Energy Levels of Light Nuclei
$A = 11$

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Abstract: An evaluation of $A = 5$–24 was published in *Nuclear Physics* 11 (1959), p. 1. This version of $A = 11$ differs from the published version in that we have corrected some errors discovered after the article went to press. Figures and introductory tables have been omitted from this manuscript. Reference key numbers have been changed to the TUNL/NNDC format.

(References closed December 1, 1958)

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Below is a list of links for items found within the PDF document. Figures from this evaluation have been scanned in and are available on this website or via the link below.

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^{11}Be

(Not illustrated)

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GENERAL:

Mass of ^{11}Be: From the decay energy, ^{11}Be$(\beta^-)^{11}$B, and using the Wapstra mass (1955WA1A) for ^{11}B, the mass excess of ^{11}Be, $M - A = 23.39 \pm 0.15$ MeV (1959WI49). The binding energies of a neutron, deuteron and triton in ^{11}Be are, respectively, 0.54, 18.4 and 15.76 MeV.

1. ^{11}Be$(\beta^-)^{11}$B $\qquad\qquad\qquad Q_m = 11.48$

The decay proceeds to ^{11}B$_{\text{g.s.}}$ and to several excited states. For the ground-state transition, $E_\beta(\text{max}) = 11.48 \pm 0.15$ MeV; $\tau_{1/2} = 13.57 \pm 0.15$ sec, $\log ft = 6.77$ (1958AL96, 1959WI49); see ^{11}B.

2. ^{9}Be$(t, p)^{11}$Be $\qquad\qquad\qquad Q_m = -1.13$

Not reported.

3. ^{11}B$(n, p)^{11}$Be $\qquad\qquad\qquad Q_m = -10.69$

At $E_n = 14.8$ MeV, an activity with a 14.1 ± 0.3 sec half-life is observed which is attributed to the β-decay of ^{11}Be formed in this reaction (1958NU40).

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^{11}B

(Figs. 16)

</div>

GENERAL:

Theory: See (1956KU1A, 1957KU58, 1958FR1C).

1. ^{7}Li$(\alpha, \gamma)^{11}$B $\qquad\qquad\qquad Q_m = 8.670$

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Table 11.1: Energy levels of ^{11}B

E_x (Mev $\pm$ keV)	J^π	τ_m (sec) or Γ (keV)	Decay	Reactions
0	$\frac{3}{2}^-$	stable	—	1, 10, 11, 12, 19, 22, 29, 30, 31, 34, 36, 38
2.127 ± 6	$\frac{1}{2}^-$	$\tau_m = (4.6 \pm 0.6) \times 10^{-15}$	γ	10, 11, 19, 22, 23, 27, 28, 36, 38
4.459 ± 8	$(\frac{5}{2}^-)$	$\tau_m = (1.17 \pm 0.17) \times 10^{-15}$	γ	1, 10, 12, 13, 19, 23, 28, 36, 38
5.035 ± 8	$(\frac{3}{2}^-)$	< 13	γ	1, 10, 19, 38
6.758 ± 7	$(\frac{7}{2}^-)$	< 13	γ	1, 10, (12), 13, 19, 22, 28, 38
6.808 ± 7	$(\frac{3}{2})^-$	< 13	γ	1, 10, (12), 19, 22, 36
7.298 ± 6	$(\frac{5}{2}^-)$	< 13	γ	1, 10, 19, 38
7.987 ± 9		< 8	γ	10, 19, 22, 28, 38
8.568 ± 5	$(\frac{1}{2}^+, \frac{3}{2}^+)$	< 8	γ	10, 19, 28, 38
8.927 ± 5	$(\frac{5}{2}^+)$	< 0.7	γ, α	1, 10, 12, 13, 19, 38
9.191 ± 5	$(\frac{7}{2}^+)$	< 0.1	γ, α	1, 10, 13, 19, 26
9.276 ± 5	$(\frac{5}{2}^+)$	5	γ, α	1, 10, 19
9.88 ± 20	$(\leq \frac{5}{2})$	160	α	4, 10
10.26	$(\leq \frac{7}{2})$	220	α	4
10.32 ± 20		45 ± 14		19
10.62		100	α	4
11.0		670	α	4
11.46		70	α, (n)	4, 18
11.68 ± 100	$(\frac{5}{2}^+, \frac{7}{2}^+)$	140	α, n	2, 4, 12, 18
11.95 ± 80	$(\frac{3}{2}^-, \frac{5}{2}^+)$	320	α, n	2, 4, 13, 18, 38
13.16		450	α, n	2, 13, 18
14.0		300	α, n	13, 18
15.1		500	α, n	13, 18
16.77		60	d, (n), p, t	6, 7, 8, 18
16.93		100	d, p, t	7, 8
17.5			d, p	8

