The Production of Neutrons and Protons by the Cosmic Radiation at 14,125 Feet

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(Received February 9, 1942)

The production of neutrons and protons in various substances by the cosmic radiation was investigated with proportional counters at the Mt. Evans Laboratory (barometer 46 cm). Neutrons were studied with counters filled with BF_3 and cadmium absorbers. The neutron counter was surrounded by water, so that nearly all the neutrons should be slow, and also so that the neutrons measured should nearly all have been produced in the water, very few of those produced elsewhere reaching the counter. Protons were observed in counters filled with CH_4. The size distribution of ionizing events was determined. Coincidences between neutron counts and shower counts were observed, suggesting a connection between the neutrons and the soft component. Estimates are given of the rates of production in various substances, these being of the order of 10^{-3} to 10^{-4} per gram per second on Mt. Evans.

INTRODUCTION

THE presence of neutrons and protons in the cosmic radiation has been the subject of much investigation. The neutrons have been studied with the aid of photographic plates,[1] proportional counters,[2] and induced radioactivity,[3] while the protons have been investigated with cloud chambers,[4] photographic plates,[5] and proportional counters.[6] The particles are believed in the main to be of secondary origin, and to have been produced by the cosmic radiation. Some theories regarding the origin of these particles have been put forward.[7, 8] In an attempt to throw further light on the process of production, the several experiments described below were performed during August, 1941, at the Mount Evans Cosmic Ray Laboratory. This laboratory is located at 14,125 feet, just below the 14,260 foot summit of Mount Evans, Colorado. The mean barometer during our stay was 46 cm, and the altitude may be taken as roughly six meters of water equivalent below the top of the atmosphere.

NEUTRON OBSERVATIONS

Neutrons were observed with the aid of a proportional counter, filled with boron trifluoride gas. Several counter tubes were used, of various sizes and various gas-pressures. Those to be discussed here, had volumes of 3551 cc and 1450 cc, with pressures of 41.5 and 75 cm, respectively, of BF_3. Several smaller counters were used as checks. The counter of volume 3551 cc and pressure 41.5 cm was also equipped with a thin glass window, through which alpha- and beta-particles could be projected into the gas of the counter, for the purpose of calibrating the pulse sizes. It will be recalled that proportional counters can be calibrated through the use of particles of known specific ionization,[9] and that the pulse sizes obtained under certain conditions can be computed,[10] and related to the size and gas-pressure of the counter and the amount of energy lost by the particle as ionization within

