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A COMPARISON OF THE NEUTRON YIELDS FROM
LOW-VOLTAGE SOURCES

John N. Cooper

ABSTRACT

The ratio of the thick-target neutron yields from the $D(t,n)He^4$ and the $D(d,n)He^3$ reactions is calculated as a function of the energy of the bombarding particles. For 60-kev particles the ratio is 108. It increases to 168 at 100 kev and to 194 for 120-kev particles.

A qualitative discussion of the yields from various deuterium targets leads to the conclusion that the greatest yield would come from the target which has the lowest stopping cross section per deuterium atom.

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A COMPARISON OF THE NEUTRON YIELDS FROM LOW-VOLTAGE SOURCES

INTRODUCTION

For many years the standard way to obtain monoergic neutrons has involved the use of a Van de Graaff generator, cyclotron, or other accelerator to produce a beam of protons, deuterons, or alpha particles which fall on a target and induce a neutron-emitting reaction. In recent years tritons have been added to the list of projectiles. All (p,n) reactions on stable nuclei are endothermic and the energy of the bombarding protons must be in excess of one Mev. On the other hand, (d,n) and (t,n) reactions are commonly exoergic, sometimes with Q's of 10 Mev or more. Some (α ,n) reactions are also exoergic, but the penetration of the Coulomb barrier requires alpha energies in the Mev region to produce substantial yields.

For a neutron source designed to operate at low voltage (~ 100 kev) the bombarding particles must be either deuterons or tritons. Further, the target nuclei must have a low atomic number if the incident particles are to have a reasonable probability of penetrating the Coulomb barrier. Deuterons and tritons are the only target nuclei which promise large yields.

The triton is an unstable nucleus which decays to He^3 with a half-life of 12 years. This disadvantage, and the relative scarcity of tritium suggest the choice of deuterons as the target nuclei. This leaves two reactions, $\text{D}(t,n)\text{He}^4$ and $\text{D}(d,n)\text{He}^3$ to be considered. The first reaction provides a more copious neutron yield, but it has the disadvantage that it uses unstable tritons.

Since tritium and deuterium are chemically equivalent it should be possible to produce two neutron sources identical except that one accelerates tritons and the other deuterons. The question which this paper endeavors to answer is, "If two sources are identical except that tritons are accelerated in one and deuterons in the other, how does the neutron yield of the triton-accelerating source compare with that of the deuteron-accelerating source?" Current literature contains sufficient information so that this question can be answered with an accuracy of perhaps 20 per cent.

THE RELATIVE THICK-TARGET YIELDS FOR THE $\text{D}(t,n)$ AND $\text{D}(d,n)$ REACTIONS

The yield from the $\text{D}(t,n)$ reaction for a thick target of deuterium ice has been measured by Bretscher and French¹ for triton bombarding energies between 15 and 127 kev. The comparable thick-target yield from the $\text{D}(d,n)$ reaction can be calculated from the measurements of Bretscher, French, and Seidl² on the yield of protons from the $\text{D}(d,p)\text{T}$ reaction. The ratio of the cross sections of the $\text{D}(d,n)$ and $\text{D}(d,p)$ reactions varies from 0.94 at 20 kev to 0.99 at 100 kev. If this information is combined with the yield from the $\text{D}(d,p)$ reaction, one can compute the yield from the $\text{D}(d,n)$ reaction. In Table I the yields from thick

targets of D_2O are shown as reported in References 1 and 2 and the ratio of the yields from the $D(t, n)$ and $D(d, n)$ reactions are calculated. In the table, N represents the thick-target yield per microcoulomb of incident particles, and R is the ratio of the thick-target yields from the $D(t, n)$ and $D(d, n)$ reactions.

Table I

Thick-Target Yields from Deuterium Ice

Bombarding energy (kev)	$N_{D(t, n)}$ (Ref 1)	$N_{D(d, p)}$ (Ref 2)	$N_{D(d, n)}$ calculated	R ratio: $N_{D(t, n)}/N_{D(d, n)}$
79.2	14.9×10^6	0.232×10^6	0.225×10^6	66
95.0	27.5×10^6	0.385×10^6	0.377×10^6	73
105.6	40.1×10^6	0.478×10^6	0.473×10^6	85

These early data suggest that the ratio of the thick-target yields for the $D(t, n)$ and the $D(d, n)$ reactions should be approximately 80 for an applied voltage of 100 kv. Although the absolute yields will be different for deuterium targets of different chemical composition, the ratio of the yields should not vary greatly.

