The Energy Distribution and Number of Cosmic-Ray Neutrons in the Free Atmosphere

S. A. KORFF AND B. HAMERMESH
New York University, New York, New York

(Received October 27, 1945)

A balloon flight to determine the energy distribution and the number of neutrons in the free atmosphere, produced by the cosmic radiation, is described. It is found that there are practically no thermal neutrons in the free atmosphere, in contrast to the fact that near the surface of the ground most of the neutrons are thermal. The number and the rate of production of the neutrons increases rapidly with elevation, in good agreement with previous measurements.

INTRODUCTION

IT is well known that, among other effects, the cosmic radiation produces neutrons in the atmosphere. These neutrons are presumably evaporated out of nuclei by high energy constituents of the radiation, and originally have comparatively high energies, of the order of a few Mev or so. The neutrons then experience elastic and inelastic collisions with the nitrogen and other nuclei in the atmosphere. Finally they become slow, and are absorbed. On the basis of such a picture, Bethe, Korff, and Placzek[1] calculated the energy distribution which was to be expected of these neutrons. These authors (to be referred to subsequently as BKP) concluded that as a consequence of capture of slow neutrons by nitrogen, there should be comparatively few slow or thermal neutrons in equilibrium in the free atmosphere. Thus the neutrons would be in a "diffusion equilibrium," in which they would be continuously being produced, slowed down, and captured, with few ever attaining thermal velocities. They (BKP) also concluded that near the surface of the earth or near the surface of water the energy distribution would be primarily determined by the water in the vicinity. Some neutrons which had been produced in the water and slowed down in the water, or which had been produced in the air and had diffused down into the water, would diffuse back up from the surface into the air and most of these would have thermal velocities. That the neutrons near the ground are largely thermal is known, because it has been found by Korff and Clarke[2] that cadmium shields cut out most of the neutrons at the surface of the ground at various elevations, e.g., sea level and Mt. Evans. The purpose of the present experiment was to study experimentally, in the free atmosphere, the energy distribution and number of the neutrons produced by the cosmic radiation.

EXPERIMENTAL PROCEDURE AND APPARATUS

In order to study the energy distribution of the neutrons, a flight employing a neutron counter was carried out. This neutron counter was carried to high elevations in a free balloon experiment in which techniques[3] which have been previously described were used. The counter used in this experiment was 100 cm long and 4.9 cm in diameter. It had a volume of 1850 cc and was filled to a pressure of 28 cm of boron trifluoride to which xenon was added to increase the pressure by two cm. It was operated at about 2000 volts. The counter was arranged in a vertical position and two shields, one made of cadmium, $\frac{1}{2}$-mm thick, the other of boron (6 mm of boron carbide), were so disposed that they would automatically at prearranged intervals slip over the counter. The entire arrangement was cyclical and was driven by a small electric motor. In the cycle used, first the boron shield would be in place around the counter for two minutes, then would follow a period of two minutes with no shield, then the cadmium shield would be in place for two minutes and then again no shield. About twelve seconds was required to change shields. The counts occurring during the interval

[1] H. A. Bethe, S. A. Korff, and G. Placzek, Phys. Rev. **57**, 573 (1940).
[2] S. A. Korff and E. T. Clarke, Phys. Rev. 61, 422 (1942).
[3] E. T. Clarke and S. A. Korff, J. Frank. Inst. **232**, 217 (1941).

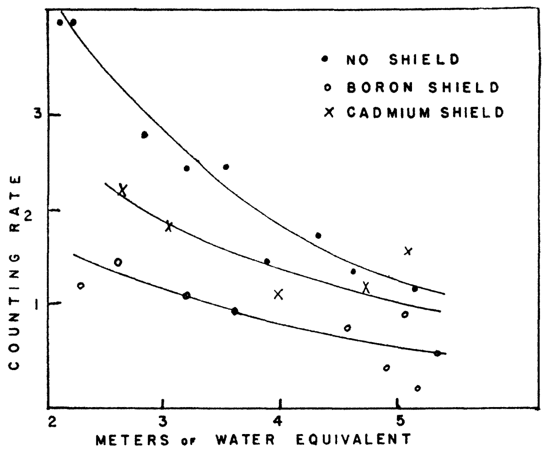

FIG. 1. Counting rate, in arbitrary units, observed with no shield and with boron shield, as a function of altitude.

while the shields were in motion were disregarded. A sliding contact caused emission of a signal which informed the observer which shield was in place. The counting rates in each of the three positions, that is, with no shield, with the cadmium shield and with the boron shield could be determined. These counting rates represented the number of counts occurring during the interval of approximately two minutes. Since the altitude of the instrument was known from the barograph which accompanied it, it was, therefore, possible to obtain the counting rate with each of the two shields separately and with no shield, as a function of elevation.

