On the Neutrons from the Deuteron-Deuteron Reaction*

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The absolute number of neutrons produced in the deuteron-deuteron reaction (abbreviated *d-d* reaction) has been determined for a target of heavy ice by measuring the scattering cross section of liquid N_2 and liquid O_2 for these neutrons, and by counting in an ionization chamber the recoils in N_2 and in O_2 gas due to the scattering of the neutrons. Applying the necessary corrections one finds 3.0×10^5 neutrons per second per microampere of deuterons at 100 kv with an estimated uncertainty of 20 percent. The absolute yield of the protons under the same conditions is $2.1\pm0.2\times10^5$; the nuclear process leading to the emission of a proton and a H^3 nucleus seems therefore somewhat less probable than the alternative process giving a neutron and a He^3 nucleus. The effective cross section for the neutron-producing reaction is roughly 2×10^{-26} at 100 kv, increasing to 4×10^{-26} at 300 kv and according to the results of Amaldi, Hafstad and Tuve to 1.3×10^{-25} at 700 kv. This reaction is therefore not a "very probable process." The scattering cross section of oxygen for these 2.4 Mev neutrons has the surprisingly low value of 0.75×10^{-24} cm², only 0.6 that of nitrogen. The cross section of hydrogen for these neutrons is 2.1×10^{-24} cm² in agreement with the theoretical value.

I. Introduction

The neutrons produced when ions of heavy hydrogen collide with heavy hydrogen nuclei are homogeneous in energy and rather copious at moderate voltages.[1] A thorough study of their number and their interaction with matter is therefore very important. It was started in this laboratory by Ladenburg, Roberts and Sampson,[2,3] using the 400 kv outfit purchased with a grant from the Rockefeller Foundation. The present paper is a continuation of this work with special emphasis on the scattering of these neutrons by light nuclei.

II. Experimental Arrangement

The experimental arrangement was essentially the same as that used by Ladenburg and Roberts, with the following improvements: The ion source, a low voltage arc of the type described by Crane, Lauritsen and Soltan,[4] was equipped with a probe-voltage supply continuously variable between zero and 6 kv, so that better focusing was obtained, especially at energies above 200 kv. The resistance for the measurement of the accelerating voltage was increased to 4×10^9 ohms so that voltages up to 400 kv could be measured exactly. The magnetically analyzed ion current received at the target amounted to some 24 microamperes of D_2 molecules or alternatively 2–3 microamperes of D atoms. The molecular beam was employed in most of the experiments both because of its large size and its known purity (comp. Roberts' paper,[3] p. 811). As a target we used heavy ice produced by condensing D_2O vapor on a Cu plate cooled by liquid air. This arrangement allows one to renew the layer of ice while the tube remains evacuated so that a fresh surface of identical properties is assured. The retarding potential on the target was increased to 135 volts for avoiding the loss of any secondary electrons from the target. The arrangement of the target, the necessary diaphragms, and the electrical connections are shown in Fig. 1. The diaphragm D_1 is grounded and is a few millimeters narrower than the charged diaphragm D_2 so that no part of the beam can hit the latter. The current carried by the beam was measured as before[3] with an integrating device acting upon a Cenco counter; this counter circuit is closed and opened simultaneously with that of the counter operated by the "scale of eight" and the linear amplifier-ionization chamber; in this way the number of discharges in the ionization chamber due to impinging protons or to recoils from impinging neutrons per microcoulomb carried by the ion

* Some of the results in this paper were presented at the Washington meeting of the American Physical Society, Phys. Rev. **51**, 1022 (1937).
[1] Oliphant, Harteck and Lord Rutherford, Proc. Roy. Soc. **A144**, 692 (1934).
[2] Ladenburg, Roberts and Sampson, Phys. Rev. **48**, 467 (1935); Ladenburg and Roberts, Phys. Rev. **50**, 1190 (1936).
[3] R. B. Roberts, Phys. Rev. **51**, 810 (1937).
[4] Crane, Lauritsen and Soltan, Phys. Rev. **45**, 507 (1934).