Unfortunately, recent data indicate that the yield for the $D(d, p)$ reaction is too high,² while the yield from the $D(t, n)$ reaction is too low,¹ even though the measurements were made with the same equipment and general procedure. Wenzel and Whaling⁴ found thick-target yields from D_2O ice to be 25 per cent less than those reported in Reference 2, while Argo, Taschek, Agnew, Hemmendinger, and Leland⁵ found cross sections for the $D(t, n)$ reaction to be appreciably greater than those of Reference 1. The data on the $T(d, n)$ and $D(d, n)$ reactions reported in Reference 3 can be shown to be in excellent agreement with References 4 and 5, so it appears that the correct values of the critical ratio R must be substantially greater than those listed in Table I.

Since the best data currently available are in the form of cross sections rather than thick-target yields, it appears that the most accurate value of the ratio of thick-target yields can be obtained as follows:

The thick-target yield from both the $D(d, n)$ and the $D(t, n)$ reactions should be given by equations of the form

$$Y = a \int_0^{E_m} \frac{\sigma(E)dE}{\epsilon(E)} \quad (1)$$

where Y is the yield, a is a constant, σ is the cross section for the appropriate reaction, E the energy and E_m the maximum energy of the incident particles, and ϵ is the stopping

cross section* per deuterium atom in the target for the incident particles of energy E. The ratio R of the yields of the D(t, n) and the D(d, n) reactions will be given by the expression

$$R = \frac{Y_{D(t, n)}}{Y_{D(d, n)}} = \frac{\int_0^{E_m} \frac{\sigma_{D(t, n)} dE}{\epsilon_t}}{\int_0^{E_m} \frac{\sigma_{D(d, n)} dE}{\epsilon_d}} \quad (2)$$

This ratio can be evaluated if the required cross sections are available as a function of energy. The energy range from 0 to 120 kev is of primary interest in this paper.

The cross section for the reaction D(d, n) has been measured by Arnold, Phillips, Sawyer, Stovall, and Tuck.³ Their experimental values are shown in column 2 of Table II.

Data on the cross section of the D(t, n) reaction for 80 to 1200 kev tritons have been published by Argo, Taschek, Agnew, Hemmendinger, and Leland.⁵ A reasonably accurate prediction of the thick-target yield from this reaction requires a knowledge of the cross section at lower triton energies. Unfortunately, acceptable measurements have not been reported in the literature. However, it is possible to calculate the D(t, n) cross section from data on the T(d, n) reaction reported in Reference 3. Since the same particles are interacting, it is only necessary to separate the energy associated with the motion of the center of mass from the energy available for the reaction in the T(d, n) reaction. Once this is done the cross section of the D(t, n) reaction can be computed.

When a particle of mass m bombards a particle of mass M at rest, the fraction $m/(M + m)$ of the kinetic energy of the incident particle is associated with the kinetic energy of the center of mass of the system, while the fraction $M/(M + m)$ of the incident kinetic energy is available for the nuclear reaction. It follows immediately that when tritons fall on deuterons only 2/5 of the triton energy is available for the reaction, while when deuterons fall on tritons, 3/5 of the deuteron energy is available. Therefore, when tritons of energy E fall on deuterons at rest, the cross section should be exactly the same as when deuterons of energy 0.667 E fall on tritons at rest. The cross section of the D(t, n) reaction for tritons of energy E can thus be found by taking the cross section of the T(d, n) reaction for deuterons of energy 0.667 E. Column 3 of Table II lists the T(d, n) reaction cross sections as measured by Arnold et al³ at Los Alamos, and column 4

* $\epsilon = \frac{1}{n} \frac{dE}{dx}$, where n is the number of target deuterons per unit volume and x is the distance of penetration into the target.

