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ANISOTROPY FACTORS FOR THE DETERMINATION OF TOTAL NEUTRON YIELD FROM THE $D(d,n)\ He^3$ AND $T(d,n)\ He^4$ Reactions

Berkeley, California

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Lawrence Ruby and Richard B. Crawford

April 9, 1963

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Please make the following corrections on subject report.

Table 2, at 475 keV and 150 deg., R_{thin} is 1.4913 instead of 1.2603.

Table 3, at 275 keV and 180 deg., R_{thin} is 0.7918 instead of 0.9718.

ANISOTROPY FACTORS FOR THE DETERMINATION OF TOTAL NEUTRON YIELD FROM THE $D(d,n)He^3$ AND $T(d,n)He^4$ REACTIONS

Lawrence Ruby and Richard B. Crawford

Lawrence Radiation Laboratory
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Berkeley, California

April 9, 1963

ABSTRACT

Tables have been computed of the anisotropy factor, R, which is useful in determining, by the associated particle method, the total neutron yield produced in the reactions $T(d,n)He^4$ and $D(d,n)He^3$. The range of incident deuteron energy covered is 25 to 500 keV, at associated particle colatitude angles of 90 to 180 deg. Thick-and thin-target cases have been treated. For the $T(d,n)He^4$ reaction, the total neutrons produced per alpha particle incident on the detector is given by the relation, $N = (4\pi/\Delta\Omega)R$. In the case of the $D(d,n)He^3$ reaction, it is more convenient to detect the protons produced in the competing reaction D(d, p)T. The total neutrons per proton incident on the detector is then given by $N = (4\pi/\Delta\Omega)R(Y_{d,n}/Y_{d,p})$, where $(Y_{d,n}/Y_{d,p})$ is the ratio of total neutrons to total protons produced. Tables of this ratio, of R, and of their product are given.

ANISOTROPY FACTORS FOR THE DETERMINATION OF TOTAL NEUTRON YIELD FROM THE $D(d, n)He^3$ AND $T(d, n)He^4$ REACTIONS†

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April 9, 1963

INTRODUCTION

The determination of neutron-source strength by the associated particle method, where possible, constitutes one of the most accurate methods of neutron-source calibration[1]. The method, in the case of the $T(d, n)He^4$ reaction, consists in measuring the number of alpha particles incident on a detector placed at an angle Φ to the incident deuteron direction, and subtending a solid angle $\Delta\Omega$ at the neutron-producing target. Then, the total number of neutrons being produced in the target per alpha particle incident on the detector is given by the relation, $N = (4\pi/\Delta\Omega)R$, where R is an anisotropy factor whose value depends on Φ and on the incident-deuteron energy. We have computed R for a variety of deuteron energies from 25 to 500 keV, for angles Φ from 90 to 180 deg, and for both thin and thick targets.

For the $D(d, n)He^3$ reaction, it is more convenient to measure the protons associated with the competing $D(d, p)T$ reaction. Therefore, we have computed the anisotropy factor R for the latter reaction. The total neutrons per proton incident on a detector that subtends a solid angle $\Delta\Omega$ is given by the expression $N = (4\pi/\Delta\Omega)R(Y_{d,n}/Y_{d,p})$, where $(Y_{d,n}/Y_{d,p})$ is the ratio of the total neutron yield to the total proton yield. We have computed R for the $D(d, p)T$ reaction versus the same energy, angle, and target-thickness parameters, as well as the product, $R(Y_{d,n}/Y_{d,p})$, for both thick and thin targets.

Information on the number of neutrons emitted into a given solid angle, per alpha particle incident on the detector, is available elsewhere[2].

METHOD

The calculations herein are an extension of the work of Benveniste and Zenger, who calculated R for the $T(d, n)He^4$ reaction at an angle of 135 deg, in the thick-target case[3]. The derivation for the quantity N which is given in the Appendix, is essentially that given by Benveniste and Zenger. In addition, we have used the same data as they for the deuteron energy loss in titanium and hydrogen, and the same assumption for the target-loading ratio--namely, Ti:H = 1:1. For the $D(d, p)T$ reaction, conflicting data exist as to the cross section and the ratio $\sigma_{d,n}/\sigma_{d,p}$. We have chosen to use the data given by J. L. Tuck[4], and have interpolated between his points

for the $T(d, n)He^4$, the $D(d, n)He^3$, and $D(d, p)T$ cross sections (see Table 1).

