deuteron energies. The two curves were adjusted to fit at 16.5 cm deuteron range. In comparison with the observations for nickel are shown the data obtained by Van Voorhis[14] for copper (the upper curve in Fig. 2). The different character of the two curves is immediately evident. The second curve in Fig. 2 through the experimental points is a plot of Sexl's formula for a nuclear radius $r_0=4.5\times10^{-13}$ cm, adjusted to fit the experimental points at 20 cm range. The agreement would appear to be satisfactory. It was found that an increase of the radius to 5.0×10^{-13} cm resulted in a curve lying completely above the experimental points, while a value of 8×10^{-13}, which Bethe's value of 13×10^{-13} for the natural radioactive elements would suppose, is very decidedly too large. Thus from the data presented here it would seem that it is not possible to account for the "flat" excitation curves observed for neutron capture reactions by solely supposing an increase in the nuclear radius.

Measurements of the radii of curvature of 300 positron tracks in a Wilson cloud chamber in a plane perpendicular to a magnetic field of 340 gauss resulted in the histogram presented in Fig. 3. Only tracks were measured which clearly originated in the target and had a length greater than 7 cm. The presence of the five tracks observed beyond the "inspection" upper limit at $H\rho$ 4400 gauss-cm (0.9 MV) may be explained either as being due to γ-rays which are known to be present but have not as yet been measured, or to the presence of a second and higher energy positron group as has been observed in other cases.[15] Decision between these alternatives must await further experiments.

It is a pleasure for the writer to acknowledge his very great indebtedness to Professor E. O. Lawrence, and to Professor J. R. Oppenheimer for his friendly advice upon the theoretical questions involved. The support of the Research Corporation, the Chemical Foundation and the Josiah Macy, Jr. Foundation at the University of California, and of the Horace H. and Mary A. Rackham Fund at the University of Michigan is also gratefully acknowledged.

[14] Van Voorhis, Phys. Rev. **50**, 895 (1936). I am much indebted to Dr. Van Voorhis for his kindness in sending me a copy of his experimental curve.

[15] E.g., Kurie, Richardson and Paxton, Phys. Rev. **49**, 368 (1936); M. V. Brown and Mitchell, Phys. Rev. **50**, 593 (1936).

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Neutron Yields from Artificial Sources

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Measurements of the total yields of neutrons from the reactions D+D, D+Li, D+Be and D+C have been carried out for the voltage range between 300 kv and 1000 kv using the observing technique developed by Amaldi and Fermi, in which the neutron source is surrounded by a large tank of water. Neutrons of all energies are thus reduced to thermal energies, and the total yield of neutrons is obtained by integration from measurements of the density of slow neutrons at various distances from the source. Similar measurements were made on the neutrons from Rn+Be, with the same geometrical conditions. The neutron yields per microampere of pure D^2 ions from the artificial sources are shown in the table below for various voltages; each entry gives the number of millicuries of Rn+Be required to give the same total yield of neutrons per second. A total yield of 25,000 neutrons per second from one millicurie of Rn+Be is calculated from the measurements of this source. Absolute yields for the various sources computed on the basis of this figure should not be considered as reliable within 20 percent, perhaps the chief error arising from the fact that the average ionization per beta-ray is assumed to be the same for the beta-rays from the rhodium detector and for those from

REACTION	300 kv	400 kv	600 kv	800 kv	1000 kv
D+$D_2O(P_2O_5)$	48	140	250	550	860
D+Li	(40)	(160)	(800)	(4200)	...
D+Be	9	100	700	2400	6800
D+C	..	...	10	140	680

the uranium standard which is used to convert the rhodium measurements into numbers of disintegrations per second. The relative yields for the artificial sources are obtained by direct comparison of the curves, and should be correspondingly more reliable. The yields for lithium are given in parenthesis because the (metallic) target was apparently not perfectly clean, the yields increasing somewhat under continued bombardment, so that a reliable distribution curve could not be obtained. The yields given were obtained on the assumption that the energies of the neutrons from Li were as high as, or higher than, the energies of the neutrons from Be. The $D_2O(P_2O_5)$ target contained 0.113 gram D_2O, 0.342 gram P_2O_5, and 0.005 gram H_2O. A check on the deuterium reaction by measurements on another target would be desirable but has not yet been carried out.

Introduction

ONE of the principal difficulties in measuring the total number of neutrons emitted by various sources arises from the fact that the neutrons are usually heterogeneous in energy. Available detectors respond differently to neutrons of different energies. The difficulty is avoided in the method of Amaldi and Fermi[1] in which all the neutrons are ultimately reduced to thermal energies by immersing the source in a large body of water, and the activity produced by these slow neutrons in a suitable detector (rhodium) is measured as a function of the distance from the source, the total activity then being obtained by integration.

Various corrections and approximations are involved in obtaining absolute values by this method, but it appears reasonable to believe that the results obtained, expressed as a total number of neutrons emitted per second, are reliable to within perhaps 20 percent on an absolute scale. This degree of accuracy is ample at present for a survey of the total neutron yields from various artificial sources at different voltages. Relative or equivalent yields, in terms of the total neutron yield of one millicurie of Rn+Be, are obtained by direct comparison of the integrated curves, with somewhat higher accuracy.

Using this technique we have carried out measurements on the neutrons emitted when deuterons were used to bombard separate targets of $D_2O+P_2O_5$, metallic lithium, metallic beryllium, and carbon in the form of Acheson graphite, the measurements extending over the voltage range from 300 to 1000 kilovolts.

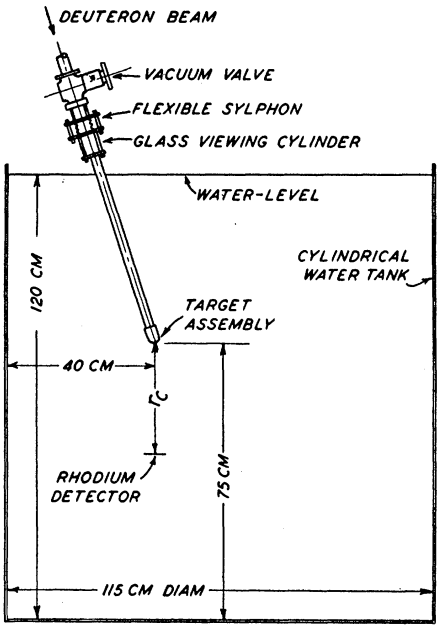

FIG. 1. Arrangement of target and water tank.

[1] Amaldi and Fermi, Ricerca Scient. **7**, 454 (1936); Phys. Rev. **50**, 899–928 (1936).

Technique

Experimental arrangement

The accelerating apparatus used in this work is that developed by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington and has been described previously.[2] Magnetic analysis of the ion beam was used throughout the observations, and the measured deuteron currents were demonstrated to be always in excess of 97 percent full speed deuterium ions (upper limit of H^1H^1 contamination much less than 2.7 percent). The arrangement of the target and water tank are shown in Fig. 1 and the details of the target assembly in Fig. 2. To insure that all the ion current measured actually was impinging on the target, provision was made for accurate axial alignment by the flexible sylphon connection shown in Fig. 1. With the solid brass hemispherical cap and the opaque

[2] Tuve, Hafstad and Dahl, Phys. Rev. **48**, 316–337 (1935); Hafstad, Heydenberg and Tuve, Phys. Rev. **50**, 504–514 (1936).

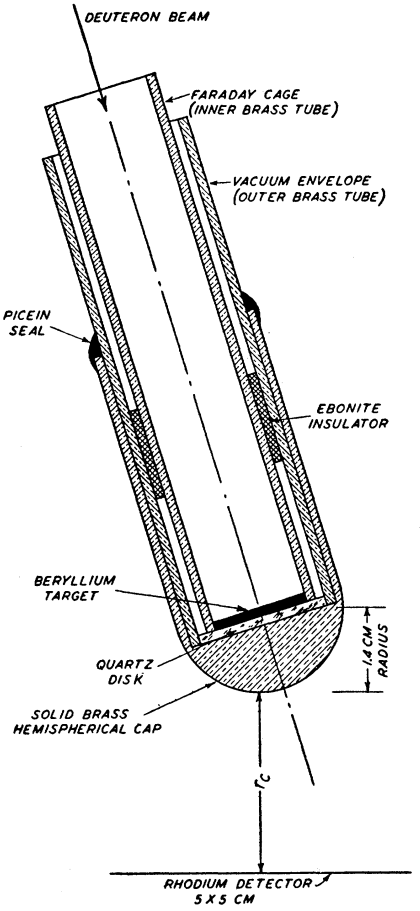

FIG. 2. Detail of target assembly.

target removed, the beam was focused through a 10-mm hole in a quartz disk within the viewing cylinder (above the water tank) and then, by means of the sylphon, the tube position was adjusted until the beam was impinging on the center of the quartz disk indicated in the target position at the end of the tube.

