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Cosmic-Ray Neutrons near the Earth*

L. D. HENDRICK AND R. D. EDGE
University of South Carolina, Columbia, South Carolina

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The altitude distribution of cosmic-ray neutrons has been measured from ground level up to 1175 ft using BF_3 detectors on a television antenna tower. Neutrons of about 1-keV energy were measured by surrounding the BF_3 counters with cadmium-coated polyethylene cylinders. The flux near the earth was found to depend strongly on the soil water content. The distribution of neutrons below 1 eV was found from the difference in count rates of bare and cadmium-covered detectors and agrees with the result of a diffusion calculation. The neutron energy spectrum was investigated at the 45- and 1175-ft levels by counting with varying thicknesses of polyethylene surrounding the detectors, but little difference between the spectra for the two levels was discernible.

INTRODUCTION

THE flux of cosmic-ray neutrons as a function of altitude has been measured extensively at high altitudes, even beyond the earth's atmosphere.[1–6] Surprisingly, no measurements have even been made in the vicinity of the earth's surface. Such data are of importance in correlating cosmic-ray neutron data on the ground with measurements made at great altitudes in the air. They are useful in environmental studies such as the investigation of cosmic-ray effects on plants and animals, and in estimating the neutron distributions which result from air bursts of nuclear weapons.[7,8] Also, an experiment has been suggested by which measurements made on cosmic-ray neutrons near the lunar surface could provide an estimate of its hydrogen content.[9] It therefore seemed desirable to measure the neutron altitude dependence near the earth's surface.

GENERAL DISCUSSION

Previous measurements of the altitude dependence of the cosmic neutron flux made at high altitudes[1–6] have established that the dependence is exponential, i.e., $e^{-x/L}$, throughout most of the atmosphere where L is the absorption length and x is the atmospheric depth in g/cm^2. The value of L is dependent on geomagnetic latitude[4] and was approximately 160 g/cm^2 here. Below ground, the decrease in flux with increasing depth is initially the same as in air, but because of rapid hardening of the primary flux at depths of 5 to 10 m the absorption length increases to 250 g/cm^2 or higher.[10] We shall assume a value of 190 g/cm^2 as a suitable average.

The free neutrons present in the atmosphere are produced by interactions of the primary radiation, composed largely of protons, with nitrogen and oxygen nuclei. Some fast neutrons with energies of 1 BeV or more are produced by direct interactions or "star" events, but the most important production mechanism is the "evaporation" process from excited nuclei, which results in a Maxwellian energy spectrum at production peaked at about 2 MeV. The rate of production of neutrons per gram per second by the primary particles has been measured at ground level in various elements by numerous experimenters[5,11–15] and is found to vary with atomic weight approximately as $A^{-1/3}$. We have determined an average value for the production rate in air which, when converted to our geomagnetic latitude of 45°N using the results of Simpson,[4] was found to be about $(1.25\pm0.20)\times10^{-5}$ neutrons per gram per second.

Upon production the "evaporation" neutrons begin to lose energy by elastic collisions and are eventually absorbed, primarily by the $N^{14}(n,p)C^{14}$ reaction. The dynamic equilibrium of the neutron energy distribution has been calculated by Edge[6] and Hess *et al.*,[16] and measured by Hess *et al.*[17] This energy spectrum is quite smooth between the production peak at 2 MeV and about 10 eV where the $N^{14}(n,p)C^{14}$ reaction becomes important, however both calculations and measurements have ignored any effects on the energy spectrum which might be introduced by the proximity of the earth.