In accordance with experimental evidence, we have assumed the $T(d, n)He^4$ reaction to be isotropic in the center-of-mass (c.m.) system, thus giving

$$\frac{d\sigma}{d\omega'} = \frac{\sigma}{4\pi} .$$

However, the $D(d, p)T$ reaction is markedly anisotropic in the c.m. system, and we have assumed a dependence of the type

$$\frac{d\sigma(\theta)}{d\omega'} = \frac{d\sigma(90\text{ deg})}{d\omega'}[1 + A\cos^2\theta + B\cos^4\theta] \approx \frac{d\sigma(90\text{ deg})}{d\omega'}[1 + (A+B)\cos^2\theta],$$

where the constant $(A + B)$ has been taken from the data of Preston et al.[5]). Using the data given in Table 1 for the total cross section, we have calculated, the differential cross section at 90 deg according to the relation

$$\frac{d\sigma(90\text{ deg})}{d\omega'} = \frac{\sigma}{\int[1 + (A+B)\cos^2\theta]\, d\omega'} = \frac{\sigma}{4\pi[1 + (A+B)/3]} .$$

COMMENTS

Values of R shown in Tables 2 and 3 have been computed to five significant figures. However, in practice, uncertainties in cross sections, target-loading ratio, and uniformity of target loading limit the accuracy to a few percent. For example, the target-loading ratio can have any value from 0:1 to 1.8:1.

Although the calculations apply to a titanium target, to a first approximation the results are independent of the particular hydrogen-occluding metal used. This follows from the fact that, for the occluding metal, the product $A[dE/d(\rho x)]$ occurs. To a first approximation, this product is independent of Z because A is roughly equal to 2Z, and, according to the data cited by Benveniste and Zenger[3]), $dE/d(\rho x)$ is inversely proportional to Z for the metals with higher Z than copper.

As Benveniste and Zenger pointed out, and as can be seen from Table 2, R for the $T(d, n)He^4$ reaction at 90 deg for a thick target, is very nearly independent of target-loading conditions. This is because, at 90 deg, $d\omega'/d\omega$ (the reciprocal of R for a thin target) is a very slowly varying function of energy, and can, therefore, be taken outside the integral. Thus, at 90 deg, R for a thick target is approximately $(d\omega/d\omega')_{average}$, where the

averaging is done over the energy interval 0 to E_1. At this angle, then, both the minimum and most accurate value of R results. Of course, the value of R for a thin target is also independent of target-loading conditions, but the utilization of sufficiently thin targets presents experimental difficulties.

APPENDIX

The following derivation resembles closely that of Benveniste and Zenger. Subscripts 1, 2, 3, and 4 are used to distinguish between the mass, energy, velocity etc., of the deuteron, triton, alpha particle, and neutron, respectively. Ordinary capital letters designate velocities or energies in the laboratory (lab) system of coordinates, while primed letters refer to the c. m. system.

The relation between the differential solid angle, $d\omega'$, occupied by the alpha particles in the c. m. system, and the corresponding value, $d\omega$, in the lab system, is given by[6]

$$\left(\frac{d\omega'}{d\omega}\right)_a = \frac{\sin\theta\, d\theta}{\sin\Phi\, d\Phi} = \frac{J\left\{\cos\Phi + \left[\left(\frac{J^2 + L}{J^2}\right) - \sin^2\Phi\right]^{1/2}\right\}^2}{\left(E_3'\right)^{1/2}\left[\left(\frac{J^2 + L}{J^2}\right) - \sin^2\Phi\right]^{1/2}} \tag{1}$$

where

$$J = \frac{(m_1 m_3 E_1)^{1/2}}{m_3 + m_4} \tag{2a}$$

and

$$L \equiv \frac{m_4(Q + E_1) - m_1 E_1}{m_3 + m_4} . \tag{2b}$$

Here, $(d\omega'/d\omega)_a$ is the rate of change of the c. m. solid angle to the lab solid angle. For a detector subtending a very small solid angle at the target, $(d\omega'/d\omega)_a$ is essentially constant over the included interval. In addition, $(d\omega'/d\omega)_a$ is the ratio of alpha particles per unit solid angle in the lab system to that in the c. m. system for a given angle and energy:

$$\frac{d\omega'}{d\omega} = \frac{N_a(\omega_a, E)}{N'_a(\omega'_a, E)} .$$

Therefore we have

$$N_a(\omega_a, E)\ \Delta\Omega_a = N'_a(\omega'_a, E) \left(\frac{d\omega'}{d\omega}\right)_{a,\,E} \Delta\Omega_a\ , \tag{3}$$

and similarly,

$$N_n(\omega_n, E)\ \Delta\Omega_n = N'_n(\omega'_n, E) \left(\frac{d\omega'}{d\omega}\right)_{n,\,E} \Delta\Omega_n\ . \tag{4}$$

But for energies at which the $T(d, n)He^4$ reaction yields neutrons isotropically in the c.m. system (up to 600 keV), we have $N'_n(\omega'_n E) = N'_a(\omega'_a E) = K(E)$.

