Investigation of the Deuteron-Deuteron Reaction[1]

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The excitation curve for the reaction $D^2+D^2\rightarrow He^3+n^1$ has been measured from 40 up to 300 kv. The yield of fast neutrons measured in the forward direction from a thick D_3PO_4 target bombarded by 100 kv deuterons is equivalent to 44 mc of radium-beryllium per microampere. The number of neutrons observed in the forward direction (estimated from the number of recoils produced in air) corresponds to 8.7×10^4 neutrons per second per μa at 100 kv over the entire solid angle if isotropic emission is assumed. However, there is a definite preponderance in the forward direction. The increase of "*C*" neutrons with the increasing thicknesses of paraffin surrounding the neutron source and the neutron detector has been measured for both the D-D neutrons and the Ra-Be neutrons. The two such curves correspond for thicknesses of paraffin greater than 5 cm. With less paraffin, relatively more neutrons are observed from the Ra-Be source. The yield of "*C*" neutrons from a D_3PO_4 target bombarded by 1 μa of 100 kv deuterons is equivalent to that of 15 mC of radium-beryllium, but the yield is very sensitive to the geometrical arrangement of the paraffin surrounding the target. The excitation curve of the reaction $D^2+D^2\rightarrow H^1+H^3$ coincides with that of the alternative reaction for the energy range measured (45–100 kv). The absolute yield of protons, after correcting for the stopping power of the target, is one proton for 6×10^6 deuterons, no correction being made for anisotropy of emission. This agrees within a factor of two within the neutron yield. No resonance was found in either excitation curve.

I. INTRODUCTION

THE disintegraton of deuterium by deuterons (D-D reaction) was shown by Oliphant, Harteck and Rutherford[2] to produce either the emission of a proton and a triterium nucleus or the emission of a neutron and a helium nucleus of mass three. The neutrons were found to be a homogeneous group of 2 Mev energy by Dee.[3] More recently the work of Bonner and Brubaker[4] gives a value of 2.4 Mev energy for the neutrons. The yield of protons for the D-D collisions was estimated by Oliphant, Harteck and Rutherford to be of the order of magnitude of 1 proton for 10^6 incident deuterons at 100 kv. The neutron yield was estimated by them to be of the same order of magnitude.

As this is the simplest reaction for which there are two modes of disintegration, it is important to measure exactly the yield of each and to find out whether the relative probability of the two modes varies with the energy of the bombarding deuterons. Also the high yield reported by Oliphant, Harteck and Rutherford indicated that this reaction might provide an intense source of neutrons of homogeneous energy. It is therefore of practical interest to ascertain what strength neutron source (as compared with a radium-beryllium neutron source) could be realized.

II. APPARATUS

The high voltage used for accelerating the ions was supplied by four 100 kv transformers and rectifier units connected in cascade. The filtering was sufficient to keep the ripple below 1 percent. Two ion sources were used. One was copied from the canal ray discharge tube described by Rutherford and Oliphant,[5] and the other was a low voltage arc similar to that described by Crane, Lauritsen and Soltan.[6] The canal ray source provided an ion beam of 100–200 μa total ion current. Of this current only 2–3 μa of mass two ions were focused on the target which was located 160 cm from the single accelerating gap. In addition light hydrogen could never be eliminated completely from the source and consequently molecular hydrogen ions appeared in the mass two spot. From the current carried by mass one and mass four spots it was estimated that 30 percent of the current in the mass two spot was carried by molecular hydrogen. It was

[1] A summary of the results of this investigation has been published in a letter to the editor, Ladenburg and Roberts, Phys. Rev. **50**, 1190(1936).
[2] Oliphant, Harteck and Rutherford, Proc. Roy. Soc. **A144**, 692 (1934).
[3] Dee, Proc. Roy. Soc. **A148**, 623 (1935).
[4] Bonner and Brubaker, Phys. Rev. **49**, 19 (1936).
[5] Oliphant and Rutherford, Proc. Roy. Soc. **A141**, 259 (1933).
[6] Crane, Lauritsen and Soltan, Phys. Rev. **45**, 507 (1934).

