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Characterization of an accelerator neutron source based on the Be(d,n) reaction

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ABSTRACT

Small accelerator neutron sources offer considerable potential for applied neutron radiography applications. Among the desirable features are relatively low costs, limited operating hazards, opportunities for tailoring primary neutron spectra, compactness and portability, and modest licensing requirements (compared to fission reactors). However, exploitation of this potential has been somewhat limited, in part, by incomplete knowledge of the primary-neutron yields and energy spectra from the favorable source reactions. This work describes an extensive experimental determination of zero-degree neutron yields and energy spectra from the ${}^9\text{Be(d,n)}{}^{10}\text{B}$ source reaction, for incident deuterons of 2.6 to 7.0 MeV on a thick beryllium metal target. This information was acquired by means of time-of-flight measurements that were conducted with a calibrated uranium fission detector. Tables and plots of neutron-producing reaction data are presented. This information provides input which will be essential for applications involving the primary spectrum as well as for the design of neutron moderators and for calculation of thermal-neutron yield factors. Such analyses will be prerequisites in assessing the suitability of this source for various possible neutron radiography applications and, also, for assisting in the design of appropriate detectors to be used in neutron imaging devices.

1. INTRODUCTION

Small accelerators can provide intense fast-neutron sources with broad energy spectra that are directly useful, e.g., in transmission radiography, radiotherapy, medical isotopes production, and radiation damage studies. Conventional neutron radiography with accelerators is a feasible alternative to fission-reactor sources if the fast neutrons are moderated. There are also basic-research applications. For example, with pulsed accelerators these sources are useful for determining neutron-detector efficiencies. Integral measurements with such spectra provide tests of differential nuclear-reaction data and very useful information on low-yielding reactions or production of long-lived radioactive products implicated in nuclear waste disposal. Differential cross section information can be deduced if measurements are made in several continuum spectra¹. Detailed energy and angular distributions are needed in order to fully exploit the potential of these neutron sources.

Deuterons with energies of several MeV incident on a thick beryllium-metal target are particularly favored as a neutron source. Beryllium can be machined into convenient shapes, is stable, and will support beam currents of 50-100 μamp with elementary target designs and cooling mechanisms. Since the Q -value of the principal reaction, ${}^9\text{Be(d,n)}{}^{10}\text{B}$, is large and positive (+ 4.36 MeV), the spectra can extend to fairly-high energies. The reaction proceeds to a number of excited states in ${}^{10}\text{B}$ which tends to smooth and broaden the spectrum and enhance total-neutron yield. In addition, there are several many-body reaction channels such as $(\text{d},2\text{n})$, (d,pn) and $(\text{d},\text{p}2\text{n})$ with negative Q values. They increase the low-energy neutron yield when energetically allowed. The neutron spectrum shape depends on incident deuteron energy, so some limited tailoring for specific applications is possible.

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Several sets of neutron energy and angular spectral data from deuteron bombardment of both thin and thick (deuterons stop in the target) beryllium targets are reported²⁻⁹. Many of these involved deuteron energies well above our domain of interest (i.e., deuterons below 7 MeV). Also, most of these investigations incorporated hydrogenous scintillators as neutron detectors, so the neutron detection sensitivity was very poor below ~ 1 MeV. We have undertaken a systematic study of the Be(d,n) thick-target spectra and their angular distributions as a function of incident-deuteron energy to address the deficiencies. Energy spectrum and angular distribution data at 7 MeV from this laboratory were reported earlier⁷. Here, results from measurements of zero-degree neutron energy spectra for incident deuterons from 2.6 to 7.0 MeV, in 0.4-MeV increments, are offered. The neutron-energy yields from about 50 keV up to ≥ 11 MeV are covered, with emphasis on the lower energies.