Previous calculations of the neutron altitude distribution near an air-earth or air-water boundary were

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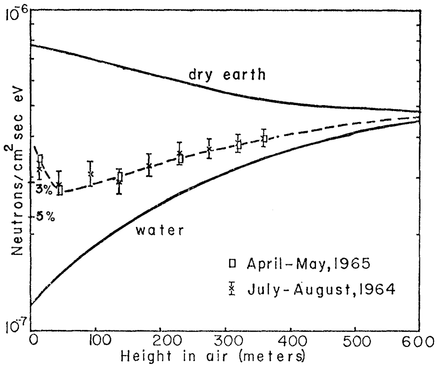

FIG. 1. Plot of neutron flux in "fast" region versus height in air. The solid curves are those calculated over dry earth and water, and the dashed curve is fitted (to them) at 1000 m of air. The calculated fluxes at ground level for 3% and 5% soil water content are shown on left axis. The errors for the points of April–May 1965 are given by the heights of the boxes.

made as early as 1940 by Bethe, Korff, and Placzek for cosmic rays[18] and more recently by Thompson, Ferguson, and Mather[8] for bomb bursts. However, these calculations were mainly concerned with slow-neutron distributions. In the measurements to be described below we have attempted to verify these calculations and also to explore the differences between the slow-neutron distribution and the distribution of neutrons with energies around 1 keV. In the discussion of the measurements which follows, we will refer to neutrons below ~1 eV as "slow" neutrons[4] and to those with energies near 1 keV as "fast" neutrons. The latter should be typical of the "smooth" region of the energy spectrum.

MEASUREMENT OF ALTITUDE DISTRIBUTIONS

BF_3 detectors were mounted on a small elevator in a 1500-ft television antenna tower to measure the neutron altitude distribution. The detector tubes were standard BF_3 counters, 2 in. in diameter by 19½ in. long, containing 96% B^{10} enriched boron trifluoride gas at 40 cm of Hg pressure. The anodes were tungsten wires, 0.002 in. in diameter with an active length of 12 in. Three of these tubes were connected in parallel and mounted 6 in. apart on the elevator roof. The counts were recorded on a scaler unit which also supplied 2600 V for the detectors. The counters were calibrated with a standard Ra-Be neutron source before and after each run to ensure there had been no drift in the sensitivity of the detecting system during the run.

"Fast"-Neutron Measurements

The data for the "fast" region was obtained by placing a 1-in.-thick cylinder of polyethylene around the detecting tubes and covering this with a cadmium sheath to stop neutrons below 1 eV in energy from entering the cylinder. One inch of polyethylene gave a maximum count rate for neutrons of about 750-eV energy.[19]

Runs of 15 min were made at 150-ft intervals up the tower. The data for each run were corrected for atmospheric pressure and humidity variations on different days and for the count rates obtained with the Ra-Be source. The results are shown in Fig. 1. Changes in the primary cosmic-ray flux from day to day during the runs, as determined from neutron-monitor data kindly supplied us by Professor J. A. Simpson (University of Chicago) were found to be insignificant.

"Slow"-Neutron Measurements

The data for the "slow" region were obtained by counting for 30 min at levels spaced 150 ft apart with the bare BF_3 tubes. These results were also corrected for pressure, humidity and source count. The counting tubes were then covered with a cadmimum sheath and counts were taken at the same levels as before. These data were subtracted from those obtained with the bare tubes and the results shown in Fig. 2 represent the total neutron flux for energies between thermal and 1 eV.

DISCUSSION OF MEASUREMENTS

The data in the "fast" region are compared in Fig. 1 with theoretical predictions obtained using a Green's-function technique on the Fermi age equation for both dry earth (assumed 69% oxygen, 24% silicon, 7% aluminum and density of 1.6 g/cm^2) and 100% water. It may be seen that the presence of moisture in the soil has a drastic effect upon the altitude dependence of neutrons with energies in the smooth region of the energy spectrum. An estimate based on the fast-neutron

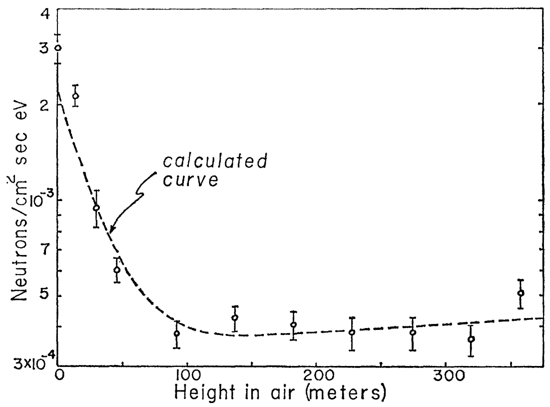

FIG. 2. Plot of neutron flux in "slow" region versus height in air. The data are fitted to the calculated curve at 100 feet (30.5 m).