TABLE I. *Composition and energy of ions of different m/e values.*

SPOT	1	2	3	4	5	6	7, 8
Current μa	0.6	1.6	2.4	15	0	3	0
Protons per μc	232	880	412	544	0	292	0
Ions and Energy	H^+, E D^+, $\frac{1}{2}$E DD^+, $\frac{1}{4}$E	HH^+, E D^+, E DD^+, $\frac{1}{2}$E	HD^+, E HHH^+, E DD^+, $\frac{3}{4}$E DDD^+, $\frac{1}{2}$E	DD^+, E HHD^+, E O^+, $\frac{1}{4}$E	HDD^+, E	DDD^+, E C^+, $\frac{1}{2}$E C^{++}, E	O^+, $\frac{1}{2}$E N^{++}, $\frac{1}{2}$E

similarly estimated that atomic and molecular ions were present in equal numbers. The advantage of this type source lies in the high percentage of atomic ions; the disadvantages are the impurity of the mass two ion beam, and the high power and high voltage required for producing the ions.

The low voltage arc was operated under different conditions from those of Crane, Lauritsen and Soltan. A potential of 110 volts was applied between the filament and the anode, and a potential of 3000 volts between the anode and the probe electrode. This source was mounted on a four section accelerating tube and would focus 20 μa of DD^+ ions in a 16 mm spot on the target with 100 kv applied to the tube. A uniform potential distribution along the tube was obtained by wrapping a spiral of 200 10 megohm resistance around it. This was found necessary to stabilize the focusing. The maximum total ion current observed was about 200 μa.

The composition of the ion currents of different e/m from the low voltage arc has been analyzed from the number of disintegrations they produce, counting protons emitted from a D_3PO_4 target bombarded by them. As the tube has four gaps, ions were also found which had been formed by the collision with the gas molecules along the path of the beam and had $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$ of the total voltage E. These ions should be present in approximately equal numbers, as the regions in which ions could be formed which would acquire these fractional voltages are equal. In addition, there may be present multiply charged ions of higher mass.

Table I shows the currents observed for the different spots, the yield of protons produced per microcoulomb (μc), and the possible ions which could be responsible for the spots.

In spite of the complexity of the beam, it becomes apparent that the spot 4 consisted entirely of deuterium molecules. The possible impurities are listed in the table. Since there are no HDD^+ ions the amount of light hydrogen is very small; therefore no HHD^+ ions are contained in spot 4. Neither are there any O^+, $\frac{1}{4}$E ions present, as spot 8 (O^+, $\frac{1}{2}$E) is absent. C^{+++} is very improbable and is for the time assumed absent. Therefore, from the yield of protons per microampere of the spot four, the expected yield of the spot six can be calculated, and is 272. If impurities existed in spot 6, the yield would appear too low. Consequently C^{++} does not exist in spot 6 and C^{+++}, being less probable than C^{++}, does not exist in spot 4. Spot 4 is thereby shown to be pure DD^+ ions. By similar reasoning the composition of the other spots can be determined. This is given in Table II.

The ratio of atoms to molecules (D^+/DD^+) turns out to be 0.08 and the ratio of light to heavy hydrogen present (H/D) is 0.03. The value of D^+/DD^+ is to be expected from Bleakney's measurements.[7] This method of analysis is probably not very accurate, but it does establish the purity of spot 4; therefore this was used for bombarding in the experiments. Incidentally, this analysis shows that the ions formed by collisions between deuterium molecules and 100 kv molecular deuterium ions are mostly atomic.

TABLE II. *Percentage of deuterium ions in the beams of various m/e values.*

Spot	1	2	3	4	5
Ion	D^+, $\frac{1}{2}$E	D^+, E	DD^+, $\frac{3}{4}$E	DD^+, E	DDD^+, E
Percent of current in spot carried by ion listed above	85	70	50	100	100

[7] Bleakney, Phys. Rev. **35**, 1180 (1930).

The voltage was measured with a generating voltmeter and with a high resistance and microammeter, and was additionally checked with a spark gap and by the magnetic analysis of the beam. The generating voltmeter was one built by Harnwell and Van Voorhis.[8] The electrical circuit, however, was changed to a two stage amplifier with a diode rectifier. Provision was made for applying a known field from a potentiometer as a check on the constancy of the amplifier. The generating voltmeter was calibrated by using an alcohol-xylol resistance and a galvanometer. The voltmeter is believed to be accurate to 5 percent in the range 80–300 kv. For greater accuracy in the voltage range up to 200 kv a permanent high resistance voltmeter was constructed of 200 1 watt 10 megohm resistance units. (International Resistance Co. type B-1.) These were wrapped in a spiral around glass rods supported by a textolite cylinder. The change in resistance from heating was negligible up to 250 kv. The accuracy of this method of voltage measurement is believed to be better than 2 percent.

