The Intensity of Neutrons of Thermal Energy in the Atmosphere at Sea Level

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The number of alpha-particles released in the disintegration of boron by neutrons in the atmosphere was measured in an ionization chamber filled with boron trifluoride. Assuming a cross section for the $n-\alpha$ reaction of 3×10^{-21} cm^2, the flux of neutrons of thermal energy was found to be 0.091 ± 0.007 per square centimeter per minute, or one thermal neutron for every 16 ionizing cosmic rays. The consequences of the formation and absorption of this intensity of neutrons are discussed.

A NUMBER of investigators[1] have reported the presence of neutrons in the atmosphere, both at sea level and at higher elevations, but no reliable reduction of the observations by applying a correction for the efficiency of detection has been made to determine the actual number of neutrons present. It has been supposed that the neutrons originate in some interaction of the cosmic radiation with matter, the evidence for this consisting of the association of neutrons with cosmic-ray showers and the rapid increase in the number of neutrons at higher elevations. The experiments described below were made in an effort to establish the number of neutrons of thermal energy present in the atmosphere at sea level.

Neutrons were detected by utilizing the alpha-particles released in the disintegration of the boron isotope of mass ten. An ionization chamber in the form of a vertical cylinder of copper 40 cm long and 7 cm in diameter was enclosed in a glass envelope and filled with boron trifluoride gas at atmospheric pressure. The collecting electrode was a fine wire through the center of the cylinder. A dry battery supplied a steady potential of 450 volts to collect the ions formed. The collecting electrode was directly connected to the grid of an FP54 Pliotron. The voltage pulse from the FP54 resulting from a spurt of ionization caused by an alpha-particle was then applied to a type 38 vacuum tube for additional amplification, and the output of this tube was capacitatively coupled to a galvanometer. The position of the galvanometer spot was continuously recorded on moving photographic paper, and the alpha-particles appeared as kicks whose heights were proportional to the amounts of ionization produced by the alpha-particles. The natural alpha-particle background of the chamber caused by radioactive impurities was determined by shielding the chamber with a thick layer of borax which absorbed all neutrons of thermal energy falling upon it. The size-frequency distribution of the alpha-particle pulses so determined is shown in curve A, Fig. 1. When the borax shield was removed a larger number of alpha-particles was observed, the increase being the number of alpha-particles resulting from the disintegration

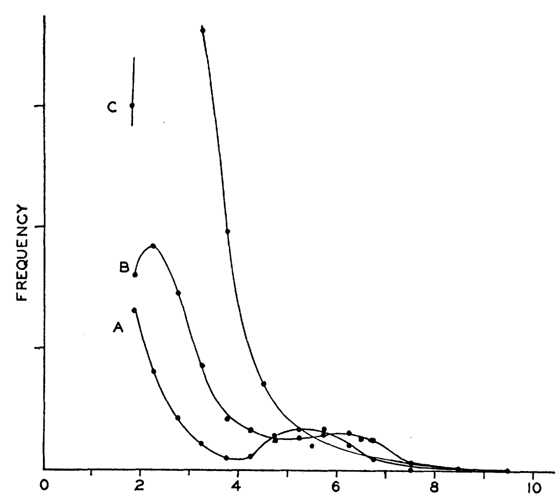

FIG. 1. Size-frequency distributions of the alpha-particles in the ionization chamber. Curve A—thick borax shield; curve B—no shield; curve C—200-milligram Ra-Be neutron source 15 meters from apparatus.

[1] G. L. Locher, Phys. Rev. **44**, 779 (1933); J. Frank. Inst. **216**, 673 (1933); *ibid.* **224**, 555 (1937); L. H. Rumbaugh and G. L. Locher, Phys. Rev. **49**, 855 (1936); E. Fünfer, Zeits. f. Physik **111**, 351 (1938); E. Schopper, Naturwiss. **25**, 557 (1937); D. K. Froman and J. C. Stearns, Phys. Rev. **54**, 969 (1938); H. von Halban, L. Kowarski, and M. Magat, Comptes rendus **208**, 572 (1939).

of the boron nuclei. The size-frequency distribution without the shield is shown in curve *B*, Fig. 1. The distribution of the disintegration alpha-particles, obtained by taking the difference between the two observed distributions, is shown in Fig. 2. The peak is quite broad, and gives definite evidence for the occurrence of several groups of alpha-particles although there is not sufficient resolution to separate the individual peaks. This is in agreement with the recently reported work of W. Maurer and J. B. Fisk.[2]

As an additional check, some observations were made with a radium-beryllium source of neutrons. A 200-milligram source was placed in another room of the laboratory at a distance of about 15 meters, and shielded with about four inches of lead. The alpha-particle distribution in the ionization chamber in the presence of this source is given as curve *C* in Fig. 1. The fact that both curve *B* and curve *C* differ from curve *A* only for the smallest sizes of the ionization spurts, and in an exactly similar manner, can be taken as good evidence that the disintegration of boron by neutrons is responsible for the observed effects. Table I shows the rates of occurrence of the alpha-particles in the different experiments.

In order to estimate the efficiency for detection of neutrons of thermal energy, it is necessary to know the cross section for the reaction involved. It has generally been supposed that the large absorption of boron for slow neutrons was the result of the reaction producing the alpha-particles, and that the contribution of other processes to the absorption was negligible. In that case it would be possible to determine the cross section from the absorption experiments. However, Maurer and Fisk[2] have recently indicated that the $B^{10}(n-p)Be^{10}$ reaction may be

TABLE I. *Rate of occurrence of alpha-particles in ionization chamber.*

Arrangement of Chamber	Total number of alpha-particles per hour	Number of disintegrations per hour
Borax shield	99± 4	
No shield	190± 6	91± 7
No shield with neutron source present	504±37	405±37
Paraffin shield	177± 8	78± 9

[2] J. B. Fisk, Phys. Rev. **55**, 1117(A) (1939).