The number of reactions per unit solid angle attributable to deuterons of energy between E and $(E + dE)$ is

$$K(E)\, dE = \eta_d \eta_t\, dx\, \frac{d\sigma}{d\omega}(E), \tag{5a}$$

or

$$K(E) = \frac{\eta_d \eta_t \frac{d\sigma}{d\omega}(E)}{\frac{dE}{dx}(E)}\ . \tag{5b}$$

We assume that neither the number of incident deuterons nor the number of tritons changes with depth in the target, i.e., with decreasing energy. Substituting Eq. (5) into (3) and (4), one can form the ratio of neutrons into a given (large) solid angle to alphas into another (small) solid angle:

$$\frac{N_n \Delta\Omega_n}{N_a \Delta\Omega_a} = \frac{\displaystyle\int_E \frac{\frac{d\sigma}{d\omega'}(E)}{\frac{dE}{dx}(E)} \int_{\Delta\Omega_n} \left(\frac{d\omega'}{d\omega}\right)_n d\omega_n\, dE}{\Delta\Omega_a \displaystyle\int_E \frac{\frac{d\sigma}{d\omega'}(E)}{\frac{dE}{dx}(E)} \left(\frac{d\omega'}{d\omega}\right)_a dE}\ . \tag{6}$$

When $\Delta\Omega_n$ is increased to 4π, the left side becomes the total neutron production per alpha particle, N:

$$N = \frac{4\pi}{\Delta\Omega_a} \frac{\int_0^E \frac{\sigma}{4\pi} \frac{dE}{dx}\, dE}{\int_0^E \frac{d\sigma}{d\omega'} \frac{dE}{dx} \left(\frac{d\omega'}{d\omega}\right)_a dE} = \frac{4\pi}{\Delta\Omega_a} R_{thick} .$$

For a thin target, the expression for N reduces to

$$N = \frac{4\pi}{\Delta\Omega_a} \left(\frac{d\omega}{d\omega'}\right)_a = \frac{4\pi}{\Delta\Omega_a} R_{thin} .$$

In a thick target, the yield of neutrons from the $D(d, n)He^3$ reaction, per proton from the competing $D(d, p)T$ reaction, is given by

$$N = \frac{4\pi}{\Delta\Omega_p} \frac{\int_0^E \frac{\sigma_{d,p}}{4\pi} \frac{dE}{dx}\, dE}{\int_0^E \frac{\sigma_{d,p}}{d\omega'} \frac{dE}{dx} \left(\frac{d\omega'}{d\omega}\right)_p dE} \frac{\int_0^E \frac{\sigma_{d,n}}{4\pi} \frac{dE}{dx}\, dE}{\int_0^E \frac{\sigma_{d,p}}{4\pi} \frac{dE}{dx}\, dE} = \frac{4\pi}{\Delta\Omega_p} R_{thick} \left(\frac{Y_{d,n}}{Y_{d,p}}\right)_{thick} .$$

For a thin target, this reduces to

$$N = \frac{4\pi}{\Delta\Omega_p} \frac{\left(\frac{\sigma_{d,p}}{4\pi}\right)}{\left(\frac{d\sigma_{d,p}}{d\omega'}\right)\left(\frac{d\omega'}{d\omega}\right)} \left(\frac{\sigma_{d,n}}{\sigma_{d,p}}\right) = \frac{4\pi}{\Delta\Omega} R_{thin} \left(\frac{Y_{d,n}}{Y_{d,p}}\right)_{thin} .$$

FOOTNOTES AND REFERENCES

†This work was done under the auspices of the U. S. Atomic Energy Commission.

1. J. B. Marion and J. L. Fowler, editors, Fast Neutron Physics (Interscience, New York, N. Y., 1960), Ch. IVB.

2. John D. Seagrave, $D(d, n)He^3$ and $T(d, n)He^4$ Neutron Source Handbook, Los Alamos Scientific Laboratory Report LAMS-2162, November 1957.

3. Jack Benveniste and Jerry Zenger, Information on the Neutrons Produced in the $H^3(d, n)He^4$ Reaction, Lawrence Radiation Laboratory Report UCRL-4266, January 1954.

4. J. L. Tuck, Nucl. Fusion 1, 201 (1961).

5. G. Preston, P. F. D. Shaw, and S. A. Young, Proc. Roy. Soc. (London) 226A, 206 (1954).

6. Robley D. Evans, The Atomic Nucleus (McGraw-Hill, New York, N. Y. 1955), Ch. XII, Eq. 2.5 ff.

Table 1. Cross section used in the computations.