As the current to the target varied somewhat, a current integrator was constructed so that the measurements could be made in terms of neutron (or proton) counts per microcoulomb. A condenser was charged by the ion current to the target, and was periodically discharged through a neon bulb and a resistance. The potential across the resistance operated a thyratron circuit which in turn closed a double pole relay. The relay shorted the condenser and registered on a counter. This integrator was found to be extremely accurate and dependable; its calibration was perfectly linear from 0.1 to 10 μa; and its range could be easily extended to higher or lower currents. Besides this recording device, a microammeter was placed in the ground return for direct reading of the ion current.

The target chamber was designed to avoid errors due to secondary electrons either entering or leaving the Faraday cage surrounding the target. The ion beam was defined by a diaphragm, and screens placed in its "shadow" trapped electrons produced when the ion beam struck this defining diaphragm. As the final check, a small permanent magnet could be placed at the mouth of the Faraday cage; when secondary electrons were present the current to the cage was affected by the magnet. Any measurements made when there was the slightest evidence of any secondary electrons were discarded.

The products of disintegration were detected by use of an ionization chamber, a linear amplifier, and a scale of eight thyraton unit built for this purpose by Dr. J. Giarratana. Four interchangeable ionization chambers were used. One was an air-filled chamber provided with aluminum windows for counting protons; the second was similar, but without windows, for counting neutrons by recoils produced in air; the third has its back surfaces coated with paraffin for counting neutrons by the recoils produced in hydrogen; and the fourth was lined with boron for counting slow neutrons. The resolving time of the counter and amplifier was investigated by Dr. Giarratana, who found that the number of counts missed was negligible for counting rates lower than 3000 per minute.

A standard neutron source of radium bromide mixed with finely powdered beryllium[9] was used both for checking the constancy of the amplifier and counter and as a standard to compare with the yields of neutrons from the deuterium targets. The strength of the source as measured by its gamma-ray activity was 15 millicuries. The neutron activity was within 10 percent of that of a radon-beryllium source of the same gamma-ray activity.

III. Targets

Targets of various deuterium containing substances have been bombarded and their behavior under bombardment as well as the neutron and proton yields observed. KOD targets were prepared by evaporating an excess of 99 percent heavy water onto a piece of clean potassium in a vacuum. The target was then heated in vacuum and the excess water removed. Targets of heavy ammonium salts were prepared by adding heavy water to the normal salt and evaporating the water to leave a crystalline target. Targets of

[8] Harnwell and Van Voorhis, Rev. Sci. Inst. **4**, 540 (1933).

[9] The radium-beryllium source was mixed by Mr. Bilstein of the Radium Chemical Co. under the supervision of Professor Ladenburg.

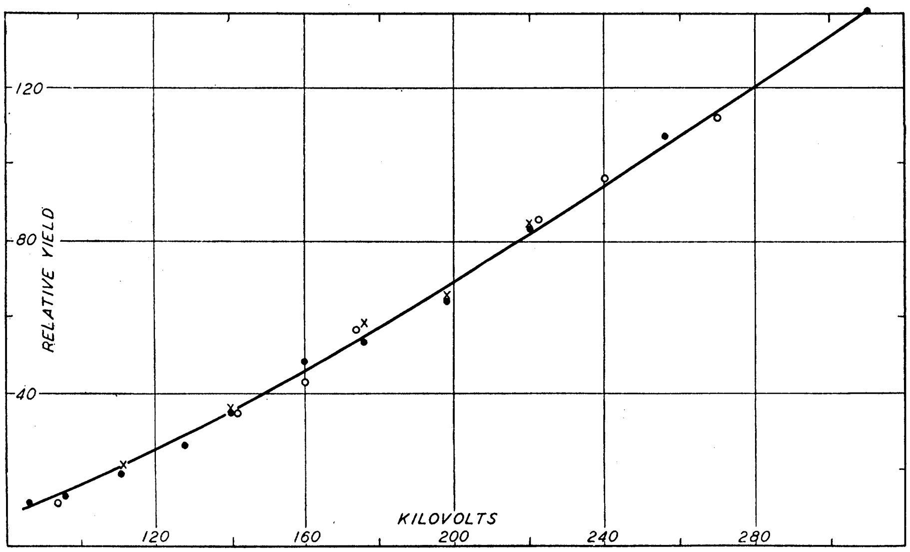

FIG. 1. Fast neutrons from KOD.