2. EXPERIMENTAL PROCEDURES AND APPARATUS

Time-of-flight techniques were used to measure the zero-degree neutron-energy spectra. Measurements were made using a fission detector that employed a ^{235}U deposit at ~ 2.65 m or a ^{238}U deposit at ~ 6.75 m and relied on ENDF/B-VI¹⁰ fission cross sections for calibration purposes. Timing considerations limited neutron flight paths to ≤ 7 m. The pulsed-deuteron-beam time resolution was monitored by observing prompt target gamma-rays with a plastic-scintillator detector located ~ 1 m downstream from the fission detector. The experiment employed accelerator pulsing repetition rates of both 1 and 2-MHz, to adequately cover the neutron energy range. Time-spectra were recorded in 512 channels with either 0.9- or 1.8- nanosec increments.

Deuterons accelerated by the Argonne Tandem Dynamitron Accelerator impinged on a thick (~ 0.75 mm) beryllium-metal target, producing neutrons by various Be(d,xn) reactions. The incident deuteron energy (2.6 to 7.0 MeV) was controlled by a slit feed-back system and a calibrated 90-degree analyzing magnet¹¹. An energy control of ± 1 keV was achieved readily for unbunched deuteron beams. However, the buncher induced an effective energy spread of ~ 10 keV. Extracted deuteron bursts from the ion source (initially 20 to 30 nanosec wide) were further time-compressed by a double klystron buncher to produce pulse widths of < 2 nanosec at the target. The total deuteron charge incident on the beryllium target was measured by a low impedance current integrator along with all recorded spectra. A non-beam target leakage current of about ~ 0.05 μamp was observed for all runs, so a correction was applied to the data. The typical time-averaged beam current on target was ~ 3 μamp at 2 MHz repetition rate. Actual beam current between the pulses was negligible. While the time resolution of the gamma-detector signal for prompt gamma-rays emitted from the beryllium target was ~ 2 nanosec, the actual time resolution of the fission detectors for monoenergetic neutrons from the $^7\text{Li}(p,n)$ and $\text{D}(d,n)$ reactions was ~ 3 nanosec. Thus, the attainable energy resolution over 6.75 m at the maximum neutron energy (11.4 MeV) was no better than ~ 0.5 MeV. This limited the spectral quality at the highest energies. At the lower neutron energies, the attainable resolution was more than adequate. Even with the shortest flight path (2.65 m) the resolution at 2 MeV neutron energy was ~ 0.1 MeV.

Spectrum measurements were made on the beam line (zero degree) using a shielded neutron-irradiation cavity¹² (with interior dimensions of $1.4 \text{ m} \times 1.6 \text{ m} \times 1.9 \text{ m}$) to contain the neutron source and reduce background at the detector. This cavity is formed by concrete blocks stacked to produce walls > 1 m thick. The interior is lined with about 20 cm of polyethylene block, a 0.5-mm-thick layer of cadmium sheet, and a 2-cm-thick layer of plywood. The beryllium target is near the center of the cavity,

where it is viewed by a collimator going through the cavity wall on the beam line. At this point, the concrete wall is 1.5-m thick. The target assembly is shown in Fig. 1 and a detailed description is given in ref. 12. It consists of a 25.4-mm-dia. by 0.75-mm-thick beryllium-metal disk mounted in a copper block. The thickness of copper behind the disk is also 0.75 mm. A tantalum aperture confines the deuteron beam to the center of the beryllium disk. A beam-pick-up tube on the beam-line near the target generates the time marker. This target assembly was intended for use with fairly-high beam currents so it is relatively massive. However, much of its bulk is in the target's outer regions which were not seen through the collimator by the fission detector.