E_1 (keV)	$T(d, n)He^4$ (mb)	$D(d, p)H^3$ (mb)	$D(d, n)He^3$ (mb)
25	125	0.70	0.707
50	1400	4.3	4.56
75	3250	10.1	11.11
100	4350	16.5	17.8
125	4650	21.6	23.7
150	4150	25.6	29.1
175	3400	29.1	34.0
200	2725	32.3	38.4
225	2150	35.2	42.4
250	1720	38.0	46.1
275	1480	40.8	49.5
300	1320	43.4	52.8
325	1180	45.8	55.9
350	1060	48.1	58.9
375	960	50.3	61.7
400	880	52.3	64.3
425	810	54.2	66.8
450	750	55.9	69.3
475	700	57.5	71.7
500	660	59.0	74.0

Table 2. $T(d, n)He^4$ reaction.

E_1 (keV)	Φ (deg)	R_{thick}	R_{thin}	Φ (deg)	R_{thick}	R_{thin}	Φ (deg)	R_{thick}	R_{thin}
25	90	1.0006	1.0011	100	1.0088	1.0178	110	1.0169	1.0344
50	90	1.0015	1.0023	100	1.0197	1.0260	110	1.0377	1.0498
75	90	1.0024	1.0034	100	1.0260	1.0327	110	1.0496	1.0621
100	90	1.0032	1.0045	100	1.0307	1.0385	110	1.0582	1.0728
125	90	1.0038	1.0057	100	1.0343	1.0438	110	1.0650	1.0825
150	90	1.0044	1.0068	100	1.0373	1.0488	110	1.0704	1.0915
175	90	1.0050	1.0080	100	1.0397	1.0534	110	1.0747	1.1000
200	90	1.0054	1.0091	100	1.0416	1.0579	110	1.0783	1.1080
225	90	1.0058	1.0102	100	1.0433	1.0622	110	1.0812	1.1158
250	90	1.0061	1.0114	100	1.0447	1.0664	110	1.0837	1.1232
275	90	1.0064	1.0125	100	1.0459	1.0704	110	1.0860	1.1304
300	90	1.0067	1.0137	100	1.0471	1.0743	110	1.0880	1.1374
325	90	1.0070	1.0149	100	1.0482	1.0782	110	1.0900	1.1443
350	90	1.0073	1.0160	100	1.0493	1.0819	110	1.0920	1.1509
375	90	1.0076	1.0172	100	1.0503	1.0856	110	1.0938	1.1575
400	90	1.0079	1.0183	100	1.0514	1.0893	110	1.0956	1.1639
425	90	1.0082	1.0195	100	1.0523	1.0928	110	1.0973	1.1702
450	90	1.0085	1.0207	100	1.0533	1.0964	110	1.0990	1.1765
475	90	1.0087	1.0218	100	1.0542	1.0999	110	1.1006	1.1826
500	90	1.0090	1.0230	100	1.0552	1.1033	110	1.1022	1.1887
25	120	1.0245	1.0502	130	1.0314	1.0648	135	1.0345	1.0714
50	120	1.0549	1.0727	130	1.0708	1.0939	135	1.0780	1.1036
75	120	1.0724	1.0906	130	1.0934	1.1172	135	1.1030	1.1294
100	120	1.0849	1.1062	130	1.1096	1.1376	135	1.1210	1.1520
125	120	1.0947	1.1204	130	1.1224	1.1561	135	1.1352	1.1726
150	120	1.1026	1.1336	130	1.1327	1.1733	135	1.1466	1.1917
175	120	1.1089	1.1459	130	1.1409	1.1895	135	1.1557	1.2098
200	120	1.1140	1.1577	130	1.1476	1.2050	135	1.1631	1.2270
225	120	1.1183	1.1690	130	1.1531	1.2198	135	1.1692	1.2435
250	120	1.1219	1.1799	130	1.1578	1.2341	135	1.1744	1.2595
275	120	1.1252	1.1905	130	1.1620	1.2480	135	1.1791	1.2750
300	120	1.1282	1.2007	130	1.1659	1.2616	135	1.1834	1.2902
325	120	1.1311	1.2108	130	1.1697	1.2748	135	1.1876	1.3050
350	120	1.1338	1.2206	130	1.1733	1.2878	135	1.1915	1.3195
375	120	1.1365	1.2302	130	1.1767	1.3005	135	1.1953	1.3338
400	120	1.1391	1.2396	130	1.1800	1.3131	135	1.1990	1.3478
425	120	1.1415	1.2489	130	1.1832	1.3254	135	1.2026	1.3616
450	120	1.1440	1.2581	130	1.1864	1.3376	135	1.2060	1.3753
475	120	1.1463	1.2671	130	1.1894	1.3496	135	1.2094	1.3888
500	120	1.1486	1.2760	130	1.1924	1.3615	135	1.2127	1.4022