Three resonances are reported below $E_\alpha = 2.5$ MeV (1951BE13, 1954HE22): see Table 11.2. Study of α-γ and γ-γ angular correlations, taken together with the relative γ-intensities, leads to the following assignments: 9.28 MeV level, $J = \frac{5}{2}^+$; 9.19 MeV, $J = \frac{5}{2}^-$; 8.93 MeV, $J = \frac{3}{2}$ or $\frac{5}{2}$; 6.81 MeV, $J = \frac{3}{2}^-$; 4.46 MeV, $J = \frac{5}{2}^-$ ((1952JO1B) and D.H. Wilkinson, private communication). The strength of the transition $(8.92 \rightarrow$ g.s.) implies E1 radiation (1958BI31). Angular distributions of

Table 11.2: Resonances in ^{7}Li$(\alpha, \gamma)^{11}$B

E_r [a]	Γ_{lab} [a]	^{11}B*	Partial widths [b], $\omega\Gamma_\gamma$ (eV) to states of ^{11}B at				
(MeV $\pm$ keV)	(keV)	(MeV)	0	2.14	4.46	5.03	6.81 [d]
0.401	< 1	8.925	0.15 [c]	< 0.003	< 0.003	≈ 0.005	< 0.003
0.819 ± 1	≈ 4	9.191	< 0.05	< 0.02	2.0	< 0.1	≈ 0.35
0.958 ± 1 [d]	7	9.280	3.5 [e]	< 0.17	8.1	< 0.4	2.4

[a] (1951BE13). See also (1954HE22).

[b] (1952JO1B) and D.H. Wilkinson, private communication: compare ^{9}Be(^{3}He, p)^{11}B and Fig. 17. (1951BE13) report total gamma widths of 0.04, 0.6 and 4.7 eV for the three resonances.

[c] (1957WA07) finds $\omega\Gamma = 9 \times 10^{-3}$ eV for the 8.9-MeV state.

[d] (1957BR18) find 957.2 ± 2 keV. According to (1958FE70) the transition from ^{11}B*(9.28) is to the 6.76-MeV level and not that at 6.81 MeV.

[e] (1958ME77) report $\omega\Gamma = 0.8$ eV: see ^{11}B$(\gamma, \alpha)^7$Li.

several gamma rays at each resonance are tabulated by (1957ME1D); no terms higher than $\cos^2\theta$ are indicated. The absence of the transition (9.28 $\rightarrow$ 2.14) speaks for $J = \frac{1}{2}^-$ for the latter (1957WI26). Angular distributions of γ-rays from the 9.28 MeV level have been measured by (1958FE70). The results are in agreement with assignments $J = \frac{5}{2}^+$ and $\frac{5}{2}^-$ for ^{11}B*(9.28, 4.46), respectively. The angular distribution of the transition 9.28 $\rightarrow$ 6.76 strongly favors $J = \frac{7}{2}^-$ for the latter. See also (1958ME77): ^{11}B$(\gamma, \alpha)^7$Li, and ^{10}B(d, p)^{11}B.

2. ^{7}Li$(\alpha, n)^{10}$B $\qquad\qquad Q_m = -2.793 \qquad\qquad E_b = 8.670$

For $E_\alpha < 5.8$ MeV, two resonances are observed; at $E_\alpha = 4.7$ MeV (broad), and 5.15 ± 0.08 MeV ($\Gamma = 0.22$ MeV) corresponding to ^{11}B*(11.68 ± 0.10, 11.95 ± 0.08) (1957BI84). A further resonance at $E_\alpha = 7.15$ MeV, ^{11}B*(13.22), is reported by (1958MA1J, 1959GI47). Calculation of $\sigma(^{10}$B(n, $\alpha)^7$Li) from the observed yield of ^{7}Li$(\alpha, n)^{10}$B gives good agreement for $E_n = 0$ to 0.8 MeV. The 5.15 MeV resonance corresponds to that reported in σ(n, α) at 0.52 MeV: $E_x = 11.95$ MeV. It is concluded that the resonance is formed by s or p-wave neutrons, $J = \frac{5}{2}^+$ or $\frac{3}{2}^-$, $\Gamma_n \approx 20$ keV and $\Gamma_\alpha \approx 300$ keV (1959GI47). See also (1950HO80).

3. ^{7}Li$(\alpha, p)^{10}$Be $\qquad\qquad Q_m = -2.566 \qquad\qquad E_b = 8.670$

See (1937EC1A).

Table 11.3: Resonances in $^7\text{Li}(\alpha, \alpha'\gamma)^7\text{Li}$ [a]

E_α (MeV)	$^{11}\text{B}^*$ (MeV)	$\Gamma_{\text{c.m.}}$ (MeV)
1.90 ± 0.01 [b]	9.88	0.16 [d]
2.50 ± 0.03 [b]	10.26	0.22 [d]
3.06 ± 0.03 [c]	10.62	0.10
3.6 ± 0.1	11.0	0.67
4.39 ± 0.01	11.46	0.07
4.6 ± 0.1	11.6	0.14
5.0 ± 0.1	11.9	0.17

[a] (1957BI84): no correction for barrier penetration effects.
[b] (1954LI48) and (1957BI84). See also (1954HE22).
[c] (1954HE22) and (1957BI84).
[d] (1954LI48) find $\Gamma_{\text{c.m.}} = 125 \pm 10$ and ≈ 155 keV for the first two levels.