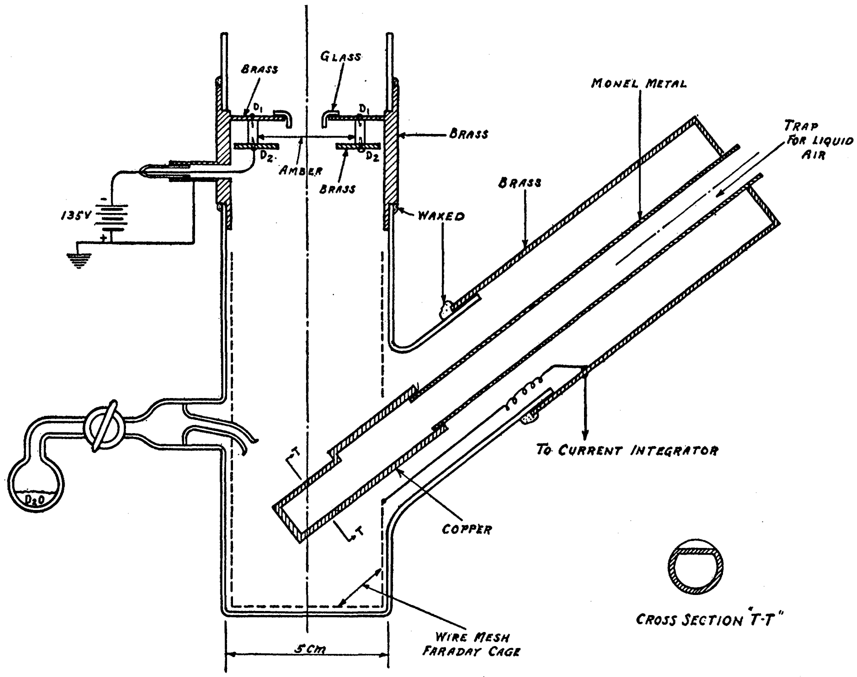

FIG. 1. Chamber for the heavy ice target.

beam was determined. This device eliminates the errors due to fluctuation of the current in the beam and together with the ice target gives results reproducible with an accuracy of a few percent.

The neutrons produced by the *d-d* reaction were measured at 90° with respect to the ion beam, so that their energy

$$E_n = \tfrac{3}{4}Q + \tfrac{1}{4}E_d = 2.44 \text{ Mev}$$

is practically independent of the deuteron energy E_d in the range studied (50 to 300 kv); here Q (3.2 Mev) is the energy balance[4a] of the reaction.

As the target of heavy ice is much more effective and constant than other targets of compounds of heavy hydrogen it seemed worth while to measure again the absolute yield of protons and neutrons produced in the *d-d* reaction. The solid angle of the measured proton beam was only 3×10^{-4}, that of the neutron beam was 0.2, as some thousand neutrons are necessary to give a measurable recoil in the ionization chamber.

III. METHOD

The principle for measuring the absolute number of neutrons was the same as that used previously by Ladenburg and Roberts: one counts the number of recoil nuclei produced when the neutrons entering the ionization chamber are scattered by the gas in it. If one knows the fraction of neutrons scattered and the percentage of scattered neutrons giving measurable recoils one can calculate the number of neutrons entering the chamber. In the previous experiments air was used as scatterer and the value of Dunning[5] for the scattering cross section of nitrogen was assumed. But the neutrons investigated by Dunning were produced by alpha-particles of radon bombarding beryllium and have energies distributed between about 100 kv and 14 Mev. We have therefore determined the scattering of the homogeneous neutrons from our *d-d* source, using as scattering agent liquid nitrogen and oxygen separately, and filled our ionization chamber alternately with these gases. As the scattering cross section obtained for these gases is very different (ratio

[4a] T. W. Bonner and W. M. Brubaker, Phys. Rev. **49**, 19 (1936).

[5] Dunning, Phys. Rev. **45**, 586 (1934); **48**, 265 (1935).

