Correlation of Meteorological Parameters with Cosmic-Ray Neutron Intensities*

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The correlation of variations in the neutron intensity of cosmic radiation with variations in meteorological conditions has been investigated at 6262 ft and at sea level over the period from 1952 to 1955. A low-energy directional neutron detector was operated during the summer months of this period to monitor the intensity of neutrons with energies less than 0.5 ev. In addition a lead-paraffin pile detector was used to monitor the moderate energy neutrons.

From the partial correlational analysis for the low-energy neutron intensity the following regression coefficients are obtained: barometric pressure (-10.9 ± 0.9) percent/cm Hg; specific humidity $(-2.0\pm2.5)\%/0.01S$, where S is the local specific humidity; local atmospheric temperature $(-0.07\pm0.09)\%/\text{F}^\circ$. For the moderate-energy neutron detector the only significant regression coefficient obtained is for barometric pressure, $\alpha=(-9.70\pm0.15)\%/$cm Hg. The results for the dependency of neutron intensity upon barometric pressure and temperature are in agreement with the predicted values, but the results for the specific humidity correlation do not agree with the theoretical predictions. The significance of the latter result is discussed.

Experiments have also been made to determine the energy spectrum of low-energy neutrons at ground elevations by using paraffin moderators of different thicknesses placed over the low-energy directional neutron detector. The observed proportion of neutrons with energy exceeding 0.6 ev is less than predicted theoretically.

I. INTRODUCTION

WHILE considerable study has been made of the cosmic-ray neutron intensities in the atmosphere[1–3] as a function of altitude, latitude, and longitude, far less attention has been devoted to the effect of changes in meteorological conditions at a given station upon neutron intensities.

Several investigations[3,4] have determined the barometric coefficient for fast neutrons. The most accurate value appears to be that reported by Simpson.[3]

The effect of temperature upon neutron intensity should be very small since the neutrons are produced by the primary cosmic radiation through a nucleonic cascade process. If the cosmic-ray neutrons attained thermal energies in the slowing down process in the atmosphere, then one might expect some temperature effect for neutrons of energies $\sim kT$. Since on the average the neutrons are slowed to 0.25–0.30 ev before capture by nitrogen,[5] the fraction of thermal energy neutrons is $\sim0.5\%$. Even if the temperature dependence of meson links in the nucleonic cascade process is included, it has been shown[3] that the total temperature coefficient should be $<-0.006\%/\text{C}^\circ$ at geomagnetic latitude $\lambda=50°$N.

The reported effect of changes in the water content of the atmosphere upon the neutron intensity appear to be anomalous. Bethe, Korff, and Placzek[1] have calculated the change in the low-energy neutron intensity due to presence of water vapor, which they attributed to the larger scattering cross section and higher efficiency of the slowing down process for neutrons by hydrogen, and concluded that it would not be significant except on hot, humid days. The results of Agnew, Bright and Froman,[6] which showed large increases in the neutron counting rate at airplane altitudes when underneath large clouds, are difficult to explain on the basis of the above-mentioned process. In any event to determine the effects of specific humidity upon the neutron intensity, measurements should be confined to the low-energy portion ($E<0.5$ ev) of the neutron energy spectrum.

Simpson[3] has developed a relationship between the observed neutron intensity at a given location and the flux of primary cosmic radiation. Hence, variations in the neutron intensity may be related to variations in the primary intensity provided the effects of the earth's atmosphere upon the neutron intensity are evaluated. The present investigation was initiated to study the

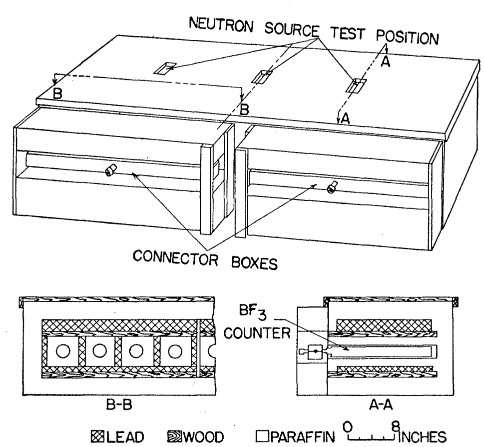

FIG. 1. Lead-paraffin neutron monitor, D-1, with eight BF_3 counters.