4. $^7\text{Li}(\alpha, \alpha')^7\text{Li}^*$ $\hspace{3cm}$ $E_\text{b} = 8.670$

Observed resonances in the yield of 0.48 MeV γ-radiation are exhibited in Table 11.3 (1954HE22, 1954LI48, 1957BI84). Sum rule limits give $J \leq \frac{5}{2}$ for the 9.88 MeV level and $J \leq \frac{7}{2}$ for the 10.26 MeV level (1954LI48).

5. $^9\text{Be}(d, \gamma)^{11}\text{B}$ $\hspace{3cm}$ $Q_\text{m} = 15.822$

This reaction has not been observed: at $E_\text{d} = 0.9$ MeV, $\sigma < 1.8$ μb; at $E_\text{d} = 1.5$ MeV, $\sigma < 20$ μb (1955AL16).

6. $^9\text{Be}(d, n)^{10}\text{B}$ $\hspace{2cm}$ $Q_\text{m} = 4.358$ $\hspace{2cm}$ $E_\text{b} = 15.822$

The cross section follows the Gamow function for $E_\text{d} = 70$ to 110 keV (1955RA14). The fast neutron and γ-ray yield rise smoothly to $E_\text{d} = 1.8$ MeV except for a broad resonance at $E_\text{d} = 1$ MeV (1949EV1A, 1955BO1A, 1957SH65). This resonance is observed in the total neutron yield and in the yield of the fast neutrons to each of the first five states of ^{10}B. Angular distributions change markedly through the resonance except for that corresponding to $^{10}\text{B}^*(3.58)$, which is dominated by stripping throughout (1957SH65). On the other hand, (1958NE38, 1959NE1A)

have obtained integrated cross sections for three separate neutron groups from $E_d = 0.5$ to 2.0 MeV and find no evidence of a resonance near 1 MeV. See also ^{10}B.

7. ^{9}Be(d, d)^{9}Be $\hspace{10em} E_b = 15.822$

In the range $E_d = 1.02$ to 1.44 MeV, two resonance anomalies are reported by (1956JU17) at $E_d = 1.162$ and 1.348 MeV corresponding to ^{11}B*(16.77, 16.93) ($\Gamma \approx 70$ and 120 keV, respectively). See also ^{9}Be.

8. (a) ^{9}Be(d, p)^{10}Be $\hspace{5em} Q_m = 4.585$ $\hspace{5em} E_b = 15.822$
   (b) ^{9}Be(d, α)^{7}Li $\hspace{5.5em} Q_m = 7.152$
   (c) ^{9}Be(d, t)^{8}Be $\hspace{5.5em} Q_m = 4.592$
   (d) ^{9}Be(d, 2α)^{3}H $\hspace{5em} Q_m = 4.686$
   (e) ^{9}Be(d, tn)^{7}Be $\hspace{5em} Q_m = -14.307$

Reaction (a) exhibits a simple Gamow dependence to 250 keV (1953SA1A). Angular distributions for $E_d < 1.5$ MeV are reported by (1952DE24, 1955JU10, 1955JU1B, 1957HY1A, 1957SM78, 1958JU38). The distributions of long-range protons for $E_d = 0.1$ to 0.2 MeV are analyzed in terms of two ^{11}B states with $J = \frac{1}{2}^-$ and $\frac{1}{2}^+$ or $J = \frac{3}{2}^-$ and $\frac{1}{2}^+$ (1957SM78). (1952CA19) reports broad maxima in the $90°$ yield of ground-state protons at $E_d \approx 0.9$, (1.3) and 2.1 MeV. (1957MC35) observe broad resonances at 1.3 and possibly at 1.8 MeV in the yield of 3.37 MeV γ-rays, in the range $E_d = 1.0$ to 5.6 MeV. No resonances are observed in the yield of 6 MeV γ-rays for $E_d = 2.0$ to 5.6 MeV. The cross section for production of ^{10}Be (reaction (a)) rises to a peak value of ≈ 0.34 b at ≈ 4 MeV and then falls almost linearly to ≈ 0.08 b at ≈ 21.5 MeV (1955HE83). See also (1957CO54).

The cross section for reaction (b) shows a simple Gamow rise to $E_d = 250$ keV (1953SA1A). Angular distributions have been measured for $E_d = 0.3$ to 0.7 MeV by (1951RE01): see also ^{7}Li. The cross section for reaction (c) has been measured for $E_d = 0.15$ to 0.62 MeV by (1952DE24), for $E_d = 0.6$ to 1.5 MeV by (1955JU10, 1955JU1B), and at several energies in the range $E_d = 3$ to 19 MeV by (1955HE83). The forward yield of tritons shows a peak at $E_d = 1.38$ MeV (1955JU10, 1955JU1B). There seems also the possibility of a resonance at $E_d = 0.87$ MeV (1958JU38). Triton angular distributions for $E_d = 0.1$ to 0.2 MeV are analyzed in terms of two ^{11}B states with $J = \frac{5}{2}^-$ and $\frac{3}{2}^+$ (1957SM78). See also (1957HY1A) and ^{8}Be.