Since in this work magnetic analysis of the ion beam was used, the only error involved in specifying the number of incident deuterons is that due to the presence of molecular H_2^+ ions in the deuteron beam. This error may be evaluated as follows. For a typical run the currents in the analyzed beams were 0.15, 1.20, 0.09, 0.26, 0.16, and 0.35 microampere for the mass-one to mass-six beams, respectively. Assuming that the mass-four beam is composed solely of D_2^+ ions and that the ratio of H_2^+ ions to H^+ ions is the same as that of D_2^+ to D^+, we find that the mass-two beam is 97.3 percent deuterium ions. The beams of mass five and mass six show that the mass-four beam contains several molecular species; the mass-two beam is correspondingly more than 97.3 percent deuterons.

All measurements of activity were made using two pieces of rhodium, each 5 cm square and 0.23 g/cm² thick. Their activity was measured with an ionization chamber similar to that used by Amaldi and Fermi,[1] filled with oxygen at a pressure of three atmospheres and connected to the exceedingly convenient Edelmann electrometer.

Effect of dimensions of source

During the measurements we adopted the convention of calling the distance between the source and the target zero (that is, $r_C=0$) when its center was in contact with the brass hemispherical cap of Fig. 2. Since the entire cap must be considered as a source of fast neutrons, and since the dimensions of the cap cannot be considered negligible in comparison with the distance between the source and the detector, we have taken as the corrected distance (r_k) the root-mean-square distance between points on the detector and on the source, assumed to be a sphere of radius 1.4 cm (water boundary). For ease in reading the figures we have arbitrarily called this r_k. The result is $r_k^2=(r_C+1.4)^2+1.4^2+(\frac{1}{3})Y^2$, where $2Y=5$ cm, the linear dimension of the detector.

Since the finite size of the source disturbs the distribution of thermal neutrons, and the above defined r_k is to some extent a conventional distance, the results obtained with the above

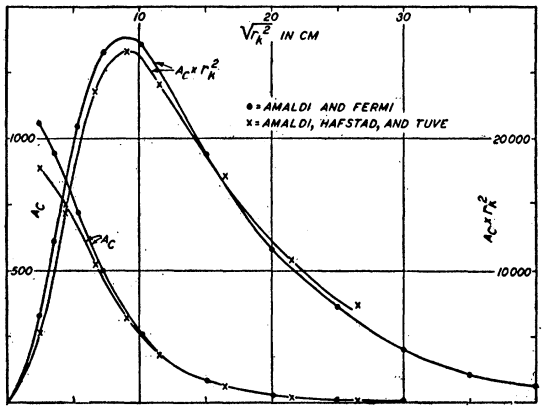

FIG. 3. Effect of geometry of source on distribution of (Rn+Be) neutrons in water.

apparatus for artificial sources are not directly comparable with the original measurements of Amaldi and Fermi[1] for (Rn+Be). To make the comparison as valid as possible, the (Rn+Be) experiments have been repeated by one of us (Amaldi), placing the (Rn+Be) source inside a brass tube of the same outside form as that for the artificial source above described. The effect of the difference in geometry is shown in Fig. 3, which shows the depression of the density of slow neutrons at small distances from the source due to the effectively larger volume of this source. The error due to this difference, however, appears to be negligible compared to other sources of error which will be discussed below.

Standardization of observations

In order to give our results in a form comparable with the results of Amaldi and Fermi, we have used the following definition of the "activability" of a detector in a given position with respect to a given artificial source at a given voltage

$$A = 1000\ (a/iU),$$

where a is the initial activity of the detector after infinite time irradiation, i is the current of deuterons in microamperes on the target, U is the activity of a standard uranium solution, as used by Amaldi and Fermi (840 disintegrations per second), measured under the same conditions as the artificial radioactivity (the same instrument, recalibrated with a uranium sub-standard immediately following each single observation, with the same sensitivity and over the same divisions of the scale, in order to avoid errors due to non-linearity). The difference between this definition and the definition used by Amaldi and Fermi is that in our case the activability is defined per microampere of current of deuterons on the target instead of per unit of (Rn+Be) neutron intensity [corresponding to about 6 mC of (Rn+Be)]. It is to be noted that one of these original units of neutron-intensity corresponds to a very small number of alpha particles impinging per second on Be, compared with the number of particles in a microampere of deuterons. Therefore, we must expect that the activabilities given in this work will be very large.

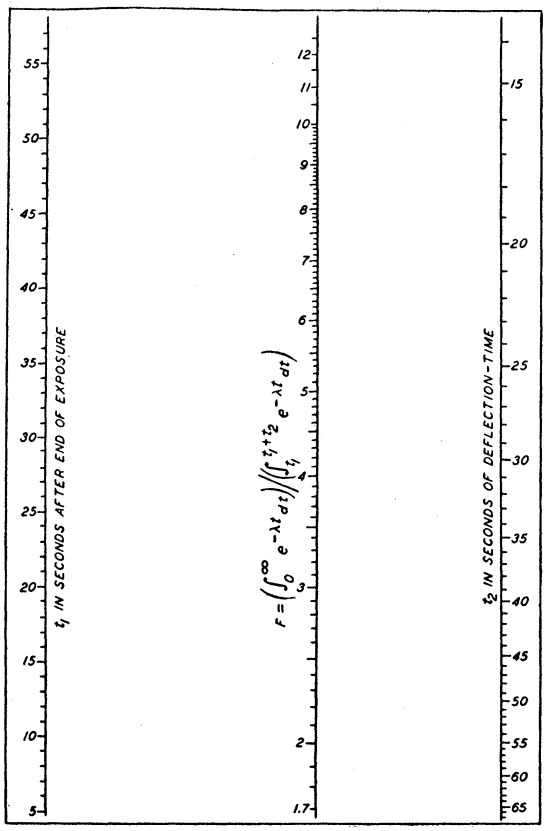

FIG. 4. Nomogram for rhodium (44 second period).

In practice, we have used a uranium preparation as our "working standard" [$UO_2(NO_3)_2$ in paraffin, spread over an area 5 by 5 cm and enclosed in 0.10 mm of aluminum foil] whose activity, compared in our laboratory with the standard solution[1] was found to be 2.5_5 times the activity of the similar preparation used in Rome as a working standard.

The initial activity a after an infinite time of irradiation is simply determined for elements with long periods. For elements with short periods, as, for instance, rhodium (44 seconds), it is convenient to follow a standard procedure in making the observations. We will explain in detail the procedure used for rhodium, with which all measurements in this work were made.

The nomogram devised and used by Amaldi and Fermi[1] is shown in Fig. 4, and is made as follows. The first two of the parallel straight lines are drawn at convenient distances one from the other, and the third is located by calculation and graphical construction. The first one is marked

off in seconds on a linear scale reading upward from a zero origin. This scale corresponds to the time t_1 between the end of the irradiation of the rhodium and the beginning of the reading of the activity. The third line is scaled in seconds (non-linear; calculated) to correspond to the time t_2 during which the ionization chamber is exposed to the rhodium for the collection of a suitable charge (time of deflection between two selected points on the electrometer-scale, calibrated by the uranium). If the reading could begin just at the moment when the irradiation is stopped ($t_1=0$), and if we could wait an infinite time ($t_2=\infty$), the number of divisions indicated by the electrometer would be proportional to the total activity of the rhodium. In practice, the reading begins some seconds after the irradiation and takes a finite time; hence the electrometer deflection is smaller than this value. The line of the nomogram between the two scales above described is accordingly scaled logarithmically to read the factor F, calculated by simple formulas, by which we must multiply the number of divisions D (corrected for the residual effect) deflected in t_2 seconds, the deflection beginning at a time t_1 seconds after the end of the irradiation, in order to obtain the number of divisions corresponding to the total activity ($t_1=0$, $t_2=\infty$). It is clear that the origin of this middle scale must be marked unity, the origins of the three scales (infinite time for scale 3) being on one straight line (which slants downward in our nomogram, for convenient location of scale values). For any given reading the factor F is then found by reading the intercept on the middle scale when the observed values of t_1 and t_2 are connected by a straight-edge.