Fission detectors have definite advantages relative to scintillators for neutron measurements: First, they are insensitive to gamma-rays. Second, the ^{235}U deposit has no low-energy limit for neutron detection. Third, the energy dependence of the detector efficiency is determined mainly by the ^{235}U and ^{238}U fission cross sections. These cross sections were obtained from the ENDF/B-VI evaluated data file¹⁰. They are quite well determined, so the associated uncertainty is small. Finally, these detectors demonstrate good stability and relatively low sensitivity to threshold settings. Some disadvantages of fission detectors should be mentioned: First, their timing resolution is decidedly inferior to hydrogenous scintillation detectors. Second, the low relative efficiency is a definite restriction. Third, the absence of a low-energy limit for the ^{235}U detector can also be a disadvantage in the sense that each measured spectrum includes unwanted neutrons produced by earlier beam pulses. This effect is magnified by long flight paths and/or high pulse-repetition rates, so ^{238}U was used at the longer distance in this experiment. However, the lower count rate associated with a smaller solid angle and smaller cross section limited its use to higher deuteron energies. These restrictions conspired to limit the spectral quality obtainable for the higher neutron energies. The configuration used for the time-of-flight measurements was a low-mass, three-electrode ion chamber¹³ with thin deposits of uranium and flowing high-purity methane gas at one atmosphere as the medium. The electrode separation was ~ 0.6 cm, with both outer electrodes at ground potential and the center electrode (biased at + 400 V) supplying the signal. Three electrodes were formed from four platinum disks (70-mm-dia. $\times$ 0.13-mm-thick) with U_3O_8 deposits on one side. These disks were arranged so there were U_3O_8 deposits on the four-interior electrode surfaces for a total thickness of ~ 2 mg U/cm^2 . These deposits were 50.8 mm diameter and were either ^{235}U (0.9% ^{234}U , 93.3% ^{235}U , 0.3% ^{236}U and 5.5% ^{238}U) or ^{238}U (natural uranium). Although the uranium deposits were quite thick, separation between the alphas and the fissions was still fairly good. With the discriminator level set high enough to eliminate all the alpha pulses, the efficiency for fission fragments detection was $\sim 90\%$. The detector was operated as a current chamber and the fast rise of the current pulse provided good timing characteristics. The configuration used for absolute neutron-yield determination had only two electrodes and contained a single 25.4-mm dia. ^{235}U deposit. Two deposits consisting of thin, uniform layers of UF_4 on 70-mm-dia. $\times$ 0.13-mm-thick stainless steel plates, were used. They contained 0.658 and 0.416 mg of 93.28% ^{235}U with a weight uncertainty of 0.5%. The separation between alphas and fission fragments in this arrangement was good, resulting in a detector efficiency of $\sim 97\%$. The principles of ion chambers detectors such as these are thoroughly discussed in ref. 14, and additional information on the uranium deposits is given in ref. 15.

3. DATA ANALYSIS AND INTERPRETATION

All time-of-flight spectra were background-corrected for a time-independent component due to very-low-energy neutrons originating from general room return and

leakage through the target-cavity walls, and for a time-correlated tail of the neutron distributions produced by the preceding beam pulse. The low-energy portion of these spectra were all similar in shape. For flight times > 350 nanosec and unit deuteron charge, an equation of the form $N(t, E_d) = A(E_d) + B(E_d)\exp(-Ct)$ fitted these spectra very well (see Fig. 2). The parameters $A(E_d)$, $B(E_d)$ and C were determined for several deuteron energies using data acquired with a 1-MHz pulse rate. As implied above, C was essentially independent of deuteron energy, with an average value of 0.00738 ± 0.00034 nanosec $^{-1}$ at a detector distance of 2.65 m. Both A and B scattered considerably but tended to increase with deuteron energy similarly to the total neutron yield. Since the collimator and detector were on the beam line, neutrons produced at the beam-pickup tube, slits and vacuum-system cold trap could be observed. However, their relative numbers were expected to be insignificant due to solid angle considerations and the intensity of the $\text{Be}(d, n)$ reaction. This was confirmed by tests using 7-MeV deuterons and a tantalum beam stop in place of Be.