Relative yields for the various groups from reactions (a), (b) and (c) are given by (1953GE01). See also (1957JA37).

The direct three-body reaction (d) does not appear to occur (1953GE01). The cross section for reaction (e) has been measured from threshold to $E_d \approx 21.5$ MeV ($\sigma \approx 80$ μb) (1955HE83).

9. $^9\text{Be}(t, n)^{11}\text{B}$ $\qquad\qquad Q_m = 9.564$

Not reported.

10. $^9\text{Be}(^3\text{He}, p)^{11}\text{B}$ $\qquad\qquad Q_m = 10.329$

Angular distributions of the protons to the ground state and several excited states of ^{11}B have been determined at various bombarding energies from 2 to 6 MeV: see ^{12}C. See also (1956HL01, 1956WO1A, 1957JO1B).

Gamma rays from the first nine excited states have been observed at $E(^3\text{He}) = 2.1$ MeV in coincidence with proton groups. The direct ground state gamma-transition is observed for all the levels. In addition the cascade through the 2.14 MeV state is observed from the 5.03, 6.81, 7.99 and 8.57 MeV states and, possibly, from the 6.76 and 8.92 MeV states, generally with an intensity comparable with that of the corresponding ground state transition. The gamma-ray width, Γ_γ, of the 8.92 MeV level is found to be comparable with its Γ_α. The decay scheme derived from this work is shown in Fig. 17 (1957FE1B, 1958FE70). The branching of the 5.03 and 7.30 MeV levels agrees with the shell-model assignments $\frac{3}{2}^-$ and $\frac{5}{2}^-$ (1957KU58, 1958FE70). At $E(^3\text{He}) = 5.7$ MeV, proton groups are reported to levels at 2.126 ± 0.010, 4.459 ± 0.010, 5.037 ± 0.010, 6.756 ± 0.010, 6.807 ± 0.010, 7.296 ± 0.010, 7.987 ± 0.010, 8.569 ± 0.010, 8.927 ± 0.010, 9.191 ± 0.010, 9.278 ± 0.010 and 9.87 ± 0.02 MeV. The 9.87 MeV state is broad, $\Gamma \approx 150$ keV (S. Hinds and R. Middleton, private communication). See also (1954MO1E, 1958BR1D, 1958SW63) and $^7\text{Li}(\alpha, \gamma)^{11}\text{B}$.

11. $^9\text{Be}(\alpha, d)^{11}\text{B}$ $\qquad\qquad Q_m = -8.022$

Deuteron groups have been observed at $E_\alpha = 21.6$ MeV to the ground and 2.14 MeV states of ^{11}B. A search in the region $E_x = 0.4$ to 1.0 MeV showed no deuteron groups with intensity greater than 0.1 of the intensity of the two observed groups (1955RA41).

12. $^{10}\text{B}(n, \gamma)^{11}\text{B}$ $\qquad\qquad Q_m = 11.464$

The thermal neutron capture cross section is 0.5 ± 0.2 b. Observed capture γ-rays are listed in Table 11.4. The relative weakness of the ground state transition suggests $J = \frac{7}{2}^+$ for the capturing level.

13. $^{10}\text{B}(n, n)^{10}\text{B}$ $\qquad\qquad\qquad\qquad\qquad\qquad E_b = 11.464$

Table 11.4: Capture γ-rays in ^{10}B(n, γ)^{11}B (1957BA18)

E_γ [a] (MeV)	Intensity [b] (%)	Γ_γ (eV)	assignment [c]
11.43 ± 0.04	0.8	0.01	C $\to$ 0
8.91 ± 0.03	6		8.93 $\to$ 0
6.98 ± 0.03	18	0.2	C $\to$ 4.46
6.74 ± 0.03	10		6.76 $\to$ 0
4.73 ± 0.03	30	0.1	$\begin{cases} \text{C} \to 6.76 \\ 9.19 \to 4.46 \text{ ?} \end{cases}$
4.47 ± 0.02	80		4.46 $\to$ 0

[a] Corrected for recoil.

[b] γ-rays per 100 radiative captures (1958BA52). $\sigma_{n,\gamma}$(total) $= 0.5 \pm 0.2$ b.

[c] C = capturing level: $Q_m = 11.464$.