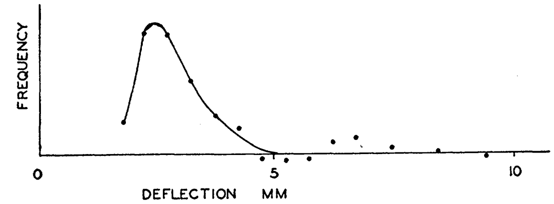

FIG. 2. Size-frequency distribution of the alpha-particles from the disintegration of the boron by neutrons in the atmosphere. This curve is the difference between curves *B* and *A* of Fig. 1.

quite as important an absorption process as the $B^{10}(n-\alpha)Li^7$ reaction. If this proves to be the case, then further experiments must be performed to determine the cross section. Pending these further investigations, we shall therefore adopt the cross section given by Livingston and Bethe[3] determined from absorption experiments which resulted in a value of $\sigma = 3\times 10^{-21}$ cm^2. The results of the experiments reported here may be easily corrected for a change in this cross section, if necessary. To calculate accurately the efficiency of the ionization chamber it would be necessary to know the angular distribution of neutron velocities. Fortunately, however, the absorption by the gas in the chamber is small, and the neutron flux may be expressed, with an error of less than five percent, as $n/N\sigma V$, where N is the number of B^{10} atoms per cubic centimeter, V the volume of the chamber, and n the number of disintegrations observed. It is necessary to correct for the absorption (about 25 percent) by the boron in the glass envelope of the chamber. Using this expression, we find that the neutron flux, that is, the number of neutrons passing through a sphere of one square centimeter cross-sectional area in unit time is 0.091 ± 0.007 cm^{-2} min.$^{-1}$. The flux of ionizing cosmic-ray particles is[4] 1.48 cm^{-2} min.$^{-1}$, so that we have one neutron of thermal energy for every 16 cosmic rays. The only other observations which allow an estimate of the actual number of neutrons present are those of Fünfer.[1] It is possible to calculate the efficiency of Fünfer's proportional counter, from the data given, to within a factor of about two. A correction of his

[3] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 340 (1937).

[4] J. C. Street and R. H. Woodward, Phys. Rev. **46**, 1029 (1934).

results in this manner gives a neutron intensity in agreement within this limit with the present experiments.

In order to detect the presence of neutrons with more than thermal energy, observations were made with a six-centimeter paraffin shield around the ionization chamber. The size-frequency distribution of alpha-particles observed was similar to curve B, Fig. 1, and the number of particles is given in Table I. It is seen to be only a little less than the number observed with no shield. A shield of the thickness used would decrease the number of thermal neutrons to less than ten percent. We must, therefore, conclude that thermal neutrons are produced in the paraffin shield either directly by the cosmic radiation or by the slowing down of fast neutrons.

It is of interest to inquire into the possible mode of formation and the disappearance of neutrons in the atmosphere. Although the experiments described above were performed inside the laboratory, for lack of more complete information, we may take them to be representative of the conditions in the free atmosphere. If this is the case, then the most probable process for the absorption of thermal neutrons will be the $N^{14}(n-p)C^{14}$ reaction. The cross section for this reaction[5] is 11.3×10^{-24} cm^2, which corresponds to an absorption coefficient of 4.8×10^{-4} cm^{-1} of standard air. Now since equilibrium exists, as many neutrons must be formed as disappear, and we must have 4.4×10^{-5} neutron of thermal energy produced per cubic centimeter per minute. If no other process is important for neutron absorption, then this figure must also represent the total production of neutrons of all energies. If we assume that all atoms in the air interact with all the ionizing cosmic rays, we may compute the cross section for the production of a neutron to be 5.5×10^{-25} cm^2. This cross section is surprisingly high, and indeed, since other absorption processes may be important, and since all cosmic rays probably do not produce neutrons, this cross section must represent only a lower limit to that of the true process. It seems likely that the neutrons are produced by high energy photons, since they seem to be associated at sea level with showers,[6] and increase with elevation as do the large bursts of ionization.[7] It is interesting to note in this connection that the nuclear disintegrations observed by Anderson and Neddermeyer[8] in cloud chambers increase with elevation in the same way, and quite probably give neutrons as disintegration products as well as the heavily ionizing particles which are observed. The total energy loss of the cosmic radiation in producing neutrons is probably negligibly small, since if we take 10^7 electron volts as the energy necessary to free a neutron from a nucleus, the energy loss in air by each cosmic ray would only be 2.3×10^5 electron volts per meter of water equivalent. The number of protons resulting from the absorption of neutrons is likewise small. Since the protons will have a range of only about one centimeter of air, there will be only one proton for every 31,000 ionizing cosmic rays crossing a given area. Such a frequency of protons would be observable in a cloud chamber if it were possible to distinguish them from the radioactive contamination.

Although the experiments described here do not represent the most precise determination that is possible, we believe that they give the number of neutrons of thermal energy at sea level to within about ten percent, an accuracy sufficient to permit an evaluation of the importance of neutrons in cosmic-ray phenomena. Further experiments are under way.

[5] J. R. Dunning, G. B. Pegram, G. A. Fink and D. P. Mitchell, Phys. Rev. **48**, 265 (1935).

[6] G. L. Locher, reference 1.

[7] E. Fünfer, reference 1.

[8] C. D. Anderson and S. H. Neddermeyer, Phys. Rev. **50**, 263 (1936).