Table 2. (Continued)

E_1 (keV)	Φ (deg)	R_{thick}	R_{thin}	Φ (deg)	R_{thick}	R_{thin}	Φ (deg)	R_{thick}	R_{thin}
25	140	1.0373	1.0775	150	1.0422	1.0880	160	1.0457	1.0958
50	140	1.0847	1.1126	150	1.0961	1.1281	160	1.1046	1.1396
75	140	1.1119	1.1408	150	1.1272	1.1604	160	1.1387	1.1750
100	140	1.1316	1.1655	150	1.1497	1.1887	160	1.1633	1.2062
125	140	1.1470	1.1880	150	1.1674	1.2146	160	1.1828	1.2347
150	140	1.1595	1.2089	150	1.1817	1.2387	160	1.1984	1.2613
175	140	1.1694	1.2287	150	1.1931	1.2616	160	1.2109	1.2865
200	140	1.1775	1.2476	150	1.2024	1.2834	160	1.2211	1.3106
225	140	1.1842	1.2657	150	1.2101	1.3045	160	1.2295	1.3339
250	140	1.1899	1.2833	150	1.2166	1.3249	160	1.2367	1.3565
275	140	1.1949	1.3004	150	1.2224	1.3447	160	1.2431	1.3785
300	140	1.1997	1.3170	150	1.2279	1.3641	160	1.2491	1.4001
325	140	1.2042	1.3334	150	1.2331	1.3831	160	1.2548	1.4212
350	140	1.2085	1.3494	150	1.2380	1.4018	160	1.2603	1.4419
375	140	1.2127	1.3651	150	1.2428	1.4202	160	1.2655	1.4624
400	140	1.2167	1.3806	150	1.2474	1.4383	160	1.2705	1.4825
425	140	1.2206	1.3959	150	1.2518	1.4562	160	1.2754	1.5025
450	140	1.2243	1.4109	150	1.2561	1.4738	160	1.2801	1.5222
475	140	1.2280	1.4259	150	1.2603	1.2603	160	1.2847	1.5417
500	140	1.2316	1.4407	150	1.2644	1.5087	160	1.2892	1.5611
25	170	1.0479	1.1006	180	1.0486	1.1023			
50	170	1.1098	1.1468	180	1.1116	1.1492			
75	170	1.1457	1.1841	180	1.1481	1.1872			
100	170	1.1717	1.2170	180	1.1746	1.2207			
125	170	1.1922	1.2472	180	1.1955	1.2514			
150	170	1.2088	1.2753	180	1.2123	1.2801			
175	170	1.2220	1.3020	180	1.2257	1.3073			
200	170	1.2327	1.3276	180	1.2367	1.3334			
225	170	1.2417	1.3523	180	1.2458	1.3586			
250	170	1.2492	1.3763	180	1.2535	1.3831			
275	170	1.2560	1.3997	180	1.2604	1.4069			
300	170	1.2623	1.4226	180	1.2668	1.4303			
325	170	1.2683	1.4450	180	1.2729	1.4532			
350	170	1.2741	1.4671	180	1.2788	1.4757			
375	170	1.2796	1.4889	180	1.2844	1.4979			
400	170	1.2849	1.5104	180	1.2898	1.5199			
425	170	1.2901	1.5316	180	1.2951	1.5416			
450	170	1.2951	1.5527	180	1.3001	1.5631			
475	170	1.2999	1.5735	180	1.3051	1.5844			
500	170	1.3047	1.5942	180	1.3099	1.6056			

Table 3. D(d, p)T reaction.

