and presumably the cross sections for photon absorption increase at even a greater rate.

In the energy region from 50 Mev to the meson threshold, the photonuclear interaction may be a combination of photoelectric effect decreasing with energy and a photomesonic effect increasing with energy.

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Collision Lengths of Neutral, Penetrating-Shower-Producing Cosmic Radiation in Light and Heavy Water*

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The collision length, L_c, of neutral penetrating-shower-producing cosmic radiation incident through a reinforced concrete roof of thickness 25 g/cm^2 at Los Alamos, New Mexico, altitude 2280 meters, was measured in light and heavy water. The values obtained were, for H_2O, $L_c=113\pm10$ g/cm^2 and for D_2O, $L_c=123\pm10$ g/cm^2. Equal masses of oxygen per unit area in the H_2O and D_2O absorbers were used for a determination of the difference between the collision cross sections of the deuteron and of the proton for the incident particles. The value obtained for this difference was $\sigma_D-\sigma_P=13\pm15$ mb.

I. INTRODUCTION

DURING the past few years much attention has been given hard-shower production by both charged and neutral high-energy cosmic-ray particles. The general purpose of work in this field is to gain an understanding of high-energy nucleon-nucleus and nucleon-nucleon interactions involving, among other phenomena, π-meson production. One of the quantities frequently measured is the collision length, which may be defined as the mean thickness of material, measured in g/cm^2, through which an incident particle travels before it undergoes a nuclear interaction.

The collision length L_c for a radiation which produces penetrating showers[1] is given by $L_c=(m/\sigma)$ g/cm^2, where, for a molecular substance, m is the mass of a molecule of the substance and σ is the sum of the effective collision cross sections for the production of penetrating showers in the nuclei composing the molecule.

It has been found that for materials of high atomic mass such as lead, the observed collision length agrees well with the calculated geometric collision length[2] $L_g=m/\sigma_g$. For materials of low atomic mass, the observed collision length is usually greater than the geometric, the difference sometimes being attributed to a "transparency" of nuclei. It is clear, however, that as the atomic number decreases the geometric collision length becomes less meaningful because it is based upon the concept of spherical nuclei of constant, uniform density.

The production of the π mesons of a penetrating shower has been described by two different processes. The plural process, proposed by Heitler and Janossy[3] assumes that the incident particle produces one meson in each collision with a nucleon and that a shower of several mesons is built up through successive collisions with several different nucleons in the same nucleus. The multiple process, proposed by Heisenberg[4] and applied by Fermi[5] in statistical calculations of shower parameters, supposes that several mesons, and possibly some nucleons, are produced in an encounter of the incident particle with a single nucleon. Lewis[6] has summarized the present state of the theory of multiple meson production by collisions of nucleons.

It has now become fairly clear that the multiple process does occur in nature and that multiplications of a shower produced in a first collision with a nucleon can take place within the struck nucleus. Thus, the best description appears to be a kind of plural process

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[1] For a discussion of this subject and references to the literature, see Bruno Rossi, *High Energy Particles* (Prentice-Hall, Inc., New York, 1952).

[2] In this paper, $\sigma_g=\pi r_0^2A^{\frac{2}{3}}$, where A is the atomic mass number and $r_0=1.37\times10^{-13}$ cm.

[3] W. Heitler and L. Janossy, Proc. Phys. Soc. (London) **A62**, 669 (1949).

[4] W. Heisenberg, Z. Physik **126**, 569 (1949).

[5] E. Fermi, Prog. Theoret. Phys. **5**, 570 (1950).

[6] H. W. Lewis, Revs. Modern Phys. **24**, 241 (1952).

not limited to the production of a single meson in each collision with a nucleon, but in which the multiple process is a proper description for each successive collision within the nucleus.

Cosmic-ray particles which produce nuclear interactions are called "N rays." At appreciable depths in the atmosphere, the N rays include primarily protons, neutrons and π mesons. Because of the very short half-lives of the π mesons, most of the N rays observed are protons and neutrons. Certainly the flux of neutral π mesons is very small because of the short mean life, estimated by Carlson, Hooper, and King[7] as about 3×10^{-14} second. This is also true with respect to V_0 particles whose mean life has been estimated as being of the order of 10^{-10} second.[8] Therefore, neutral N rays are believed to consist almost exclusively of high-energy neutrons.