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[1] Bethe, Korff, and Placzek, Phys. Rev. **57**, 573 (1940).

[2] L. C. L. Yuan, Phys. Rev. **81**, 175 (1951). W. P. Staker, Phys. Rev. **80**, 52 (1950). J. A. Simpson, Phys. Rev. **73**, 1389 (1948); **74**, 1214 (1948); **76**, 165 (1949); **83**, 1174 (1951) and references therein.

[3] J. A. Simpson, Phys. Rev. **90**, 934 (1953) and references therein.

[4] V. Cocconi Tongiorgi, Phys. Rev. **76**, 517 (1949).

[5] W. Heisenberg, *Cosmic Radiation* (Dover Publications, New York, 1946), p. 152.

[6] Agnew, Bright, and Froman, Phys. Rev. **72**, 203 (1947).

effect of barometric pressure, atmospheric temperature, specific humidity, precipitation, and cloud cover upon the low-energy ($E<0.5$ ev) atmospheric neutrons and also upon the moderate-energy neutrons as measured by locally produced neutrons in lead-paraffin piles both at Durham, New Hampshire (sea level) and Mt. Washington (elevation 6262 ft).

II. APPARATUS AND METHODS OF MEASUREMENT

Two types of cosmic-ray neutron monitors were employed which differed in neutron energy response. Both monitors employed commercial boron trifluoride proportional counters enriched in B^{10} isotope.[7] In Fig. 1 is shown a section of the lead-paraffin pile used to monitor the moderate-energy neutrons, hereafter referred to as *D*-1. The regular geometric arrangement of the lead and paraffin permits enlargement of the basic unit of *D*-1 to contain any number of BF_3 counter tubes. The counting rate of the tubes placed in such an arrangement is due principally to neutrons originating from stars produced in the lead and paraffin.

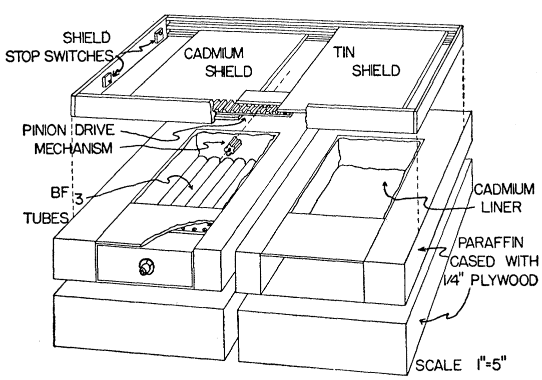

FIG. 2. Low-energy directional neutron detector, *D*-2, with five BF_3 counters in each half-section.

The second type of neutron monitor used, hereafter referred to as *D*-2, is shown in Fig. 2. *D*-2 is more sensitive to neutrons of energy less than 0.5 ev, and is designed to minimize the effect of changes in local surroundings.

D-2 is practically opaque to neutrons incident on any surface except the top. By alternating each hour Cd and Sn shields of 0.033-in. thickness over the top of the two sections of *D*-2, the resulting difference in hourly counting rates is then proportional to the number of neutrons with energies less than 0.5 ev. The thickness of the paraffin for the sides and bottom was determined by requiring that the maximum of the energy distribution at the cadmium lining for neutrons of $\sim$1-Mev energy incident on the outside be much less than the Cd cutoff and that at the same time *D*-2 be of reasonable physical size.

[7] Boron trifluoride counters (2×14 inches) supplied by Nancy Wood Counter Laboratories, Chicago, Illinois.