E_1 (keV)	Φ (deg)	R_{thick}	$R_{thick}\left(\frac{Y_{d,n}}{Y_{d,p}}\right)_{thick}$	R_{thin}	$R_{thin}\left(\frac{Y_{d,n}}{Y_{d,p}}\right)_{thin}$	Φ (deg)	R_{thick}	$R_{thick}\left(\frac{Y_{d,n}}{Y_{d,p}}\right)_{thick}$	R_{thin}	$R_{thin}\left(\frac{Y_{d,n}}{Y_{d,p}}\right)_{thin}$
25	90	1.0853	1.0961	1.0853	1.0961	100	1.0862	1.0970	1.0862	1.0970
50	90	1.1076	1.1562	1.1187	1.1858	100	1.1079	1.1564	1.1185	1.1857
75	90	1.1300	1.2117	1.1535	1.2688	100	1.1287	1.2103	1.1504	1.2654
100	90	1.1527	1.2637	1.1880	1.3425	100	1.1492	1.2599	1.1807	1.3342
125	90	1.1744	1.3103	1.2207	1.4074	100	1.1683	1.3036	1.2085	1.3934
150	90	1.1949	1.3518	1.2530	1.4660	100	1.1860	1.3417	1.2352	1.4451
175	90	1.2145	1.3894	1.2834	1.5196	100	1.2025	1.3757	1.2596	1.4913
200	90	1.2332	1.4243	1.3119	1.5691	100	1.2180	1.4067	1.2819	1.5331
225	90	1.2514	1.4574	1.3402	1.6176	100	1.2328	1.4357	1.3033	1.5731
250	90	1.2693	1.4893	1.3681	1.6636	100	1.2470	1.4632	1.3240	1.6100
275	90	1.2869	1.5201	1.3941	1.7064	100	1.2608	1.4893	1.3428	1.6436
300	90	1.3040	1.5497	1.4167	1.7440	100	1.2740	1.5141	1.3588	1.6726
325	90	1.3204	1.5778	1.4375	1.7782	100	1.2865	1.5373	1.3730	1.6984
350	90	1.3360	1.6044	1.4550	1.8071	100	1.2981	1.5589	1.3847	1.7198
375	90	1.3504	1.6290	1.4676	1.8286	100	1.3088	1.5788	1.3929	1.7355
400	90	1.3634	1.6512	1.4739	1.8395	100	1.3183	1.5965	1.3967	1.7431
425	90	1.3749	1.6708	1.4772	1.8465	100	1.3265	1.6120	1.3985	1.7481
450	90	1.3848	1.6879	1.4774	1.8497	100	1.3336	1.6255	1.3982	1.7505
475	90	1.3932	1.7028	1.4746	1.8491	100	1.3395	1.6372	1.3959	1.7505
500	90	1.4001	1.7154	1.4688	1.8433	100	1.3444	1.6472	1.3918	1.7467
25	110	1.0723	1.0830	1.0723	1.0830	120	1.0478	1.0583	1.0478	1.0583
50	110	1.0896	1.1374	1.0981	1.1640	120	1.0589	1.1053	1.0642	1.1281
75	110	1.1054	1.1853	1.1214	1.2335	120	1.0679	1.1451	1.0766	1.1843
100	110	1.1202	1.2281	1.1423	1.2908	120	1.0755	1.1791	1.0864	1.2277
125	110	1.1334	1.2646	1.1605	1.3381	120	1.0818	1.2071	1.0943	1.2617
150	110	1.1452	1.2956	1.1772	1.3773	120	1.0871	1.2299	1.1008	1.2879
175	110	1.1559	1.3224	1.1919	1.4112	120	1.0916	1.2489	1.1061	1.3096
200	110	1.1657	1.3463	1.2048	1.4410	120	1.0955	1.2653	1.1105	1.3282
225	110	1.1748	1.3682	1.2168	1.4686	120	1.0990	1.2799	1.1142	1.3448
250	110	1.1833	1.3884	1.2278	1.4931	120	1.1020	1.2930	1.1172	1.3586
275	110	1.1914	1.4073	1.2376	1.5148	120	1.1048	1.3050	1.1198	1.3706
300	110	1.1989	1.4248	1.2456	1.5333	120	1.1073	1.3159	1.1219	1.3810
325	110	1.2059	1.4410	1.2526	1.5495	120	1.1095	1.3258	1.1237	1.3900
350	110	1.2123	1.4559	1.2582	1.5627	120	1.1114	1.3348	1.1252	1.3975
375	110	1.2181	1.4694	1.2622	1.5727	120	1.1132	1.3429	1.1266	1.4038
400	110	1.2232	1.4813	1.2642	1.5777	120	1.1149	1.3502	1.1280	1.4078
425	110	1.2276	1.4918	1.2653	1.5817	120	1.1164	1.3566	1.1294	1.4118
450	110	1.2314	1.5010	1.2656	1.5845	120	1.1178	1.3625	1.1309	1.4158
475	110	1.2346	1.5090	1.2651	1.5864	120	1.1191	1.3678	1.1324	1.4200
500	110	1.2373	1.5160	1.2638	1.5861	120	1.1204	1.3727	1.1341	1.4233

Table 3. (Continued)