By integrating we see that to obtain the initial activity we divide the total activity FD by the mean life $\tau=63.5$ seconds (half-life = 44 seconds). If the rhodium has been irradiated t seconds, we must divide its activity (initial or total) by $(1-2^{-t/44})$ in order to obtain the activity corresponding to infinite time of irradiation. In general, we irradiated for only 60 seconds, in order to be able to neglect the activity of the second period of this element (4.2 minutes). Even with infinite time of irradiation the activity of this second period is only one-tenth of the 44-second activity.[3,4] Readings were made at regular 10-minute intervals, so each piece of rhodium was used again only after 20 minutes had elapsed. The initial activity a corresponding to an infinite time of irradiation is accordingly given, from the observations after 60 seconds irradiation, by

$$a=F\cdot D/[63.5(1-2^{-60/44})]=F\cdot D\cdot 0.0257.$$

We will designate the standard uranium solution and its activity by U. If the activity of this uranium standard is read over the same divisions of the scale as was the rhodium (correcting for residual in each case) and we call t_U the corresponding time, the activity U of this preparation is given by D/t_U and the activability of rhodium, according to the definition above, by

$$A=25.7Ft_U/i.$$

In order to make a large number of measurements rapidly, it is convenient to determine experimentally the various factors for a second nomogram, characteristic of the ionization chamber and the electrometer. This second nomogram is used to obtain the value of the deflection time for the standard, t_U, when the electrometer is set for a given sensitivity (divisions per volt) and the deflection occurs between any two points on the scale. However, in this work we have actually measured D/t_U after each rhodium observation.

The activability above defined corresponds to the ionization of rhodium divided by the ionization of uranium. In order to express the activability in numbers of disintegrations per second, we must introduce the quantities η and η_U which represent the mean ionization per beta-particle respectively of rhodium and UX_2 in the ionization chamber used. The uranium preparation corresponds to 840 disintegrations per second; therefore, we must multiply the activability by 840 η_U/η in order to obtain the corresponding number of disintegrations per second. The factor η_U/η is unknown, although it might be measured by a suitable experiment. In the calculation of the results we have assumed $(\eta_U/\eta)=1$. The error due to this assumption can be evaluated from the

[3] E. Amaldi, O. D'Agostino, E. Fermi, B. Pontecorvo, F. Rasetti, and E. Segrè, Proc. Roy. Soc. **A149**, 522–558 (1935).

[4] E. Amaldi and E. Fermi, reference 1, Ricerca Scient. **7**, 443 (1935); E. Segrè, Ricerca Scient. **7**, 389 (1936).

results obtained by Amaldi and Fermi on the number of neutrons of group C (thermal neutrons) coming out from a block of paraffin containing the source of fast neutrons (the "numerosity"). This number was measured by observing the activities of different elements. The differences between the results obtained with different elements are certainly due in great part to the different ionizations of the beta particles of different elements. From a consideration of these data and the fact that the energies of the beta particles from the two elements are nearly equal (half-thickness in aluminum 0.10 g/cm^2 for UX_2; 0.15 for Rh, 44 sec.), we believe that the error due to the assumption $\eta_U = \eta$ will not be larger than 20 percent in the resulting absolute numerical yields.

Correction for absorption within the detector

The absorption coefficient of electrons of Rh in Rh is $\mu = 7.3$ cm^2/g. If we indicate by $f(Kx)$ the absorption curve of neutrons in rhodium (K = absorption-coefficient of neutrons in rhodium and $f(Kx) = e^{-Kx}$ if the impinging neutrons form a parallel beam), it is clear that the effective thickness of a rhodium detector of thickness δ is

$$\delta_{\text{eff}} = \int_0^{\delta} f(Kx) e^{-\mu x} dx \qquad (1)$$

if the neutrons impinge on only one surface of the detector and we measure its activity on the same face. If the neutrons impinge on both faces of the detector, it is necessary to sum two expressions similar to (1).

If the detector is inside a hydrogenated substance under such conditions that the density of neutrons close to the detector is about constant, it is more correct to take for $f(Kx)$ the absorption curve $b(Kx)$ corresponding to the cosine law;[1] if the detector is outside the hydrogenated substance but close to its surface, or inside but with a total absorber of thermal neutrons on one side, it is more correct to take for $f(Kx)$ the curve $c(Kx)$ corresponding[1] to the angular law $\cos\theta + \sqrt{3}\cos^2\theta$. In the following paragraphs we will calculate this correction under these conditions.

For our rhodium detector $\delta = 0.23$ g/cm^2 and $K = 0.7$ cm^2/g for thermal neutrons (group C, strongly absorbed by Cd). In order to calculate δ_{eff} we notice that $c(Kx)$ can be represented for $0 \leqq x \leqq \delta$ with an exponential $e^{-K_{\text{eff}}x}$ with a good approximation. We determine K_{eff} as follows:[1] $c(0.7 \times 0.23) = 0.69 = e^{-K_{\text{eff}} 0.23}$; $K_{\text{eff}} = 0.37/0.23 = 1.6$; $\delta_{\text{eff}} = (1 - e^{-(\mu + K_{\text{eff}})\delta})/(\mu + K_{\text{eff}}) = 0.098$ g/cm^2.

Correction for presence of group D

With our detector the total activity (group C + group D) measured on the face towards the source is, within the experimental error, equal to the total activity measured on the other face. On the other hand, the activity due to group D alone (activity of rhodium with cadmium over both faces) measured on the face opposite to the source is equal to 93 percent of the activity measured on the face towards the source. This different behavior of our rhodium detector in groups C and D is due to the difference between its absorption coefficients for these two groups (group C, 0.7, and group D, 1.8 cm^2/g). For the artificial sources we have always measured the activity of our rhodium detector on the face towards the source; in order to obtain the mean value of the activity due to group D which would be measured on both faces we have multiplied the observed activity due to group D, measured on the face towards the source, by 1.93/2.

We know also that the ratio of the activity due to group D to the total activity is not constant but is a function of the distance from the source. Such a function has been measured by one of us (Amaldi) in the case of the source (Rn+Be); we have found that this ratio is equal to 0.11_4 for $r_C = 0$ and decreases about linearly up to $r_C = 15$ cm, where it reaches a value of about 0.057; beyond this distance it remains constant. Such a constant value is reached at a distance where fast and slow neutrons are in equilibrium (see below).

In the case of the artificial sources we have measured the activity using cadmium with the rhodium only at $r_C = 0$, 2.5, and 5 cm. For larger distances we have calculated the activity of rhodium with cadmium by applying the criteria deduced from the data with the source (Rn+Be). It is to be noted that the distance from the source where fast and slow neutrons are in equilibrium is different for different sources.

Space distribution of neutrons in water

Let us consider a point source emitting neutrons of some million volts energy at the center of

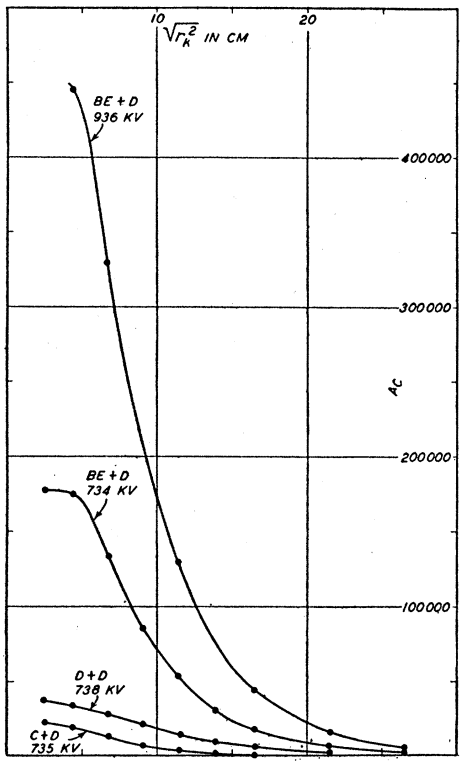

FIG. 5. Thermal neutrons in water at different linear distances from the source.

a very large water tank. The fast neutrons, through successive impacts with hydrogen atoms of water, lose energy until they reach the energy of thermal agitation. At the same time, the mean free path, which for neutrons of some million volts energy is of the order of 5 cm, decreases rapidly and reaches a value a little over one cm. This value of the mean free path remains constant for all lower energies down to the point where, in the impact of neutron and proton, the chemical bond of the hydrogen atom in the molecule can no longer be neglected with respect to the energy of the incident neutron. In practice the mean free path of neutrons in water is about one cm for neutron energies from say 10,000 volts down to energies of the order of one volt. For energies of the impinging neutron lower than one volt, the chemical bond of the hydrogen atom changes very strongly the law of scattering (of neutrons by protons) in such a way that the mean free path of thermal neutrons in water is about 0.35 cm. The neutrons which have reached thermal energy will diffuse through water and will traverse, on the average, 140 mean free paths before being captured by the protons with formation of deuterons. If we call r the distance from the source of fast neutrons, it is clear that the density of thermal neutrons is a function of r which decreases with increasing r. In order to determine the density of thermal neutrons in water as a function of the distance from the source, we can use the activity induced by thermal neutrons in a detector, for instance, rhodium. We know that this element is sensitive to thermal neutrons (group C) and also to neutrons of about 1 volt energy (group D). In order to determine the part of the activity of rhodium due to thermal neutrons only, it is necessary to observe the difference of the activities of rhodium with and without a cadmium screen on each side thick enough to absorb all impinging thermal neutrons (in practice we have used cadmium of 0.43 g/cm^2).