Table II

Cross Sections for the D(d, n) and D(T, n) Reactions

Energy of bombarding particle (kev)	Cross Sections, σ in Barns				$\frac{\sigma_{D(t, n)}}{\sigma_{D(d, n)}}$
	D(d, n) (Ref 3)	T(d, n) (Ref 3)	D(t, n) Calculated	D(t, n) (Ref 5)	
9		0.000939			
13	0.0000329	0.00780	0.0008		.24
19	0.000200	0.0448	0.0070		35
22	0.000367	0.0859	0.015		41
25	0.000592	0.144	0.027		46
30	0.00108	0.278	0.057		53
33	0.00146	0.394	0.0859		59
36	0.00188	0.519	0.125		66
40	0.00243	0.723	0.180		80
46	0.00342	1.11	0.304		89
53	0.00478	1.62	0.498		104
60	0.00625	2.18	0.723		116
67	0.00786	2.82	1.01		128
73	0.00930	3.36	1.31		141
80	0.0109	3.93	1.64	1.76	150
87	-----	-----	-----	2.21	--
93	0.0136	4.74	2.35		173
96	-----	-----	-----	2.62	--
100	0.0152	4.90	2.78		183
104	-----	-----	-----	3.11	--
107	0.0166	4.95	3.20		193
110	0.0170	4.95	3.38		199
113	0.0174	4.94	3.56		204
114	-----	-----	-----	3.67	--
120		4.70	3.93		
124	-----	-----	-----	4.13	

gives the cross section of the $D(t, n)$ cross section calculated from the data in column 3. A rough check on the accuracy of these assumptions is possible for the higher energies in that the cross sections for the $D(t, n)$ reaction as measured by Argo et al⁵ are available above 80 kev bombarding energy. These cross sections are listed in column 5. The last column of Table II lists the ratio of the $D(t, n)$ cross section to the $D(d, n)$ cross section as found by taking the ratio of the numbers in column 4 to those in column 2.

The stopping cross sections for deuterons and tritons in practical target materials have not been reported. Nevertheless, it is possible to estimate the relative stopping cross sections with moderate accuracy (probably better than 20 per cent). The stopping cross section of a given material for various bombarding particles depends only on the charge and the velocity of the bombarding particle, since this cross section is determined almost entirely by the interactions between the charge on the bombarding particle and the electrons of the stopping material. Therefore identical stopping cross sections are expected for protons, deuterons, and tritons of the same velocity. The stopping cross section for 50-kev protons should be the same as that for 100-kev deuterons and for 150-kev tritons.

The curve of stopping power as a function of energy for any sort of incident-charged particle and stopping material shows an approximate $E^{1/2}$ rise in the low-energy region, a maximum at some intermediate energy, and a gradual decrease in stopping power as higher energies are reached. For the region under consideration here (deuterons and tritons of 120 kev and less), the stopping power obeys the $E^{1/2}$ law moderately well. Wenzel and Whaling⁶ have measured the stopping cross section of deuterium ice for protons. Their data are reproduced in Table III along with the ratio of the stopping cross section to the square root of the proton energy. The last two columns of the table show

Table III
The Stopping Cross Section of D_2O for Protons
(Reference 6)

Proton energy E_p (kev)	$\epsilon \times 10^{-15}$ (ev - cm ²)	$\frac{\epsilon \times 10^{-15}}{\sqrt{E_p}}$	Deuteron energy (kev)	Triton energy (kev)
18	15.6	3.7	36	54
20	17.4	3.9	40	60
30	20.4	3.7	60	90
40	22.6	3.6	80	120
50	23.5	3.3	100	150
60	24.0	3.1	120	180
70	24.1	2.9	140	210
80	24.0	2.7	160	240

the corresponding deuteron and triton energies at which these particles have the same velocities as the protons. It is seen that for protons up to about 50 kev, deuterons up to 100 kev, and tritons up to 150 kev, the stopping cross section is roughly proportional to the square root of the energy of the incident particle.

Arnold, Phillips et al³ have measured the relative stopping power of silicon monoxide foil as a function of deuteron energy. Their data are shown in Table IV along with calculations of the ratio of the loss to the square root of the energy. Once again it is found that over the region from 0 to 100 kev the stopping cross section varies approximately as $E^{1/2}$.

