Thick Target Yields from the (d,n) Reaction at 10 Mev*

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The neutron yield from thick targets of Be, B, C, Al, Ni, Cu, Mo, Ta, W, Pt, and Au, bombarded with 10-Mev deuterons, has been determined by comparing the manganese activity ($MnSO_4$ in solution, in a large tank) after bombardment, with the activity produced by a standard Ra-Be source placed at the same position as the target. Some less reliable data on P, Mn, and Sb, obtained by a different method, are included.

INTRODUCTION

THE production of neutrons by deuteron bombardment was discovered by Crane and Lauritsen,[1] who used Li and Be targets. This type of source gives, at medium bombarding energies, large neutron intensities and is quite applicable to many types of experiments. Although absolute yields from various targets are of considerable value in planning experiments and add to nuclear knowledge in general, until recently, the only available data were at low energy or were thin target data for some particular reaction in which emitted charged particles could be counted. The present experiments describe a determination of the thick target yields for a number of targets bombarded with 10-Mev deuterons.

EXPERIMENTAL ARRANGEMENT

In order to avoid the troublesome corrections necessary with most available neutron detectors, because of their selective response to neutrons of different energy, this experiment was done by immersing the source in a large tank of water in which all of the neutrons are assumed ultimately to be reduced to thermal energies. A suitable detector is dissolved in the water and the activity induced in this detector, which accurately averages over energy and angle, is a measure of the total number of neutrons produced. The detector in this case was a quantity of manganese (in the form of manganese sulfate), which has a convenient absorption cross section and half-life.

The source of deuterons in this experiment was the magnetically analyzed beam from the University of Illinois cyclotron,[2] the energy of which was determined to be 10.00 ± 0.07 Mev by a range-energy measurement. The physical arrangement of the apparatus is shown in Fig. 1. The deuteron beam emerging from the cyclotron is stopped down to one inch diameter at the main target box T, is magnetically analyzed and stopped down to a one-half inch diameter at the analyzer magnet A. The analyzed beam then passes into a hole E, in the shielding water tanks (which contain a saturated solution of boric acid) around the cyclotron. After the beam traverses the shielding water tanks, it passes into an adjustable brass tube which is insulated by hard rubber bushings from the cyclotron exit tube and the water tank, B. This tube passes through Wilson seals and connects the exit tube of the cyclotron with the experimental tank, B, containing water and manganese sulfate. At the end of this tube, which serves also as a faraday cage, the target is held by means of a threaded Lucite bushing. At the front end of this tube, another aperture is provided which is insulated from the faraday tube and serves to keep deuterons which are scattered by the collimating holes from entering the faraday tube. Figure 2 shows a detail of the target assembly and the connection between the cyclotron exit tube and the tank B. The tank B was a cube approximately one meter on a side and contained 1000 liters of water in which approximately 450 pounds of manganese sulfate was dissolved. The adjustable tube connecting the cyclotron exit tube with the tank B was

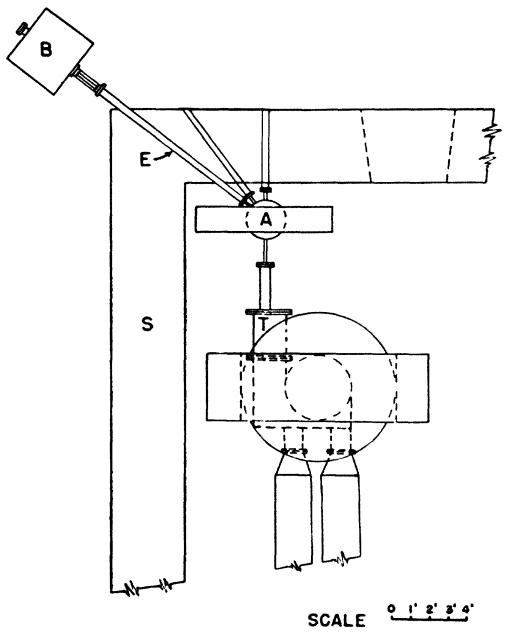

FIG. 1. Physical arrangement of apparatus. T is the main cyclotron target, A the analyzer magnet, E the exit tube, and B the experimental tank containing $MnSO_4$ in 1000 liters of water.