The epithermal scattering cross section (free) is 3.6 ± 0.2 b (1958HU18). Broad maxima appear in the total cross section at $E_n = 1.9$ and 2.8 MeV (1951BO45) and at 4 MeV (1957HU1D); additional peaks near 0.2 and 0.4 MeV may be indicated (1951BO45). Differential cross sections have been measured at $E_n = 0.55$, 1.00 and 1.50 MeV: derived phase shifts are $\delta_0 = -53.5°$ at $E_n = 0.55$ MeV, $\delta_0 = -60.7°$, $\delta_1 = -4.0°$ at $E_n = 1.00$ MeV, and $\delta_0 = -66.9°$, $\delta_1 = -10.3°$, $\delta_2 = -2.9°$ at $E_n = 1.50$ MeV (1955WI25). The total cross section decreases from ≈ 1.9 b at 4.4 MeV to 1.6 b at 5.6 MeV and then remains approximately constant at ≈ 1.5 b from 6 to 9.7 MeV (1954NE1A, 1956BE98). At $E_n = 14$ MeV it is 1.47 ± 0.03 b (1952CO41) and it remains nearly constant to 18 MeV (1954CO16: $\sigma = 1.45 \pm 0.02$ b). See (1957HU1D).

14. ^{10}B(n, n')^{10}B* $E_b = 11.456$

See (1952PH01) and (1956DA23).

15. ^{10}B(n, p)^{10}Be $Q_m = 0.227$ $E_b = 11.464$

The thermal cross section is < 0.2 b (1958HU18); the cross section for fast pile neutrons is 3 mb (1948EG1A).

16. ^{10}B(n, d)^{9}Be $Q_m = -4.358$ $E_b = 11.464$

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At $E_n = 14$ MeV, the integrated cross sections ($0°$ to $90°$, c.m.) for the transitions to the ground and the 2.4 MeV states of ^{9}Be are 21 ± 3 mb and 16 ± 2 mb, respectively (1954RI15). See also (1956FR18).

17. ^{10}B(n, t)^{8}Be $\qquad\qquad Q_m = 0.234 \qquad\qquad E_b = 11.464$

For $E_n = 5.20$ MeV, production of tritons appears to be mainly via ^{10}B(n, α)^{7}Li*(4.7) and direct three-body breakup (1956FR18). Cross sections at $E_n = 4, 5.6, 9.6$ and 14.1 MeV are $95 \pm 10, 230 \pm 25, 125 \pm 15$ and 85 ± 6 mb, respectively (1958WY67).

18. ^{10}B(n, α)^{7}Li $\qquad\qquad Q_m = 2.793 \qquad\qquad E_b = 11.464$

Recent values for the thermal neutron absorption cross section in natural boron are 749 ± 4 b (1953CA45), 755 ± 3 b (1953HA1C), 744 ± 20 b (1954SC87), 764 ± 3 b (1954VO1A) and 760 ± 3 b (1956CO1E). (1958HU18) give 755 ± 2 b for the thermal absorption cross section in "U. S. standard" boron and 3813 b for the thermal isotropic cross section; see also (1957HU1D). The cross section follows the $1/v$ law from 7×10^{-4} eV to 100 keV (1955HU1B, 1957BI84). (1957BI1F) report $\sigma_{\text{total}} = 642/\sqrt{E_n} + 2.45$ b for $E_n = 3$ to 70 keV. The data from $E_n = 0$ to 250 keV can be satisfactorily interpreted in terms of the ^{11}B levels at 11.46 and 11.68 MeV ($E_n = 0$ and 140 keV) observed in ^{7}Li(α, α')^{7}Li* (1957BI84). (1957BE71) find, on the other hand, that deviations from the $1/v$ law for $E_n < 1$ MeV indicate a single broad level at $E_n \approx 250$ keV with $J = \frac{5}{2}^+$ or $\frac{7}{2}^+$, $\Gamma_\alpha \approx 400$ keV, $\Gamma_n \approx 200$ keV. A pronounced resonance is observed at $E_n = 1.86$ MeV: $\Gamma_{\text{c.m.}} = 0.45$ MeV ((1957BI84) and (1951PE18); see also (1950ST1A) and (1952BI1A)). There are indications of less pronounced resonances at 0.53, 2.8 and 4.1 MeV (with $\Gamma_{\text{c.m.}} = 0.10$, 0.3 and 0.5 MeV) in the energy range to $E_n = 4.8$ MeV (1957BI84). The ratio of ground state to excited state transition varies strongly with energy: see (1952AJ38, 1954DE38, 1958BU02).

Cross sections for production of $2\alpha + t$ either through the 4.6 MeV level of ^{7}Li or via three-body breakup have been determined for $E_n = 4$ to 19.5 MeV. A strong maximum near $E_n = 5.6$ MeV may indicate a resonance near ^{11}B*(16.6) (1956FR18, 1958WY66). See also (1955AJ61).

19. ^{10}B(d, p)^{11}B $\qquad\qquad Q_m = 9.237$

Proton groups reported by (1951VA1A) and (1953EL12) are listed in Table 11.5. No other levels are observed below $E_x = 11.46$ MeV: the known levels observed in ^{7}Li(α, α')^{7}Li are presumably too wide to be seen here. See also (1954KH1A, 1955KH35).