If the detector were very thin, its activity would be proportional to the density of thermal neutrons in water close to the detector; in our case the detector can be considered thin for group C and thick for group D; we must introduce, therefore, a small correction as explained in the paragraphs above. Fig. 5 shows the activability A_C due to group C of our detector as a function of the distance from the source, using different sources of fast neutrons as indicated.

These curves, multiplied by the square of the distance from the source, are shown in Fig. 6. The meaning of these last curves is evident; they are proportional to the function $n(r)dr$, which represents the number of thermal neutrons contained between two spheres of radius r and $r+dr$.

In order to determine the total number of fast neutrons emitted from the source, it will be necessary to calculate the integral of $n(r)dr$ from zero to infinity. This integral (properly normalized in terms of the detector constants and geometry—see B_C below) divided by the diffusion length resulting in capture (thermal neutrons) gives the total neutron emission from the source; see Section 12, Eq. (27), and Section 7, Eq. (12), of reference 1, above. The curves of Fig. 6 are equal to $n(r)$ multiplied by a factor which depends on the thickness of the detector, on its absorption coefficients for neutrons and electrons, and on the value of the albedo (reflection coefficient of water for thermal neutrons).

Correction for disturbance produced by the detector

The facts that thermal neutrons have a very high albedo in water ($\beta=0.83$), and that the detector absorbs more than an infinitesimal number of neutrons, give rise to a depression of the density of thermal neutrons in the region close to the detector. It is possible to take into account all of these effects in determining the proportionality factor between $n(r)$ and $A_C r^2$; the result is, however, very sensitive to small errors in the absorption-coefficients of the detector for neutrons and electrons.

Therefore, it is convenient to use an experimental arrangement in which thermal neutrons traverse the detector only once. For this purpose we have measured the activability B_C on one face of our detector due to thermal neutrons when it is screened on the other face by a cadmium sheet, thick enough to absorb all impinging thermal neutrons (0.43 g/cm²). Under these conditions thermal neutrons impinge on the detector only on the exposed face, and if they are not captured by the rhodium nuclei, they are absorbed by the cadmium.

In this case, however, it is evident that the activability B_C is a function of the orientation of the detector with respect to the source of fast neutrons; therefore, it is necessary to take a mean value of B_C on all orientations. In practice it is sufficient to take the average of the two values of B_C obtained when we have the exposed face of rhodium, or conversely the face protected by cadmium, oriented toward the source of fast neutrons. Remembering that the activity of rhodium is due in part to group D, B_C will be the difference between this mean value and the mean value of the activabilities of rhodium measured on both its faces when it is screened on both sides by cadmium.

Calculation of the total number of neutrons emitted

The activability B_C is given by[5]

$$B_C = K\delta S q \lambda N^{\frac{1}{2}}(1000/Ui), \qquad (2)$$

where $K=0.7$ cm²/g is the absorption coefficient of rhodium for thermal neutrons, $N=140$ is the average number of mean free paths traversed by a thermal neutron before being captured by a proton, $\lambda=0.35$ cm is their mean free path in water (in paraffin $\lambda=0.30$ cm—we have assumed λ inversely proportional to the density of hydrogen atoms), and S and δ are the area and the thickness of the detector. In order to take into account the absorption of electrons in the mass of the detector we must substitute for δ the magnitude δ_{eff} (see preceding section). Finally q is the number of thermal neutrons produced per second and per cm³ in water in the region close to the detector. It is evident that q is a function of the distance from the source of fast neutrons. If now

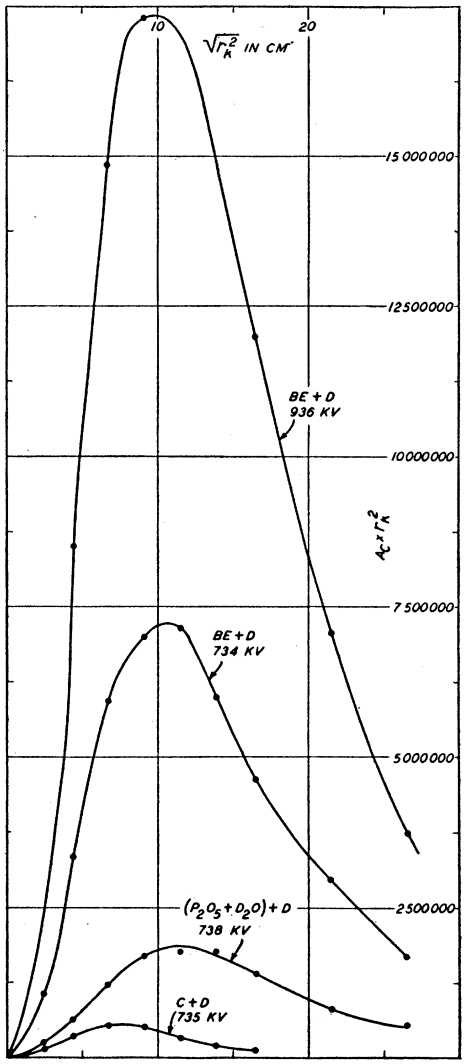

FIG. 6. Thermal neutrons in water between successive spherical shells.

[5] E. Fermi, Ricerca Scient. 7, 13 (1936).

we want to know the number of disintegrations corresponding to the activability B_C, we must multiply the left side of (2) by $840(\eta_U/\eta)$.

If we integrate this expression over all the volume and we call $Q=\int q d\tau$ the total number of fast neutrons emitted per second from the source (the capture cross section of protons seems to be considerable only for neutrons of thermal energy), we have (see reference 1, Eq. (27)):

$$Q/i=0.84(\eta_U/\eta)\int B_C d\tau/K\lambda N^{\frac{1}{2}}S\delta_{\text{eff}}$$
$$=0.118(\eta_U/\eta)\int B_C d\tau. \quad (3)$$

In order to calculate $\int B_C d\tau$ we make the reasonable assumption that B_C is proportional to A_C; therefore, by measuring B_C at a given distance from the source ($r_k^2=4.4$ cm), as was done separately for each of the sources (reactions) used below, we can write

$$\int B_C d\tau=4\pi[B_C(4.4)/A_C(4.4)]\int_0^\infty A_C r^2 dr. \quad (4)$$

In order to calculate the integral of the right side of Eq. (4), we need to extrapolate $A_C(r)r^2$ for large values of r. In practice this function for large values of r can be represented by an exponential $e^{-r/\Lambda}$. In our case the determination of such an exponential is not very accurate because it would be necessary to measure A_C with high accuracy up to distances from the source much larger than the greatest distance we have used ($r_C=25$ cm). However, the value of the integral is not very sensitive to errors on the value of Λ; we will see later how small this sensitivity is.

Approximation involved for large values of r

In reality, the curves of Fig. 6 will not be accurately exponential for large values of r. It is easy to understand qualitatively the general slope of these curves if we consider that the fast neutrons emitted from the source can be considered as a primary radiation which is absorbed in water with formation of a secondary radiation (thermal neutrons) softer than the primary one (mean free path of fast neutrons 4 or 5 cm, mean free path of thermal neutrons 0.35 cm). At large distances from the source the secondary radiation is in equilibrium with the primary one; both decrease with increasing r, corresponding to the absorption law of the primary radiation (fast neutrons). It is to be noted that in this consideration the expression "absorption of the primary radiation" does not mean a real absorption but a diffusion process in which neutrons lose energy in such a way that their mean free path decreases very rapidly.

From these rough considerations it is clear that the slope of $A_C r^2$, for large values of r, is connected with the mean free path λ_0 in water of fast neutrons emitted from the source. An exact calculation of $A_C r^2$ for large values of r presents some difficulties; it is, however, possible to make the following rough considerations suggested by G. C. Wick.