about 1.7 : 1) we get in this way two nearly independent measurements of the neutron yield. The percentage of scattered neutrons giving measurable recoils was determined as follows: The linear amplifier, scale-of-eight unit is adjusted to reject pulses below a definite size by means of a selector tube between the amplifier and the scale of eight.[5a] The voltage output of the linear amplifier was determined in terms of ion pairs in the chamber by the use of Th C′ alpha-particles. The voltage of the minimum effective pulse was determined by operating the linear amplifier on variable artificial pulses of known size, obtained from a relaxation oscillator. If I is the energy in electron volts for producing one ion pair, m the number of ions corresponding to the limit just determined, then $T=mI$, the energy for producing m ions, is just the lower limit of the energy of recoil nuclei which give measurable kicks. The scattering angle θ of these neutrons is easily calculated from conservation of energy and momentum in the scattering process and is given by the equation

$$\cos\theta=\frac{2M_n-k(M_n+M)}{2M_n(1-k)^{\frac{1}{2}}},\quad k=\frac{T}{E_n},$$

where E_n is the energy of the impinging neutrons, M_n their mass, M the mass of the scattered nuclei. For example for

$$m=2100,\ I=33\ \text{ev},\ T=69\ \text{kv},\ k=0.0285,\ M=14$$

we find $\cos\theta=0.79$, $\theta=37°$; therefore all neutrons scattered through an angle $\geqslant 37°$ give recoils measured in the chamber under the prevailing conditions. Assuming isotropic distribution of the scattered neutrons in a system where the center of gravity is at rest—for $M=14$ or 16 the distribution is practically also isotropic in the room system—one gets as the fraction of neutrons scattered through 37° or more, relative to 4π, the value 0.895. Therefore the number of recoils measured has to be multiplied by 1.12 to obtain the total number of recoils due to all the scattered neutrons. The range of the recoiling N and O nuclei is so short that their paths are essentially entirely in the chamber.

[5a] J. Giarratana, R. S. I. 8, 390 (1937).

If σ is the scattering cross section for the gas used, t the thickness of the gas layer, N the number of nuclei per cc, n_0 the unknown number of neutrons entering the chamber, n the total number of recoils, $n_0-n=n_0e^{-\sigma Nt}$ and as σNt is of the order of 10^{-4}, $n_0=n/\sigma Nt$. Our procedure consists therefore in two steps, (1) the measurement of the scattering cross section, (2) the measurement of the number of recoils of N and O.

IV. Measurement of the Scattering Cross Section

The scattering cross sections were measured by a transmission method essentially similar to that used by Dunning.[5] The neutrons were detected by a small paraffin-lined ionization chamber of 2.5 cm diameter placed 27 cm from the target. The scatterers were cylinders of 2 cm diameter placed midway between the target and the detector. In the case of O_2 and N_2, where we used the pure liquefied gases, these were small cylindrical Dewars; for other materials solid cylinders were employed. We used a beam of about 20 microamperes of D_2 molecules at 280 kv, which gave about 500 counts/min. under our conditions.

Two corrections must be applied to the measured transmission. First one must correct for that fraction of the neutrons measured which does not come directly from the target, but is scattered into the chamber from parts of the apparatus near the target. This number is small, because our paraffin-lined ionization chamber has maximum response to neutrons incident from the forward direction. The actual correction was determined by measuring the variation of the counting rate with the distance between the active part of the target[6] and the ionization chamber. It is found upon varying this distance between 12 and 40 cm that the inverse square law is fulfilled if one assumes that the number of neutrons not coming directly from the target is

[6] The active part of the target was a narrow line of about 1 cm length normal to the direction from the target to the middle of the chamber. The spot where the deuteron beam actually hit the ice target—visible by bright bluish luminescence—was a kind of ellipse, but the target made only a very small angle with the direction to the chamber, so that the ellipse appeared from the chamber nearly as a line. It is useful not to concentrate the beam in a very small spot on the target, otherwise the ice is removed too rapidly.

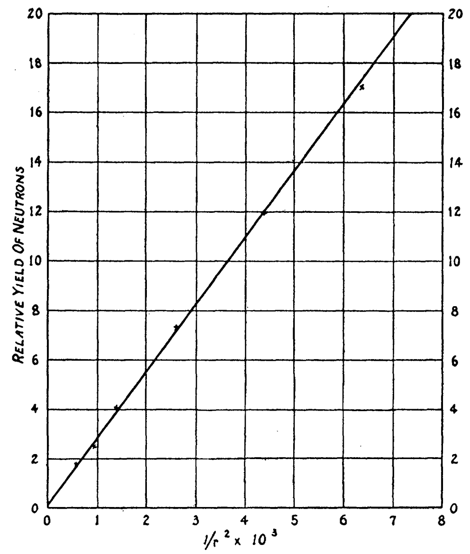

FIG. 2. The change of the yield of neutrons with the distance from the target.

roughly independent of the distance from the target, and amounts to about 3 percent of the total yield at 27 cm (see Fig. 2).