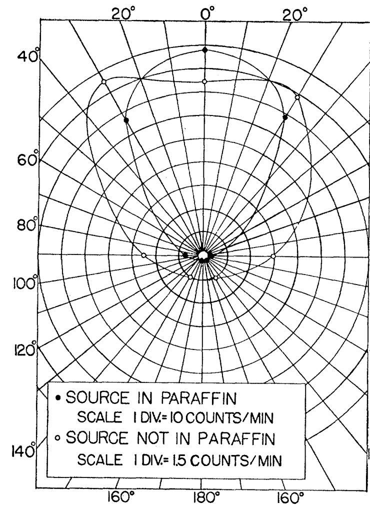

FIG. 3. Directional selectivity of low-energy neutron detector measured with a Ra-Be source.

The directional selectivity of *D*-2 was measured by placing a Ra-Be neutron source at different positions equidistant from the center of the BF_3 tubes and in a plane perpendicular to the axis of the tubes. The results of this test are shown in Fig. 3. Since the energy distribution of neutrons from a Ra-Be source surrounded by 7.5 cm paraffin approximates that of cosmic-ray neutrons, it can be expected that the response of *D*-2 should be the same for cosmic-ray neutrons.

The electronic systems for both *D*-1 and *D*-2 are identical and are of the conventional type used for proportional counting. The positive high voltage applied to the BF_3 tubes was regulated at 2400 ± 10 volts. To maintain a check on the operational stability, dual electronic systems were used for each detector. The over-all stability of both detecting systems was checked periodically by a Ra-Be neutron source and by means of calibrated test pulses.

III. REDUCTION OF DATA AND EXPERIMENTAL RESULTS

A. Low-Energy Neutron Detector *D*-2

Data obtained with detector *D*-2 operating at Mt. Washington during the summer months of 1953–1955 have been correlated with the meteorological data recorded at the Mt. Washington Observatory for corresponding periods. A linear correlation of neutron counting rate, N, with the meteorological parameters—barometric pressure, specific humidity, and local ground temperatures—was assumed:

$$N=N_0+b_{NB\cdot S\theta}B+b_{NS\cdot B\theta}S+b_{N\theta\cdot BS}\theta, \qquad (1)$$

where N_0=neutron counting rate under arbitrarily defined standard atmospheric conditions, B=baro-

TABLE I. Partial correlation of 12-hr average neutron counting rate for detector *D*-2 with barometric pressure, specific humidity, and temperature at elevation 6262 ft, geomagnetic latitude 55.5°N.

Period	1953 July 21–September 13	1954 July 3–August 31	1955 June 9–September 13 (*D*-2*a*)	1955 June 9–September 13 (*D*-2*b*)
Mean 12-hr average counting rate (÷2) hr^{-1}	216	245	222	214
Standard deviation of counting rate, σ, hr^{-1}	16	18	14	12
$b_{NB\cdot S\theta}$, hr^{-1} in. Hg	-43.5 ± 22.4	-72 ± 9	-61.7 ± 5.5	-59.8 ± 5.3
$C_{NB\cdot S\theta}$, %/in. Hg	-20.1 ± 10.2	-29.5 ± 3.6	-27.8 ± 2.5	-28.0 ± 2.5
$b_{NS\cdot B\theta}$, hr^{-1}/unit S	-9380 ± 5520	2850 ± 1790	-452 ± 554	-370 ± 541
$C_{NS\cdot B\theta}$, %/0.01S	-43 ± 25	$+12\pm7$	-2.0 ± 2.5	-1.7 ± 2.5
$b_{N\theta\cdot BS}$, hr^{-1}/F°	$+2.92\pm1.82$	-1.7 ± 0.5	-0.16 ± 0.19	$+0.09\pm0.19$
$C_{N\theta\cdot BS}$, %/F°	$+1.34\pm0.84$	-0.7 ± 0.2	-0.07 ± 0.09	$+0.04\pm0.09$
$\beta_{NB\cdot S\theta}$	0.16	0.67	0.63	0.70
$\beta_{NS\cdot B\theta}$	0.64	0.22	0.079	0.075
$\beta_{N\theta\cdot BS}$	0.63	0.46	0.100	0.056
R	0.22	0.74	0.66	0.71
Q, standard estimate of error, hr^{-1}	15	12	10.7	8.7
R'	0.21	0.29	0.29	0.26