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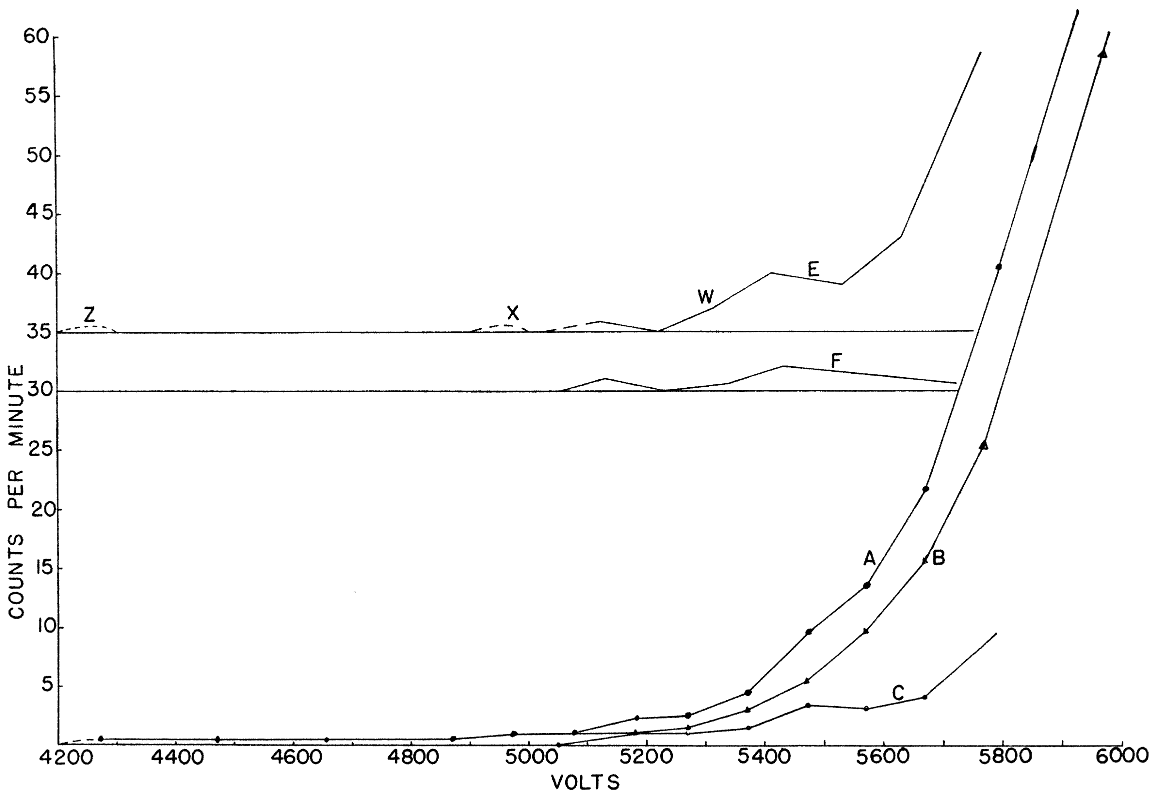

FIG. 1. Counting rate of neutron counter filled with BF_3 at 74 cm on Mt. Evans. Curve *A* without, curve *B* with cadmium shield over counter. Curve *C* is difference due to cadmium shield. Curves *E* and *F* are pulse-size distributions, being differentials of *A* and *C*, respectively, *E* representing the total number of pulses observed, and *F* due to neutrons. The very largest pulses are due to giant showers and contamination alphas, and hence are not affected by the cadmium.

the counter. It will also be recalled[9] that at any voltage, the counter and recording circuit detect all pulses greater than a certain minimum size, and that therefore the differential with respect to voltage of the curve of counting-rate as a function of the voltage gives the pulse-size distribution.

The neutron counters were surrounded with water. This was accomplished by standing a sufficient number of 5-gallon cans filled with water around the counter, so that any particle from the outside had to pass through 30 to 80 cm of water. Whereas the amount and geometrical arrangement of the water were by no means ideal, the arrangement of the water has been found by several observers to make little experimentally detectible difference, a fact again noted in the present work. The purpose of the water was to insure that most of the neutrons reaching the counter would be slow, and further, the thickness was such that practically no neutrons reached the counter from the outside, all those counted having been produced in the water. A thin (0.7 mm) cadmium shield could be slipped over the counter, and the counting rates were determined with and without this cadmium shield. Such a thin shield had a very small mass compared to the other matter around the counter, and presumably only had the effect of absorbing slow neutrons from the water. It would have no appreciable effect on other components of the radiation.

The observed counting rates as a function of voltage found with the counter of 1450 cc mentioned above, are shown in Fig. 1, with and without cadmium, in curves *A* and *B*. Curve *C* is the difference between *A* and *B*, and hence represents the neutrons which did not get through the cadmium. Curve *E* is the pulse size distribution, being the differential of *A*, for all the pulses. It will be seen that there are a few (*z*) very large pulses (mostly giant showers), a few pulses (x) somewhat larger than those due to neutron-disintegration alphas (mostly contamination alphas from the counter cylinder), and quite a number of about the size of the neutron induced pulses (w) and smaller. Curve F is the differential of C, or the pulse-size distribution among the neutrons. Unfortunately the process of differentiation tends to accentuate errors, and hence the accuracy of the pulse-size distribution curve is not as good as that of the integral counting-rate curve.