Let us consider a source emitting neutrons of energy E_0 and mean free path in water λ_0; we will call primary neutrons all neutrons of energy between E_0 and $(E_0-\Delta E)$, where ΔE is small. One neutron emitted from the source with energy E_0 after some collision in water will have lost, on the average, a large fraction of its energy; we can, however, consider the probability that after n impacts the energy of the neutron considered is contained between E_0 and $(E_0-\Delta E)$. It is evident that neutrons which satisfy this condition cannot have suffered any great deviation from the initial direction of motion; in all impacts they must have been deviated through a very small angle. Now it can be shown that the probability that a neutron after n impacts has energy between E_0 and $(E_0-\Delta E)$ is

$$(1/n!)(\Delta E/E_0)^n.$$

On the other hand, the probability that a neutron diffusing with mean free path λ_0, after n impacts is at distance between r and $(r+dr)$ from the starting point is

$$(1/n!)(r^n/\lambda_0^{(n+1)})e^{-r/\lambda_0}dr.$$

Therefore, the number of neutrons which arrive at distance r from the source with energy between E_0 and $(E_0-\Delta E)$ is represented roughly by

$$e^{-r/\lambda_0}\sum_0^\infty(1/\lambda_0^{(n+1)})(\Delta E/E_0)^n[r^n/(n!)^2]$$
$$\sim\text{const. } r^{-1/4}e^{-r/\lambda_0}\exp\{2[(\Delta E/E_0)(r/\lambda_0)]^{\frac{1}{2}}\}. \quad (5)$$

From this equation we see that from the meas-

urement of $A_C r^2$ it is possible to obtain λ_0 because

$$-1/\lambda_0 = \lim_{r\to\infty} (\log A_C r^2)/r. \qquad (6)$$

However, it is evident that this method is not convenient for an experimental determination because in practice A_C is measured only up to distances of the order of some decimeters. If the source emits neutrons of different energies, the method permits, in principle, the determination of the mean free path of the fastest component.

It is also evident that $A_C r^2$ is not much different from an exponential $e^{-r/\Lambda}$ where Λ is an empirical length not connected by any simple relation to λ_0. The experimental determination of Λ for different sources of neutrons permits, however, the establishment of the order of increasing mean free path, and therefore energy. With sources which emit neutrons of several different energies, the situation is much more complicated.

Another parameter, whose value is connected with Λ and which is very useful in characterizing different sources of fast neutrons, is

$$(r^2)_{Av} = \int_0^\infty n(r) r^2 dr \Big/ \int_0^\infty n(r) dr,$$

that is, the average of the square of the distance from the source of fast neutrons reached by the slow neutrons[1,5]. This $(r^2)_{Av}$ depends very strongly on the value of Λ. In the present work the determination of Λ is not accurate enough to calculate $(r^2)_{Av}$ for different sources. However, we are able to make some qualitative considerations regarding the energy of the fast neutrons emitted from the different sources, starting from a comparison of their space distributions of thermal neutrons in water.

TABLE I. *(D+D) at 738 kv (phosphorus pentoxide+heavy water target); distribution of thermal neutrons in water.*

r_C	$(r_k^2)^{\frac{1}{2}}$	A_C+A_D	A_D	A_D corr.	A_C	$A_C r_k^2$
0	2.45	42100±1500		(4800)	37300	224000
2.5	4.4	37500±1300	4120	3980	33520	640000
5	6.7	29500± 600	2500	2410	27090	1220000
7.5	9.1	22100± 400		(1500)	20600	1700000
10	11.5	14200± 200		(900)	13300	1770000
12.5	13.9	9550± 200		(540)	9010	1770000
15	16.5	5440± 300		(310)	5130	1400000
20	21.5	1860± 150		(106)	1750	810000
25	26.5	830± 40		(47)	780	547000

EXPERIMENTAL RESULTS

(Rn+Be)

The reaction which gives rise to neutrons is ${}_4Be^9+{}_2He^4\rightarrow{}_6C^{12}+{}_0n^1$. The space distribution in water of thermal neutrons obtained from a source (Rn+Be) was measured by Amaldi and Fermi.[1] However, the geometry in the experiments of these authors was very different from the geometry used in the present work for the artificial sources. Therefore, as previously stated, these measurements were repeated with the source (Rn+Be) inside a brass tube of the same form as that of the artificial source (Fig. 2). The details of the disposition used have been given above.

In Fig. 3 the activability of the rhodium detector is plotted against the corrected distance (curves A_C); the corresponding scale is given on the left-hand side. The upper curve represents the results of Amaldi and Fermi. We see that at small distances the relatively small volume of our source gives rise to a perturbation in the density of thermal neutrons of about 20 percent. In the same figure we see these two curves multiplied by r_k^2 (right-hand scale). For very large distances from the source the two curves must coincide. The curve of Amaldi and Fermi was measured up to distances of 40 cm; therefore, we have extrapolated our curve $A_C r^2$ using the same Λ. We find (Eq. (4))

$$\int_0^{24} A_C r^2 dr + 1.06\times10^5 \int_{24}^\infty e^{-r/9.45} dr$$
$$= 38.7\times10^4 + 7.9\times10^4 = 46.6\times10^4,$$
$$\int B_C d\tau = 4\pi(1.66/753)46.6\times10^4 = 1.29\times10^6.$$

From this value we find (Eq. (3)) $Q/I=150{,}000$ neutrons per second per unit[1] of neutron intensity. If we remember that one unit of neutron intensity corresponds to about 6 mC of radon plus beryllium, we find 25,000 neutrons per second per millicurie of (Rn+Be).

The value given by Amaldi and Fermi is 27,000. The difference arises for two different reasons besides errors: In the calculation of Amaldi and Fermi $\lambda=0.3$ cm was used, that is, the mean free path of thermal neutrons in paraffin instead of in water; also the value of N was a little different. Taking all this into account

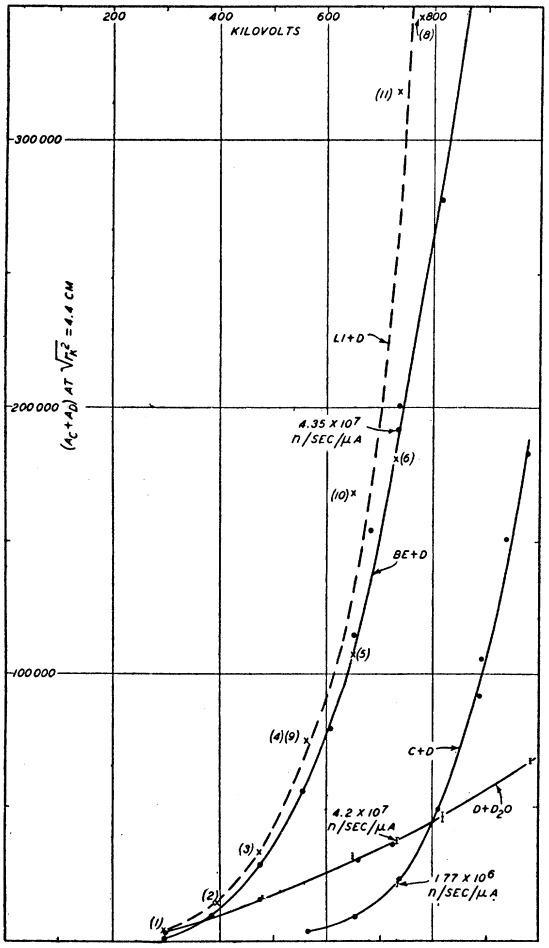

FIG. 7. Thermal neutrons at fixed distance, source at various voltages, for several deuteron reactions. (For absolute yield multiply curve for D+D_2O by 0.93.)

we find from the data of Amaldi and Fermi a value of 24,000 neutrons per second per millicurie. Thus in spite of the slightly higher value of $\int B_C d\tau$ we find a lower number of neutrons. This result is due in great part to the fact that the area of the detector of Amaldi and Fermi is larger than the area of our detector. It may be recalled that the rhodium used by Amaldi and Fermi[1] was 0.36 g/cm² thick ($\delta_{\text{eff}}=0.108$ g/cm²) and 28 cm² in area. The activity measured with the ionization chamber is not proportional to the area because beta particles emitted close to the edge of the detector "see" the ionization chamber through a smaller solid angle. It would be more correct to introduce an effective surface $S_{\text{eff}}<S$ whose value would depend on the geometrical disposition of the chamber. We will neglect this correction and conclude that the number of neutrons emitted from a source of (Rn+Be) is about 25,000 neutrons per second per millicurie.

If we remember that the alpha-particles of Ra C′ (7.68×10^6 volts) are at least three times more efficient[1] than the alpha-particles of Rn (5.49×10^6 volts) and Ra A (6.00×10^6 volts), which are also active in (Rn+Be) neutron sources, we can conclude that $(5\times3.7\times10^7/2.5\times10^4)$ $\leq$7000 alpha-particles of 5.5 to 6 million volts energy impinging on Be are necessary for the emission of one neutron. The yield found by this method is much higher than the yield given for this reaction by other authors.[6] We must notice further, however, that in a source of the type used by Amaldi and Fermi a non-negligible fraction of the alpha-particles emitted from (Rn+Ra A+Ra C) impinges on the walls of the small glass tube and not on Be. The error due to this fact is in the sense that even the above yield of the beryllium reaction is too low.