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[1] Crane, Lauritsen, and Solton, Phys. Rev. 44, 514 (1933); 44, 692 (1933).
[2] Kruger *et al.*, Rev. Sci. Instr. 15, 333 (1944).

electrostatically shielded. Through this shield, electrical contact was made to the tube and to an electronic beam current integrator or Q-meter, which measured the total charge striking the target. The Q-meter was an adaption of a circuit designed by Meagher for another experiment.[3] The Q-meter was calibrated with a standard voltage, measured on a precision meter which was impressed across standard resistors. These resistors were vacuum-sealed Hi-Meg resistors manufactured by the Victoreen Instrument Company, and were calibrated by the National Bureau of Standards at various temperatures with an accuracy of one-half percent. The integrator circuit was found to be linear within experimental accuracy from 10^{-11} to 10^{-7} ampere and the actual beam currents used in the experiment were all between 2×10^{-9} and 3×10^{-10} ampere.

The detection of the induced activity in the $MnSO_4$ solution was done in the following manner: A thin-walled Geiger counter was suspended vertically in the liquid on a level with the center line of the beam and

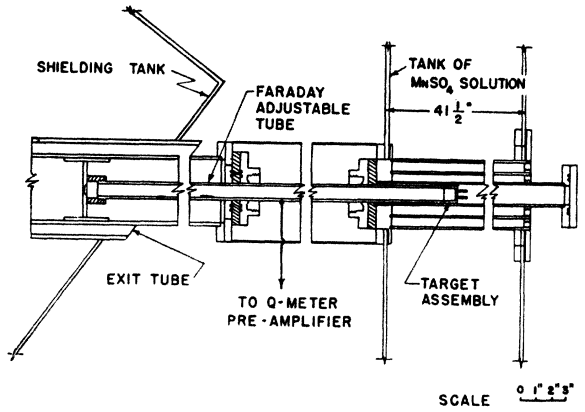

FIG. 2. Details of the target assembly.

equidistant from this center line, one end, and one side of the tank. During each bombardment and all during the detection of the manganese activity, the liquid in the tank was completely mixed by a large motor-driven stirrer. The activity was measured in the large tank rather than in a small sample removed to another part of the laboratory for several reasons: (1) it was found that the observed activity was quite insensitive to the exact position of the counter in the tank, so there were no geometrical factors which had to be kept fixed, (2) no accurately measured quantity of the liquid need be taken, and (3) the large amount of liquid around the counter caused the counting rate to be higher than would be the case with a smaller sample and also served as a very good shield to background radiation from outside the tank. The background count of the arrangement remained at 20 ± 1 counts/minute throughout the experiment. Moreover, when all the shielding water tanks were in place and the analyzer magnet set so that no beam appeared outside the shielding tanks, a ten-microampere beam of deuterons on the main cyclotron target for thirty minutes did not affect the background rate inside the tank of $MnSO_4$ solution.

The method of alignment of apparatus and taking data was as follows: The tank was leveled and lined up visually with the exit tube of the cyclotron; then a thin aluminum foil was coated with willemite and placed at the target position. The whole assembly was pumped down and a deuteron beam obtained. The fluorescent spot on the willemite was observed through a glass plate sealed on the rear of the tank and the final tank adjustment made so that the beam spot was centered on the target and did not move as the position of the target was changed back and forth within the tank. The beam spot did not move as the analyzer magnet field was swung through resonance but simply appeared and disappeared. These visual observations were made frequently during the course of the experiment, and at no time was the beam ever observed to strike any object but the target. In addition, the target was occasionally removed and the beam allowed to pass completely through the tank. During these runs the Q-meter on its most sensitive scale failed to indicate any charge striking the adjustable tube.

Before each bombardment the Q-meter was calibrated and a deuteron beam obtained at the main cyclotron target. When the beam became steady, the cyclotron deflector voltage was turned down and the analyzer magnet turned on. The deflector voltage was then raised to give a beam at the experimental stations. By this method, it was possible to get a beam to the target inside the tank B which rose rapidly to a given value. The beam into the tank was held to approximately 0.01 microampere, which was of the order of 10^{-3} of the beam current to the main cyclotron target. Bombardments lasted usually from ten to thirty minutes, and the external beam and main cyclotron beam were monitored visually and kept constant by small adjustments of the cyclotron magnetic field.

After a bombardment was completed, the activity in the tank was observed with the Geiger counter, and its decay was followed for at least one half-life of the manganese activity. No activity was ever observed other than the 2.59-hour[4] manganese except in the case of the carbon and boron carbide targets, where the activities due to the 9.93-minute N^{13} and the 20.5-minute[4] C^{11} formed in the target were observed.