The neutron-energy scale was derived from knowledge of the time calibration of the detector system, of the distance from the neutron source to the center of the detector, and of a well-established energy for at least one point in the time spectrum. Distances were measured directly with an error of ± 2 mm. The detector system time scale was deduced with an electronic time calibrator. Three prominent features of the spectra served to establish known energy points. One was the location of the maximum neutron energy kinematically allowed by the ${}^9\text{Be}(d, n){}^{10}\text{B}$ ground-state transition. A group of three closely spaced levels in ${}^{10}\text{B}$ (at 5.11, 5.16 and 5.18 MeV 18) produced a prominent "edge" in the spectrum. Finally, a less obvious edge, produced by the 5.92-MeV level in ${}^{10}\text{B}$, was visible in most spectra. All neutron energy calculations were relativistic and used evaluated nuclear mass values 17 . The derived energy scale was verified by observing several neutron transmission resonances with known energies. Those examined were: lithium, 260 keV 18 ; fluorine, 97.5 keV 19 ; boron, 430 and 1265 keV 20 ; carbon, 2078 keV 20 . The time spectra were transformed into energy spectra with group widths of ~ 50 keV at the lowest energies and widths the equivalent of a single time channel at the highest energies. These bin structures were not identical for all measurements, but the spectra were adjusted to be similar at 0.25- and 2.5-MeV. Corrections were applied for air transmission and detector efficiency energy dependence, using oxygen, nitrogen and fission cross sections from ENDF/B-VI 10 . Data from the 1- and 2-MHz measurements with the ${}^{235}\text{U}$ detector at 2.65 m were merged by normalizing each spectrum to unity and then using the 2-MHz results above 0.250 MeV neutron energy and the 1-MHz results elsewhere. These composite spectra and spectra from the ${}^{238}\text{U}$ detector were renormalized to equal integrals above 2.5 MeV.

The zero-degree neutron yield/sr/unit charge, $Y(E_n)$, is related to the number of fissions detected, F , by the formula $(F-f)h/(Q-q) = (4\pi)^{-1}Y(E_n)\Omega(N/A)\langle\sigma(E_d)\rangle$, for small solid angle, where f is the room background, Q is the total charge on the target, q is the leakage-current correction, Ω is the solid angle in sr, N is the total number of uranium atoms in the deposit, A is the deposit area, and $\langle\sigma(E_d)\rangle$ is the deposit fission cross section averaged over the neutron spectrum produced by deuterons with energy E_d . Parameter h is a factor to correct for fission-event losses due to finite uranium-deposit-thickness and discriminator-setting effects. For those measurements with the ${}^{235}\text{U}$ detector at 2.65 m, N , A and Ω were not well known. Since they were constant, relative yields could be calculated. An absolute yield was measured at 7.0 MeV under conditions where N , A and Ω were well determined, so the relative yields were normalized to this value. To present the results more compactly, each spectrum was represented by a curve drawn through the data points, and values were read off for a selected set of energies. Also, each spectrum was renormalized so

its integral was equal to the total zero-degree neutron yield.

4. RESULTS AND DISCUSSION

Results from the present Be(d,n) zero-degree neutron-energy-spectrum measurements for 2.6- to 7.0-MeV deuterons are summarized in Table 1 and Fig. 3. For deuteron energies of 5.8 through 7.0 MeV, the spectral information above 2.5-MeV neutron energy is based on data obtained from use of ^{238}U in the detector placed at 6.75 m. For all other deuteron energies, and for all neutron energies below 2.5 MeV, the results are derived from measurements with ^{235}U in the detector placed at 2.65 m. Statistical errors are $< 2\%$ over most of the neutron-energy range, but increase to $\sim 5\%$ at the very lowest energies. The background-correction systematic error may also be that large for this energy region. All the spectrum shapes are similar. The "edges" associated with transitions to the ^{10}B ground state, to three closely-spaced levels at 5.11, 5.16 and 5.18 MeV, and to a level at 5.92 MeV are easily identified. Characteristic features associated with other ^{10}B levels can also be discerned, particularly at the lower deuteron energies. All neutron spectra for $E_d > 5.4$ MeV show a well-defined peak at ~ 0.8 MeV. This phenomenon was observed earlier by Lone et al.⁴ and ⁵ and also by Brede et al.⁹. It has been attributed to excitation of the 2.43-MeV level in ^9Be by an inelastic process, followed by its decay to ^8Be by neutron emission.

Crametz, Knitter and Smith⁶ have reported a detailed measurement of the Be(d,n) spectrum for 7-MeV deuterons; their results have been employed often for nuclear-data studies. Smith et al.²¹ have used the code STAYSL to adjust this spectrum in order to give consistent results with a set of well-determined dosimetry reactions. These equivalent spectra are compared with the present result in Fig. 4. They are in good agreement below ~ 6 MeV, but diverge at higher energies. The principal effect of the STAYSL adjustment was reduced neutron yield at the upper energies, thereby producing better agreement with the present spectral determination.