The same counter was also operated at Denver University, barometer 63.1 cm, for the purpose of obtaining comparable data to permit the estimation of the increase of the neutron intensity as a function of elevation. The same geometrical arrangement was used. The cadmium shield reduced the counting rate from 12.0 to 8.5 counts per minute, thus indicating about 3.5 ± 0.5 counts per minute owing to slow neutrons at this elevation compared to 15 ± 1 at the top of Mount Evans. Since the difference in elevation corresponds to nearly 2 meters of water equivalent, the neutrons are seen to increase with elevation by a factor of about 2 per meter of water in this interval. This increase is faster than that of the total intensity of the radiation, but roughly equal to that of the soft component. It may be pointed out again that because the neutrons do not travel through large fractions of the atmosphere before they are absorbed, one would expect the altitude dependence of the neutrons to be the same as that of the producing agency. Hence the altitude dependence suggests an association of the neutrons with the soft component.

COINCIDENCE EXPERIMENTS

The second experiment consisted of observing coincident discharges between the neutron counter and a tray of ordinary Geiger counters arranged to detect showers. The tray comprised 25 counters 1 cm in diameter and 30 cm long, arranged side by side in a horizontal plane and so connected[11] that at least two had to discharge simultaneously in order to record as a shower. The neutron counter could also be connected, and neutron-shower coincidences were recorded. The resolving time was adjusted to 10^{-4} second, so that neutrons formed in any process could have time to be slowed down before being captured. Because of the slow counting rate, accidentals within this time-limit were negligible. Water was arranged around the neutron counter in the same way as described above, and a cadmium shield could be slipped over the neutron counter. Directly above the shower tray were two 1-cm Pb slabs, for the purpose of producing additional showers. The neutron counter was placed above the lead, to minimize the counts due to large showers produced in the lead which might cause the neutron counter to discharge. The counting rates of neutron-shower coincidences were observed, with and without the cadmium shield.

It was found that the coincidence counting rate with the cadmium shield was 0.22 per minute while without the shield it was 0.396 ± 0.03 per minute. It appears improbable that the cadmium shield could influence the counting rate in any way except through absorption of slow neutrons, and the count with the cadmium in place thus permitted the background rate to be determined. The background will evidently include accidentals, contributions due to large showers, counts produced by faster neutrons, and other highly ionizing events. The difference between the two observed counting rates is therefore that due to neutrons which were actually produced in some process connected with the shower.

PROTON OBSERVATIONS

Several proportional counters were also operated, with methane, for the purpose of studying the protons produced by the cosmic radiation. One counter was identical with the large neutron counter described above, being 3551 cc in volume and filled to 41.5 cm with CH_4. The other two counters had cylinders 25.4 cm long and 9 cm in diameter, and were filled to 21.4 cm with CH_4. Each was equipped with a thin window for the admission of alpha- and beta-particles for calibration. The cylinders of the latter two were made of lead and of aluminum, all other counter cylinders being of copper. These elements were used in order to ascertain whether any difference in the rates of production of particles in the various different elements could be observed. Since the lead and aluminum counters are otherwise identical, their counting rates can be compared directly. The quantitative interpre-