E_1 (keV)	Φ (deg)	R_{thick}	$R_{thick}\left(\frac{Y_{d,n}}{Y_{d,p}}\right)_{thick}$	R_{thin}	$R_{thin}\left(\frac{Y_{d,n}}{Y_{d,p}}\right)_{thin}$	Φ (deg)	R_{thick}	$R_{thick}\left(\frac{Y_{d,n}}{Y_{d,p}}\right)_{thick}$	R_{thin}	$R_{thin}\left(\frac{Y_{d,n}}{Y_{d,p}}\right)_{thin}$
25	130	1.0180	1.0282	1.0180	1.0282	135	1.0027	1.0127	1.0027	1.0127
50	130	1.0224	1.0672	1.0245	1.0860	135	1.0040	1.0480	1.0046	1.0649
75	130	1.0247	1.0987	1.0264	1.1291	135	1.0032	1.0758	1.0020	1.1022
100	130	1.0256	1.1244	1.0263	1.1598	135	1.0012	1.0977	0.9977	1.1274
125	130	1.0257	1.1444	1.0255	1.1824	135	0.9987	1.1144	0.9934	1.1454
150	130	1.0253	1.1599	1.0238	1.1978	135	0.9961	1.1268	0.9886	1.1567
175	130	1.0246	1.1722	1.0220	1.2101	135	0.9933	1.1364	0.9842	1.1653
200	130	1.0238	1.1824	1.0203	1.2202	135	0.9907	1.1442	0.9803	1.1724
225	130	1.0228	1.1912	1.0182	1.2290	135	0.9881	1.1507	0.9763	1.1784
250	130	1.0218	1.1989	1.0160	1.2355	135	0.9855	1.1563	0.9723	1.1823
275	130	1.0206	1.2056	1.0140	1.2412	135	0.9829	1.1610	0.9689	1.1859
300	130	1.0195	1.2115	1.0126	1.2465	135	0.9805	1.1652	0.9664	1.1896
325	130	1.0184	1.2169	1.0114	1.2511	135	0.9783	1.1690	0.9644	1.1929
350	130	1.0174	1.2218	1.0108	1.2555	135	0.9763	1.1725	0.9632	1.1963
375	130	1.0166	1.2263	1.0112	1.2599	135	0.9747	1.1758	0.9633	1.2003
400	130	1.0161	1.2305	1.0127	1.2639	135	0.9735	1.1789	0.9651	1.2045
425	130	1.0158	1.2344	1.0148	1.2685	135	0.9727	1.1820	0.9676	1.2095
450	130	1.0159	1.2382	1.0176	1.2740	135	0.9723	1.1852	0.9710	1.2156
475	130	1.0162	1.2420	1.0209	1.2802	135	0.9724	1.1885	0.9751	1.2227
500	130	1.0168	1.2458	1.0250	1.2863	135	0.9729	1.1920	0.9801	1.2300
25	140	0.9878	0.9977	0.9878	0.9977	150	0.9610	0.9706	0.9610	0.9706
50	140	0.9863	1.0295	0.9856	1.0447	150	0.9549	0.9968	0.9520	1.0091
75	140	0.9829	1.0539	0.9789	1.0768	150	0.9472	1.0157	0.9391	1.0330
100	140	0.9783	1.0726	0.9712	1.0974	150	0.9387	1.0291	0.9260	1.0464
125	140	0.9736	1.0863	0.9639	1.1114	150	0.9306	1.0383	0.9145	1.0545
150	140	0.9690	1.0962	0.9566	1.1192	150	0.9231	1.0443	0.9037	1.0573
175	140	0.9646	1.1035	0.9502	1.1250	150	0.9163	1.0482	0.8944	1.0590
200	140	0.9604	1.1092	0.9446	1.1297	150	0.9100	1.0510	0.8866	1.0604
225	140	0.9565	1.1139	0.9391	1.1335	150	0.9043	1.0531	0.8793	1.0613
250	140	0.9527	1.1178	0.9338	1.1355	150	0.8988	1.0546	0.8724	1.0609
275	140	0.9491	1.1210	0.9293	1.1375	150	0.8938	1.0557	0.8667	1.0609
300	140	0.9457	1.1239	0.9261	1.1401	150	0.8891	1.0566	0.8627	1.0620
325	140	0.9426	1.1264	0.9236	1.1424	150	0.8850	1.0575	0.8596	1.0633
350	140	0.9399	1.1288	0.9221	1.1452	150	0.8814	1.0585	0.8578	1.0654
375	140	0.9377	1.1311	0.9221	1.1490	150	0.8784	1.0596	0.8580	1.0690
400	140	0.9360	1.1335	0.9241	1.1533	150	0.8761	1.0610	0.8605	1.0739
425	140	0.9348	1.1360	0.9271	1.1588	150	0.8746	1.0628	0.8641	1.0801
450	140	0.9342	1.1387	0.9309	1.1655	150	0.8737	1.0650	0.8688	1.0877
475	140	0.9341	1.1417	0.9357	1.1734	150	0.8735	1.0677	0.8746	1.0968
500	140	0.9345	1.1450	0.9415	1.1816	150	0.8740	1.0708	0.8817	1.1065