A second correction arises from the fact that a certain fraction of the neutrons deflected by the scatterer still enter the chamber and are counted. This correction has been calculated in the same way as by Amaldi and Fermi,[7] with the assumption of isotropic scattering. This method holds accurately only in the case of very thin scatterers, a condition not fulfilled in these experiments, as one needs about 10 cm of liquid O_2 to get an accurately measurable effect. However with the large target-detector separation used, the correction amounts to only a few percent of the measured transmission, and further corrections would be of a higher order. The mean free paths calculated from the scattering cross sections are in every case more than twice the length of the scatterer used, so that no corrections need be made for multiple scattering. Both corrections described act to decrease the measured transmission and thus to increase the cross section.

V. Results and Accuracy

The final results are collected in Table I where Dunning's values for the inhomogeneous neutrons from radon-beryllium are also given; as far as we see his values are not corrected for the neutrons scattered into the chamber. Besides N and O we have investigated some other substances easily obtainable, although a systematic investigation of the scattering for these homogeneous neutrons is outside the scope of the present paper.

Table I contains the transmission observed for the different substances, the corrected values of the transmission and the total cross section σ which is proportional to the logarithm of the reciprocal transmission. The inaccuracy of σ is estimated to be less than 10 percent except in the case of oxygen where due to the small scattering the uncertainty may be as high as 15 percent. The cross section given contains of course the effect of absorption of the neutrons besides that of elastic and inelastic scattering. As it is known the former does not amount to more than 10 percent of the total for fast neutrons.[8] Our value for the absolute yield of neutrons based on the cross section of nitrogen is not appreciably influenced by this complication inasmuch as in the absorption process heavy ions are produced having sufficient energy to be detectable in the ionization chamber. As far as it is known oxygen does not absorb *d-d* neutrons, and inelastic scattering of these neutrons does not occur with atoms higher than fluorine. The abnormally low cross section of oxygen, not previously known, is perhaps due to the closed shell of the nucleus, containing 8 protons and 8 neutrons. It may be interesting to measure the scattering of oxygen with widely different neutron energies.

TABLE I. *Transmission coefficients of neutrons in various substances and the total absorption and scattering cross section.*

Element	Z	g/cm²	Observed Trans-mission	Corrected Trans-mission	$\sigma \times 10^{24}$	$\sigma \times 10^{24}$ (Dunning)
H (paraffin)	1	2.60	0.55	0.51	2.11	1.68
C	6	8.41	.55	.52	1.57	1.65
N	7	8.10	.67	.65	1.27	1.76
O	8	11.4	.75	.72	.75	—
Al	13	10.8	.62	.60	2.16	2.4

[7] Amaldi and Fermi, Phys. Rev. **50**, 899 (1936), especially p. 915.

[8] Dunning, Pegram, Fink and Mitchell, Phys. Rev. **48**, 265 (1935).

The cross section of H is much higher than Dunning's value for the Rn-Be neutrons, somewhat higher than the value which Booth and Hurst[9] found recently for the *d-d* neutrons ($(1.8\pm0.4)\times10^{-24}$), and is in agreement with the value 2.16×10^{-24} predicted by theory[10] for neutrons of 2.44 Mev, assuming the binding energy of the singlet state of the deuteron to be 0.13 Mev.

VI. Measurement of the Number of Recoils in N and O and the Absolute Number of Neutrons

The number of recoil N and O nuclei due to neutrons which enter the ionization chamber and are scattered in it was measured with the same device as used in the scattering experiments described before, but the ionization chamber was filled with nitrogen or with oxygen and its electrodes were not lined with paraffin. On account of the lower sensitivity of this chamber to neutrons the distance from the target was reduced to 10 cm and the diameter of the chamber increased from 2.5 to 5.0 cm. The low scattering cross section of oxygen resulted in a correspondingly lower yield when oxygen instead of nitrogen was used. Two different runs gave as ratio O_2/N_2 0.61_8 and 0.60_2; the ratio of the two cross sections is $0.75/1.27=0.59_2$. The difference between these values is well within the experimental error. Therefore the absolute number of neutrons calculated from these results is the same in both cases.