The neutron-spectrum information presented here corresponds to neutrons emitted at zero degrees for the source assembly shown in Fig. 1. The only corrections applied to the data that affect spectral shapes was removal of the time-uncorrelated, very-low-energy neutron background and the contributions from earlier beam pulses, as discussed above. The spectra were not corrected for in-scattering and transmission by the source assembly. However, the neutron spectrum from 7-MeV deuterons on a thick Be target was examined in some detail. The transmission-correction factor for the ^{235}U -loaded detector, averaged over the this spectrum, is ~ 1.04 while the corresponding in-scattering factor is ~ 0.97 . In terms of total count rates, these effects just about cancel, but the impact on the spectrum shape is considerable at the lowest energies. The transmission effect only removes neutrons from the spectrum, but scattering perturbations reduce their energies and thus lead to yield enhancements at the lower energies. The combined effect was estimated by a Monte Carlo calculation, assuming that inelastic-neutron emission was isotropic and had an evaporation energy distribution. The required scattering cross sections and elastic scattering angular distributions were obtained from ENDF/B-VI¹⁰ while the neutron-source angular distribution was derived from Smith et al.⁷. Above 0.4 MeV neutron energy, the shape correction is $< 3\%$. However, it increases rapidly with decreasing neutron energy to $\sim 15\%$ at 0.1 MeV. Fortunately, the fraction of the total neutron yield with energies below 0.4 MeV is small and shows little change with E_d . It increases slightly with decreasing deuteron energy, i.e., it goes from 0.037 at $E_d = 7.0$ MeV to 0.046 at $E_d = 2.6$ MeV. This analysis could not be repeated for the other spectra from this set since no requisite Be(d,n) neutron-emission angular

distribution information was available at deuteron energies other than 7.0 MeV to enable the calculations to be made. However, since qualitatively similar results are anticipated at the other energies, the data in Table 1 and Fig. 3 should represent the thick-target spectra above 0.4 MeV quite well, but give systematically large neutron yields at the lowest energies.

The total zero-degree neutron yields from this work are shown in Fig. 5. An absolute measurement at 7.0-MeV deuteron energy gave 4.65×10^9 neutrons/sr/ μ C. This was used to normalize the relative-yield results at all deuteron energies. The data are fitted well by the formula $Y_n(E_d) = 10^9 \times (-0.3819 + 0.1740 E_d - 0.00137 E_d^2 + 0.01131 E_d^3)$, where Y_n is in units of neutrons/sr/ μ C and E_d is in MeV. Others experimenters⁵ and ⁹, working at higher deuteron energies, found that an equation of the form $Y_n = A E_d^b$ also fits such yield data quite well. For the present work, the constants $A = 1.909 \times 10^7$ /sr/ μ C and $b = 2.84$, give the best fit of this formula for $E_n > 0.05$ MeV. The yields for $E_n > 0.4$ MeV and $E_n > 2.0$ -MeV are compared in Fig. 6 with other measured values. Lone et al.⁵ reported yields for $E_n > 0.4$ MeV at three deuteron energies below 7 MeV. They are in very good agreement with the present results (Fig. 6). Brede et al.⁹ have measured yields for $E_n > 2$ MeV at higher deuteron energies. The dashed line in Fig. 6 represents a best fit of $Y_n = A E_d^b$ to their higher-energy results (the constants are $A = 1.01 \times 10^7$ /sr/ μ C and $b = 2.95$), as extrapolated to below 7 MeV. Agreement with the present results is good above $E_d = 4$ MeV but is progressively worse as E_d decreases. The principal systematic errors for the absolute measurement are: geometry factor, 0.6%; uranium sample weight, 0.5%; detector efficiency corrections, 0.5%; scattering and transmission corrections, 1.1%; room return background correction, 1.0%; deuteron charge measurement, 2.0%; and ^{235}U cross section, 3.0%. The total systematic error is $\sim 4.0\%$.