In the measurement of collision lengths of charged N rays by counter arrangements it is difficult to arrive at unambiguous results. However, in 1940 Rossi and Regener[9] devised a coincidence-anticoincidence system which can be used for unambiguous measurements of the collision length of neutral N rays. Adaptations of this system have been used by several experimenters,[10–14] and equipment similar to that used by Pomeroy[12] and Rollosson[13] was used in this experiment.

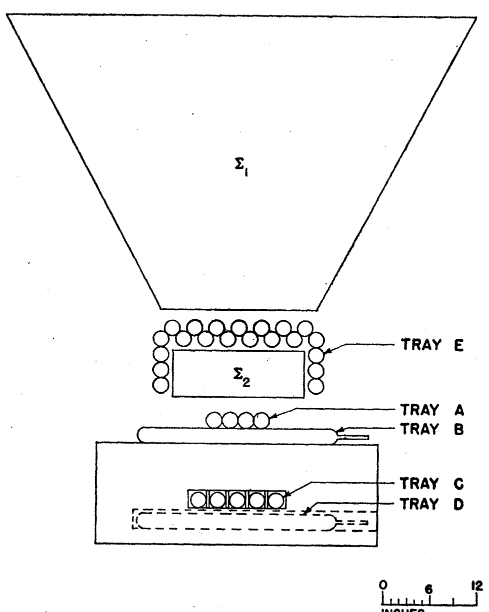

FIG. 1. End view of the apparatus.

[7] Carlson, Hooper, and King, Phil. Mag. **41**, 701 (1950).
[8] Fretter, May, and Nakada, Phys. Rev. **89**, 168 (1953); Leighton, Wanlass, and Anderson, Phys. Rev. **89**, 148 (1953).
[9] Bruno Rossi and Victor H. Regener, Phys. Rev. **58**, 837 (1940).
[10] L. Janossy and G. D. Rochester, Proc. Roy. Soc. (London) **A182**, 180 (1943).
[11] Walker, Walker, and Greisen, Phys. Rev. **80**, 546 (1950).
[12] David Pomeroy, Phys. Rev. **84**, 77 (1951).
[13] G. W. Rollosson, Phys. Rev. **87**, 71 (1952).
[14] H. W. Boehmer and H. S. Bridge, Phys. Rev. **85**, 863 (1952).

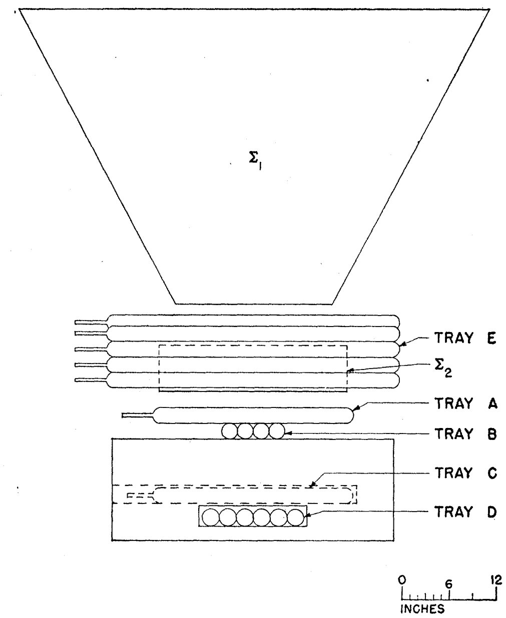

FIG. 2. Side view of the apparatus.

The purpose of this experiment was to measure the collision lengths of neutral N rays (predominantly neutrons) in light and heavy water and to find the difference in the collision cross sections of the deuteron and the proton for these rays.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

Two elevations of the Geiger counter and absorber arrangement are shown in Figs. 1 and 2. All of the equipment below Σ_1 was mounted upon a car which could be moved under either of two stainless steel tanks, Σ_1, one of which contained H_2O and the other D_2O. The depths of water were adjusted so that the amount of oxygen per cm^2 was the same for both tanks. The two tanks were set up under as nearly identical roof sections as possible, and the positions of the tanks were interchanged twice so that the effect of the slight variation in roof thickness could be eliminated.