Assuming at first isotropic distribution of the neutrons produced in the *d-d* reaction we get as total number emitted from the D_2O target under a solid angle of 4π for 1 microampere of deuterons at 100 kv $2.3_4\times10^5$ neutrons per second. This value is calculated by taking care of the correction of 12 percent due to low energy recoils not counted as mentioned before. It may be too high by an unknown, but small fraction due to neutrons not coming directly from the target, but scattered from surrounding material. We estimate this fraction to be certainly smaller than 10 percent, considering the very low value of stray neutrons (3 percent) found in the scattering experiments with the paraffin chamber at the large distance of 27 cm from the target. The number of recoils obtained when the ionization chamber is put below the target, so that the neutrons come out in the direction of the bombarding beam, is nearly twice as great as that observed at 90° to the beam. This large anisotropy has been studied carefully by Kempton, Browne and Maasdorp.[11] It can be represented by the function[12]

$$f(\theta)=1+0.8\cos^2\theta,$$

where θ is the angle between the direction of the bombarding beam and that of the emitted particles. Therefore we must multiply the yield calculated for an isotropic distribution from the measurements at 90° by

$$\tfrac{1}{2}\int_0^\pi(1+0.8\cos^2\theta)\sin\theta d\theta=1.266$$

so that the total number of neutrons under the conditions mentioned becomes 2.96×10^5 per sec. per microampere of deuterons at 100 kv.

We have also measured the total number of protons under the same conditions using thin aluminum windows in the path of the protons so that only the last centimeter of their range was effective in the chamber. We applied the precautions mentioned in Roberts' paper to avoid missing any protons. The result of our measurement is—under the assumption of isotropic distribution—that 1.65×10^5 protons are emitted per second from a fresh surface of heavy ice when bombarded by 1 microampere of deuterons at 100 kv. This value is about 40 percent smaller than the number of neutrons found under identical conditions. It seems therefore that the *d-d* reaction producing neutrons and He^3 is somewhat more probable than that producing protons and H^3. Theoretical considerations based on the hypothesis of identical specific nuclear forces between the elementary particles[13] lead to the result that

[9] Booth and Hurst, Nature **138**, 1011 (1936). These authors have, according to their complete paper (Proc. Roy. Soc. **A161**, 248 (1937)) used the neutrons of 2.9 Mev emitted in the forward direction with respect to the incident deuterons (note added in proof).

[10] See Bethe and Bacher, Rev. Mod. Phys. **8**, 83 (1936); Eq. (62).

[11] Kempton, Browne and Maasdorp, Proc. Roy. Soc. **A157**, 396 (1936).

[12] Compare L. I. Schiff, Phys. Rev. **51**, 783 (1937).

[13] M. H. Johnson, Phys. Rev. **51**, 779 (1937).

