Neutron Production by Cosmic Rays at Sea Level*

A. R. TOBEY† AND C. G. MONTGOMERY
Sloane Physics Laboratory, Yale University,‡ New Haven, Connecticut
(Received October 2, 1950)

Neutrons produced by the cosmic radiation at sea level in paraffin, aluminum, and lead have been measured in a boron-filled ionization chamber provided with boron guard rings. Proper application of the diffusion theory of slow neutrons was possible and absolute values of the rate of production of neutrons per gram per second were obtained.

I. INTRODUCTION

SEVERAL observers[1–4] have utilized the alpha-particles produced in the disintegration of B^{10} to estimate the number of slow neutrons that are the products of nuclear interactions of the cosmic radiation at sea level. In these experiments no account was taken of the effect of the detector on the neutron density in its neighborhood. In the measurements described here,[5] the geometrical conditions were such that the counting rate of the detector could be rigorously related to the rate of production of neutrons in the vicinity.

II. APPARATUS

The measurements were made in a large block of paraffin 65 cm wide, 65 cm high, and 93 cm long with the detector placed at the center of the block. The paraffin served a double role as neutron producer and moderator. Investigation of aluminum and lead was accomplished by placing sheets of these materials in a lattice structure in such a manner as to maintain a nearly homogeneous mixture with the paraffin throughout the block. The detector was a cylindrical ionization chamber filled with boron trifluoride of natural isotopic concentration. Guard cylinders also containing BF_3

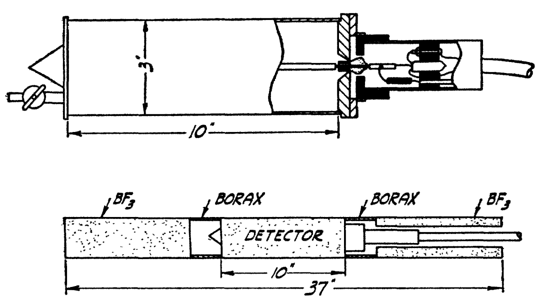

FIG. 1. Ionization chamber and arrangement of guard rings.

were placed at each end of the chamber as indicated in Fig. 1. The amount of borax and the pressure of the gas in each chamber were adjusted so that the amount of boron per unit length of the assembly was constant. The chamber was constructed of copper and the dimensions are given in Table I. The chamber was filled to 1 atmosphere pressure at 0°C. The center conductor was supported at both ends by Stupakoff seals. No guard rings were provided.

The chamber was operated with a positive potential of 450 volts applied to the outer electrode. The inner collecting electrode was within a fraction of a volt of ground potential and was connected to the grid of a VX-41 electrometer tube with a grid leak resistor of 10^{12} ohms. A switch was provided for grounding the grid. The electrometer tube was coupled directly to a balanced amplifier consisting of a pair of 6SH7 tubes. A 6-μf capacitor coupled the amplifier to a critically damped galvanometer with a free period of 1.1 sec and a sensitivity of 7.7×10^{-9} amp mm^{-1} at 1 meter. Light reflected from the galvanometer mirror fell on a slit behind which a strip of photographic paper (Eastman #797) moved at the rate of 40.8 in. hr^{-1}. An alpha-particle from a neutron capture produced a deflection of about 8 mm. By examining the record a pulse-height frequency distribution curve was obtained.

Some pulses observed corresponded to alpha-particles emitted from the chamber walls. Background measurements were taken with the chamber surrounded by a layer of borax at least 2 in. thick. Outside the borax, paraffin was placed in the same amount as was used for the neutron measurements. In some of the preliminary runs it was found that an appreciable number of neutrons were entering the detector from outside the paraffin block by traveling along the detector axis. These neutrons were eliminated by thick borax absorbers placed over the ends of the detector.

Observations were made with the large paraffin block of 770 lb and with the same amount of paraffin mixed

TABLE I. Dimensions of ionization chamber.

Inside diameter of cylinder	7.42 cm
Thickness of wall	0.10
Diameter of inner conductor	0.476
Inside length	25.40
Volume	1094. cm^3

* A portion of a thesis submitted by A. R. T. to the Graduate School of Yale University, May, 1948.
† Now at Armour Institute of Technology.
‡ Assisted by the Joint Program of the ONR and AEC.
1 C. G. Montgomery and D. D. Montgomery, Phys. Rev. 56, 10 (1939).
2 S. A. Korff and E. T. Clarke, Phys. Rev. 61, 422 (1942).
3 M. Kupferberg and S. A. Korff, Phys. Rev. 65, 253 (1944).
4 B. Hamermesh and S. A. Korff, Phys. Rev. 70, 429 (1946).
5 A preliminary amount of these experiments has been published: Phys. Rev. 75, 894 (1948). The results of subsequent experiments at mountain altitudes are given in Phys. Rev. 76, 1478 (1949).