The counters were connected to recording equipment in such a manner that counts were recorded when a given counter in tray A and a given counter in tray B were in coincidence with two counters of a certain portion of tray C, and with one counter of a certain portion of tray D, respectively. The choice of those portions of trays C and D which, in combination with given counters in trays A and B contributed to fivefold coincidences, was made in such a way that all straight lines drawn through discharging counters would lie inside Σ_1. The requirement for two counters to be discharged in tray C insured that the count represented a shower of at least two ionizing particles, and the thickness of 6 inches of lead between trays B and C insured that recorded showers originating in Σ_2 were made up of penetrating particles. Half-inch lead plates were inserted between adjacent counters in tray C to reduce the registering of local soft showers and knock-on electrons. Except when the background was being counted, $\sum_2$ was filled with lead to a thickness of six inches. Background counts were obtained with this lead removed from $\sum_2$. Fivefold coincidence counts made in this way are designated PS, penetrating showers.

The record of the number of fivefold coincidence counts which appeared under the described conditions, but in anticoincidence with tray E, formed the main portion of the experiment. Events of this type resulted mainly from penetrating showers which orginated in the lead of $\sum_2$ by non-ionizing (neutral) rays. These coincidence-anticoincidence counts are designated NPS.

The equipment was thus designed to record penetrating showers produced in $\sum_2$ by non-ionizing particles which have traversed $\sum_1$ without a nuclear interaction. If the neutral particle had undergone an interaction in $\sum_1$, we assume that it would have been accompanied by charged particles as it reached tray E, and the event would not have been recorded as of the NPS type. As the thickness of $\sum_1$ is increased, an exponential decrease in the number of showers produced in $\sum_2$ by non-ionizing primaries is expected. Such an exponential decrease provides a measure of the collision length of the shower-producing radiation in $\sum_1$.

It should be observed that a nuclear collision of the incident neutron in $\sum_1$ might conceivably lead to the transfer of only a small fraction of its energy to ionizing secondaries. These low-energy secondaries might be absorbed in $\sum_1$ before reaching the anticoincidence tray E, and the primary neutron might still be able to produce a penetrating shower in $\sum_2$ and, thus, an NPS count. If this process does happen the magnitude of the effect would certainly be dependent upon the thickness of absorber in $\sum_1$. Thus one could not, in general, expect an exponential decrease of the NPS counts with thickness of absorber in $\sum_1$, and consequently, one could not obtain an unambiguous experimental result for the collision length. However, the data from previous experiments[13–15] performed under similar conditions seem to show an exponential decrease of the NPS rate with thickness in $\sum_1$. This indicates that the primary neutron does not penetrate beyond the distance which is penetrated in $\sum_1$ by its ionizing secondaries. This supports the view that an experiment of the present type does measure the collision length for nuclear interactions of high-energy non-ionizing N-rays.

The circuits were arranged in such a way that the discharge of any counter in tray E resulted in the formation of a blocking gate about 100 microseconds long which prevented the recording of any fivefold coincidence on the NPS recorder during the time of this gate. The fivefold coincidence pulse was delayed about 9 microseconds after formation before being fed into the anticoincidence circuit in order to take account of the possibility that a counter in tray E was slow in response. The electronic circuits employed were similar to those used by Pomeroy[12] and by Rollosson,[13] and the counter tubes were of the type described by Regener.[16]

Isotopic analysis of the heavy water showed the hydrogen content to be more than 99 percent deuterium. The correction for the presence of ordinary hydrogen in the heavy water is much less than the relevant statistical errors and it has been neglected. Chemical analyses of the H_2O and D_2O showed the presence of a few parts per million of the more common elements of low and intermediate atomic mass, but the effect of these small amounts of impurity was calculated to be entirely negligible in this experiment. Construction of most of the equipment and preliminary tests were carried out at the Department of Physics of the University of New Mexico. The equipment was then installed at Los Alamos for the duration of the experiment. The elevation was 2280 meters.

Runs, usually of duration about 24 hours each, were made alternately under the tanks containing H_2O and D_2O. The number of penetrating showers PS and NPS and the time were recorded for each run. Similar runs were made with the tanks empty, and some data were taken with fillings of intermediate depth.