Finally, average neutron energies $\langle E_n \rangle$ were computed for all spectra. They exhibit a linear dependence on E_d which can be expressed well by the formula $\langle E_n \rangle = (1.210 + 0.277 E_d)$ MeV. These average energies are in fair agreement with those reported by Lone et al.⁵, although they seem to be systematically larger by about 0.2 MeV. A linear extrapolation of the results of Brede et al.⁹ agrees well near $E_d = 7$ MeV but diverges at the lower energies.

5. FUTURE WORK

Further studies are needed to adequately characterize the Be(d,n) spectra for the present deuteron energy range. In particular, neutron-emission angular distributions similar to those made at $E_d = 7$ MeV are required at lower deuteron energies. The Be(p,n) thick-target reaction is also a prolific source of fast neutrons. Some preliminary neutron yield and spectral measurements were made at this laboratory but the results have not been published. Since the proton reaction on Be leads to neutron spectra which are quite different from those produced by deuterons, additional spectrum-tailoring opportunities would be afforded for applications if these source spectra were well known. In order for these reactions to be useful as potential accelerator neutron sources in conventional radiography, measurements should be made of thermal-neutron-yield profiles for benchmark moderator designs. These data would confirm the results of Monte Carlo analyses which employed known neutron source representations and ENDF/B-VI¹⁰ neutron capture and scattering cross sections.

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Table 1: Zero-degree neutron yield as a function of the incident deuteron energy*

E_n (MeV)	E_d (MeV)											
	7.0	6.6	6.2	5.8	5.4	5.0	4.6	4.2	3.8	3.4	3.0	2.6
0.06	2894	1685	1386	2002	905	842	392	642	399	309	93	NM#
0.10	3891	2748	2456	3116	1580	1860	984	1117	773	627	314	NM
0.20	4691	3861	3678	3376	2679	2457	1534	1696	1249	989	633	475
0.30	5818	4856	4325	3844	3381	2681	2346	1724	1428	1174	901	691
0.40	6220	5092	4996	4221	3775	3104	2661	2059	1639	1345	1092	866
0.50	6514	5744	5065	4421	3965	3110	2779	2199	1817	1409	1193	1024
0.60	6551	5754	5171	4649	3971	3462	2893	2426	2008	1599	1346	1019
0.70	7102	6114	5507	4713	4290	3770	3170	2533	2117	1662	1395	1111
0.80	9469	8018	7178	5898	5098	4266	3443	2718	2244	1829	1407	1185
0.90	8986	7950	7159	5910	5080	4411	3703	2881	2254	1936	1675	1113
1.00	8602	7462	6722	5869	5247	4464	3805	2899	2397	2039	1747	1177
1.20	8954	8085	6873	6100	5523	4564	3768	3134	2669	2373	1904	1470
1.40	9243	7922	7092	6322	5562	4646	4075	3227	2791	2709	1813	1714
1.60	9654	8123	7099	6530	5753	4812	4263	3471	3241	2738	2111	1972
1.80	9651	8444	7464	6836	5825	4854	4304	3621	3379	2512	2360	265
2.00	9780	8394	7731	6752	5708	4989	4378	3891	3378	2672	2504	146
2.20	9717	8735	7587	6539	5738	4762	4427	4001	2872	2785	662	69
2.40	9525	8551	7570	6267	5449	4638	4475	3663	2995	2575	152	43
2.60	9058	8358	6971	6003	5125	4419	4366	3187	3076	507	66	47
2.80	9050	8227	6348	6134	5033	4459	3789	3235	2960	179	59	57
3.00	8833	7833	6266	5277	4951	4546	3389	3361	781	132	97	110
3.20	8452	7110	6359	5445	5076	4082	3439	3010	267	155	122	116
3.40	8149	7133	6307	5076	4877	3861	3598	855	180	199	170	67
3.60	7720	6993	5654	5235	4210	3674	2188	316	241	210	178	49
3.80	7389	6540	5499	5086	3832	3737	469	251	269	268	121	66
4.00	6964	6243	5506	4417	4077	2853	371	315	285	233	91	78
4.20	6871	6081	5440	4001	3691	1106	353	315	314	168	95	95
4.40	6352	5637	4731	4108	2412	442	389	341	290	125	114	121
4.60	5971	5639	4191	4352	733	431	409	389	217	169	138	117
4.80	5816	5096	4031	3243	500	417	450	358	186	191	157	126
5.00	5553	4352	4113	997	512	452	479	286	215	226	178	143
5.20	4937	3939	3895	498	584	486	409	279	255	274	210	181
5.40	4109	4027	1391	517	607	569	360	317	299	286	232	203
5.60	4083	3554	584	593	639	516	418	349	335	280	244	227
5.80	4093	1110	600	561	633	459	460	378	344	296	237	237
6.00	3370	730	581	635	584	485	475	399	345	294	250	220

