is the zero angle formula obtained by Schiff,[2] normalized to 1 erg/cm² beam energy. Our notation is that of Heitler,[3] *viz.*, E_-, p_-, θ_- are, respectively, the electron total energy, momentum $\times c$, and angle relative to the photon. The same symbols with subscript $+$ refer to the positron. μ is the electron rest energy, and k_0 is the maximum energy of the bremsstrahlung spectrum. $N_-(E_-,\theta_-,k_0)$ is the number of electrons per hydrogen nucleus per erg/cm² beam energy per Mev electron energy per steradian.

$$I_-(E_-,\theta_-,k_0)=\int_{E_-}^{k_0} N_-(E_-',\theta_-,k_0)dE_-'$$

is the number of electrons whose energy exceeds E_-, per hydrogen nucleus per erg/cm² beam energy per steradian.

Hough's expression results from an approximate integration of the Bethe-Heitler differential cross section over positron angles, and is valid for energies E_+, $E_-\gg\mu$ and angles $\theta_-\gg\mu/E_-$. Outer screening is neglected. For electron energies near the maximum energy k_0 of the bremsstrahlung spectrum, the number of electrons N_- receives significant contributions from

* Assisted by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission, and by a grant from the National Science Foundation.

[1] P. V. C. Hough, Phys. Rev. **74**, 80 (1948), his formula 2.
[2] L. I. Schiff, Phys. Rev. **83**, 252 (1951).
[3] W. Heitler, *Quantum Theory of Radiation* (Oxford University Press, London, 1949), second edition, p. 196.