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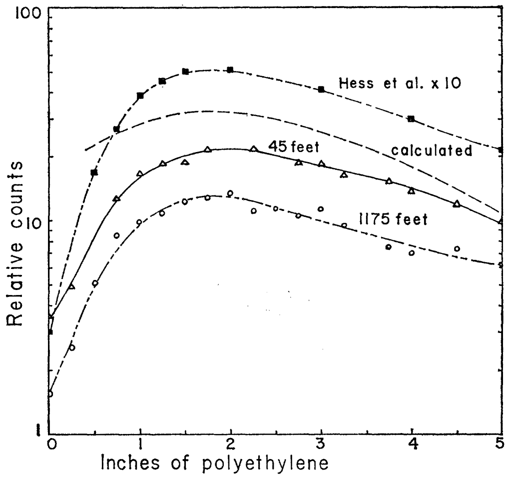

FIG. 3. Relative count rate versus polyethylene thickness.

data indicates that the soil water content was 3% to 5% while the value obtained from a soil sample was 3.7%. Wet earth thus tends to soak up fast neutrons from the air and slow them down rapidly. Many of these slow neutrons then diffuse back into the air and are subsequently absorbed by the $N^{14}(n,p)C^{14}$ reaction. It should be apparent that this process would distort considerably any measurement of the neutron spectrum made below 400–500 m altitude. The upward turn in the experimental curve below 100 m is probably due to the few fast neutrons produced in the earth which escape before being slowed down, since the net production rate in earth is greater than in air because of the difference in composition.

The calculated curve shown in Fig. 2 is the result of a diffusion calculation above dry earth. Since the detector is sensitive to all neutrons below $\sim$1 eV, the total flux of neutrons between 1 eV and thermal energies in air, as calculated from slowing down theory, was added to the result of a thermal-diffusion calculation. However, the flux of neutrons between thermal and 1 eV diffusing from earth was not included and this is probably the reason that the calculation is too low for the lowest two points.

SOURCES OF ERROR

The data for the "fast" region were not corrected for neutrons produced in the polyethylene cylinders; however, an approximate calculation indicates that this would account for only 3.2% of the total count rate while the statistical error of the best point is about 3.7%.

The statistical error of the points for the slow neutrons is about 8%. The number of neutrons produced in the tower itself was found to be insignificant.

The count rate of the bare BF_3 detectors at ground level was used to calculate the neutron production rate from the relation given by Bethe *et al.*[18] The result of 0.90×10^{-5} neutrons/g sec compares favorably with the value of 1.25×10^{-5} obtained from other experiments and used in the calculations.

ENERGY-SPECTRUM MEASUREMENTS

Since the neutron energy spectrum should change as ground level is approached, measurements were made at two different heights on the tower in an attempt to detect this change. Using one of the BF_3 counters described previously, surrounded by polyethylene cylinders of different thicknesses, two sets of data were taken at both the 45- and 1175-ft levels. The relative count rates for each level are plotted versus polyethylene thickness in Fig. 3 along with the data of Hess *et al.*[17] for an altitude of 5300 ft and magnetic latitude of 44°N. Also shown is a curve calculated using the measured sensitivities of different polyethylene thicknesses as a function of energy determined by Hess *et al.*[17] in conjunction with the theoretical energy spectrum. The discrepancy between theory and experiment at small thicknesses arises because the detection-energy sensitivities are not well known in this region. Very little difference is discernible in the measured curves using this technique.

ACKNOWLEDGMENTS

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