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$Be^9(d,n)B^{10}$ Cross Section in the Range 0 to 2.8 MeV

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ABSTRACT

The total $Be^9(d,n)B^{10},B^{10*}$ cross section is constructed by theoretically completing an experimental partial absolute cross section and using it to normalize a relative measurement which in turn was extrapolated to below 0.5 MeV by the relative energy dependence of the coulomb penetration factor.

As a result of recent interest in the $Be^9(d,n)$ reaction as a neutron source, we have determined its cross section for total neutron production in the 0- to 2.8-MeV range. We were able to find partial absolute cross sections[1] at 1.1 MeV and above, to which we add theoretical estimates of the remaining partial cross sections achieving thereby the total (d,n) cross section. This result was used to normalize a relative measurement[2] that, in turn, was extended to low energies by the relative energy dependence of the coulomb penetration factor.

RESULTS

The $Be^9(d,n)B^{10},B^{10*}$ cross section is given by Eq. (1) for energies $E \leq 0.2$ MeV, and in Table I for E = 0.05 to 2.785 MeV, all in millibarns.

$$\sigma \approx \frac{1.94 \times 10^5}{E} \cdot e^{-5.965E^{-\frac{1}{2}}} \quad \text{(mb)} \qquad (1)$$

E in MeV and $E \leq 0.2$ MeV.

The relative error of the Koltay versus the Siemssen et al. results at 1.1 and 1.55 MeV is ±12%. To that one must add the experimental error of the relative point[2] at 0.5 MeV that is used to normalize the lower energy coulomb extrapolation, namely 26%. In addition, consistency checks among experiments, 0.5 to 0.6 MeV, and several coulomb extrapolations lead to confidence levels of about ±5% in the transition from 0.5 MeV to lower energies. On the other end of the energy range, our highest point (2.785 MeV) may be taken to have a theoretical probable error of about 16 mb out of 428 mb, (say we missed a spin assignment or a transmission by a factor of 2), which is 3.7%, with experimental error in the 20% neighborhood. Consequently, these results must certainly be regarded as approximate and errors of the order of 29% cannot be excluded.

TABLE I

$Be^9(d,n)B^{10}$ CROSS SECTION

E_{MeV}	σ(mb)
0.05	1×10^{-5}
0.1	0.0125
0.2	1.56
0.3	12.5
0.4	38.7
0.5	77.7
0.6	112
0.7	158
0.8	217
0.9	298
1.0	348
1.05	364
1.1	337
1.2	280
1.3	236
1.37	228
1.4	230
1.5	283
1.6	384
1.95	413
2.37	433
2.785	428

CALCULATIONAL METHOD

From Siemseen, Cosack, and Felst[1] we have an absolute measurement of $\sigma[\mathrm{Be}^9(d,n)\mathrm{B}^{10},\mathrm{B}^{10*}]$ to the first five levels of B^{10}, including ground state, from 1.1 to 2.785 MeV laboratory deuteron energy. These levels we label 0, 1, 2, 3, 4 and they are given in Table III. Table II (taken from Ref. 3) gives the character of the levels.

TABLE II

LEVELS OF B^{10}

Level Number	Energy (MeV)	J^π,T	Q $\mathrm{Be}^9(d,n)$ (MeV)(Ref.4)	Reaction Statistical Wt for ℓ
0	0	3+,0	4.363	
1	0.7173	1+,0	3.6457	
2	1.74	0+,1	2.623	
3	2.154	1+,0	2.209	
4	3.585	2+,0	0.778	ℓ=1:0.125
5	4.774	(2+),0	-0.411	as level 4
6	5.114	(2-),0	-0.751	ℓ=0:.0167;2:.25
7	5.164	2+,1	-0.801	as level 4
8	5.183	1+,0	-0.820	ℓ=1:0.208
9	5.923	2+,0	-1.560	as level 4
10	6.029	4+	-1.666	ℓ=1:0.0139
11	6.133	2+assumed	-1.770	as level 4
12	6.566	2+assumed	-2.203	as level 4

TABLE III

$\sigma[\mathrm{Be}^9(d,n)\mathrm{B}^{10},\mathrm{B}^{10*}]^1$

IN MILLIBARNS

To Level of B^{10}	0	1	2	3	4
Deuteron Energy (MeV)					
1.1	81	95	13	49	57
1.55	82	107	12	58	72
1.95	91.5	108.5	12	54	61
2.37	85.5	99.7	11.8	49	64.1
2.785	76	83	11.8	40.7	60.5

For a precise calculation of the contributions to levels 5 through 12 we need the relevant compound nucleus theory plus stripping theory with the associated input parameters.[5] In the absence of these and in keeping with the accuracy and paucity of the data we have, it is appropriate to use simpler methods. Accordingly we calculate the cross section to the higher levels by multiplying the known cross section to level four by penetrability and statistical weight ratios between level four and the desired level. Lacking intermediate state spin and orbital parameters and because of the low deuteron energy, we take the incoming deuteron orbital angular momentum to be zero, and then weight every possible resulting angular momentum path equally, which procedure is really accurate on the average only. In our energy range for the final states of level 4 and above, we need only consider outgoing ℓ = 0, 1, 2 because the penetration of higher ℓ channels is quite negligible to our accuracy. The reaction statistical weight found therefore by simple counting is listed in Table II, fifth column. For levels 5, 7, 9, 11, and 12 the statistical factor drops out because they have the same spin, parity, and isospin as level 4, (2+,0), so statistical errors to these levels may be considered of a lower order, or zero.

For the relative angular momentum barrier penetration we use the simple formulas of Blatt and Weisskopf[6] with a well depth of (49.3-0.33E)MeV and an effective radius of 2.7 fermis.[7] Table IV shows the partial cross section to the higher excited states of B^{10} thus obtained. Table IV also gives the total (d,n) cross section from levels 0 to 12 of Tables III and IV.

TABLE IV

$\sigma[\mathrm{Be}^9(d,n)\mathrm{B}^{10*}]$ IN MILLIBARNS

To Level B^{10}	5	6	7	8	9	10	11	12	Sum 0 to 12
Deuteron Energy (MeV)		(Sum ℓ=0,2)							
1.1	14.2	7.2	1.3	1.3	0	0	0	0	319
1.55	30.1	13.4	13.5	13.5	0	0	0	0	401.5
1.95	32.5	13.1	20.	19.9	0.3	0	0	0	413
2.37	40.0	15.6	28.8	28.7	7.2	.5	2.5	0	433
2.785	41.9	16.6	32.8	32.8	14.3	1.3	14.8	1.	428

We use the results at 1.1 and 1.55 MeV weighted 0.8 and 0.2 respectively, to normalize Koltay's relative curve[2] which with Table IV gives the cross-section from 0.5 to 2.785 MeV. For the remainder we assume that the dominant energy dependence is that of the coulomb barrier penetration, which has been verified for the simple formula (1) up to 0.25 MeV (Ref. 8) and for a WKBJ coulomb penetration up to

0.9 (Ref. 2). We use a more accurate machine calculation of the coulomb transmission for a Be^9-d reaction radius of 7 fermis, provided for us by G. M. Hale[9], to extrapolate the cross section from 0.5 to 0.2 MeV and then use Eq. (1) for the lower energies.

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