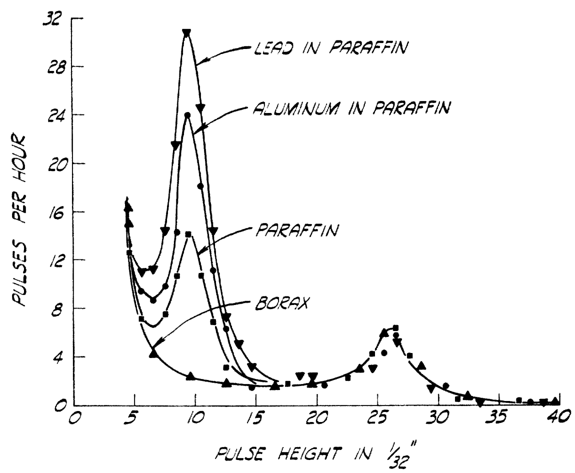

FIG. 2. Pulse-height distributions observed.

with 517 lb of lead and with 749 lb of aluminum. The lead was in the form of square sheets 5 in. on a side and 0.26 in. thick. Smaller pieces were cut and carefully arranged in the region near the detector so as to maintain a constant average density of lead and paraffin. The aluminum was in sheets 6.5 cm wide, 93 cm long, and 1.9 cm thick. Here also smaller pieces were used near the detector. Measurements were taken for each substance in several runs of five hours each to ensure constancy of operating conditions.

The apparatus was located in New Haven (60 meters elevation) on the second floor of a light wooden building in a room at an outside corner.

III. RESULTS

The principal observations resulted in the size distribution curves shown in Fig. 2. The peak caused by the neutrons is seen to be large compared with the background and well resolved. The total number of neutron pulses from paraffin, for example, is equal to the area between the background curve and paraffin curve. This area is best determined by counting the pulses greater than about $\frac{3}{16}$ in. For the smaller pulses some uncertainty exists because of confusion with the ion-chamber noise. The background was therefore subtracted from the number of pulses of each size and a symmetrical difference curve was plotted. An estimate of the area under the difference curve for sizes less than $\frac{3}{16}$ in. was taken to be the correct number of counts. Because of the finite resolving time two closely spaced pulses would be counted as one. The necessary correction was estimated using a resolving time of 0.5 sec. Each of these small corrections was less than the statistical uncertainty of the measurements. The peak at large pulse sizes was probably caused by radioactive contamination on the inner surface of the chamber.

TABLE II. Assumed values of nuclear cross sections in barns.

Substance	Total cross section	Capture cross section
H	41	0.29
B	830	830
C	4.6	0.0045
Al	1.6	0.23
Pb	11	0.17
Paraffin	86.4	0.59

TABLE III. Values of derived constants.

Substance	Diffusion length (cm)	Neutron mean life (sec)	Average density metal (g/cm³)	Average density paraffin (g/cm³)	$1/\phi$
BF_3 at 1 atmos	25.9	179	——	——	——
Paraffin	2.16	180	——	0.87	1.69
Pb par.	2.19	178	0.56	0.83	1.67
Al par.	2.57	197	0.64	0.66	2.03

TABLE IV. Rates of neutron production in units of 10^{-5} g^{-1} sec^{-1}.

Substance	Rate	Rate corrected for cosmic-ray absorption
Paraffin	1.98 ± 0.07	2.6
C	2.31 ± 0.08	3.0
Al	3.49 ± 0.20	5.2
Pb	6.47 ± 0.24	8.7

To calculate the rate of production of neutrons from the observed number of pulses, use was made of diffusion theory. The neutrons, produced at high energy, were rapidly slowed down to thermal energies in the paraffin and a continuous distribution of thermal neutron sources was effectively present. Since this work was done, diffusion calculations have been published by Draper.[6] His result can be written [see Eq. (14) of reference 6] as

$$\Sigma_i q_i \rho_i = n\tau_B / V_B \tau \phi, \tag{1}$$

where q_i and ρ_i are the rate of production of neutrons g^{-1} sec^{-1} and the average density of the ith component of the mixture surrounding the detector, n is the number of pulses per second, V_B the volume of BF_3, τ and τ_B are the mean lives of a thermal neutron in the mixture and in the BF_3 and ϕ is a diffusion factor. The value of ϕ is given by

$$\frac{1}{\phi}=\frac{1}{\rho}+\tfrac{1}{2}k^2\frac{\tau r_B}{\tau_B L}\left[\frac{iH_0^{(1)}(ir_B/L)}{H_1^{(1)}(ir_B/L)}\right], \tag{2}$$

where k is the ratio of the detector radius r_B to the radius of the hole in the surrounding medium, L the diffusion length in the medium and $H_0^{(1)}$ and $H_1^{(1)}$ are the Hankel functions of the first kind. The quantity ρ is representative of the variation of neutron density over the volume of the counter. Its value is calculated also in reference 6. By some simplifying assumptions which are valid for the present experiment, it can be shown that

$$\rho=\frac{-2iJ_1(ir_B/L_B)}{(r_B/L_B)J_0(ir_B/L_B)}, \tag{3}$$

[6] J. E. Draper, Nucleonics 6, No. 3, 32 (1950).

where L_B is the diffusion length in the detector. In these experiments $\rho=0.996$. It can also be shown that a similar correction for the finite size of the paraffin is entirely negligible.