As a neutron standard, a source consisting of 500 milligrams of radium element (about 900 milligrams of radium salt) intimately mixed with 3 grams of 325 mesh beryllium powder was used. The density of this source was 1.8 g/cc. Since the experiments were performed, this source has been calibrated at Argonne National Laboratory; and, allowing for Po growth between the time of the experiments and the time of calibration,

[3] R. E. Meagher, Phys. Rev. 78, 667 (1950).

[4] These periods are taken from the Segrè chart.

the strength of this source at the time of the experiment was $6.08\pm0.37\times10^6$ neutrons/second. Bombardments were made frequently during the experiments with this source held in the target assembly at the same position in the tank as the targets during deuteron bombardment.

The counting rates observed as a function of time after the end of bombardment were corrected for counter resolving time in the usual manner. Another correction must be made at low counting rates, for, if in order to get a statistically significant number of counts it is necessary to count for a period of time during which the source decays appreciably, the observed rate is not the true rate at one-half of the time interval, but is equal to the time rate at some earlier time. Thus, let $R(t)$ be the real counting rate at any time t; then the number of counts recorded between t_1 and t_2 is

$$\int_{t_1}^{t_2} R(t)dt=\int_{t_1}^{t_2} R(t_1)\exp(-\lambda t)dt$$
$$=[R(t_1)/\lambda][\exp(-\lambda t_1)-\exp(-\lambda t_2)],$$

so that the average observed rate is

$$[R(t_1)/\lambda(t_2-t_1)][\exp(-\lambda t_1)-\exp(\lambda t_2)].$$

This must equal the true rate at some time t_3 and so is equal to

$$R(t_1)\exp(-\lambda t_3),$$

so that

$$\exp(-\lambda t_3)=[\exp(-\lambda t_1)-\exp(-\lambda t_2)]/\lambda(t_2-t_1)$$

and

$$t_3-t_1=(1/\lambda)\ln\{(t_2-t_1)/1-\exp\lambda(t_2-t_1)\}$$

may be used to find the time at which the observed rate is equal to the true rate.

After the above corrections are made and background and activities due to previous bombardments are subtracted, the activity induced in the manganese can be extrapolated back to the time at which the bombardment ended. If the bombardment was constant, this will give a number which is proportional to

$$(K/\lambda)[1-\exp(\lambda T)],$$

where K is the rate of production of neutrons, λ is the decay constant of the manganese, and T is the bombardment time. Since in these experiments only the activity induced in the manganese is used and the physical arrangement remained the same, if the observed activities at the end of bombardment are divided by $[1-\exp(-\lambda T)]$, the number obtained is proportional to the rate of production of neutrons. If the bombardment was not constant, the activity produced at the end of bombardment will be proportional to

$$(K/\lambda)[1-\exp(-\lambda T)]+\exp(-\lambda T)\int_0^T f(t)\exp(\lambda t)dt,$$

where $f(t)$ is the fluctuation from the average rate, K, of production of neutrons and $\langle f(t)\rangle_{Av}=0$. This additional term is estimated to be less than 2 percent of the total activity in the present experiments, and agreement between different bombardments of the same target confirm this. If the fraction of neutrons absorbed in the manganese is the same for the Ra-Be source as for the (d,n) source, the ratio of the two yields for a bombardment time long compared with $1/\lambda$ is equal to the equivalent number of Kg of Ra-Be per microampere and, knowing the number of neutrons per second emitted by the Ra-Be source, one can determine the number of neutrons per second per microampere emitted from the (d,n) reaction.

In order to check the assumption that the fraction of neutrons absorbed in the manganese is the same for the Ra-Be source as for the (d,n) sources, a number of checks were made:

(1) When the level of manganese solution in the tank was lowered and the yield redetermined from a Be target, no change in the yield was noted.

(2) In order to check whether differential absorption was occurring because of the difference in angular distribution of neutrons from the Ra-Be and (d,n) sources, the position of the sources in the tank of manganese solution was changed in the direction of the incident deuteron beam so that the hole in the tank in the straight through position subtended a larger angle at the target. Although, when the sources were placed sufficiently near the exit hole, a decrease in manganese activity was noted, for each the ratio remained constant within experimental error, indicating that no errors were arising from this source. This point was checked further by using a Lucite plug which completely filled the last one-half of the tube through the tank and redetermining the yield from a Be target; again no change in yield was noted.

All targets were thick compared with the range of the deuterons and, except in the case of boron, were composed of reagent grade material. To get the yield from boron, a quantity of granular boron carbide was packed into a cavity in a brass block and bonded together with a very dilute solution of collodion in acetone. The yield from boron is determined when the yield from carbon and the atomic stopping power of boron and carbon are known.