Some of the runs were made with lead in position $\sum_2$, some without. A few NPS counts were always observed with no lead in position $\sum_2$. At least some of these arose from showers formed in counter walls and the supports for tray E, and some may have come from wide-angle showers produced in the main lead shield by rays incident at a large zenith angle.

The anticoincidence tray E was not 100 percent efficient. Its inefficiency was measured frequently by moving the equipment away from both tanks, placing tray B above tray E, and connecting two counters in tray C together. Thus single ionizing rays passing through the system could cause counts on the PS recorder but, since these rays would have to pass through tray E, no counts should be recorded on the NPS recorder. However, some NPS counts, arising in part possibly from side showers and accidental coincidences, were always found. The inefficiency ϵ defined as the ratio NPS/PS for this case, was assumed to have the same value during normal operations and this value was used to correct the observed rate of NPS counts. In general, daily checks were made upon the operation of the individual counters and the electronic circuits.

III. CORRECTIONS AND TREATMENT OF DATA

The barometric pressure was recorded and corrections were applied to the data for variations of the pressure from an arbitrary standard value near the mean.

[15] K. Sitte, Phys. Rev. **78**, 714 (1950).

[16] Victor H. Regener, Rev. Sci. Instr. **18**, 267 (1947).

TABLE I. Observed counts and corrections.

No. of runs	Σ_1 in g/cm²	Σ_2	PS counts, obs	NPS counts, obs	Corrections to NPS counts N-S Av	Ineff.	Pressure	NPS corrected
45	85.09, D_2O	6 in. Pb	35 210	2459	−4.05	−444.0	−8.86	2002.1
16	85.09, D_2O	0	15 824	386	−1.06	−199.3	+1.07	186.7
34	76.6, H_2O	6 in. Pb	28 035	1962	−8.19	−354.0	−15.89	1583.9
15	76.6, H_2O	0	17 733	400	− 2.09	−223.5	−0.10	174.3
11	0	6 in. Pb	9868	1068	+14.00	−124.5	−35.24	922.3
8	0	0	8487	292	+5.11	−106.9	−8.85	181.4
4	37.6, H_2O	6 in. Pb	3332	293	−5.12	−42.0	−7.32	238.6
4	37.6, H_2O	0	4863	112	−1.96	−61.3	−3.26	45.5
1	50.8, H_2O	6 in. Pb	688	65	−1.14	−8.7	...[a]	55.2
1	50.8, H_2O	0	610	14	−0.24	−7.7	...[a]	6.1
1	27.0, H_2O	6 in. Pb	484	44	−0.77	−6.1	...[a]	37.1
1	27.0, H_2O	0	1094	27	−0.47	−13.8	...[a]	12.7

[a] The barometric pressure was not read, but the correction is negligible compared with the statistical error for a small number of counts.

The absorption of the roof was not quite the same for the two tank positions, designated N (north) and S (south), and the times spent with the equipment in each position for each arrangement of $\sum_1$ and $\sum_2$ were usually somewhat different. A weighted average of the ratio of the NPS counting rates in the two positions for the same absorber conditions showed that the counting rate in the north position exceeded that in the south position by 3.5 percent. That is, each differed from the average by 1.75 percent. Let t_N and t_S be the times spent in positions N and S, respectively, and let N_N and N_S be the corresponding numbers of NPS counts in the two positions. Then, in order to reduce the total number of counts to the basis of average position, the following corrections were applied:

$$+0.0175N_S(t_S-t_N)/t_S,\text{ if } t_S>t_N,$$

and

$$-0.0175N_N(t_N-t_S)/t_N,\text{ if } t_N>t_S.$$

All data were reduced to average values for the N and S positions by applying the correction terms given above.

A correction for inefficiency ϵ of tray E was made by subtracting the quantity $\epsilon\times$PS from the observed number of NPS counts for each configuration of the absorbers $\sum_1$ and $\sum_2$.

The absorption length of neutral, penetrating-shower-producing rays in air is[12] 115 g/cm² = 3.33 inches Hg. Thus the intensity of incident radiation at pressure p (measured in inches Hg) is given by

$$I_p=I_{p0}\exp[-(p-p_0)/3.33]=I_{p0}\exp(-0.3\Delta p)\approx I_{p0}(1-0.3\Delta p),$$

where I_{p0} is the intensity expected at an arbitrary pressure p_0, chosen near the mean pressure, and $\Delta p=p-p_0$. Thus, in order to bring the results to a common barometric pressure basis, a correction of $0.3\Delta p\times$NPS was added to the NPS count for each run after the correction for inefficiency of tray E had been made.