(D+D)

The reaction which gives the neutrons in this case is

$$_1D^2+D^2\rightarrow{}_2He^3+{}_0n^1.$$

The target, the constancy of which was tested by the satisfactory consistency of our observed points on the neutron yield curve during two days of observations, was prepared by adding excess heavy water (99 percent) to dry P_2O_5 in a copper cup and inserting this target immediately into the tube. It is unfortunate that we had time

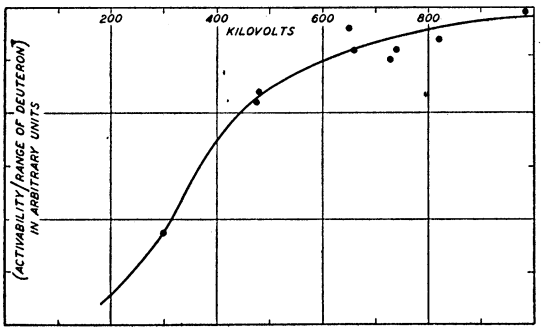

FIG. 8. Efficiency curve for D+D reaction.

[6] See, for example, R. Jaeckel, Zeits. f. Physik **91**, 493–510 (1934); F. A. Paneth and H. Loleit, Nature **136**, 950 (1935); F. A. Paneth and E. Glückaut, Proc. Roy. Soc., **A157**, 412 (1936); G. A. Fink, Phys. Rev., **50**, 738 (1936).

to make observations only on a single deuterium target. It obviously would be desirable to check the yields observed by measurements on other targets, with independent chemical analyses, but opportunity for this has not been presented. We have no reason to suspect our present results, but the possibility of an error of a few percent should be borne in mind (percentage of water in P_2O_5 mixtures depends on the equilibrium reached).

In order to determine the percentage of deuterium in the target, we adopted the following procedure: In removing the target a stopwatch was started at the instant when air was allowed to come in contact with the target, and then the increase in weight was observed as a function of time by frequent measurements on a sensitive balance over a period of about 15 minutes. It was found that the weight increased linearly due to the absorption of water from the air. Extrapolating to time zero, the weight of the target as bombarded was found to be 0.460 gram.

By chemical analysis, for which we are indebted to Dr. P. H. Emmett of the United States Department of Agriculture, it was found that the quantity of P_2O_5 contained in the target was 0.342 gram, and a sample of the original dry P_2O_5 showed that this material contained 1.4 percent of (ordinary) water. The quantity of heavy water in this target, which was used for all the work here reported, was therefore $[0.460-(0.342+0.005)]=0.113$ gram. Since we used 99 percent heavy water, the amount of pure heavy water in our target was 0.112 gram.

In order to obtain the neutron yields from deuterium targets of other composition, or to calculate the absolute yield of the deuterium reaction, it is necessary to divide the observed yield by the fraction of the total stopping power of our $D_2O(P_2O_5)$ target, which was actually deuterium. Unfortunately, the stopping powers for no elements have been measured for deuterons. The stopping power of phosphorus for alpha-particles is not listed in the table given by Rutherford, Chadwick, and Ellis (p. 100) but the values for Si (1.23) and Cl (1.76) indicate that it may be reasonable to take 1.5 as the value for this element. The stopping power for protons of moderate velocity in hydrogen relative to air is given by Blackett and Lees,[7] being 0.24, 0.22, and

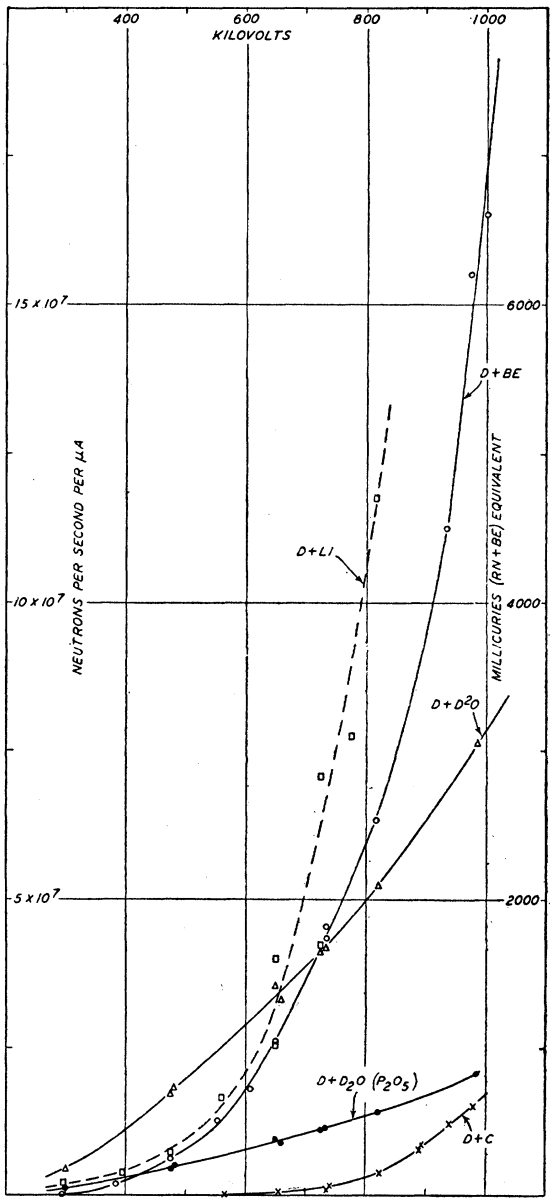

FIG. 9. Total neutron yields at various voltages for several deuteron reactions. (Multiply curve for $D+D_2O$ by 0.93.)

0.217 for protons of range 0.5, 1.0, and 2.0 cm, respectively. We accordingly accept 0.22 as reasonable for the stopping power of deuterons in deuterium, relative to air, for the velocities we have used. For alpha-particles in oxygen the SP relative to air varies from 1.07 to 0.98 (Rutherford, Chadwick and Ellis, p. 97). For our case in which the velocity of the particles is low, we have arbitrarily taken the SP of deuterons in

[7] P. M. S. Blackett and D. S. Lees, Proc. Roy. Soc. **A134**, 658–671 (1932).

TABLE II. *(D+Be) distribution of thermal neutrons in water.*

	734 kv					936 kv		
$(r_k^2)^{\frac{1}{2}}$	A_C+A_D	A_D	A_D corr.	A_C	A_Cr^2	A_C+A_D	A_C	A_Cr^2
2.45	198500	22400	21600	176900	1060000			
4.4	192000±200	18000	17400	174600	3340000	494000±6500	446000	8520000
6.7	144000	12500	12100	131900	5930000	360000	330000	14850000
9.1	90800		(6170)	84630	6980000			
11.5	57400		(3620)	53780	7160000	139000	130000	17300000
13.9	32400		(1850)	30550	6010000			
16.5	18100		(1030)	17070	4640000	46800	44100	12000000
21.5	6840		(390)	6450	2980000	16200	15300	7070000
26.5	2570		(150)	2420	1690000	5690	5370	3750000

oxygen as unity relative to air. The total stopping power of our target was accordingly

$$\begin{aligned}SP&=(0.112/20)(2\times0.22+1)\\&\quad+(0.342/142)(2\times1.5+5\times1)\\&\quad+[(0.005+0.001)/18](2\times0.22+1)\\&=0.00807+0.01927+0.00048=0.0278.\end{aligned}$$

Of this total stopping power 0.00807, or 29 percent, was then due to D_2O. The stopping power of the deuterium alone was (0.44/1.44) = 30.6 percent of the stopping power of the heavy water, or 8.88 percent of the total target. [Note: The curves for (D+D_2O) in Figs. 7 and 9 are drawn assuming 27 percent, instead of 29 percent, for the stopping power of the heavy water in our target, on the basis of preliminary calculations.]

In Table I are collected the experimental data for an energy of the impinging deuterons of 738 kv. The third column contains the total activability of our detector at different distances; we give the quadratic error calculated from two or three readings for each value. Column four contains the rhodium activability with a cadmium sheet on both sides of the detector, as measured on the rhodium face towards the source. Column five contains the preceding value multiplied by 1.93/2; the values in brackets are calculated as explained above. Columns six and seven represent respectively A_C (difference of the data of columns three and five) and $A_Cr_k^2$.