The nuclear cross sections used in the calculations are given in Table II. In Table III are the derived constants to be substituted in Eqs. (1–3). By combining the rates of production observed for paraffin and for the mixtures, the individual rates of production were obtained. There are given[7] in Table IV. The value for carbon was calculated from that found for paraffin assuming that the hydrogen did not contribute and that the composition was C_nH_{2n}.

Owing to the absorption of the radiation responsible for neutron production in the paraffin and in the metal some correction should be applied to the rates observed directly. With the paraffin alone present 29 g/cm² of paraffin was above the detector. The aluminum added an additional 28 g/cm² and the lead 19.5 g/cm². An approximate correction has been made as follows. The variation of the number of neutrons with elevation corresponds to a mean free path[5] in air of about 150 g/cm². It was assumed that this mean free path varies as the cube root of the mass number of the nucleus. Thus for lead, for example, the value of 366 g/cm² was calculated. The observed rates were then multiplied by the appropriate absorption correction factors and the results are given in the last column of Table IV. The corrected rates are, of course, uncertain not only because of inaccuracies in the assumed absorption coefficients but also from the neglect of possible transition effects.

[7] In the preliminary account of the exponents given in reference 5, the value for aluminum was in error because of a numerical mistake.

PHYSICAL REVIEW VOLUME 81, NUMBER 4 FEBRUARY 15, 1951

Alpha-Particle Groups from the $N^{14}(d, \alpha)C^{12}$ and $N^{15}(d, \alpha)C^{13}$ Reactions*

R. MALM† AND W. W. BUECHNER
Physics Department and Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received October 26, 1950)

The alpha-particle groups from N^{14} and N^{15} targets bombarded with 1.4-Mev deuterons have been studied using a magnetic spectrometer. The Q-value for the $N^{14}(d, \alpha)C^{12}$ reaction is found to be 13.575 ±0.012 Mev, and the energies of the excited states observed in C^{12} are 4.438±0.014 and 9.620±0.013 Mev. For the $N^{15}(d, \alpha)C^{13}$ reaction, the Q-value is measured as 7.681±0.006 with excited states in C^{13} at 3.083 ±0.005 and 3.677±0.005 Mev.

I. INTRODUCTION

AMONG the various methods of exciting and studying the bound energy states of C^{12} and C^{13}, the $N^{14}(d, \alpha)C^{12}$ and $N^{15}(d, \alpha)C^{13}$ reactions have high Q-values, making them particularly suitable for investigating these nuclei over a wide range of excitation. The studies of the first reaction have shown[1,2] the presence of levels in C^{12} at 4.5 and 7.0 Mev, in general agreement with the results from other reactions. These results have recently been summarized by Hornyak, *et al.*[3] In the case of the $N^{15}(d, \alpha)C^{13}$ reaction, only the highest energy group of alpha-particles which is associated with the formation of C^{13} in the ground state has been observed.[1] With the objective of investigating these nuclei over a wider range of excitation, we have studied the alpha-particle groups emitted by thin targets containing N^{14} and N^{15} when bombarded with 1.4-Mev deuterons.

II. APPARATUS AND EXPERIMENTAL PROCEDURE

The experimental equipment has been described in previous papers.[4,5] Magnetic analysis was used both in the selection of the incident beam of deuterons of known energy and the investigation of the disintegration alpha-particles. The angle of observation was 90° with respect to the deuteron beam, and photographic detection was employed.

The energies of the observed alpha-particle groups were computed from measurements of the radii of curvature and the corresponding magnetic fields. The fields were measured with an analytical balance-type fluxmeter. The fluxmeter was calibrated on the basis of Brigg's value[6] for the Hr of RaC′ alpha-particles, from Lewis and Bowden's value[7] for the ratio of the

* This work has been assisted by the joint program of the ONR and AEC.

† AEC Predoctoral Fellow, now at Argonne Laboratories.

[1] M. G. Holloway and B. L. Moore, Phys. Rev. **58**, 847 (1940).

[2] Guggenheimer, Heitler, and Powell, Proc. Roy. Soc. (London) **A190**, 196 (1947).

[3] Hornyak, Lauritsen, Morrison, and Fowler, Revs. Modern Phys. **22**, 291 (1950).

[4] Buechner, Strait, Stergiopoulos, and Sperduto, Phys. Rev. **74**, 1569 (1948).

[5] R. Malm and W. W. Buechner, Phys. Rev. **80**, 771 (1950).

[6] G. H. Briggs, Proc. Roy. Soc. (London) **A157**, 183 (1936).

[7] W. B. Lewis and B. V. Bowden, Proc. Roy. Soc. (London) **A145**, 250 (1934).