Table IV
Relative Stopping Power of SiO Foil for Deuterons³

Deuteron energy E_d (kev)	Energy loss in foil (from curve) (volts)	Loss/ $\sqrt{E_d}$	Corresponding triton energy
10	2500	790	15
20	4000	895	30
30	4800	875	45
40	5300	837	60
50	6000	845	75
60	6400	825	90
70	6800	813	105
80	7100	795	120
90	7300	769	135
100	7500	750	150
110	7700	735	165
120	7850	715	180

Since the energy regions under consideration are those in which the stopping cross sections are proportional to the square root of the energy, it is possible

to write for protons $\epsilon_p = k_p E_p^{1/2}$, for deuterons $\epsilon_d = k_d E_d^{1/2}$, and for tritons

$\epsilon_t = k_t E_t^{1/2}$. If the velocity rather than the energy is made the independent

variable, these equations may be rewritten in the form $\epsilon_p = k_p v_p \sqrt{m_p/2}$,

$\epsilon_d = k_d v_d \sqrt{m_d/2}$, and $\epsilon_t = k_t v_t \sqrt{m_t/2}$. The stopping cross sections are the

same for all these particles when the velocities are the same. If v_d is equal to

v_p , ϵ_d is equal to ϵ_p , and $k_d \sqrt{m_d} = k_p \sqrt{m_p}$. Therefore, $k_d = k_p / \sqrt{2}$.

Similarly $k_t = k_p / \sqrt{3}$.

Equation 2 can now be written in the form

$$R = \frac{Y_{D(t,n)}}{Y_{D(d,n)}} = \frac{\int_0^{E_m} \frac{\sqrt{3} \sigma_{D(t,n)} dE}{k_p E^{1/2}}}{\int_0^{E_m} \frac{\sqrt{2} \sigma_{D(d,n)} dE}{k_p E^{1/2}}} = \frac{\int_0^{E_m} \sqrt{3} \sigma_{D(t,n)} E^{-1/2} dE}{\int_0^{E_m} \sqrt{2} \sigma_{D(d,n)} E^{-1/2} dE} \quad (3)$$

The integrands of Equation 3 were calculated from the data of Table II and are shown in Table V. The integrations, which give the relative yields for thick targets, were performed graphically for a series of values of E_m . The relative yields are listed as a function of the energy of the bombarding particles in Table V and are plotted in Fig. 1.

Table V

Ratio of Thick-Target Yields for the $D(t,n)$ and $D(d,n)$ Reactions

Energy of bombarding particle, E_m (kev)	$\int_0^{E_m} \frac{\sqrt{3} \sigma_{D(t,n)} dE}{E^{1/2}}$	$\int_0^{E_m} \frac{\sqrt{2} \sigma_{D(d,n)} dE}{D E^{1/2}}$	Ratio of thick-target yields, R
25	0.047	0.00086	49
30	0.115	0.00205	56
33	0.181	0.00301	60
36	0.274	0.00421	65
40	0.445	0.00619	72
46	0.820	0.00995	82
53	1.51	0.0158	96
60	2.49	0.0230	108
67	3.80	0.0318	119
73	5.23	0.0405	129
80	7.25	0.0519	140
93	12.1	0.0761	159
100	15.2	0.0906	168
107	18.8	0.106	177
110	20.4	0.113	181
113	22.2	0.120	185
120	26.4	0.136	194

The last column of Table V shows R, the ratio of the thick-target yields from the $D(t,n)$ and $D(d,n)$ reactions. The values are plotted in Fig. 2. It is seen

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FIG. 1 THE RELATIVE THICK-TARGET NEUTRON YIELDS FROM THE $D(d,n)$ AND $D(t,n)$ REACTIONS AS A FUNCTION OF THE ENERGY OF THE BOMBARDING PARTICLES

FIG. 2 THE RATIO R OF THE THICK-TARGET NEUTRON YIELD FROM THE $D(t,n)$ REACTION TO THAT FROM THE $D(d,n)$ REACTION AS A FUNCTION OF THE ENERGY OF THE BOMBARDING PARTICLES

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that for 100-kev bombarding particles R is approximately 170. The principal reason that the ratio in question increases as the bombarding energy is raised is that the reaction $D(t, n)He^4$ has a broad resonance near 165 kev,⁵ while the $D(d, n)He^3$ reaction has no resonances in this region.