D_3PO_4 were prepared by adding 99 percent D_2O to anhydrous P_2O_5.

The behavior of the targets under bombardment varied greatly. A KOD target was bombarded for half an hour with 2 μa of deuterons at 160 kv. In this time the neutron yield fell from 103 counts per minute to 43 per minute. After this initial drop the yield remained within 10 percent of an average value of 45 per minute during a series of measurements lasting five hours. This behavior was typical of all KOD targets used. Targets of ammonium sulphate and chloride were less durable. A thin layer (0.2 mm) of ammonium sulphate was bombarded for half an hour with 6 μa 100 kv deuterons and the yield fell to zero. The target was then examined and it was found that the salt was completely removed in a 16 mm spot where the beam had hit. The D_3PO_4 target was by far the most satisfactory. Several days bombardment had no effect on the yield; it was easy to prepare, and it gave off very little gas for currents up to 12 μa.

IV. Fast Neutrons

The variation of the yield of fast neutrons with voltage has been measured from 45 to 300 kv with especial emphasis on the voltages below 100 kv.[10] The yield has also been measured under conditions which permit a calculation of the absolute number of neutrons.

For the voltage variation of the yield from 85 to 300 kv a thick KOD target was bombarded

[10] All voltages refer to the energy of atomic ions.

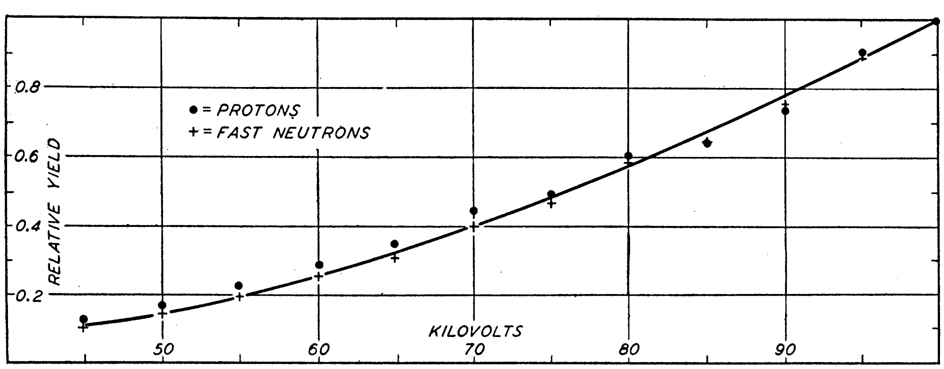

FIG. 2. Protons and fast neutrons from D_3PO_4.

with deuterons from the canal-ray source. The paraffin lined ionization chamber, used to detect the neutrons, was located directly below the target in the direction of the beam. The yield was measured at a standard voltage (160 kv) after every measurement at a different voltage as a check on the constancy of the target. The variation of the yield with the voltage is shown in Fig. 1. The points include values from three different runs on two different KOD targets and each point represents at least 1000 counts.

The yield from a D_3PO_4 target was measured with greater accuracy in the range 45 to 100 kv by use of the molecular ions from the low voltage arc, and by measuring the voltage with a high resistance voltmeter. 100 kv was taken as the standard voltage for these measurements and it might be noted that 16 out of 26 values of the yield at 100 kv fell within 4 percent (the statistical fluctuation) of the mean value. Each point on the graph shown in Fig. 2 represents the mean of several separate measurements.

Measurements of the fast neutrons showed that the number emitted in the forward direction was definitely greater than the number emitted normally to the impinging deuteron beam. The difference was much more than would be expected from consideration of the motion of the center of mass of the two deuterons. This is in accordance with the measurements of Kempton, Browne and Maasdorp.[11] The excitation curve will be influenced by this anisotropy but only insofar as this increases with the energy of the bombarding deuterons. A part of the observed increase with voltage of the number of neutrons emitted in the forward direction must, therefore, be ascribed to the increased concentration of neutrons in that direction, due to the moving center of gravity of the system and to an "abnormal" effect which, according to Kempton, Browne and Maasdorp, is not very sensitive to the velocity of the impinging deuterons. The angular distribution is not determined exactly enough to warrant more than an estimate of the correction involved. This is about 15 percent at 300 kv for the solid angle subtended by the target, and the correction decreases with the voltage.