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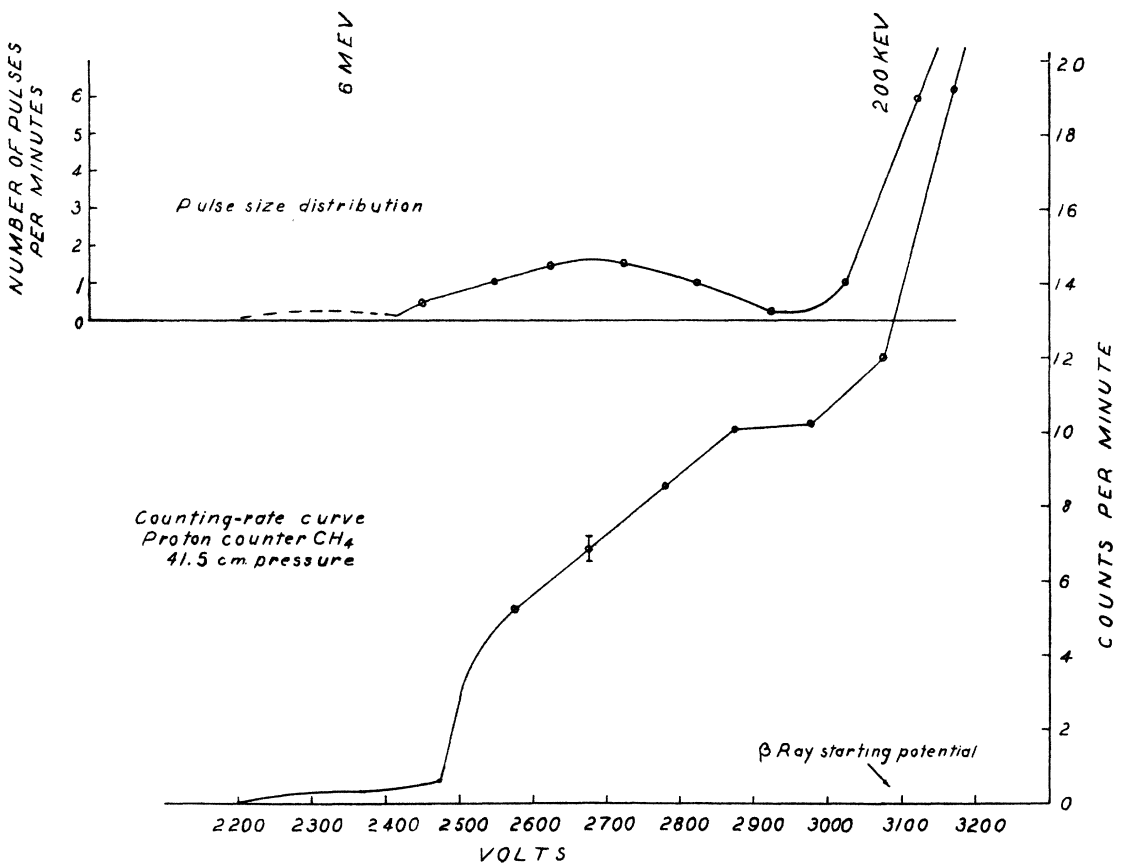

FIG. 2. Counting rate of proton counter, filled with CH_4 on Mt. Evans. Upper curve is differential of observed curve below, and shows size distribution of ionizing events. This counter does not detect slow neutrons.

tation in terms of rates of production is discussed below.

The counting rate of the copper cylinder counter is shown in Fig. 2, as is the pulse-size distribution observed in this counter. Because of the different counter lengths, the counting rate of the copper cylinder counter was reduced to a value per unit length before comparing with the other counters. Under comparable conditions, the counting rates of the several counters were

$$n_{Al} : n_{Cu} : n_{Pb} = 7 : 4.5 : 7 \quad \pm 0.5 \text{ counts per minute,}$$

where the metal of which the cylinder is made is indicated by the subscript. The cylinder, about 1 mm of lead or equivalent, was thick compared to the range for most of the protons observed.