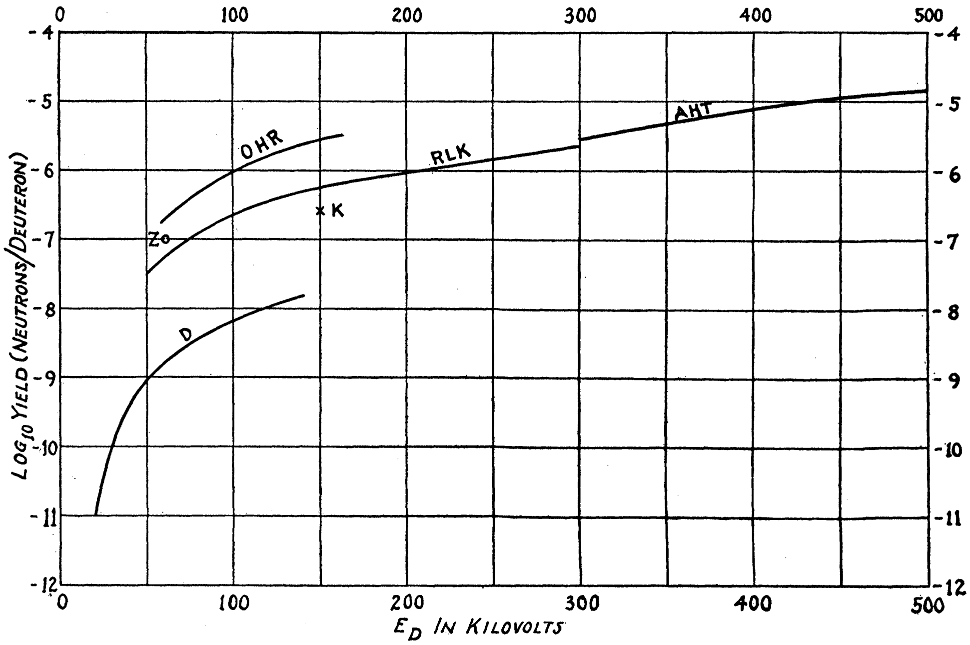

FIG. 3. The absolute yield of the deuteron-deuteron collision between 20 and 500 kv OHR = Oliphant-Harteck-Rutherford; RLK = Roberts-Ladenburg-Kanner; Z = Zinn-Seeley; AHT = Amaldi-Hafstad-Tuve; K = Kallmann-Kuhn; D = Doepel.

both reactions should be equally probable, confirmed roughly by earlier investigators.

The value found by Ladenburg and Roberts for the total number of protons emitted when a $(D_2O)(P_2O_5)$ target was bombarded under the same conditions was 7×10^4/sec., showing that our ice target is about 2.4 times as effective.

The data on the absolute number of neutrons emitted from an ice target under standard conditions allow us to calculate that we get 1 count in the paraffin lined chamber for 1600 impinging neutrons, and that 8000 neutrons hitting the N_2 filled chamber produce one count under our conditions of selection and amplification.

VII. Comparison with Other Investigators

The most reliable other measurements of the absolute yield of neutrons from the *d-d* reaction are those of Amaldi, Hafstad and Tuve[14] (A.H.T.). These authors have already compared their results with the older ones of Ladenburg-Roberts and found a satisfactory agreement. But the comparison can now be made much more accurate. A.H.T. used the method developed by Amaldi and Fermi[15] for the neutrons from a radon-beryllium mixture. They slowed down the neutrons to thermal energies in large amounts of water and measured the density of the slow neutrons by integration at various distances from the source; this density in turn was determined by counting the electrons given off from an activated sheet of rhodium. Although this rather indirect way of counting the neutrons is different in every respect from our method—which of course has also to be considered as indirect—the results agree as well as can be expected. We can compare these results directly at 300 kv, which is our highest and their lowest energy point. At this voltage (Fig. 4) we find for the ice target used

$$2.96\times10.1\times10^5 \text{ sec.}^{-1}\,\mu a^{-1}=3.0\times10^6 \text{ sec.}^{-1}\,\mu a^{-1}.$$

A.H.T. (reference 14, p. 908) found 11.3×10^6 neutrons/sec.$\cdot\mu$A of deuterons at 738 kv bombarding a target of heavy phosphoric acid and calculate as yield for a target of D_2O from the stopping power of these targets

$$1/0.29=3.45 \text{ times as much, that is } 39\times10^6.$$

[14] Amaldi, Hafstad and Tuve, Phys. Rev. **51**, 896 (1937).

[15] Amaldi and Fermi, Phys. Rev. **50**, 899 (1936).

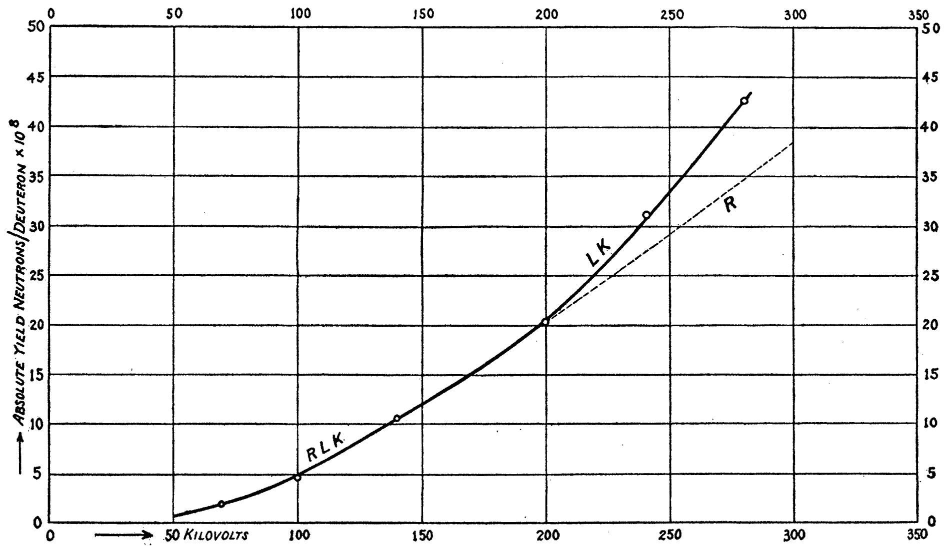

FIG. 4. Absolute yield of neutrons from D on D_2O.