metric pressure,[8] S=local specific humidity (mass of water per unit mass of moist air), θ=local ground temperature, $b_{NB\cdot S\theta}$=net regression of the neutron counting rate on the barometric pressure with temperature and specific humidity constant, $b_{NS\cdot B\theta}$=net regression of the neutron counting rate on specific humidity with barometric pressure and temperature held constant, $b_{N\theta\cdot BS}$=net regression of the neutron counting rate on the temperature with barometric pressure and specific humidity held constant. It should be noted we have assumed that the neutron counting rate depends linearly upon the atmospheric pressure which is only a first approximation since $N=N_0e^{-\alpha(p-p_0)}$, where N=neutron counting rate at pressure p, N_0 =neutron counting rate at pressure p_0, α=pressure coefficient, appears to fit the experimental data best.[2–4] For the ordinary pressure variations observed and the statistical accuracy of the counting rates for *D*-2, the first order approximation of a linear correlation is sufficiently accurate.

The results of the correlational analysis for 1953–1955 are given in Table I. In these results no significance should be attached to the higher counting rate during 1954 since a slightly different arrangement of BF_3 tubes was used. It is apparent that the correlational analysis for the 1955 run is the most significant and the results from both halves of *D*-2 are shown separately, designated as *D*-2*a* and *D*-2*b*. The multiple correlation coefficient R is much larger than the multiple correlation coefficient with the barometric effect excluded, R', except for 1953 when R itself is small. This shows the predominant meteorological factor to be the barometric pressure. This is also verified by the values of the β coefficients, defined by $\beta_{12\cdot34}=b_{12\cdot34}\ \sigma_1/\sigma_2$, where σ_1 =standard deviation in variable 1, and σ_2=standard deviation in variable 2. The values of the relative barometric coefficient, $C_{NB\cdot S\theta}=\alpha$, are in agreement with previously cited results[2–4] within experimental errors.

The relative regression coefficient for the neutron intensity with local ground temperature is negligibly small for the data obtained in 1955. The large positive coefficient for 1953 was probably due to the temperature dependence of the background of the BF_3 tubes, as some tubes were found to have backgrounds which depended critically upon temperature.[9] The negative temperature coefficient obtained in 1954 is not felt to be any more significant than the values for 1955, since the total number of 12-hour periods is less and three BF_3 tubes were removed from *D*-2 because of spurious background counting rates.

The dependence of the low-energy neutron intensity upon specific humidity is not in agreement with theoretical predictions. It would be expected that the number of low-energy neutrons would increase with increasing water vapor content of the atmosphere, for the efficiency of the slowing down process is greater under these conditions owing to the additional hydrogen atoms. A calculation of the effect of the addition of water, either as a vapor or a liquid, upon the slowing down process of neutrons yields the results shown in Table II assuming the fraction N/N_0 of neutrons of initial energy E which attain the energy E_2 without capture, is

$$\exp\left(-\int_{E_2}^{E}\frac{\sigma_{\text{cap}}}{\sigma_{\text{cap}}+\sigma_{\text{scat}}}\right)\frac{dE}{\Delta E},$$

[8] The relation between the barometric pressure measured at a mountain station and the air mass above the mountain is complicated by the effect of the high wind velocities at these elevations. The barometric pressure recorded at Mt. Washington is partially corrected for the effect of the wind velocity by use of a Pitot tube. For details, see R. D. Falconer, Trans. Am. Geophys. Union **28**, 385 (1947).

