PHYSICAL REVIEW VOLUME 71, NUMBER 12 JUNE 15, 1947

The Production of Nucleons by the Cosmic Radiation

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(Received March 1, 1947)

The production of protons and neutrons at an elevation of 14,156 feet by the cosmic radiation was studied with the aid of proportional counters. The production of more than one neutron at a time was found to take place. The rate of occurrence of multiple neutron productions was found to be much less frequent than that of single neutrons, even taking the usual distribution into account. The number and rate of production of protons was also determined and was found to be roughly the same as that of the neutrons.

INTRODUCTION

CONTINUING our study[1] of the neutrons and protons associated with the cosmic radiation, a series of tests was carried out during July, 1946, at the Cosmic Ray Laboratory of the University of Denver, located at 14,156 feet (4315 m) elevation on Mt. Evans,[2] Colorado. The experiments were designed to explore two questions: (1) Are neutrons produced singly or in multiples? (2) What can be said about the energy-distribution and number of protons? The affirmative answer to (1) has already been reported by us,[3] and constitutes the first experimental proof that there exist multiple production processes for neutron-production, analogous to multiple production of protons in "stars" in photographic emulsions.

NEUTRON MEASUREMENTS

The neutron experiments were designed to test whether neutrons were produced singly or in groups of more than one at a time. For this purpose, two large neutron counters were arranged to operate in coincidence. The counters were 15 cm in diameter and 150 cm long, and were filled with ordinary BF_3 to a pressure of 30 cm Hg, plus 2 cm argon. They were arranged side by side, in a horizontal plane with their axes parallel and the outsides separated by about 2 cm. The operating potential was between 2000 and 4000 volts. The two counters had been simultaneously filled on a manifold so as to assure identical gas content. The central wires were connected to a conventional Rossi coincidence circuit.

The counters were mounted so that a cadmium shield, 1 mm thick, could be slipped over them or withdrawn. In order to insure that most of the neutrons reaching the counters should be slow, 40 five-gallon cans of water were stacked around so that the counters were effectively inside a large quantity of water. Further, a mass of about 600 pounds of lead was arranged above the counters, in a layer 7 cm thick, to provide some heavy nuclei in which the neutron production might take place.

A reduction in the coincidence counting rate of 0.15 count per minute was found to be produced by the addition of the cadmium shield. Keeping all factors such as voltage and circuit sensitivity as constant as possible, the two counter wires were then connected to a single channel of the same amplifier and recorder, and a single counting rate of the two counters together in parallel was next determined. Thus under comparable conditions, the cadmium shield produced a reduction of 32 counts per minute in the rate of counting single neutrons. The cadmium difference test is necessary, since even in coincidence the arrangement has a definite background; thus for example, giant showers will cause a discharge in both counters. A series of experimental tests for accidentals was made.

DISCUSSION OF NEUTRON MEASUREMENTS

The evidence of the "stars" in photographic emulsions indicates that processes occur in which several ionizing particles are ejected or evaporated out of nuclei. It appears improbable that

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[1] S. A. Korff and E. T. Clarke, Phys. Rev. **61**, 422 (1942); S. A. Korff and B. Hamermesh, Phys. Rev. **69**, 155 (1946). (See these papers for further bibliography.)
[2] Latitude 39° 35′ North, longitude 105° 38′ West, Geomagnetic latitude 48° 23′ North; elevation from latest Forest Service survey, slightly modifying previously published altitudes.
[3] S. A. Korff and B. Hamermesh, Phys. Rev. **70**, 429L (1946).

several protons or other charged fragments could leave a nucleus without at the same time approximately the same number of neutrons departing. The observation of coincident neutrons, then, is an extension of the "star" observations, in that it indicates that such multiple processes do indeed take place, for neutrons as well as for ionizing particles.

The efficiency of detection may be considered. Since we are concerned with cadmium differences, we are dealing with thermal or nearly thermal neutrons. For such neutrons, a rough estimate of the detection efficiency is possible. The probability G that a neutron shall produce a count is then given by:

$$G = Lpd\sigma, \tag{1}$$

where d is the mean path length of the neutron passing through the counter, p is the pressure of BF_3 in atmospheres, and L is the Loschmidt number, 2.7×10^{19} molecules per cc at S.T.P., and σ is the capture cross section of BF_3 for neutrons. In this case, p being 30/76 atmos., $\sigma=550\times10^{-24}$ cm^2, if d is assumed 15 cm (one diameter) then G is about 8.8 percent. The coincidence counting efficiency will be the square of the single counting efficiency, or 0.77 percent. This assumes that the two detectors are independent, that neither absorbs a large fraction of the total number of neutrons, and that the mean diffusion distance of the neutrons is long compared to the dimensions of the detector.