DISCUSSION

It will be recalled[7] that a detector surrounded by water will be activated at a rate n counts per second, related to q_w, the rate of production of neutrons per gram per second in the water, through

$$q_w = (n/V)(\sigma_w/\sigma_D)(1245/p), \qquad (1)$$

where V is the volume of the counter, p the pressure of the gas in it, 1245 is a constant equal to the standard volume $2.24 \times 10^4/18$, the 18 being the molecular weight of water, σ_w is the capture cross section of water for slow neutrons, and σ_D that of boron. Using this relationship, and the observed counting rate of the counter $n = 0.1$ counts per second (corresponding to the difference between the counts with and without cadmium), $V = 1450$ cc, $p = 74/76$ atmos., and taking σ_w and σ_D as 0.5 and 550×10^{-24}, respectively, we find the rate of production of neutrons in water at the level of the top of Mount Evans to be 2×10^{-4} per gram per second; while at Denver it is 5×10^{-5} per gram per second. It must be pointed out that Eq. (1) assumes that all the disintegrations occurring in the volume V are recorded. Thus V is the effective volume of the counter, a quantity smaller than the volume of the cylinder by an amount equal to the end and side corrections, since alpha-particles produced near the ends or sides may collide with the walls before expending all their energy as ionization in the gas. Thus the effective volume corrections depend on the pressure and may be calculated for any given arrangement. By applying this active volume correction, V in the case cited is about 900 cc, and the values of q for neutrons become 3×10^{-4} and 8×10^{-5} per gram per second in water at Mount Evans and Denver, respectively.

The coincidence experiments also indicate a connection between the neutrons and the soft component. We may inquire what fraction of the total showers S are showers in which a neutron is produced. Let E_n be the efficiency of the neutron counter, which counts neutrons at the rate C_n. Then the total number of neutrons will be C_n/E_n, passing through the counter per unit time. If neutron-shower coincidences are observed at a rate C_c, and if Z is the total number of events in which both a shower and a neutron was produced, then

$$Z/S=C_c/E_nC_s. \tag{2}$$

In this case, C_c was 0.2, C_s, the counting rate for showers, was 100, and E_n, for thermal neutrons, is given by

$$E_n=Np\sigma L, \tag{3}$$

where N is the Loschmidt number, p the gas pressure in atmos., L the average path length for neutrons passing through the counter, and σ the capture cross section of the detecting gas molecule for the neutrons to be measured. In the counters used, L was 7 cm, σ was taken as 550×10^{-24}, a figure which has the isotope ratio already included, and which assumes, as is the case here, that substantially all the neutrons are thermal, E_n was about 0.1. Hence Z/s is about 0.02, or about two percent of all the showers are events in which a neutron is produced also.

The rate of production of the protons Q per gram per second can be related, as has been shown,[6] to the counting rate N_p, through the expression

$$N_p=S\int_0^{E_{\max}} I(E)dE=SQR(E_{\max}), \tag{4}$$

where S is the effective area of the counter, $I(E)$ is the flux of protons per cm sq. per sec. with energies in the interval dE, and $R(E_{\max})$ is the range corresponding to the maximum value of the proton energy E which can be detected in the particular counter used. It is evident that if Q is to be in grams, R must be in grams. There were about 0.1 count per second due to protons in the counter and its cross-sectional area S was about 500 sq. cm. In this case, $R(E_{\max})$ was about 400 cm of standard air, or dividing by the density, 0.4 g; and hence Q is about 5×10^{-4} per gram, which is of the same order of magnitude as the rate of production of neutrons.

In the counters with lead and aluminum cylinders, the rates of production per gram in Pb and Al, Q_{Pb} and Q_{Al}, will be related to the respective counting rates N in the ratio

$$Q_{Al}/Q_{Pb}=(N_{Al}/N_{Pb})\cdot(S_{Al}/S_{Pb})\cdot(\mu_{Pb}/\mu_{Al}) =1.86\pm0\ 3, \tag{5}$$

where μ is the atomic weight and S the relative stopping power per atom of each substance indicated by its subscript. Hence Q_{Pb} and Q_{Al} may be expressed in terms of production cross section σ which will have the ratio

$$\sigma_{Al}/\sigma_{Pb}=(N_{Al}/N_{Pb})\cdot(S_{Al}/S_{Pb})=0.3. \tag{6}$$

The counting rate of the copper cylinder counter may be similarly considered, and the ratio of $\sigma_{Al}:\sigma_{Cu}$ obtained. It is found that the results may be expressed in the ratio

$$\sigma_{Al}:\sigma_{Cu}:\sigma_{Pb};\quad 1:1\pm0.2:3\pm0.3. \tag{7}$$

It will be noted that σ increases more slowly than Z, the ratios of the Z's being roughly 1 : 2.2 : 6.5, which suggests that possibly in heavier nuclei some screening occurs, decreasing the probability of proton emission below a direct proportionality with the number of protons Z.