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

Another point discussed by Kempton, Browne and Maasdorp should also be mentioned, namely the possible error in the excitation curve introduced by the variations in the energy of the neutrons with the energy of the impinging deuterons. They showed that the measured number of recoils in their high pressure helium chamber was quite sensitive to neutron energy. However, this effect is not believed to be as important in the case of a paraffin lined chamber where the selection level was adjusted to count only those protons which traversed the chamber at the end of their range. The main effect in this case would be to shift the layer in which those protons were produced deeper into the paraffin.

The yield of neutrons from different targets was compared with the neutrons from the radium-beryllium source. Four cm of lead was placed between the target and the ionization chamber so that the target could be replaced by the radium-beryllium source with no gamma-ray interference. The target was then bombarded with 100 kv deuterons and the neutrons were counted. Then the Ra-Be source was placed to approximate as closely as possible the position of the target and the neutrons from it were counted. The stray count, subtracted from the DD neutron count, was taken with all the apparatus running but without deflecting the beam to the target. The results in terms of millicuries equivalent per μa are: KOD target, 8.5 mC/μa; D_3PO_4 target, 44 mC/μa. The KOD target had been bombarded until it had reached an equilibrium of about $\frac{1}{2}$ of its original effectiveness.

Counts were also taken with the air-filled chamber located directly below the target. From the number of counts observed and the geometry of the chamber, the number of neutrons passing through the chamber can be estimated by use of Dunning's[12] value for the cross section for scattering. Assuming that every neutron scattered through an angle of 15° or more produces a measurable recoil atom, the number of neutrons traversing the chamber under a solid angle of $4\pi/20$, 8 from a D_3PO_4 target bombarded by 1 μa of 100 kv deuterons is 4.2×10^3 per second. This corresponds to a total of 8.7×10^4 neutrons per

[12] Dunning, Pegram, Fink and Mitchell, Phys. Rev. **48**, 365 (1935).

second over 4π if the neutrons were emitted isotropically.* Correcting for the stopping power of the target by multiplying by the ratio of the number of electrons of a molecule of the target material to the number of deuterium atoms therein, the yield for DD collisions is 1 neutron for 4×10^6 impinging deuterons.

However, the recoil atom must possess a certain minimum energy to produce sufficient ionization in the chamber to actuate the counter. An upper limit of this minimum is determined by the ionization of a proton which is known to actuate the counter, and this corresponds to scattering of the neutrons through an angle of about 90°. If, then, the neutrons are scattered isotropically, the number missed as at most 50 percent of the number scattered through 15° or more. If the minimum number of ion pairs is as low as 1000, the fraction missed will be only 4 percent. The yield calculated above may then be low by as much as a factor of two.

On account of the high ionizing power and the short range of the recoil atoms, very few of those produced in the volume of the chamber were lost by striking the walls before expending their energy in ionizing the gas. Also, very few neutrons were scattered back into the ionization chamber. This was shown by coating the front of the collecting electrode with paraffin. A 10 percent increase in the count was observed as compared with a 400 percent increase when the back of the same plate was coated. A correction for the anisotropy of neutron emission mentioned above might decrease the yield by 30 percent. The effect of disintegration of the aluminum by the fast neutrons is believed to be slight because of the relatively small cross sections for this process.

TABLE III. *Comparison of the relative ease in slowing down neutrons from a radium-beryllium source and from the deuterium on deuterium reaction.*

Thickness of paraffin	Counts/min.	Counts/min. with Cd shield	Counts/min. C neutrons
15 mC Ra-Be Neutron Source			
0.00 cm	30	30	0
1.75	102	37	65
3.50	231	44	187
5.00	432	50	373
8.25	545	49	496
10.75	596	50	546
DD Neutrons per μa			
0.00	13.4	13.5	0.0
1.75	18.7	10.7	8.0
3.50	74.0	20.0	54.0
5.00	156.5	20.8	135.7
8.25	206.5	21.0	185.5
10.75	226.5	20.2	206.3

* An error has been found in the solid angle previously used (Phys. Rev. **50**, 1190 (1936)) for calculation of the neutron yield.