It is further evident that if neutrons are produced in events in which 3 or more are set free at once, than the probability of one neutron passing through each of the two counters is increased. The number distribution of protons in stars was determined from the data by Heisenberg and his collaborators,[4] and was found to be of the form

$$R = AN^{-s}, \tag{2}$$

where R is the number of stars having N protons, A is a constant and s is determined experimentally as about 2. Let us assume that a similar distribution applies to the neutrons. Then the total number of neutrons in stars of all sizes per unit area, and per unit time is:

$$\begin{aligned}\Sigma RN &= \Sigma NAN^{-2},\\ &= \Sigma AN^{-1}.\end{aligned} \tag{3}$$

This series is convergent since the unlikely event of a completely disintegrating lead nucleus would only produce 120 neutrons, and the average number of neutrons per star is about 3.

We might therefore expect that the number of neutrons counted in coincidence should be about $\frac{3}{2}\times8.8$ percent of the number counted by a single counter. The actual number observed was considerably less than this figure. Hence we may conclude either that Eq. (2) which is derived from the proton star data for stars of 2 or more particles does not correctly describe the ratio of events in which one and two neutrons are produced, or that the geometry of the experiment was such that at least 90 percent of the doubles were not detected. Further, we may assume that some neutrons are produced in stars and others are left over from originally fast neutrons which were produced elsewhere by some other mechanism.

The absolute number of slow neutrons was not determined in this experiment. The number cannot be computed from the data cited above, because the amplifier sensitivity was kept low, in order to eliminate accidentals, and in consequence some neutrons were missed. The number at Mt. Evans is, however, already known. It will be recalled that, in determining the number of neutrons, a curve of counting-rate as a function of counter-voltage or amplifier sensitivity is desirable, which shall extend into the beta-counting domain, for some neutrons produce pulses of the same order of size as those produced by slow betas. Such curves have been obtained, and the figures are: 0.91 neutron per S.T.P. liter of ordinary BF_3 per minute at sea level (100 m) inside thin (10 cm) paraffin shield,[5] and 0.97 inside thick (50 cm) paraffin,[6] while on Mt. Evans, 10 neutrons per liter per minute were counted inside 50 cm water.[1] The rate of increase with elevation is about 11 in 4 meters of water equivalent, or a factor of 1.8 per meter of water. As has been pointed out before, this rate of increase is about the same as that of the soft component while it is greater than that of the mesotron component near sea level. Assuming all the neutrons to have been produced in the water, a rate of production

[4] W. Heisenberg et al., *Cosmic Radiation* (1943).

[5] C. G. and D. D. Montgomery, Phys. Rev. **56**, 10 (1939).

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

of 2×10^{-4} neutron per gram and per second at the 6-meter level on Mt. Evans[1] was found. The rates of production of neutrons determined in balloon flights,[1] are all probably too low because of the low amplifier bias settings necessary to insure that noise is not counted.

PROTON EXPERIMENTS

In order to study the number of protons, a proton counter was employed. This counter was 75 cm long, 15 cm in diameter and filled with methane (CH_4) to a pressure of 48 cm Hg. It was operated in the proportional region, and the number of pulses as a function of voltage was determined. The cylinder was of brass, about 3 mm thick. Hence no protons of less than 15-Mev energy could have entered the counter from outside.

The counting rates obtained with this counter are shown in Fig. 1. In this figure, the curve is the observed counting rate as a function of voltage.

DISCUSSION OF PROTON EXPERIMENTS

Inspection of Fig. 1, shows a group of pulses extending to low voltages. These are the background contamination-alpha-particles. They were counted at about 1.2 per minute, which for an inside cylinder area of something over 6000 cm^2, corresponds to about 2×10^{-4} alpha per cm^2 per minute. The counter used in the 1941 tests had about the same amount of contamination; i.e., a trifle less than half the area and about half the number of alphas per minute.

The main group of protons is seen to be represented by a hump in the differentiated curve suggesting that most of the protons lose about 1 to 2 Mev in traversing the counter. Either the protons had about this energy, or they were higher energy protons which reached the opposite wall having lost 1 to 2 Mev in transit. For example, a 10-Mev proton has a range of about 1 meter in air at S.T.P., and hence in 15 or 20 cm path through methane at 48-cm pressure may lose around 1 to 2 Mev.

The maximum in the curve below the beta-ray threshold is at about 35 to 41, counts per minute. This compares with 10 to 12 in the 1941 experiments. The increase is of the order of a factor of 3.4 as compared to a ratio of cross-sectional areas

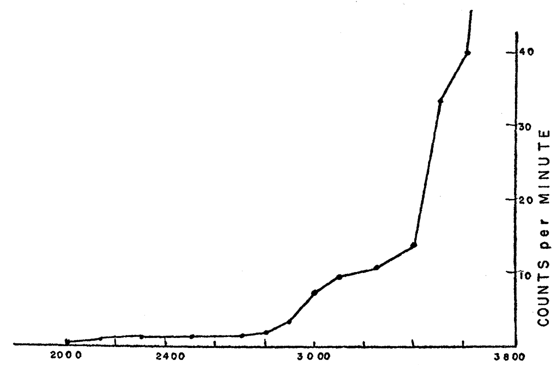

FIG. 1. Curve of counting-rate as a function of voltage for proportional counter filled with methane. Observed at Mt. Evans, altitude 14,156 ft. The pulses at 2000 to 2400 volts are caused by alpha-particle contamination in the counter, those between 3000 and 3600 volts are produced by heavily ionizing events including protons, giant showers, and nuclear disintegrations. This counter started counting beta-particles at about 3600 volts, and the counting rate rises very rapidly at voltages above 3600 due to slow electrons and slow mesotrons.