The ratio of the yield at 738 and 300 kv can be calculated from their data to be 11 so that their yield for 300 kv deuterons bombarding D_2O was 3.5×10^6 sec.$^{-1}$ μa^{-1}.

The agreement is equally within the experimental error, if we use our factor of 2.4 instead of the value 3.45 to reduce the target of heavy phosphoric acid to a target of D_2O giving

$$2.4\times10^6 \text{ sec.}^{-1}\ \mu a^{-1}.$$

In Fig. 3 are plotted Roberts', our and A.H.T.'s values of the absolute yield (neutrons per deuteron) on a logarithmic scale, calculated for a pure deuterium target taking care of the stopping power of the target used[16] (compare Roberts' paper, p. 817, and A.H.T., p. 908). The figure shows that also the increase with voltage above 300 kv according to A.H.T. agrees well with our curve at lower voltages. In these units the absolute yield is 3×10^{-8} at 50, 2.4×10^{-7} at 100, 2.4×10^{-6} at 300, and 15×10^{-6} at 500 kv.

The figure contains further the values given by some other investigators. Oliphant, Harteck and Lord Rutherford,[1] who measured in their pioneer work the number of protons and estimated the yield of neutrons to be of the same order, found somewhat higher values than we. Doepel,[17] who measured down to 10 kv, got much lower yields; the reason for this discrepancy is not definitely known, but it seems probable that the solid compounds NaOD, $Ca(OD)_2$, D_3PO_4 which he used as targets are not as effective nor as reliable as targets of heavy ice. Durhop's results[17a] at the very low voltage of 5 to 20 kv are obtained with a LiD target without magnetic analysis; his absolute values are only estimated (10^{-12} at 10 kv and 5×10^{-11} at 20 kv). The values of Zinn-Seeley[18] at 60 kv and of Kallmann-Kuhn[19] at 150 kv are obtained without magnetic analysis and therefore only approximately comparable; they are in accordance with our values within a factor of 2. Kallmann-Kuhn give the reason why Alexopoulos' results[20] (which are not plotted in our curve) are appreciably higher than all the other values: he counted the neutrons with Geiger-Müller tubes which responded not only to heavy particles but also to electrons which are apparently released by neutrons through a process not fully understood today.[21]

[16] Here we use the factor 5 to reduce both A.H.T.'s and, our results from an ice target to a pure deuterium target.

[17] Doepel, Ann. d. Physik (5) **28**, 87 (1937). We have increased his values by a factor of 7, for reducing them to a pure *d*-target in the same way as our results.

[17a] Durhop, Camb. Phil. Soc. **32**, 643 (1936).

[18] Zinn-Seeley, Phys. Rev. **50**, 1101 (1936).

[19] Kallmann-Kuhn, Naturwiss. **25**, 231 (1937).

[20] Alexopoulos, Helv. Acta **8**, 601 (1935).

[21] See Seishi Kikuchi, Hiroo Aoki and Kôdi Husimi, Proc. Physico-Mathem. Soc. Japan (3) **18**, 727 (1936).

VIII. Effective Cross Section of the *d-d* Reaction

It is of some theoretical interest to calculate the effective cross section for the investigated nuclear reaction. As the range of 100 kv D_2 ions in water is of the order of 10^{-4} cm it was not possible to use an "infinitely thin" target. But it is possible to calculate the cross section from the increase of the yield with voltage $\Delta y/\Delta v$, if the increase of the range with voltage $\Delta x/\Delta v$ is known in the same voltage region.[21a] These values can be estimated from calculations of proton ranges by Mano[22] and by Bethe,[23] and from measurements of Parkinson, Herb, Bellamy, and Hudson[24] for proton ranges in air and aluminum down to 200 and 120 kv, respectively, and under the reasonable assumption that a deuteron of the same velocity as a proton, having twice its energy, has also twice the range.