The angular distribution of protons leading to the ground state ($J = \frac{3}{2}^-$) shows a well-developed $l_n = 1$ stripping pattern at all energies $\gtrsim 2.0$ MeV (1954EV1A, 1958EV01: 7.7 MeV), (1953HO48: 8 MeV), (1956ZE1A: 10 MeV), (1957LE1F: 15.1 MeV), (1956MA69: 1.0 to 3.0

Table 11.5: Proton groups from ^{10}B(d, p)^{11}B

^{11}B* [a] (MeV ± keV)	Γ (keV)	$d\sigma/d\Omega$ [b] (mb/sr)	l_n	J^π	Λ_n [c]
0 ± 11		2	1 [d]	$\frac{3}{2}^-$	5.0
2.138 ± 9	< 15	0.4	1 [e]	$\frac{1}{2}^-$ [e]	0.9
4.459 ± 8	< 15	1.2	1 [d]	$\frac{3}{2}^-, \frac{5}{2}^-$ [f]	1.6
5.034 ± 8	< 15	1.0	1 [d]		0.5
6.758 ± 7	< 15	2	1 [g]	$\frac{5}{2}^-, \frac{7}{2}^-$ [f]	5.7
6.808 ± 7	< 15	0.2			weak [g]
7.298 ± 6	< 15	1.2			weak [g]
7.987 ± 9	< 10				weak [g]
8.568 ± 5	< 10	0.3	(2) [g]	$(\frac{1}{2}^+, \frac{3}{2}^+)$	weak [g]
8.927 ± 5	< 4	5	2, 0 [g]	$\frac{5}{2}^+, (\frac{7}{2}^+)$	
9.191 ± 5	< 10	8	0 [g]	$(\frac{5}{2}^+), \frac{7}{2}^+$	
9.276 ± 5	< 10	4	0 [g]	$\frac{5}{2}^+, (\frac{7}{2}^+)$	
10.32 ± 20	54 ± 17 [h]				

[a] (1951VA1A, 1953EL12): stated errors refer to Q-values.

[b] Approximate differential cross sections in mb/sr at $\theta = 90°$, $E_d = 1.51$ MeV (1951VA1A).

[c] Relative neutron capture probability (1954EV1A: $E_d = 7.7$ MeV).

[d] (1954EV1A: $E_d = 7.7$ MeV).

[e] See text.

[f] From p-γ correlation (1957CO54).

[g] (1958BI31).

[h] The width of this state suggests that it is not to be identified with that observed at 10.26 MeV in ^{7}Li(α, α')^{7}Li.

MeV); see, however, (1957CO54). Even below $E_d = 1$ MeV, stripping appears to play an important role in formation of this level (1954BU06, 1954PA28, 1957HA1H). The relatively large neutron capture probability suggests a single-particle character (1953HO48, 1954EV1A). See also (1957CO54, 1957HA1H). The polarization has been studied by (1958HE47, 1958HI74).

For the 2.1 MeV state, the evidence is not so clear: the pattern though generally of an $l_n = 1$ shape (see, however, (1954PA28, 1957LE1F)) shows strong variations with energy (1954EV1A, 1956MA69, 1956ZE1A, 1957CO54, 1957LE1F, 1958EV01). An $l_n = 1$ formation implies $\frac{3}{2}^- \leq J \leq \frac{9}{2}^-$, in contradiction to the shell-model expectation that the state should have $J = \frac{1}{2}^-$; however to form such a state requires $l_n = 3$, involving rearrangement of several nucleons and hence a low probability (1956MA69, 1958EV01). The more probable mode of formation would appear to involve a nucleon exchange (1958EV01) or a spin reversal of the outgoing proton (1957WI26). The observation that the polarization of protons for this state is opposite to those corresponding to the ground state is consistent with either point of view, and permits $\frac{1}{2}^- \leq J \leq \frac{11}{2}^-$ (1958HE47). Support for the assignment $J = \frac{1}{2}$ is found in the observed isotropy of the p-γ correlation (see below): see also ^{11}B(p, p')^{11}B* and (1957WI26, 1958BO1C).

The 4.46, 5.03 and 6.76 MeV states are also formed by $l_n = 1$. The large neutron capture probability for the 6.76 MeV state indicates that it has a single-particle character (1954EV1A, 1958BI31). See also (1957CO54, 1957SJ1C). The next four states appear only weakly and probably arise from configuration mixing (1958BI31).

For the 8.92 MeV state, $l_n = 2$ with a small admixture of $l_n = 0$ is indicated; $J = \frac{5}{2}^+, \frac{7}{2}^+$. The large γ-width suggests $J = \frac{5}{2}^+$. The 9.19 and 9.28 MeV state are formed with $l_n = 0$, $J = \frac{5}{2}^+$ or $\frac{7}{2}^+$; the intensity ratio is consistent with $J(9.19) = \frac{7}{2}^+$, $J(9.28) = \frac{5}{2}^+$. Again, the high relative intensities suggest that these three are single-particle states, formed by direct capture into the 1d, 2s, shell (1958BI31); see also ^{7}Li(α, γ)^{11}B.