The background NPS counts, obtained with the lead removed from $\sum_2$, were corrected in the same manner as the other NPS counts. As will be seen later, the background counting rate varies, within experimental error, at the same exponential rate with depth of water in $\sum_1$ as does the NPS counting rate when lead is present at $\sum_2$. Thus, for calculations of collision lengths it does not matter, except for the accumulation of errors, whether or not the background rate is subtracted from the otherwise corrected NPS rates.

Let σ_P, σ_D, and σ_O be the collision cross sections of the hydrogen, deuterium, and oxygen nuclei, respectively, for neutral N rays, and let L_{c1} and L_{c2} be the collision lengths for these rays in light and heavy water, respectively. Let R_0, R_1, and R_2 be the corrected rates of production of penetrating showers in $\sum_2$ by neutral N rays with $\sum_1=0$ (the empty steel tank), with $\sum_1=x_1$ g/cm² H_2O and with $\sum_1=x_2$ g/cm² D_2O, respectively. Let m_1 and m_2 be the molecular masses of light and heavy water, respectively. Then, if the number of penetrating showers produced in $\sum_2$ by neutral N rays is a decreasing exponential function of the depth of water in $\sum_1$,

$$R_1=R_0\exp(-x_1/L_{c1}),\quad\text{and}\quad R_2=R_0\exp(-x_2/L_{c2}),\tag{1}$$

where

$$L_{c1}=m_1/(2\sigma_P+\sigma_O),\quad\text{and}\quad L_{c2}=m_2/(2\sigma_D+\sigma_O).\tag{2}$$

From the four equations above,

$$R_1/R_2=\exp(x_2/L_{c2}-x_1/L_{c1})=\exp\{2[(x_2\sigma_D/m_2)-(x_1\sigma_p/m_1)]+[(x_2/m_2)-(x_1/m_1)]\sigma_O\}.\tag{3}$$

If the depths of water are chosen such that

$$x_2/m_2=x_1/m_1,\tag{4}$$

as was done for a part of this experiment, (3) reduces to $R_1/R_2=\exp[2x_1(\sigma_D-\sigma_P)/m_1]$, from which

$$\sigma_D-\sigma_P=(m_1/2x_1)\ln(R_1/R_2).\tag{5}$$

From (1) and (2) we get

$$L_{c1}=x_1/\ln(R_0/R_1),\tag{6}$$

$$L_{c2}=x_2/\ln(R_0/R_2).\tag{7}$$

Equations (5), (6), and (7) were used to calculate the results of this experiment.

IV. EXPERIMENTAL DATA

The inefficiency of tray E was determined in 24 runs which resulted in a total of 80 851 PS counts and 1020 NPS counts. This gives $\epsilon = 1020/80851 = 0.0126 \pm 0.0004$. Table I gives the magnitudes of the various corrections and the corrected values of the total NPS counts.

Table II gives the total time of running under each condition, the corrected total NPS counts, and the values of the corrected counting rates. All errors quoted represent standard deviations.

The uncorrected NPS counting rates obtained in individual runs under six different combinations of $\sum_1$ and $\sum_2$, and the individual values of the inefficiency, are plotted against the date of observation in Fig. 3. Some of the deviations of the individual points from the mean values are reduced when corrections are made for the barometric pressure and for the position (north or south) of the apparatus. However, it is clear from observation of Fig. 3 that no large change in the sensitivity of the detection equipment took place during the period of the experiment.

The logarithms of the corrected NPS counting rates observed with $\sum_1$ composed of light water are plotted in Fig. 4 against depth of water for $\sum_2 = 0$ and for $\sum_2 = 6$ inches Pb. Both curves have the same slope within experimental error. One interpretation of this fact is that most of the background counts ($\sum_2 = 0$) arise from rays incident through $\sum_1$ and thus are subject to absorption by the water in it.