RESULTS

The counting rates obtained with and without the boron shield were plotted as a function of position in the atmosphere expressed in meters of water equivalent below the top and are shown in Fig. 1. The solid points represent the counting rate with no shield, and the circles represent the counting rate with the boron shield in place. A smooth curve has been drawn (by inspection) through the experimental points. The differences between the two smooth curves, i.e., the difference between the counting rates with and without the boron shield is presented in Fig. 2. We shall call this curve the "boron difference." The difference curve represents the effect produced by the shield and indicates the amount of the radiation which was cut out by that shield. Each point in Fig. 1 is based on the number of counts which occurred during an interval of approximately two minutes. In computing the number of counts occurring in each interval, a correction was made for the length of time during which the instrument was not sensitive to the cosmic radiation because it was recording the temperature or the pressure or the shield position, or the shield was in motion. The approximate accuracy may be judged from the statistical scatter of the points in Figs. 1 and 2.

DISCUSSION

Consider the quantities measured by the counter with the shields as described above. The counter employs a boron gas and a count occurs each time a neutron is captured by B^{10} nucleus. Since the boron capture cross section for neutrons follows the $(1/v)$ law, the counter will detect neutrons of all energies, from thermal up to hundreds of volts. At still greater energies the detector continues to be sensitive but the cross-section decreases to so small a value that competing processes, e.g., recoils, become the predominating factor. The counter thus measures neutrons of all energies, efficiently by capture in the low energy region, inefficiently by capture in the intermediate energy region, and inefficiently by recoil at high energies. Most of the counts, in a neutron diffusion equilibrium such as exists in the atmosphere, will be produced by neutrons

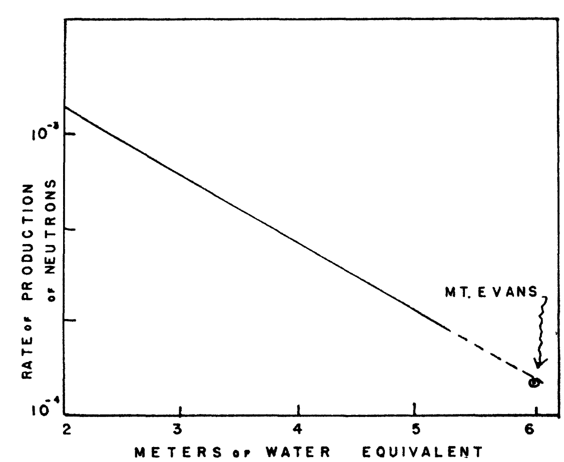

FIG. 2. Rate of production of neutrons by the cosmic radiation in the atmosphere; q, per gram per second, derived from Fig. 1, as a function of altitude. Point at 6 meters previously observed on Mt. Evans, for comparison.

in the lower energy ranges, and by thermal neutrons if such exist.

A cadmium shield, by virtue of the extremely large capture cross section of cadmium for thermal neutrons, will exclude thermal neutrons. Since, however, cadmium absorption does not follow the $(1/v)$ law, such a shield will not obstruct the passage of neutrons whose energy is a volt or more. The difference in the counting rate of a boron-trifluoride counter, with and without a cadmium shield, serves to determine the number of thermal or very slow (say below 0.3 volt) neutrons. On the other hand, the boron shield has the same dependence of efficiency on energy as has the detector. Hence the fraction of the neutrons which get through the absorber and are detected by the detector is independent of the energy.

At any given velocity the intensity (or number of neutrons per second) getting through the absorber, I, is related to the number I_0 incident in the absorber, through the equation

$$I = I_0 e^{-\alpha x}, \qquad (1)$$

where x is the thickness of the absorber and α is the absorption coefficient, which is defined by

$$\alpha = Nd\sigma/w, \qquad (2)$$

where N is Avogadro's number, d the density of the absorber, σ the capture cross section of the absorber for neutrons of the velocity under discussion, and w the atomic weight of the absorber. In this case x was about 0.6 cm, d was about unity, and w about 56. Assuming four boron atoms per molecule and taking σ as 550×10^{-24} sq. cm for thermal neutrons (a figure which already includes the B^{10}:B^{11} isotope ratio) we find that no detectible number of neutrons will get through the boron shield at thermal velocities. Indeed, applying the $(1/v)$ law to the value of σ in Eq. (2), we find that not one percent of incident neutrons will get through the boron shield unless their energies are nearly ten times thermal.* At this energy the sensitivity of the detector is one-tenth of what it is for a thermal neutron, and hence the number detected is correspondingly less. At high energies, when, because of the $(1/v)$ law, σ in Eq. (2) becomes small, the exponential in Eq. (1) may be expanded and written in terms of its first two series members. The number of neutrons detected, N, will be related to the number N_0 incident in the absorber by