Gamma rays reported by (1955BE81) and (1955SA1B) are listed in Table 11.6. The p-γ angular correlation through the 2.14 MeV state is isotropic to $\approx 4\%$, consistent with $J = \frac{1}{2}$: see (1953TH1B, 1955GO1D, 1956GO1L, 1956GO1M, 1956GO39, 1957GA1B). The angular correlation through 4.46 MeV state is consistent with $J = \frac{3}{2}^-$ or $\frac{5}{2}^-$; that through the 6.76 MeV state rules out $J = \frac{3}{2}$ and suggest $J = \frac{9}{2}$ is unlikely for that state (1957CO54). See also (1956VA17).

20. ^{10}B(t, d)^{11}B $Q_m = 5.205$

Not reported.

21. ^{10}B(α, ^{3}He)^{11}B $Q_m = -9.114$

Not reported.

Table 11.6: γ-rays from ^{10}B(d, p)^{11}B

E_γ [a] (MeV)	σ(total) [b] (mb)	E_γ [c] (MeV)	I [d] (relative)	Assignment ^{11}B*
4.49 ± 0.05	5.0	4.46 ± 0.04	14	$4.46 \to 0$
5.03 ± 0.03	3.0	5.03 ± 0.09	6	$5.03 \to 0$
6.75 ± 0.03	5.4	6.78 ± 0.07	6	$6.76 \to 0$
7.30 ± 0.03	6.0	7.29 ± 0.04	5	$7.30 \to 0$
		8.27 ± 0.09	4	
8.57 ± 0.04	1.8			$8.57 \to 0$
8.93 ± 0.04	8.1	8.87 ± 0.02	11	$8.93 \to 0$
4.73 ± 0.03	6.3	4.75 ± 0.03	6	$9.19 \to 4.46$

[a] (1955BE81): Doppler corrected.
[b] Average value $E_d = 0$ to 2.0 MeV (1955BE81).
[c] (1955SA1B): no Doppler correction.
[d] Relative intensity (1955SA1B): ($E_d = 1.4$ MeV).

22. ^{11}Be(β^-)^{11}B $Q_m = 11.48$

The decay properties of ^{11}Be are exhibited in Table 11.7. The transition energy to the ground state is $E_\beta(\max) = 11.48 \pm 0.15$ MeV; $\tau_{1/2} = 13.57 \pm 0.15$ sec, $\log ft = 6.77$ (1958AL96, 1959WI49), $\tau_{1/2} = 14.1 \pm 0.3$ sec (1958NU40). The transition probabilities to ^{11}B$_{g.s.}$, $J = \frac{3}{2}^-$, and ^{11}B*(2.1), $J = \frac{1}{2}^-$, suggest $J = \frac{1}{2}^-$ for ^{11}Be, but it is not clear why the transition should be so much inhibited as compared with other allowed transitions (1959WI49).

23. ^{11}B(γ, γ)^{11}B

The mean life of the 4.46 MeV level, determined by resonance absorption and scattering is $\tau_m = 1.17 \pm 0.17 \times 10^{-15}$ sec, assuming $J = \frac{5}{2}$. On the same assumption, the intensity ratio of quadrupole to dipole transitions is ≤ 0.2 (1958RA14). A mean life of $\approx 1.5 \times 10^{-15}$ sec is calculated by (1957KU58).

A similar experiment yields $\tau_m = (4.6 \pm 0.6) \times 10^{-15}$ sec for the 2.1 MeV state, assuming $J = \frac{1}{2}$. The result does not distinguish $J = \frac{1}{2}^-$ from $J = \frac{1}{2}^+$, but the shortness of the lifetime excludes $J > \frac{1}{2}$ (1958ME79): see (1957WI26: ^{11}B(p, p')^{11}B*). A calculation in intermediate coupling, assuming an M1 transition yields $\tau_m = (2.5$ to $5) \times 10^{-15}$ sec (1957KU58). See also (1958MC1D).

Table 11.7: Beta decay of ^{11}Be (1958AL96, 1959WI49)

^{11}B* (MeV)	J^π	% betas	$\log ft$	E_γ (MeV $\pm$ keV)	% gammas [a]
0	$\frac{3}{2}^-$	61	6.77		
2.138	$\frac{1}{2}^-$	29	6.63	2.121 ± 10	32
4.459	$(\frac{5}{2}^-)$	≤ 0.2	≥ 8.2		
5.034		≤ 0.2	≥ 8.2		
6.758 $\Big\}$ 6.808		6.5	5.93	$\begin{cases} 6.76 \pm 30 \\ 4.64 \pm 20 \end{cases}$	4.4 / 2.1
7.298		≤ 1.5	≥ 6.4		
7.987		4.1	5.53	$\begin{cases} 7.97 \pm 30 \\ 5.86 \pm 40 \end{cases}$	1.7 / 2.4
8.568		≤ 0.3	≥ 6.3		
8.927		≤ 0.15	≥ 6.3		

[a] Relative to all β-transitions.