Examination of the data in Table II shows that, for $\sum_2 = 6$ inches Pb, the counting rate with $\sum_1 = 85.09$ g/cm^2 of D_2O is slightly, but insignificantly, less than that with $\sum_1 = 76.6$ g/cm^2 of H_2O. These depths of

TABLE II. Rates of production of penetrating showers by neutral N rays.

No. of runs	Σ_1 in g/cm^2	Σ_2	Total time in hours	Corrected total NPS counts	NPS counting rate in hr^{-1}
45	85.09, D_2O	6 in. Pb	1097.8	2002.1±50	1.825±0.045
16	85.09, D_2O	0	364	186.7±20	0.512±0.055
34	76.6, H_2O	6 in. Pb	855.6	1583.9±44	1.851±0.051
15	76.6, H_2O	0	392.4	174.3±20	0.445±0.051
11	0	6 in. Pb	253.7	922.3±34	3.64 ±0.13
8	0	0	193.4	181.4±17	0.94 ±0.09
4	37.6, H_2O	6 in. Pb	94.7	238.6±17	2.52 ±0.18
4	37.6, H_2O	0	96.4	45.5±10.6	0.47 ±0.11
1	50.8, H_2O	6 in. Pb	22	55.2± 8.1	2.51 ±0.37
1	50.8, H_2O	0	15	6.1± 3.8	0.41 ±0.25
1	27.0, H_2O	6 in. Pb	14	37.1± 6.6	2.65 ±0.47
1	27.0, H_2O	0	24	12.7± 5.2	0.53 ±0.22

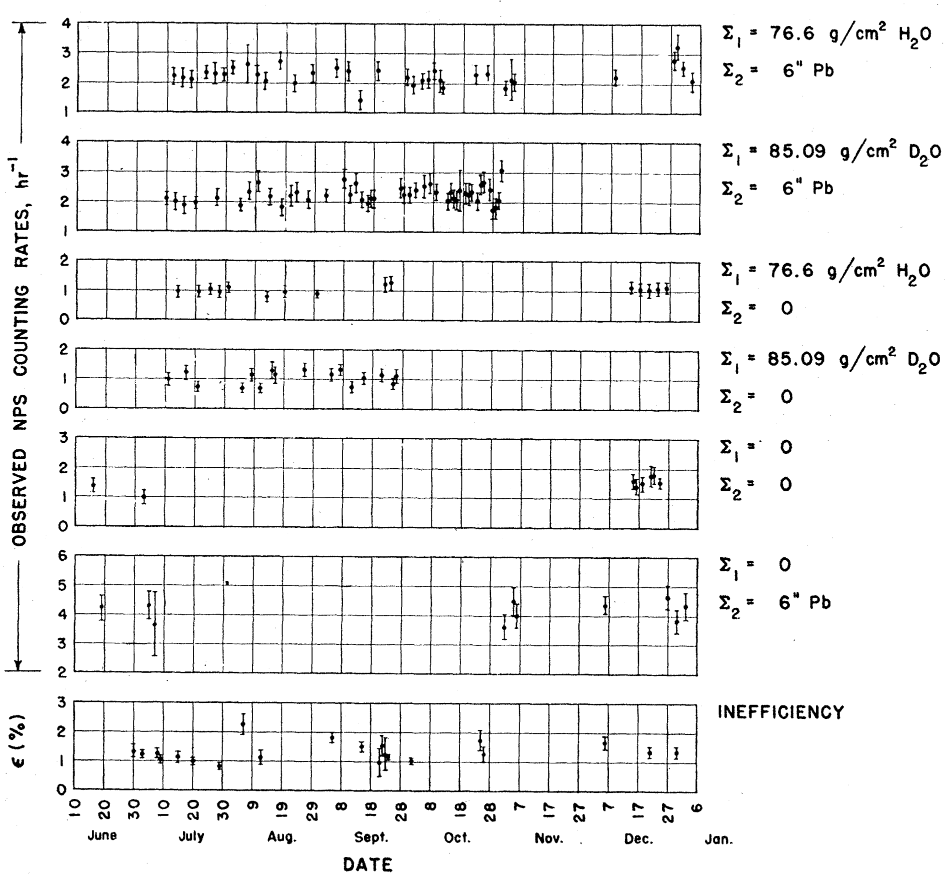

FIG. 3. Uncorrected counting rates and inefficiency as observed throughout the period of experimentation.