of 2.3 and a volume ratio of 3.7 between the 1946 and 1941 counters. We have pointed out before that the majority of the protons are produced in the walls and not in the gas of the counter, there being only about 8 grams of gas in our 1946 counter. It had heretofore been assumed that the increase in the number of protons counted, in going to a larger counter with substantially the same gas pressure, would be proportional to the increase in area. The fact that the increase is faster than the increase in area but less than that of volume, suggests that the processes actually occurring are complex and may involve a volume dependent process superposed on one dependent on the area.

The possible entities capable of causing the counter to discharge are (a) contamination alphas, (b) protons, stars and other disintergrations, (c) giant showers, and (d) recoils due to fast neutrons. Slow mesotrons and betas are counted only at the highest voltages. Only process (d) is volume-dependent.

It will be noted that the curve has a definite hump just before the beta-ray counting potential is reached. This same hump was observed in 1941. The definite maximum occurring in pulses of a certain size argues against any monotonically rising distribution such as postulated by Heisenberg and his collaborators.[4] It will be recalled that they derived, from a study of stars, a distribution described by Eq. (2), in terms of energy per star.

If it is assumed that all the counts are due to protons, then the number of protons may be directly computed from the counting rate and the counter area. If, on the other hand, some of the counts are ascribed to recoil protons produced by fast neutrons, then the efficiency of the counter fast neutrons is given by Eq. (1) modified by taking σ as the recoil cross section. Taking, in this case, $P=48/76$ atmos. $\sigma=10^{-24}$ cm^2, $d=15$ cm, we find $G=0.0255$ percent.

The number of counts per minute N will be related to the flux i of particle per minute producing the counts through:

$$N=iAG,$$

where A is the cross-sectional area of the counter, in this case 1125 cm^2. Hence if all 32 counts per minute are ascribed to recoils due to fast neutrons, a fast neutron flux of 11 neutrons per cm^2 per minute is required. On the other hand, since the efficiency of detection of protons is so nearly unity, a flux of 0.028 proton per cm^2 per minute will suffice to account for the observed rate. If the number of fast protons and neutrons is equal, then almost all the counts are due to protons, because of the low neutron recoil efficiency.

Consideration of recoils from the wall shows that these are more probable than recoils within the gas by a factor of five or more, depending on what energy is assumed for the neutrons. However, it will still be true that, for an equal flux of neutrons and protrons, most of the counts will be due to protons.

The proton experiments described above do not permit separate evaluation of the numbers of protons or fast neutrons, but only allow limits to be assigned to both possibilities. A set of experiments, designed further to resolve the factors involved and so study the altitude dependence of each, is being undertaken.

A rough evaluation of the rate of production of protons in the walls of the counter may be made if one assumes that the number of protons counted is the number produced in the walls which emerge into the active volume. The photographic plate evidence shows that star particles are produced with spherical symmetry, with no strong dependence on the direction of the producing entity. Consequently, one-half of the protons will be produced with directions away from the sensitive part of the counter. Of the remainder, one-half of those produced within one "range" of the surface will not emerge due to obliquity. If the range R of a proton is taken as 1 gram of matter, and the surface area S of this counter as 1125 cm^2, then the total counting rate $N=SQR$. Since 0.5 count per second was recorded, the rate of production Q is 5×10^{-4} per gram per second. The true rate of production is four times this, or 2×10^{-3} since not all protons produced were counted; but if an average of 3 protons are produced at once, there are about 7×10^{-4} production events per gram per second. This figure is of the same order of magnitude but somewhat larger than that derived for neutrons. This suggests that, if protons and neutrons are produced at about the same rate, not all the neutrons are detected and hence we may be underestimating the rate of production of neutrons.

The figure of 2×10^{-3} proton per gram per second may be compared to that deducible from Hazen's data.[7] Hazen observed 58 stars and estimates 5800 stars in 8500 photographs. He had about 46 kg of lead in his chamber. If his chamber was sensitive for 0.1 second, then his rate of production would be $(5800/8500)=Q\times(46\times10^3)\times0.1$ whence $Q=1.6\times10^{-4}$ per gram per second, easily in agreement with our figure in view of the crudity of the assumptions.

ACKNOWLEDGMENTS

The authors are indebted to the Research Corporation for financial support of the above investigations. The use of the Mt. Evans Laboratory was made available through the courtesy of the University of Denver. The authors received enthusiastic cooperation and assistance, without which the work could never have been carried out, from Professors Byron Cohn and Mario Iona of the University of Denver. Messrs. L. G. Collyer and A. Krumbein of the New York University staff accompanied the expedition and rendered material assistance, as also did Charles C. Renshaw II and Thomas Baker. To all of these persons, our thanks are hereby expressed.

[7] W. E. Hazen, Phys. Rev. **65**, 67 (1944).