Table 1: (continued)

E_n (MeV)	E_d (MeV)											
	7.0	6.6	6.2	5.8	5.4	5.0	4.6	4.2	3.8	3.4	3.0	2.6
6.30	734	559	582	680	474	457	483	364	310	278	236	158
6.40	699	594	570	587	454	455	470	356	311	259	221	134
6.60	631	614	579	407	460	451	419	322	281	236	181	88
6.80	635	607	606	407	495	426	375	313	278	206	140	72
7.00	652	644	455	408	494	391	368	318	269	172	109	38
7.30	654	550	421	444	503	409	392	309	221	108	67	6
7.60	651	483	486	529	457	396	368	285	159	56	29	0
7.90	531	535	522	512	444	401	295	212	106	21	8	0
8.20	584	598	556	443	398	360	230	146	54	0	2	0
8.50	568	538	529	472	342	302	140	86	17	0	0	0
8.80	546	545	443	374	273	220	64	30	3	0	0	0
9.10	552	460	394	370	178	135	18	7	0	0	0	0
9.50	423	348	360	175	70	60	0	0	0	0	0	0
9.90	343	302	238	141	19	15	0	0	0	0	0	0
10.30	280	237	169	9	0	0	0	0	0	0	0	0
10.70	243	192	56	1	0	0	0	0	0	0	0	0
11.10	164	74	9	0	0	0	0	0	0	0	0	0
11.50	70	4	0	0	0	0	0	0	0	0	0	0
11.90	0	0	0	0	0	0	0	0	0	0	0	0

* The listed values are in units of $10^{-5} \times Y(E_n) / \text{MeV/sr}/\mu\text{C}$.

NM=Not measured.

Fig. 1. A schematic drawing showing the beryllium target assembly. Components are:
A) Be-target element; B) Be-target clamp;
C) Target body; D) Copper cooling tube;
E) Aperture plate holder; F) Ta aperture plate;
G) O-ring; H) O-ring retainer;
I) Accelerator beam tube. J) Nylon screw.

Fig. 2. Thick-target ${}^9\text{Be}(d,n)$ spectra for 7-MeV deuteron energy at 1- and 2-MHz repetition rates normalized to the same total deuteron current. The solid-curve line is the background to be subtracted from the 2-MHz spectrum. The dashed line is the time-independent background.

Fig. 3. A summary of the ${}^9\text{Be}(d,n)$ thick-target spectra for deuteron energies of 2.6 to 7 MeV in steps of 0.4 MeV.

Fig. 4. A comparison of the spectrum for 7-MeV deuteron energy (—) with the data of Crametz et al.⁶ (---) and with the modified spectrum of Smith et al.²¹ (***) .

Fig. 5. The ${}^9\text{Be}(\text{d},\text{n})$ thick-target yield at zero degrees. The solid curve is the 3rd order polynomial fit described in the text.

Fig. 6. The ${}^9\text{Be}(d,n)$ thick target yield for $E_n > 0.4 \text{ MeV}$ and $E_n > 2 \text{ MeV}$. The (o) and (●) are this experiment. The (*) are from Lone et al.⁵ The (---) is an extrapolation of the empirical curve of Brede et al.⁹.

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