$$N = N_0 E_d(v) E_a(v), \qquad (3)$$

where $E_d(v)$ and $E_a(v)$ are the efficiencies of the detector and absorber, each a function of the velocity. The efficiency of a detector is the fraction of the neutrons incident upon it which are detected, and the efficiency of an absorber we define as the fraction of the number of neutrons incident upon it, which penetrate it. These two efficiencies are, as we have pointed out, reciprocal functions of the velocity and hence N/N_0 is independent of the velocity. In these experiments, N/N_0 is small. The boron may be thought of as excluding neutrons of all energies. Thus the cadmium difference should be a measure of the number of thermal neutrons, while the boron difference should be a measure of all the neutrons.

Now the BKP calculations predicted that in the free atmosphere there should be practically no thermal neutrons: while near the ground many of those present might be thermal. Hence we might expect the boron difference to be determined by the total number of neutrons, a quantity known to increase rapidly with elevation, while the cadmium difference should be small after the instrument had left the ground. Inspection of Fig. 1 shows that this expectation was admirably fulfilled. The experiment may, therefore, be regarded as a verification of the BKP postulates.

The BKP energy distribution also checks with that found near the surface of the ground. It will be recalled that Korff and Kupferberg[4] operated a large neutron counter near sea level with a boron and a cadmium shield. The boron difference was found to be only about ten percent greater than the cadmium difference, indicating that almost all the neutrons were thermal. The counter used in the flight discussed in the present paper was much smaller, and operation at sea level gave so low a neutron counting rate (boron difference) that the measurement at sea level

* The exponent in Eq. (1) becomes unity in this experiment for a neutron energy of about 33 electron volts.

[4] S. A. Korff and M. Kupferberg, Phys. Rev. 65, 253(A) (1944).

with the flight set had small statistical accuracy. On the other hand the larger counter could not be flown for reasons of weight.

It will be seen in Fig. 1 that the counting rate when the boron shield is in place is not zero. There is always a background present, which is produced by several agencies, namely (a) natural contamination alpha-particles, (b) cores of giant showers, (c) protons and nuclear explosion processes and stars, and (d) neutrons which got in through those areas which the shield did not cover, e.g., the ends. This background increases slowly with elevation. This is to be expected, since, while (a) should be independent of altitude, the remaining agencies will show an altitude dependence.

The question has been raised as to whether there is any appreciable "mass effect" in the flight experiment. By this is meant that if a mass, such as the shield, surrounds the counter, the various components of the cosmic radiation might (a) produce any secondary effects in such a mass which would actuate the counter or (b) such a mass might exclude from the counter some heavily ionizing events which might cause it to count. In other words, would a proportional counter, not sensitive to neutrons, have its counting rate altered appreciably by the presence around it of a mass equivalent to half a millimeter of cadmium? The fact that the cadmium difference is so very nearly zero indicates that the mass effect is negligible, unless one makes the improbable assumption that the mass effect is exactly equal and opposite to the number of thermal neutrons at each elevation.

The counting rate of the counter may be expressed in terms of the rate of production q of neutrons per gram per second in the atmosphere. It was shown in the BKP calculations that the relation between these quantities was given by the equation:

$$q = 22.4 \times 10^3 n\sigma_A / VP\sigma_B w, \tag{4}$$

where n is the number of counts per second (the boron difference), V is the volume of the counter, p the pressure in atmospheres of BF_3, w the average atomic weight of the surrounding substance in which the production takes place, σ_A and σ_B are the cross sections for capture of the air and of the detector, respectively. Taking w as 29, and σ_A and σ_B as 1.5 and 550 each $\times 10^{-24}$ sq. cm, respectively, and the dimensions of the counter as stated above, the value for q at the highest elevation reached in this flight, two meters of water equivalent, was about 1.75×10^{-3} neutrons per gram per second. A scale of values of q is shown on Fig. 2.

In order to compare this with the values of q obtained in other experiments, the point determined on Mt. Evans[2] is also shown on Fig. 2. Satisfactory agreement is found with the number of neutrons obtained in a different experiment and with another counter.