The most questionable assumption involved in the calculations above is that the stopping power follows the $E^{1/2}$ function. For some target materials this assumption will introduce a negligible error, but for other target materials it may contribute a substantial error.

Any thin layer of foreign material on the target surface will lower the yields substantially since it will reduce the effective energy of the bombarding particles. Further, it will lower the yield for bombarding deuterons much more than for tritons, since deuterons of a given energy lose more energy in passing through a thin layer than do tritons of the same original energy. For the low bombarding energies under consideration the incident particles are all stopped in a very short distance and the utmost care must be taken to avoid any surface contamination on the target.

OTHER CONSIDERATIONS

The neutron yield from a thick target is inversely proportional to the stopping cross section per target deuteron. Deuterium ice is clearly a good target material, but ideally a thick target which is solid at ordinary temperatures would be preferred. The deuterides of very light elements are obvious possibilities, since the atomic stopping power of any element is roughly proportional to $Z^{1/2}$. Lithium deuteride is a promising compound, although one would prefer a substance having a larger ratio of deuterons to other atoms.

Further consideration of LiD targets reveals the possibility that a few additional neutrons may be produced by reactions involving the Li nuclei. The highly exoergic ($Q = 15$ Mev) $Li^7(d, n)Be^8$ reaction is a copious fast-neutron source for deuterons with energies in the Mev region. For 100-kev deuterons its contribution will be small* compared to that from the $D(d, n)$ reaction, but by no means negligible. Phillips⁷ has measured the cross section for the $Li(d, n)Be^8$ reaction.

* At very low bombarding energies, where resonances may be neglected, the dominant term in the expression for the cross section is determined by the probability of penetrating the Coulomb barrier. For target nuclei of atomic number Z and bombarding particles of charge z , the barrier term involves e^{-G} , where $G = \frac{1}{2} 4\pi^2 Zze^2 / hv$ and v is the velocity of the bombarding particle. For the $D(d, n)$ reaction at 100 kev $G \sim 4.44$, while for the $Li^7(d, n)$ reaction $G \sim 13.3$. The penetration factor for the Li reaction is $e^{-8.9} \sim 10^{-4}$ of that for the $D(d, p)$ and $D(d, n)$ reactions.

At 40 kev this cross section is about 1.6×10^{-4} times that of the total DD cross section. At 100 kev the factor has increased to 0.016. Since only half of the DD reactions break up with the emission of a neutron, the cross section of the $\text{Li}(d, n)$ reaction is about three per cent of the cross section for the $\text{D}(d, n)$ reaction at 100 kev. The $\text{Li}^7(p, \gamma)\text{Be}^8$ reaction, excited by protons from the $\text{D}(d, p)\text{T}$ reaction, is a secondary process which might produce a few photoneutrons and photofissions as well as yielding high-energy tritons. Still other neutron yielding reactions are possible in the lithium, and the over-all contribution from the lithium transmutations would probably be between two and five per cent of the neutron yield from the $\text{D}(d, n)$ reaction for 100-kev deuterons falling on thick LiD targets.

In addition to the simple cross section for neutron production, one must consider certain other features of the $\text{D}(t, n)$ and $\text{D}(d, n)$ reactions which have bearing on their relative usefulness. Slightly over half of the excited He^4 nuclei produced by deuteron capture in deuterium decay to protons and tritons. These tritons, though not very numerous, might interact to contribute a few more neutrons. The energy release from the $\text{D}(t, n)$ reaction is substantially greater ($Q = 17.6$ Mev) than that of the $\text{D}(d, n)$ reaction ($Q = 3.3$ Mev). Consequently, the neutrons from the triton reaction have far greater velocities. Whether or not this is an advantage is an open question. Further study could give a definitive answer.

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