EXPERIMENTAL RESULTS

A preliminary report[5] of some of these data was given previously. Table I shows a summary of the results expressed in kg Ra-Be equivalent per microampere and neutrons per second per microampere.

The asterisks indicate values which were determined by using a target in the main cyclotron target box and detecting the neutrons by means of a gold foil imbedded in paraffin. These values were normalized to the values

[5] L. W. Smith and P. G. Kruger, Phys. Rev. 74, 1258(A) (1948).

TABLE I. Summary of data of neutron yields from the (d,n) reaction in thick targets.

Target	Z	kg Ra-Be equivalent	n/μa sec (10^{-10})
Be	4	2.66	3.23 ±0.24
B	5	1.58	1.91 ±0.14
C	6	0.98	1.19 ±0.22
Al	13	0.72	0.87 ±0.07
P*	15	0.86	1.05 ±0.31
Mn*	25	0.63	0.76 ±0.22
Ni	28	0.26	0.33 ±0.03
Cu	29	0.45	0.55 ±0.05
Mo	42	0.35	0.42 ±0.05
Sb*	51	0.28	0.35 ±0.10
Ta	73	0.062	0.074±0.014
W	74	0.058	0.070±0.005
Pt	78	0.050	0.060±0.008
Au	79	0.039	0.047±0.006

for Be and W targets obtained from the manganese tank detection method after subtracting the continuous neutron background which exists inside the shielding tanks around the cyclotron. This continuous background is approximately 0.4×10^{10} neutrons/second/microampere near the main cyclotron target.

DISCUSSION

There is not much data available for comparison with the above results. In the case of Be, one can extrapolate the low energy data of Amaldi, Hafstad, and Tuve,[6] assuming a Gamow potential and taking into account the increase of range with energy. The result is 3×10^{10} neutrons/sec/μa, and the agreement is probably fortuitous. Lawrence and Cooksey[7] report a yield, with 5-Mev deuterons, of approximately 30×10^{10} neutrons/sec/μa. This value is considerably higher than would be expected from the present data. More recent measurements by Aebersold[8] with an ionization chamber indicate a neutron yield at 8 Mev of 2.38×10^{3} curies of Rn-Be equivalent per microampere. This is in reasonable agreement with the present results although, since the results of Aebersold are for neutrons in the forward direction, his value should be somewhat high. Fermi[9] estimates the yield at 8 Mev to be 10^{10} neutrons/second/microampere.

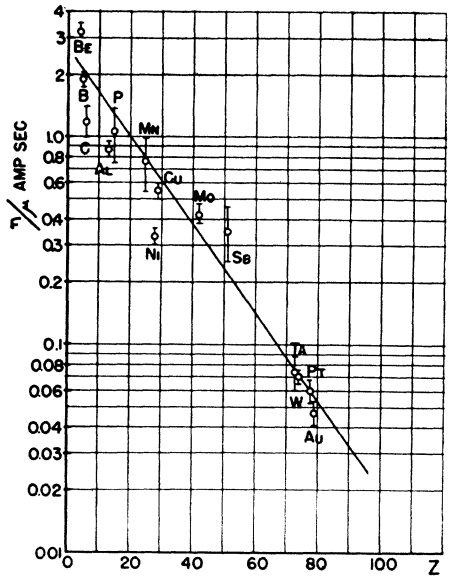

FIG. 3. Neutron yield, showing the number of neutrons per microampere sec($\times10^{-10}$), *vs* Z.

In the case of carbon, the extrapolation of Amaldi, Hafstad, and Tuve's data gives 0.3×10^{10} neutrons/sec/μa. The agreement is not too bad considering the errors which are introduced in such an extrapolation.

Allen *et al.*[10] have reported the fast neutron yield and angular distribution of various thick targets bombarded with 15-Mev deuterons. They find the yield per second per microampere, N, to decrease with nuclear charge, Z, of the target according to the approximate empirical equation,

$$\log N = 10.18 - 0.0234Z.$$

As shown in Fig. 3, the present data also may be approximated by a curve of the same general nature, although there are deviations as large as a factor of two.

[6] Amaldi, Hafstad, and Tuve, Phys. Rev. **51**, 896 (1937).
[7] E. O. Lawrence and D. Cooksey, Phys. Rev. **50**, 1131 (1936).
[8] P. C. Aebersold and G. A. Anslow, Phys. Rev. **69**, 1 (1946).
[9] E. Fermi, "Neutron physics," MDDC-320 (1946), unpublished.
[10] Allen, Nechaj, Sun, and Jennings, NP-1507 (1950), unpublished.