The density of neutrons ρ per cc is related to the rate of production q by the equation

$$\rho = qtd, \tag{5}$$

where t is the average lifetime of the neutrons, i.e., the time-interval between their production and absorption. If we take t as between 0.1 and 0.2 second,[5] and the density of air d as 10^{-4} gram/cc at this elevation, ρ at two meters of water equivalent will be between 3.5 and 7×10^{-8} neutron per cc. It should be noted that this value is independent of velocity and refers to neutrons of all velocities.

The increase of the rate of production of neutrons with elevation is a factor of about seven in the 4-meter interval from 6 to 2 meters of water equivalent. This corresponds to an average factor of about 1.55 per meter of water in this interval.

ACKNOWLEDGMENTS

The flight described was launched from the grounds of the University of Chicago. The authors wish to extend their especial thanks to Professor Schein and to all of his staff for the most effective, extensive, and pleasant cooperation it has been our pleasure to experience. Financial support was received from the Carnegie Institution of Washington. The instrument, and especially the automatic shield-positioning mechanism, was built by L. G. Collyer; and S. Friedland of New York University assisted with various operations.

Note added in proof by H. A. Bethe,* S. A. Korff, and G. Placzek.** The question has

[5] S. A. Korff, Rev. Mod. Phys. 11, 211 (1939).

been raised as to just how much the cadmium shield may be expected to cut out. Now the equilibrium energy of neutrons in nitrogen may be defined as that energy at which the capture and scattering cross sections are equal. Taking the values cited in previous work, this energy is about 0.1 ev. If we take the cadmium cutoff as about 0.3 or 0.4 ev, the reduction effected by the cadmium shield ought to be about in the ratio of the square roots of the energies, i.e., between 1.7 and 2 for the cadmium values mentioned. Inspection of Fig. 1 shows that the cadmium curve lies approximately half-way between the boron curve and the unshielded one.

* Cornell University, Ithaca, New York.
** Los Alamos, New Mexico.

PHYSICAL REVIEW VOLUME 69, NUMBERS 5 AND 6 MARCH 1 AND 15, 1946

The Structure of Cosmic-Ray Air Showers

KONRAD L. KINGSHILL AND LLOYD G. LEWIS
Ryerson Physical Laboratory, The University of Chicago, Chicago, Illinois

(September 27, 1945)

Bursts of ionization occurring in each of two thin-walled unshielded ionization chambers were measured at Chicago (elevation 190 meters), with the same apparatus used at Echo Lake (elevation 3100 meters). A comparison of the size-frequency distribution curve for bursts occurring in a single chamber at Chicago with the corresponding curve observed at Echo Lake shows that the altitude dependence for bursts containing more than 50 particles is similar to the altitude dependence of large air showers measured with Geiger-Müller counters. In contrast to this, the altitude dependence for the largest bursts is much greater. The ratio of the coincident burst rate to the single chamber burst rate is as low at Chicago as at Echo Lake. If one assumes the validity of the cascade theory of showers and of the theory of multiple scattering of electrons in air, one must conclude from these data that showers exhibiting these narrow regions of high particle density cannot originate close to the top of the atmosphere. The data presented in this paper, together with the data of Lapp and of Carmichael, show that the slope of the size-frequency distribution curve for bursts in a single chamber is dependent upon the chamber wall.

MEASUREMENTS with two thin-walled unshielded ionization chambers at Echo Lake, Colorado,[1] revealed the presence of many relatively narrow cosmic-ray air showers. These showers were more numerous and had a much smaller lateral extension of their high particle density region than is anticipated[2,3] on the basis of cascade theory applied to primary electrons. This result at Echo Lake makes the sea-level rates for the single bursts and for coincident bursts of particular interest, since the comparison of the two sets of data might give a clue to the vertical structure of air showers.

APPARATUS

The ionization chambers and the associated d.c. amplifiers[1] were used under exactly the same conditions as at Echo Lake. The galvanometers, however, were adjusted for a higher current sensitivity, so that bursts containing more than 30 particles could be measured. This higher sensitivity could be used at Chicago since the accidental coincidence rate is negligible for bursts considerably smaller than 80 particles. The precision with which the occurrence of a coincidence could be determined was increased by changing the rate of travel of the galvanometer film from 75 mm/hr. to 300 mm/hr. This made it possible to determine a burst coincidence to within 0.1 second (the collection time of the ions was 0.4 second).[1]

The whole apparatus was placed in the same portable houses used in the burst investigations at Echo Lake. It should be pointed out here that, in addition to the thin roof described previously, the walls and the floors of these

[1] L. G. Lewis, Phys. Rev. **67**, 228 (1945).
[2] L. Wolfenstein, Phys. Rev. **67**, 238 (1945).
[3] H. Euler, Zeits. f. Physik **116**, 73 (1940).