V. Slow Neutrons

The increase of neutrons absorbable by 0.6 mm of cadmium with increasing thicknesses of paraffin cylinders surrounding both the neutron source and the ionization chamber has been measured, both for the DD and the Ra–Be neutrons. Five cylindrical shells of paraffin were cast, each with an inside diameter of 6.5 cm, and a height of 24 cm. At the center was placed a lead cylinder of 6.5 cm diameter and 4 cm height. The neutron source was placed directly above the lead and the boron lined ionization chamber directly below. The sources used were the 15 mC Ra–Be source and a KOD target bombarded by 160 kv deuterons. Measurements were made with and without a 0.6 mm cadmium shield surrounding the ionization chamber.

A KOD target was used which had been bombarded until it had reached an equilibrium; no change in the target was observed during the experiments. The stray count for the DD neutrons was taken with all the apparatus running but without deflecting the beam to the target. The deuteron current was about 2μa. The results corrected for strays are listed in Table III.

The increase of the C neutrons is also plotted in Fig. 3, the two curves being arbitrarily fitted at 8.25 cm. The curve for the Ra-Be neutrons is higher for the thin shells, showing that those neutrons are "easier" to slow down than those from the DD reaction.

With a D_3PO_4 target bombarded by 1 μa of 100 kv deuterons, the yield of slow neutrons produced in 7.5 cm of paraffin was equivalent to that of 15 mC of Ra-Be. The same target gave an equivalent of 44 mC per μa when the fast neutrons were counted. The main reason for this difference and for the difference in the curves (Fig. 3) is probably the higher initial proportion

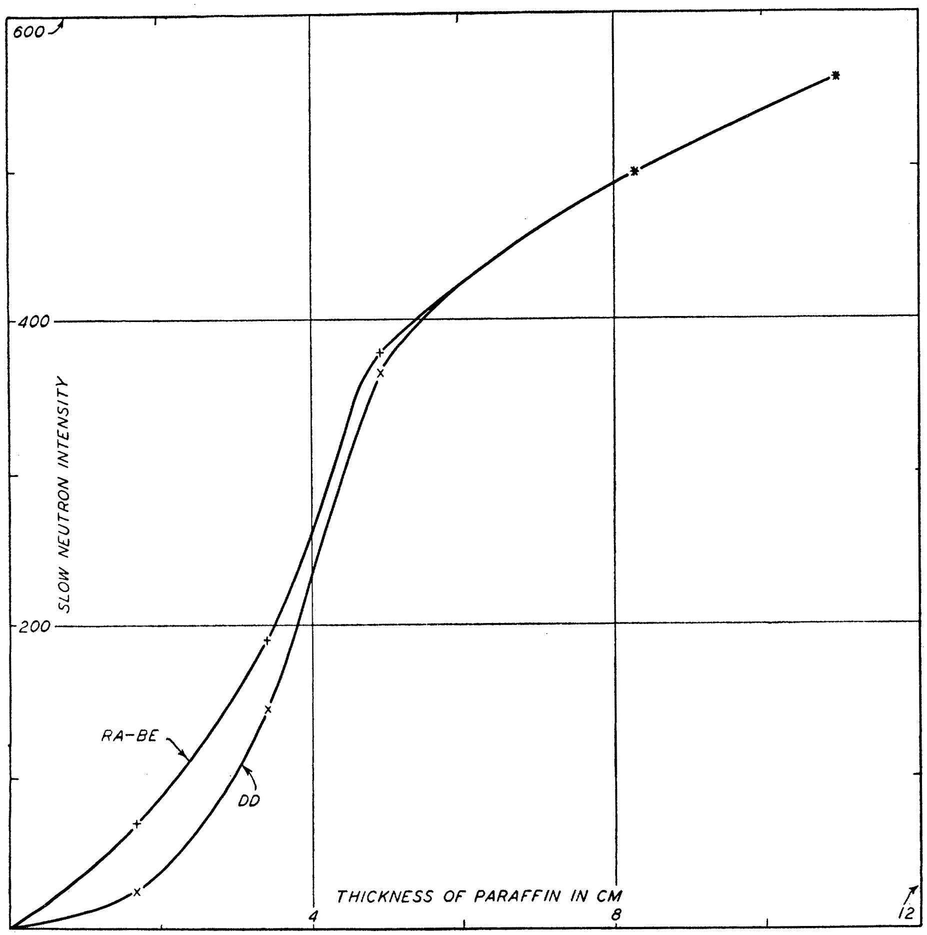

FIG. 3. Increase in number of slow neutrons observed with increasing thickness of paraffin.