Some protons will also be produced in the gas (CH_4) of the counters. If the volume of gas within the cylinder is 1416 cc at 0.28 atmos. pressure, the s.t.p. density of CH_4 being 0.00072 g/cc, then the total mass of gas is 0.285 gram, and if Q is about 10^{-3} per gram, we would expect a contribution of about 1.7×10^{-2} count per minute, or about one percent of the observed counting rate. Most of the protons will be produced in the walls or gas, for it would require a proton of about 80 Mev to penetrate through the thick cylinder and glass envelope to reach the interior from any region of production outside the counter. The protons producing the counts must be within the last 30 Mev of the ends of their ranges in passing through the counters in order to lose enough energy per traversal to count.

Giant showers will trip the neutron-shower coincidence arrangement, since they cause two or more of the shower counters to discharge, and might easily also cause several hundred electrons to pass through the neutron counter, thus producing as much ionization as a disintegration-alpha. In order to set a limit to the number of counts due to such showers, we took advantage of the opportunity provided by the presence on Mt. Evans of a cloud chamber belonging to Wilson Powell. The neutron-shower arrangement was set up directly above his cloud chamber and neutron-shower coincidences caused to trip the chamber. The resulting photographs showed one to two giant showers per hour, a figure which may be seen to account for ten to twenty percent of the observed "neutron-shower coincidence" counts.

The background counting rate of the neutron-shower coincidences, found when cadmium surrounded the neutron counter was 0.22 per min. But the giant shower rate, capable of tripping this arrangement was found to be of the order of 0.03 per min. It is clear that there are some additional processes taking place in which large amounts of ionization are liberated but a small number of particles are involved, which may possibly be protons produced by events connected with the soft component.

Some attempts have been made to explain the production of heavy particles by the cosmic radiation on the basis of various hypotheses. The possibility that the neutrons are in part produced by photons has been discussed.[7] Such processes are known for photons of 17 Mev and less,[12] but the cross sections at these energies are not large enough to enable the known density of photons in the cosmic radiation to be considered as having produced all the observed neutrons. Yet it must be recalled that the cross section for the production of photo-neutrons is known to increase with energy up to the present observable limit at 17 Mev and may reasonably be assumed to increase further up to several times this energy. A cross section of about 10^{-26} sq. cm will suffice to explain all the neutrons on this basis.

The suggestion has been made[8] that electrons produce "star" explosion processes, and that these may be the origin of the neutrons. While it is quite evident that an electron of, say 10^9 ev has ample energy to penetrate a nucleus and cause it to "explode," yet it is necessary to postulate a fairly large cross section if this process is to account for all the neutrons. We are aware of no process by which the abundant low energy cosmic-ray electrons may produce nuclear disintegrations; yet the equally abundant low energy photons are known so to do. It seems probable that in actuality several processes are involved and that the cross section for each is a different function of the energy.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the helpful assistance received from J. C. Stearns and the University of Denver in connection with the use of the Mount Evans Cosmic Ray Laboratory and the operation of the counter at Denver. Financial support was received from the Carnegie Institution of Washington. We are indebted to Wilson Powell for extensive collaboration in connection with the cloud-chamber study. The counters and thin windows were constructed by Austin Nester. The investigation was started while the authors were on the staff of the Bartol Research Foundation and concluded at New York University.

[12] H. Bothe and W. Gentner, Naturwiss. 25, 90, 126, 191, and 284 (1937).