[9] Lockwood, Woods, and Bennett, Rev. Sci. Instr. **25**, 446 (1954).

where

$$\sigma_{\text{cap}} = \frac{0.31 \times 10^{-24}}{\sqrt{E}} \text{ cm}^2,$$

$$\sigma_{\text{scat}} = 8.5 \times 10^{-24} \text{ cm}^2,$$

and

$$\Delta E/E = 2A/(A+1)^2 = K.$$

The appropriate values of K for dry air and moist air are used in the calculation. The effect of changes in the water content of the atmosphere upon the neutron production has been considered negligible.

From this calculation the most probable energy prior to capture is 0.34 ev for dry air and 0.28 ev for moist air, and an increase of about $8\%/0.01S$ would be expected for the fraction of neutrons with $E \leqslant 0.5$ ev.

If any significance is to be attached to the values of $C_{NS \cdot B\theta}$ given, then there is no consistent agreement with theoretical predictions. The fluctuations in the specific humidity during each of these three periods are approximately the same as indicated by the standard deviations in the specific humidity: 1953, $\sigma = 2.2 \times 10^{-3}$; 1954, $\sigma = 1.35 \times 10^{-3}$; 1955, $\sigma = 2.5 \times 10^{-3}$. It seems evident that there is no appreciable change in the neutron intensity under conditions of high specific humidity. The lack of any significant correlation may be due to the fact that the experiments were not conducted in the free atmosphere and that the local specific humidity is not a true indication of the average specific humidity over a large fraction of the mean distance travelled by the neutrons in slowing down. A correlation of upper air data from the Portland, Maine, weather station with the counting rate of D-2 was not significant.

The effect of changes in cloud cover upon the observed low-energy neutron intensity has been found to be negligible, which does not agree with the results of Agnew, Bright, and Froman.[6]

The effect of world-wide neutron intensity-time variations upon these correlations is negligible owing to absence of any variations greater than the statistical uncertainty, $\sigma_0 = 2.5\%$, in the 12-hour average neutron counting rate for D-2 during these periods. Referring to Table I, the neutron intensity-time variations in 1953 were on the average $<1\%$, with a maximum intensity variation of 2%; in 1954, $<1\%$, and 2.5%, respectively; in 1955, $<1.5\%$ and 2.5%, respectively.

B. Moderate Energy Neutron Detector D-1

Table III presents the results of a similar correlational analysis of the data obtained from detectors of the type D-1 during 1953–1954 at Mt. Washington and Durham. D-1 consisted of five BF_3 tubes in 1953 and eight BF_3 tubes in 1954–1955.

From Table III it is apparent that the only meteorological variation producing a detectable change in the neutron counting rate of a type D-1 detector is the barometric pressure. The values of α in Tables I and III agree, recognizing that the values for type D-1 detector will be ~ 3 percent lower due to the inclusion of the background counting rate of the BF_3 counters. As the counting rate N depends linearly upon barometric pressure B only to a first approximation, a simple correlation of $\ln N$ with B during this period of a minimum in worldwide intensity-time variations was made to give a more precise value of $\alpha = -9.70 \pm 0.15\%/\text{cm}$ Hg, which is now being used to correct the observed neutron counting rate to a standard station pressure.

TABLE II. Calculated effect of humidity on the slowing down of neutrons in air.

Energy, E_2 (ev)	10	5	1	0.5	0.2	0.1	0.05	0.02	0.01
N/N_0, dry air (percent)	82	76	55	44	27	16	8.4	2.2	0.6
N/N_0, moist air (percent) $S = 0.012$	84	79	59	47	31	20	11	3.3	1.0

C. Determination of Energy Spectrum of Low-Energy Cosmic-Ray Neutrons

From Table II it is seen that the energy distribution of cosmic-ray neutrons should be changed by the presence of water vapor in the atmosphere. To analyze this effect, the energy distribution of at least the low-energy portion of the atmospheric neutrons should be measured. If thin shields of different materials, the transmission coefficients of which have a different functional energy dependence upon the neutron energy for $E < 0.5$ ev, are placed directly over D-2, two difficulties are encountered. First, the neutron production in the materials must be equal and as small as possible. Second, the total cross sections of the materials must be relatively large ($\sigma_T > 50$ barns) and vary rapidly with neutron energy. It is difficult to simultaneously satisfy both of these conditions.