of relatively slow neutrons from the Ra-Be, which give no measurable recoils. Also, the anisotropy of the neutron emission from the deuterium accounts partially for the difference, as the fast neutrons were counted in the forward direction whereas the paraffin surrounding the target did not slow down neutrons emitted in that direction.

VI. Protons

The yield of protons from various deuterium containing targets has been measured and the variation of the yield with the voltage for a D_3PO_4 target has also been observed. The protons emitted from the target at an angle of 90° to the incident beam passed through an aluminum window 0.0025 cm thick and 0.6 cm in diameter. Immediately outside the window was one of four interchangeable defining diaphragms 1 to 4 mm in diameter which were beveled to a thin edge. The ionization chamber was placed 4 mm in back of the diaphragm. 1.6 cm holes in its shield and high voltage electrode covered with aluminum foil admitted the protons to the chamber. In this way it was insured that the beam of protons was limited only by the one defining diaphragm and that the exact position of the chamber would have no effect on the number of protons counted. The stopping power of the foils and the intervening air spaces was such that a piece of Cellophane of 1.7 cm stopping power could be inserted without affecting the count. The insertion of the Cellophane did, however, increase the size of the pulses of the amplifier. A second Cellophane foil would stop the protons completely so that the last two centimeters of the proton range were effective in the ionization chamber.

In magnitude the kicks from the protons, as observed on the oscillograph, were about twice the noise level. Consequently, it was possible to vary the bias of the selector tube in the counter from the setting corresponding to a selection level just below the peak of a proton kick to one just above the noise level without affecting the counting rate. As further evidence that the counter was not missing any protons, a visual count of kicks on the oscillograph was compared with the electrical count. The two agreed to the accuracy expected from the visual counting; the electrical count was always a little higher. In addition, counts were taken at different currents and with different diaphragms. All were consistent after the proper correction for solid angle or current had been made.

The procedure in the measurement of the voltage variation of the proton yield was the same as for the fast neutrons. 100 kv was again taken as the standard voltage and the yield at this voltage was checked continually. The yield was measured every five kilovolts from 40 to 100 kv. Each point on the graph shown in Fig. 2 represents the average of several measurements, none of which deviated from the mean by more than 5 percent.

The yield at 100 kv was measured using targets of D_3PO_4, $(ND_4)_2SO_4$ and ND_4Cl. The absolute yields have been calculated from the protons observed at 90° an the assumption of an isotropic emission of the protons. The factor used for correcting for the stopping power of the target is the ratio of the total number of electrons in the molecule of the target material to the number of D atoms. The results are listed in Table IV.

The anisotropy does not affect the excitation curve for the protons as they were observed at 90° to the incident beam. The absolute yield is increased if a correction is made for the anisotropy but not by more than a factor of 1.5.

VII. Discussion

The excitation curves for the neutrons (Fig. 1) agree quite well with the excitation curve given by Oliphant, Harteck and Rutherford between 40 and 140 kv and with the neutron curve of Alexopoulos[13] for the same voltage range. The excitation curves for the protons and neutrons (Fig. 1) from 45 to 100 kv coincide.

The absolute yield of neutrons calculated from the measurements with the air chamber is approximately 1 neutron for 4×10^6 deuterons. The correction for the anisotropy decreases the yield by about 30 percent, but due to the uncertainty of the selection level, the measurement may be low by as much as 50 percent. The neutron yield does not agree with that given by Alexopoulos. His figure (1 neutron for 1.6×10^6 deuterons) is appreciably higher than mine, although it does not include any correction for the composition of the target. On the other hand, the yield found recently by R. Doepel[14] is only 1/120 of mine.