This last can be extrapolated for large values of r by means of the exponential $7.1\times10^6e^{-r/10}$; we find

$$\int_0^{24}A_Cr^2dr+7.1\times10^6\int_{21}^{\infty}e^{-r/10}dr$$
$$=26.5\times10^6+6.4\times10^6=32.9\times10^6.$$

Using the value $B_C(4.4)=(12400+11100)/2-3980=7770$ we have

$$\int B_Cd\tau=4\pi(7770/33500)32.9\times10^6=9.58\times10^7.$$

Therefore, $Q/i=1.13\times10^7$ neutrons per second per microampere of deuterons at 738 kv impinging on the heavy phosphoric acid target. In order to obtain the number of neutrons corresponding to a heavy water target, we must divide the preceding value by 0.29; we have, therefore, $Q/i=3.90\times10^7$ neutrons per second per microampere of deuterons at 738 kv impinging on a heavy water target. For a pure deuterium target we again divide this value by 0.31, and since one microampere corresponds to 6.25×10^{12} deuterons per second we have a yield corresponding roughly to 43,000 deuterons of energy 738 kv impinging on a pure deuterium target per neutron emitted. We must notice that the value of $\int B_Cd\tau$ changes only by six percent if we extrapolate A_Cr^2 with $e^{-r/13}$; from this example we see that the number of neutrons emitted from a source found by this method is not very sensitive to errors in the value of Λ.

In order to determine the yield of this reaction as a function of the voltage, we have measured

TABLE III. *(D+C) at 735 kv, distribution of thermal neutrons in water.*

$(r_k^2)^{\frac{1}{2}}$	A_C+A_D	A_D	A_D corr.	A_C	A_Cr^2
2.45	25400±500	3440	3320	22080	132500
4.4	21900±600	2860	2760	19140	366000
6.7	13500±600	1350	1300	12200	549000
9.1	6710±150		(537)	6170	509000
11.5	2760±200		(193)	2570	342000
13.9	1210± 40		(79)	1130	222000
16.5	526± 20		(34)	492	134000

the total activity of our rhodium detector at a given distance from the source $[(r_k^2)^{\frac{1}{2}}=4.4$ cm$]$ for different energies of the impinging deuterons. The results are plotted in Fig. 7; some points are given with the quadratic error, the others were measured only once; some were measured hours later, or the next day, in order to check the constancy of the target. With a current of about 2 microamperes we see that the target is very satisfactory on this point. The arrow corresponds to the energy of the impinging deuterons of 738 kv, for which we have determined the number of emitted neutrons from the above experiment.

In Fig. 8 is plotted the ratio of the activabilities of rhodium given in Fig. 7 to the range of deuterons, against the energy of these last; in order to calculate the range of the deuterons, we have used the data of Blackett and Lees[7] on the range of protons of low energy in hydrogen. We have made the reasonable assumption that a deuteron of a given velocity, having an energy twice that of a proton, also has a double range. There is some indication from Fig. 8 that for low energies of the impinging deuterons the yield increases more than the range; for energies higher than 500 kv the ratio yield to range seems to be constant.

(D+Li)

The reactions involved are probably ${}_3Li^7+{}_1D^2 \rightarrow {}_4Be^8+{}_0n^1$ and ${}_3Li^7+{}_1D^2 \rightarrow 2{}_2He^4+{}_0n^1$. Some undoubtedly also arise from Li^6 reactions. The target of lithium was cut under petroleum and was put in a tube in a current of helium; nevertheless, the readings did not check one another, the yield increasing with continued bombardment. Therefore, we did not measure the curve of the activity as a function of the distance from the source at a given voltage, but only some points of the yield curve at a given distance $[(r_k^2)^{\frac{1}{2}}=4.4$ cm$]$ as a function of the voltage. In Fig. 7 the points measured for this reaction are indicated by small crosses; the number written against each cross corresponds to the order of the successive readings. The points do not repeat; nevertheless, we can conclude that, on the average, they are a little higher than the points of Be for the same voltage. If we take into account the fact that the neutrons emitted from Li are faster than neutrons emitted from Be^8 we conclude that Li emits, for the same energy of the impinging deuterons, more neutrons than Be. This reaction must be further investigated. The excitation curve (total neutrons emitted) for Li given in Fig. 9 is calculated assuming that the $A_C r^2$ curve for Li is the same as that measured for Be.

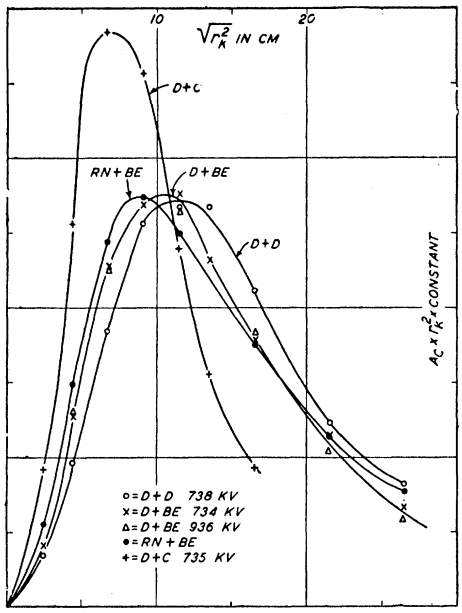

FIG. 10. Thermal neutrons in water between successive spherical shells (ordinates adjusted to give equal areas under curves).

(D+Be)

The reaction is ${}_4Be^9+{}_1D^2 \rightarrow {}_5B^{10}+{}_0n^1$. The Be target was a piece of solid metallic beryllium (impurity one percent of iron). Table II is similar to Table I; the activability as a function of the distance was measured for two different energies of the impinging neutrons, namely, 734 and 936 kv. The two curves are proportional. $A_C r^2$ can be represented fairly well for large values of r by $4.5\times10^7\times e^{-r/8}$ at 734 kv and by $10.3\times10^7\times e^{-r/8}$ at 936 kv.

At 734 kv we have

$$\int_0^{24} A_C r^2 dr + 4.5\times10^7 \int_{24}^{\infty} e^{-r/8} dr = 10.37\times10^7+1.79\times10^7=12.16\times10^7.$$

[8] T. W. Bonner and W. M. Brubaker, Phys. Rev. **48**, 742–746 (1935).

From the value $B_C(4.4)=(64900+53800)/2-17400=41900$ we have

$$\int B_C d\tau = 4\pi(41900/175000)1.22\times10^8=3.68\times10^8.$$

We conclude $Q/i=4.35\times10^7$ neutrons per second per microampere of deuterons at 734 kv impinging on Be, or $(6.25\times10^{12})/(4.35\times10^7)=144000$ deuterons at 734 kv impinging on Be per neutron emitted. The curve of the total activability at a given distance $[(r_k^2)^{\frac{1}{2}}=4.4$ cm$]$ as a function of the voltage is given in Fig. 7; the arrow corresponds to 4.35×10^7 neutrons per second per microampere, as found above.

(D+C)

The reaction is ${}_6C^{12}+{}_1D^2\rightarrow{}_7N^{13}+{}_0n^1$. The target was a piece of Acheson graphite. Table III is similar to Tables I and II for an energy of the impinging deuterons of 735 kv. $A_C r^2$ is represented fairly well for large values of r, by $3.64\times10^6\times e^{-r/5}$. We have

$$\int_0^{16} A_C r^2 dr+3.64\times10^6\int_{16}^{\infty} e^{-r/5}dr = 51.2\times10^5+7.4\times10^5=58.6\times10^5.$$

$B_C(4.4)=(7450+5880/2)-2760=3900$; $\int B_C d\tau = 4\pi(3900/19100)5.86\times10^6=15\times10^6 Q/i=1.77\times10^6$ neutrons per second per microampere of deuterons at 735 kv impinging on C, or 3,500,000 deuterons of 735 kv energy impinging on C per neutron emitted. Fig. 7 contains also the neutron yield of carbon as a function of the voltage of the impinging deuterons.

Summary and Discussion

Neutron yields

Since, due to differences in initial neutron energies, the numbers of neutrons emitted in various reactions are not directly proportional to the activabilities, the data of Fig. 7 have been replotted in Fig. 9 with a uniform scale for neutron yields per microampere. In other words, the total yield of neutrons has been evaluated from $\int A_C r^2$ or by measuring the distribution of thermal neutrons throughout the water tank at a particular value of the bombarding voltage (indicated by an arrow for each curve of Fig. 9), and this total yield has been multiplied by the ratio of the activabilities of the rhodium detector at a fixed position in the water for the different voltages used, thus giving the total neutron yield as a function of the voltage for each reaction. The distribution curve in water is thus assumed not to vary appreciably with the energy of the incident neutrons. Adopting from above the value 1 mC (Rn+Be) $\leqq$25000 neutrons per second, an immediate comparison with radon-beryllium sources can be made. This comparison is given by the second scale of ordinates. For convenient reference curves for both (D+D_2O) and [D+D_2O(P_2O_5)] have been given.