Table 3. (Continued)

E_1 (keV)	Φ (deg)	R_{thick}	$R_{thick}\left(\frac{Y_{d,n}}{Y_{d,p}}\right)_{thick}$	R_{thin}	$R_{thin}\left(\frac{Y_{d,n}}{Y_{d,p}}\right)_{thin}$	Φ (deg)	R_{thick}	$R_{thick}\left(\frac{Y_{d,n}}{Y_{d,p}}\right)_{thick}$	R_{thin}	$R_{thin}\left(\frac{Y_{d,n}}{Y_{d,p}}\right)_{thin}$
25	160	0.9403	0.9497	0.9403	0.9497	170	0.9273	0.9366	0.9273	0.9366
50	160	0.9310	0.9718	0.9266	0.9822	170	0.9162	0.9563	0.9110	0.9656
75	160	0.9204	0.9870	0.9095	1.0005	170	0.9040	0.9693	0.8915	0.9807
100	160	0.9094	0.9970	0.8931	1.0092	170	0.8915	0.9773	0.8733	0.9868
125	160	0.8991	1.0032	0.8791	1.0136	170	0.8801	0.9819	0.8580	0.9892
150	160	0.8899	1.0067	0.8662	1.0134	170	0.8699	0.9841	0.8440	0.9875
175	160	0.8816	1.0085	0.8554	1.0128	170	0.8608	0.9848	0.8324	0.9856
200	160	0.8741	1.0095	0.8465	1.0124	170	0.8527	0.9848	0.8230	0.9843
225	160	0.8673	1.0100	0.8382	1.0117	170	0.8454	0.9845	0.8145	0.9828
250	160	0.8610	1.0102	0.8305	1.0099	170	0.8386	0.9840	0.8063	0.9804
275	160	0.8551	1.0100	0.8243	1.0089	170	0.8324	0.9832	0.7998	0.9790
300	160	0.8498	1.0099	0.8200	1.0094	170	0.8268	0.9825	0.7954	0.9792
325	160	0.8451	1.0099	0.8166	1.0102	170	0.8219	0.9821	0.7921	0.9798
350	160	0.8411	1.0101	0.8149	1.0121	170	0.8176	0.9819	0.7904	0.9817
375	160	0.8377	1.0106	0.8152	1.0158	170	0.8142	0.9821	0.7909	0.9854
400	160	0.8352	1.0115	0.8182	1.0211	170	0.8116	0.9829	0.7941	0.9910
425	160	0.8336	1.0130	0.8223	1.0279	170	0.8099	0.9842	0.7985	0.9981
450	160	0.8327	1.0150	0.8276	1.0362	170	0.8090	0.9861	0.8042	1.0068
475	160	0.8325	1.0175	0.8341	1.0460	170	0.8089	0.9886	0.8111	1.0172
500	160	0.8330	1.0206	0.8420	1.0567	170	0.8095	0.9918	0.8194	1.0283
25	180	0.9229	0.9321	0.9229	0.9321					
50	180	0.9112	0.9511	0.9057	0.9600					
75	180	0.8984	0.9634	0.8855	0.9740					
100	180	0.8855	0.9708	0.8667	0.9793					
125	180	0.8737	0.9748	0.8509	0.9811					
150	180	0.8632	0.9766	0.8367	0.9789					
175	180	0.8539	0.9769	0.8249	0.9767					
200	180	0.8456	0.9766	0.8152	0.9750					
225	180	0.8381	0.9761	0.8064	0.9733					
250	180	0.8313	0.9753	0.7984	0.9708					
275	180	0.8249	0.9744	0.9718	0.9692					
300	180	0.8192	0.9736	0.7874	0.9693					
325	180	0.8142	0.9730	0.7841	0.9699					
350	180	0.8099	0.9727	0.7824	0.9718					
375	180	0.8064	0.9728	0.7830	0.9756					
400	180	0.8038	0.9735	0.7863	0.9813					
425	180	0.8021	0.9748	0.7908	0.9885					
450	180	0.8013	0.9767	0.7966	0.9973					
475	180	0.8012	0.9792	0.8037	1.0078					
500	180	0.8018	0.9824	0.8121	1.0192					

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