Kikuchi, Aoki and Husimi[15] made an estimate of the yield of neutrons from the D−D reaction as compared with the Ra-Be source by counting slow neutrons. Their results agree approximately

[13] Alexopoulos, Helv. Phys. Acta. **8**, 513, 601 (1935).
[14] Doepel, Ann. d. Physik **28**, 87 (1937).
[15] Kikuchi, Aoki and Husimi, Proc. Phys. Math. Soc. Jap. **18**, 122 (1936).

Table IV. *Yields for 100 kv deuterons on various targets.*

Target	D_3PO_4	$D_3PO_4+D_2O$	ND_4CL	$(ND_4)_2SO_4$	$(ND_4)_2SO_4$
Protons per μ-coulomb observed	1.125	1.32	1.82	1.7	0.48
Total protons per incident deuteron	0.986×10^{-8}	1.115×10^{-8}	1.6×10^{-8}	1.49×10^{-8}	0.42×10^{-8}
D atoms in molecule per total H+D atoms	1	1	0.81	0.87	0.25
Correction factor total electrons per D atom	50/3	46/3	28/3.2	70/7	70/2
Yield for DD collisions	1.64×10^{-7}	1.71×10^{-7}	1.4×10^{-7}	1.49×10^{-7}	1.47×10^{-7}

with mine but they did not analyze their beam magnetically, so that no accurate comparison is possible.

The absolute yield of protons (1 proton for 6×10^6 deuterons) was calculated assuming an isotropic angular distribution of the protons. This yield is smaller than that reported by Oliphant, Harteck and Rutherford who estimated the yield to be of the order of magnitude of 1 proton for 10^6 deuterons when observed at the same angle as in my experiments.

These experiments were done under the direction of Professor Rudolf Ladenburg, to whom I am greatly indebted for his supervision and help. I also wish to express my appreciation to Dr. Giarratana and Mr. Beers for their valuable assistance, to my wife for her help in taking the readings, and to the staff of the Palmer Physical Laboratory for their work in preparing apparatus. Most of the equipment was purchased from a special grant to Professor Ladenburg from the Rockefeller Foundation.

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A Wilson Cloud Chamber Investigation of the Alpha-Particles from Uranium

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The *mean ranges* of the alpha-particles emitted by uranium have been determined in terms of the *mean range* of polonium alpha-particles. The ratios obtained for the *mean ranges* are, for U I/Po, 0.6904±0.0007, and for U II/Po, 0.8357±0.0008. These correspond to *mean air ranges* of 2.63 and 3.18 cm, for the particles from U I and U II, respectively, in dry air at normal pressure and at 15°C, on the basis of the present polonium value of 3.80 cm. The straggling coefficient was determined for the polonium alpha-particles used as the reference range group in the experiment and gave a value considerably closer to theoretical prediction than the usual experimental results. Possible evidence for the existence of a new alpha-emitting isotope of uranium is suggested in the data. The *mean air range* for the new group is believed to be in the vicinity of 2.9 cm. An identification with the actino-uranium isotope of approximately this range suggested by Wilkins as the parent of the actinium series and with Dempster's 235 uranium isotope is proposed.

PRECISE data on the characteristics of the alpha-particles from uranium have been sought for many years. It was of particular importance to the development of the general theory of the disintegration sequence in the uranium family when the alpha-emission from uranium was first definitely resolved by Laurence's[1] data into two range groups. The presence of two isotopes was thus indicated, but a still closer scrutiny of this subject seems worthwhile at the present time.

In the first place it seems advisable to establish the ranges of the alpha-particles from the known isotopes U I and U II with considerably higher precision than has so far been realized. This precision is deemed especially desirable because of the recent advances toward more precise theoretical formulation of the mechanics of alpha emission. Furthermore, this investigation was prompted by the fact that from several independent lines of reasoning the conclusion has been reached that uranium may be more complex than range data have so far indicated and that U I and U II may well have associated with them very small amounts of isotopes whose alpha-rays remain as yet undemonstrated in any direct fashion. These suspected isotopes are believed to be the missing long-lived parent, or parents, of the actinium series of radioelements; and their detection would consequently be a matter of some significance.

The presentation of the arguments which proceed to the conclusion that the parent of the actinium family will be found as an alpha-emitting isotope of uranium, present on earth today only in a small amount, would be too

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[1] G. C. Laurence, Phil. Mag. 27, 690 (1914).