These results may be compared with those of other investigators. The first measurements on the yield of the (D+D) neutron reactions are due to Oliphant, Harteck, and Rutherford.[9] In order to compare our value with their result, we may make use of the yield ratio of 8 for 300 kv to 100 kv deuterons given by Ladenburg and Roberts.[10] With our data this gives a yield of one neutron per 4×10^6 deuterons at 100 kv to be compared with that of one per 1×10^6 reported by the Cavendish investigators, and one per 6×10^6 reported by Ladenburg and Roberts. These results, as well as those of Alexopoulos[11] who gives a yield of one neutron per 0.7×10^6 deuterons at 140 kv, may therefore be considered to be in reasonably good agreement, since hitherto no method involving the integration of the total neutron intensity has been used. The results of Alexopoulos[11] appear to be open to question.

Agreement is also obtained with the observation of Ladenburg, Roberts, and Sampson[12] that at 100 kv a total ion current of 100 microamperes produces an activity in silver equal to that produced by 400 mC of (Rn+Be) if we assume that 10 percent of their beam was deuterons, which appears reasonable.

However, at 730 kv Bonner and Brubaker[13]

[9] Oliphant, Harteck, and Rutherford, Proc. Roy. Soc. **A144**, 692–703 (1934).
[10] Ladenburg and Roberts, Phys. Rev. **50**, 1190 (1936).
[11] K. D. Alexopoulos, *Promotionsarbeit von der Eidg. Tech. Hochschule* (Zürich, 1935); H. Kallman and E. Kuhn, Naturwiss. **15**, 231–232 (1937).
[12] Ladenburg, Roberts, and Sampson, Phys. Rev. **48**, 467 (1935).
[13] Bonner and Brubaker, Phys. Rev. **49**, 19–21 (1936).

give a yield for the (D+D) reaction of only one neutron per 10^7 deuterons, which is two hundred times smaller than our yield at that voltage. Similarly, for the (D+Be) reaction their yield at 730 kv is about one per 5.5×10^7 compared to our yield of one per 1.4×10^5, again smaller by a factor of several hundred. Crane, Lauritsen, and Soltan[14] have given yields which are also very low. These large differences between the Pasadena results and our own are probably to be ascribed to their use of an alternating current voltage on their tube and lack of analysis of the ion-beam striking their targets.

Extrapolating our data for the (D+Be) reaction to 1300 kv, we find that the yield reported by Livingston, Henderson, and Lawrence[15] is 30 times *smaller* than we would expect at this voltage, while at 5 million volts Lawrence and Cooksey[16] report a neutron yield more than 10^5 times that from one curie of (Rn+Be) when a beryllium target is bombarded by 7 microamperes of deuterons. This is a yield per microampere more than 2000 times *larger* than our yield, and much larger than can be accounted for by assuming a Gamow exponential and extrapolating from one million to five million volts, taking into account the increased deuteron range. The Berkeley value corresponds to an absolute yield of one neutron emitted per 17 incident deuterons.[17]

Neutron energies

The space distributions of thermal neutrons from the different sources are not determined accurately enough in our observations to permit a calculation of the mean value of the square of the distance from the source. We can, however, make some qualitative considerations by comparing the space distributions of thermal neutrons from different sources in order to interpret our curves in terms of known data on the energy of the emitted neutrons. In Fig. 10 the curves of Fig. 6, reduced to the equal areas from 0 up to $(r_k^2)^{\frac{1}{2}}=24$ cm, are drawn. We have used this normalization, instead of dividing by the area of the curves from zero up to infinity, in order to avoid introducing uncertainties due to the values of Λ.

From Fig. 10 we see that the maxima of the curves are at different distances from the source. The order of decreasing distance is (D+D), (D+Be), (Rn+Be), (D+C). The neutrons emitted from monochromatic artificial sources have somewhat different energies in different directions with respect to the incident beam, following the law of conservation of momentum. In the case of (D+D), with an energy of 1000 kv for the incident particles, the energy of the neutrons emitted at 90° to the beam will be about 2.5 million volts according to Bonner and Brubaker.[18]

The neutrons emitted from carbon reaction have a very low energy; the data of Tuve and Hafstad[19] indicate (at 735 kv for the impinging deuterons) an upper limit of 1000 kv. The data of Bonner and Brubaker[20] (reaction energy −0.37 million volts) give 240 kv for neutrons at 90° with the impinging beam. The neutrons emitted from this reaction are also homogeneous; therefore, the position of the maxima of the curves given in Figs. 5, 6, 8, and 10 is connected with the law by which the same curves decrease for large values of r.

In the case of (D+Be) and (Rn+Be) the spectrum of the emitted neutrons is complex.[20, 21] Therefore, it is possible to have curves with the maxima very close to the source and decreasing at the same time only slowly with the distance from the source. Such a behavior must be interpreted as due to the superposition of neutrons of very low and very high energy. This seems to be the case of (Rn+Be). The curve of this reaction has the maximum closer to the source than the curve of (D+Be), and at the same time there is some indication that

[14] Crane, Lauritsen, and Soltan, Phys. Rev. **45**, 507–512 (1934).
[15] Livingston, Henderson, and Lawrence, Phys. Rev. **44**, 782 (1933).
[16] Lawrence and Cooksey, Phys. Rev. **50**, 1131–1140 (1936).
[17] While working on another problem we have observed that the neutrons and gamma-rays from D+Be at 1000 kv give discharge rates per microampere for a Victoreen condenser dosimeter roughly 1/100 of the rates reported for a duplicate instrument at Berkeley when operating the cyclotron at 5 to 6 Mev. This would indicate any equivalent neutron yield of 10^4 curies from the cyclotron, in agreement with Aebersold's later estimate.
[18] Bonner and Brubaker, Phys. Rev. **49**, 19–21 (1936).
[19] Tuve and Hafstad, Phys. Rev. **48**, 106–107 (1935).
[20] Bonner and Brubaker, Phys. Rev. **50**, 308–314 (1936).
[21] J. R. Dunning, Phys. Rev. **45**, 586–600 (1934); G. Bernardini and D. Bocciarelli, Ricerca Scient. **7**, 129 (1936), and Rend. Acc. Lincei **24**, 132 (1936).

for high values of r it decreases more slowly. We know that from the (Rn+Be) reaction there are emitted, in considerable numbers, neutrons of 4.8 to 6.5 million volts energy. If we could measure the space distribution up to higher distances, we must expect the curve of (Rn+Be) to decrease more slowly than the curve of (D+D). The small distance from the source of the maximum of the curve of (Rn+Be) and also the high absolute number of neutrons found with our method for this reaction indicate that relatively high numbers of neutrons of low energy are emitted from (Rn+Be) sources.

The (D+Be) reaction gives rise also to a complex spectrum of neutrons as shown by Bonner and Brubaker;[20] from the spectrum given by these authors it seems reasonable to find that the curve of Fig. 10 relative to this reaction has the maximum closer to the source than does the (D+D) reaction.

Artificial production of radioactive isotopes

The problem of evaluating the quantity of artificial substances that can be prepared using slow neutrons is now reduced to the evaluation of the fraction of the neutrons emitted from a source which can be absorbed from the substance we wish to make radioactive. It is evident that the most convenient way is to irradiate substances in solution.

First, we must choose the dimensions of the tank containing the solution corresponding to the distribution of thermal neutrons in water of the source of fast neutrons used. By surrounding the solution tank with water we will avoid the border disturbance, and we will be able to evaluate the fraction of fast neutrons lost. For instance, with a source of (D+Be) and a solution tank of 50 cm diameter we lose 15 percent of the fast neutrons emitted from the source. The remaining 85 percent is slowed down by the water and is absorbed by the hydrogen atoms ($\sigma_H = 0.31 \times 10^{-24}$ cm^2) or by other nuclei present in solution ($\sigma_A = KM1.66 \times 10^{-24}$ cm^2, where K is absorption coefficient for thermal neutrons in cm^2/g, and M is atomic mass). In order to obtain a reasonable quantity of radioactive substance of a kind A, we need to prepare a solution with a concentration n_A large enough to have $\sigma_A n_A$ of the same order of magnitude or larger than $\sigma_H n_H$. This condition can be easily satisfied for many elements. The difficulty arises in many cases when we need to concentrate the active product by chemical separation, following the method of Szilard and Chambers.[22] In other cases, however (iodine, manganese, arsenic, etc.), very simple processes are known which may be used to separate the active material. For instance, by irradiating a concentrated solution of sodium permanganate of convenient dimensions it is possible to absorb about 50 percent of the emitted fast neutrons; the active material can be separated by a simple filtration.

Assuming the useful absorption of 20 percent of the neutrons emitted, the number of millicuries of an activated radio element produced by bombardment for a time equal to twice the half-life of the element produced is conveniently obtained by dividing the (Rn+Be) equivalent of the artificial neutron source, expressed in millicuries, by the approximate factor 10,000. This factor is obviously independent of the half-life of the radio element produced.

[22] L. Szilard and T. A. Chambers, Nature **134**, 462 (1934).