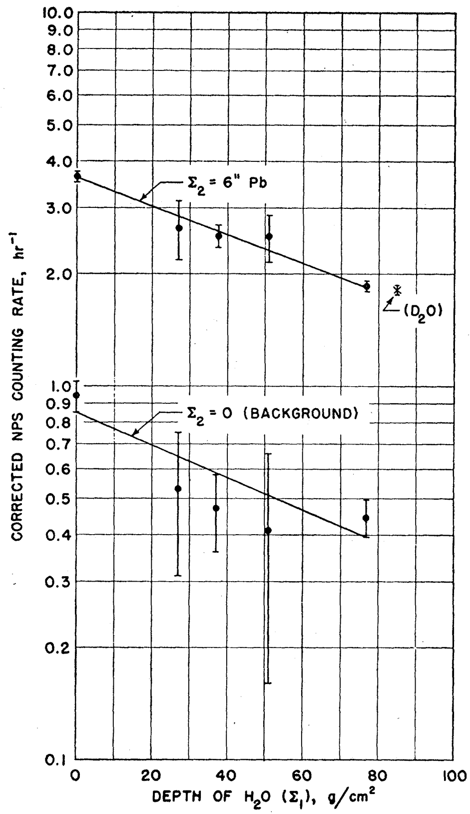

FIG. 4. Absorption of neutral N rays by light water.

heavy and light water contain the same amounts of oxygen per unit area, i.e., they satisfy Eq. (4). Thus the small difference in these counting rates has the right sign to correspond with the cross section of the deuteron being greater than that of the proton, even though this difference is less than its statistical error. The difference between the corresponding background rates ($\sum_2=0$) has the opposite sign, but it is also less than its statistical error. There is no obvious reason for the background to be less when $\sum_1$ is filled with light water than when it is filled with the corresponding depth of heavy water and, possibly, the reverse might be expected. If the true background with light water is equal to or greater than that for heavy water, perhaps the best value of the background for both cases would be the weighted average of the two values given in Table II. This average is 0.477 ± 0.037 count per hour. However, the statistical errors are sufficiently large to include the possibility that the true background values are equal, or even inverted in magnitude, and the value of $\sigma_D-\sigma_P$ has been calculated using the individual background values observed in the experiment.

V. RESULTS

Using the data of Table II, Eq. (5) gives $\sigma_D-\sigma_P=13\pm15$ millibarns. (If the average background rate had been used, as indicated in the preceding paragraph, the result would have been $\sigma_D-\sigma_P=4\pm12$ mb.) Similarly, Eqs. (6) and (7) give the collision length in H_2O, $L_{c1}=113\pm12$ g/cm^2 and in D_2O, $L_{c2}=123\pm13$ g/cm^2. If the background values ($\sum_2=0$) are not subtracted from the corrected counting rates, the values of L_{c1} and L_{c2} obtained are the same as above but the calculated standard deviations are ±9 g/cm^2 in each case. An estimated standard deviation of ±10 g/cm^2 for each collision length is perhaps a reasonable value. The value of the collision length in H_2O is in reasonable agreement with Rollosson's[13] value of 98 ± 13 g/cm^2 measured in New Mexico at an altitude of 2770 meters. The geometrical collision lengths are $L_{g1}=61$ g/cm^2 in H_2O and $L_{g2}=59$ g/cm^2 in D_2O.

It should be noted that the measured difference of about 13 millibarns between the cross sections of the deuteron and the proton is small compared with $\pi r_0^2=59$ millibarns, the "geometric" cross section of the proton. One might expect the loosely bound deuteron to have a cross section equal to the sum of the proton and neutron cross sections. On this basis $\sigma_D-\sigma_P$ would be a measure of the (n,n) cross section which would be expected to be about the same size as the (n,p) cross section. Thus, it seems reasonable, and consistent with the rather large value obtained for the collision length in water, to assume that the absolute cross sections for penetrating-shower production in hydrogen and deuterium are both small. In fact, a collision length in water as large as 113 g/cm^2 seems to point to a degree of "transparency" even for the oxygen nucleus.

VI. ACKNOWLEDGMENTS

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