The excitation function for the *d-d* reaction has recently been measured by Roberts,[3] and is in agreement with the measurements of Oliphant, Harteck and Lord Rutherford[1] and of Alexopoulos[20] in the region covered by these investigators (up to 150 kv). Since we now have available a larger voltmeter resistance which enables us to make accurate measurements up to 400 kv[25] we have checked the excitation function for neutrons at 90° to the bombarding beam where the neutron energy is practically independent of the energy of the deuterons (comp. p. 4). For the higher voltages we used the beam of atomic deuterons; its purity was demonstrated by the agreement of its yield at 140 kv with the yield of the molecular beam at 280 kv. Our results agree up to 200 kv with the former ones reduced to an ice target, but are somewhat higher at higher voltages (Fig. 4).[25a] The values of the effective cross section for the neutron producing reaction are about 2×10^{-26} cm^2 at 100 kv increasing to 4×10^{-26} at 300 kv; they are rather inaccurate due to the uncertainty in the range energy relation at these low energies.[26] But the order of magnitude is certainly right and the observed increase of the cross section from 100 to 300 kv is real in spite of the low "potential barrier" of the D nucleus and is still noticeable* up to about 700 kv in the measurements of Amaldi, Hafstad and Tuve.[26a] These cross sections appear rather low and show that the nuclear process considered is not a "very probable reaction" as has often been assumed;[27] for the square of the wave-length λ of the incident particles or rather the expression $\lambda^2/4\pi$ —which is usually taken for the order of the probability that the bombarding particle performs a nuclear collision[28]—is about $4\cdot10^{-24}$ cm^2 at 300 kv. The relatively low probability of our nuclear process may be connected in some way with the other anomaly, namely the departure from spherical symmetry in the angular distribution of protons and neutrons (compare Schiff[12]).

IX. Acknowledgment

Most of the equipment used in these experiments was purchased by means of a special grant from the Rockefeller Foundation for which we are greatly indebted. We also wish to express our appreciation to Dr. C. C. Van Voorhis for his valuable assistance in part of this work.

[21a] The cross section is then $\Delta y/\Delta x\cdot N$, where N, the number of D nuclei in the target, is in our case 6.7×10^{22}/cm^3.

[22] Mano, J. de phys. **5**, 632 (1934).

[23] Bethe, unpublished. We thank Professor Bethe for making his data available to us.

[24] Parkinson, Herb, Bellamy and Hudson, Bulletin A. P. S. Madison, report No. 20. We wish to thank also these authors for permission to use their values before publication. They differ from the calculated values of Mano and Bethe appreciably below 500 kv.

[25] Previously the voltages over 200 kv were measured with the less accurate generating voltmeter.

[25a] In Fig. 4 only the new values are plotted as points, the remainder of the curve is taken over from Roberts' data.

[26] We have assumed for the increase of the range of 100 kv deuterons in ice 1.0×10^{-9} cm/volt and at 300 kv 1.3×10^{-9} cm/volt.

* *Note added in proof:* Bethe (Rev. Mod. Phys., **9**, 214 (1937) gives the value 2.2×10^{-26} cm^2 for σ at 750 kv, smaller than our calculated value by a factor of 6. The principal discrepancy appears to lie in Bethe's values of "p" (n sec^{-1} d^{-1} on a D_2O target), which are lower than those of A.H.T. by a factor of about 9. He calculates $\Delta X/\Delta E$ to be about 1.2×10^{-9} cm/volt at 750 kv.

[26a] We find from their data (Fig. 9 of reference 14) the increase of yield Δy for an ice target between 600 and 800 kv to be $2\times10^7/6.24\times10^{12}$ and from the range-energy relations mentioned the increase of range for deuterons Δx to be 3.5×10^{-4} cm, therefore the corresponding cross section σ is 1.3×10^{-25} cm^2.

[27] See for example M. Goldhaber, Proc. Camb. Phil. Soc. **30**, 561 (1934).

[28] Compare J. D. Cockcroft, International Conference on Physics, London, 1936, p. 126 and Ostrofsky, Breit and Johnson, Phys. Rev. **49**, 22 (1936).