Therefore, an alternative method of estimating the low-energy neutron spectrum was sought. Different thicknesses of a single moderator, paraffin, were placed over one-half of detector D-2, which was modified to reduce the solid angle of acceptance for neutrons. If the known theoretical energy spectrum for neutrons is assumed, then the number of neutrons which will be slowed down by different moderator thicknesses to energies <0.4 ev can be calculated. The theoretical variation in the number of neutrons having $E > 0.4$ ev can be compared with the Sn-Cd difference in counting rate for D-2. If corrections are applied for the scattering, albedo effect, and efficiency of the BF_3 tube arrangement measured with a Ra-Be neutron source surrounded by 3 inches of paraffin, and a factor included for the neutron production in the paraffin, it is found that the observed energy spectrum of neutrons is shifted more toward lower energies in comparison with the theo-

TABLE III. Partial correlation of 12-hr average neutron counting rate for D-1 detectors with barometric pressure, specific humidity, and temperature at elevation 6262 ft, geomagnetic latitude 55.5°N (Mt. Washington), and at sea level, geomagnetic latitude 54°N (Durham).

Period	Mt. Washington 1953 July 21–September 13	1954 June 12–September 16	1955 June 12–June 21 July 9–July 21	Durham 1954[b] January 12–May 3
Mean 12-hr average counting rate (÷8), hr^{-1}	1907	3744	3693	353.7
Standard deviation of counting rate, hr^{-1}	62	158	150	25.4
R	−0.944	−0.9809	−0.9951	−0.983
$b_{NB\cdot S\theta}$ hr^{-1}/in. Hg	−463	−932	−892	−88.4
$C_{NB\cdot S\theta}$ %/in. Hg ($=\alpha$)[a]	−24.3±1.1	−24.9±0.4	−24.2±0.4	−25.0±0.4
$C_{NB\cdot S\theta}$ %/cm Hg[a]	−9.6±0.5	−9.8±0.2	−9.5±0.2	−9.84±0.15
$b_{NS\cdot B\theta}$ hr^{-1}/unit S	4730			
$C_{NS\cdot B\theta}$ %/0.01S	+2.48±2.80			
$b_{N\theta\cdot BS}$ hr^{-1}/F°	−1.73			
$C_{N\theta\cdot BS}$ %/F°	−0.09±0.09			
Q, standard estimate of error (%)	1.1	9.8	0.4	1.3

[a] Relative barometric pressure coefficient defined as b_{NB}/N, where N = total counting rate including background of BF_3 counters. This background is 3% of N.
[b] D-1 type detector using 4 sections only.

retical spectrum. In particular, the fraction of neutrons with $0.6<E<25$ ev seems to be $\frac{1}{3}$ that predicted; the fraction with 0.6 ev$<E<$300 kev is larger but this latter result is subject to greater uncertainty.

IV. CONCLUSIONS

The only important meteorological parameter in producing changes in the cosmic-ray neutron intensity is the barometric pressure. The average barometric coefficient α has been determined to be (-9.7 ± 0.2) percent/cm Hg from several different correlational analyses. Changes in local specific humidity, precipitation, cloud cover, and temperature apparently do not produce a measurable effect upon the neutron intensity as monitored by either type of detector. The absence of a significant correlation for the neutron counting rate of detector D-2 with the latter meteorological parameters may be due to: (a) the order of magnitude of this effect; (b) the fact that local meteorological parameters were used; (c) the location of the monitor at ground elevations rather than in the free atmosphere. A detector sensitivity of at least an order of magnitude greater would be required to measure the changes in the low-energy neutron spectrum due to variations in the specific humidity.

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