24. ^{11}B(γ, n)^{10}B $\qquad\qquad Q_m = -11.464$

See (1951SH63) and (1955TI1A).

25. ^{11}B(γ, t)^{4}He + ^{4}He $\qquad\qquad Q_m = -11.136$

See (1955AJ61).

26. ^{11}B(γ, α)^{7}Li $\qquad\qquad Q_m = -8.670$

Resonance absorption of 9.19 MeV radiation yields $\Gamma < 100$ eV, $(2J + 1)\Gamma_\gamma \approx 0.8$ eV for ^{11}B*(9.19) (1958ME77).

27. ^{11}B(n, n$'$)^{11}B*
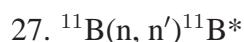
At $E_n = 4.5$ MeV, a 2.2 MeV γ-ray is reported (1955GR18, 1956DA01). See also (1954SC85).

28. ^{11}B(p, p$'$)^{11}B*

At $E_p = 3.58$ MeV, a 2.134 ± 0.005 MeV γ-ray is observed (1957MC35); see also (1953HU29). The mean lifetime of the 2.14 MeV state has been determined by a Doppler shift measurement to be $< 4 \times 10^{-14}$ sec (1957WI26): see ^{11}B(γ, γ)^{11}B. It is pointed out that the observed isotropy in ^{10}B(d, pγ)^{11}B requires a nearly pure E2 transition if $J = \frac{3}{2}^-$ and the present lifetime value excludes E2. On the other hand, the lifetime is quite consistent with M1 (1957WI26). The 2.14 MeV γ-ray exhibits $< 2.0 \times 10^{-3}$ part of circular polarization; this observation places an upper limit of $F^2 \lesssim 1 \times 10^{-7}$ for the intensity of the parity non-conserving part of the wave function (1958WI41).

At $E_p = 185$ MeV, inelastic groups with $Q = -4.7$, -6.6 and -8.5 MeV are observed; the latter shows strong forward peaking and is attributed to a spin flip of a target nucleon, indicating $J = \frac{1}{2}^-$, $\frac{3}{2}^-$ or $\frac{5}{2}^-$ (1958TY46). See also (1955AJ61, 1956ST1D) and ^{12}C.

29. ^{11}B(d, d$'$)^{11}B*

Ground state deuterons have been observed at $E_d = 4.2$ MeV (1955KH35).

30. ^{11}C(β^+)^{11}B $Q_m = 1.981$

See ^{11}C.

31. ^{12}C(γ, p)^{11}B $Q_m = -15.958$

See ^{12}C.

32. ^{12}C(p, 2p)^{11}B $Q_m = -15.958$

At $E_p = 185$ MeV, the summed proton spectrum shows peaks attributed to removal of p- and s-protons (1958MA1B, 1958TY47).

33. (a) ^{12}C(n, d)^{11}B $Q_m = -13.731$
    (b) ^{12}C(d, ^{3}He)^{11}B $Q_m = -10.465$

Not reported.

34. ^{12}C(t, α)^{11}B $Q_m = 3.855$

This reaction has been observed at $E_t = 1.4$ MeV (1955CU17). See also (1958JA06).

35. (a) ^{13}C(n, t)^{11}B $Q_m = -12.419$
    (b) ^{13}C(p, ^{3}He)^{11}B $Q_m = -13.184$

Not reported.

36. ^{13}C(d, α)^{11}B $Q_m = 5.167$

Alpha-particle groups have been observed corresponding to ^{11}B*(2.107 ± 0.017) (1951LI29) and ^{11}B*(4.45, 6.83) (1953SP1A). A 4.46 MeV γ-ray observed by (1955BE62) in (^{13}C + d) is definitely assigned to the present reaction by (1958RA13). See also (1955AJ61).

37. ^{14}C(p, α)^{11}B $Q_m = -0.780$

Not reported.

38. ^{14}N(n, α)^{11}B $Q_m = -0.152$

Q_0-values of -0.12 ± 0.06 and -0.18 ± 0.05 MeV are reported by (1958DO63). See also (1952LI24).

<div align="center">

^{11}C

(Fig. 18)

</div>

GENERAL:

Theory: See (1956KU1A, 1957KU58, 1958FR1C).

1. ^{11}C(β^+)^{11}B $\qquad\qquad\qquad\qquad Q_\mathrm{m} = 1.981$

The spectrum is simple; $E_{\beta^+}(\max) = 968 \pm 8$ keV (1954WO23). The mean of half-lives reported in (1955AJ61) is 20.36 ± 0.05 min. Recent values of the half-lives are 20.26 ± 0.1 min (1955BA63), 20.8 ± 0.2 min (1957PR53) and 20.11 ± 0.13 min (1958AR15); $\log ft = 3.62$ (1954WO23). The ratio of K-capture to positron emission is 0.19 ± 0.03 % (1957SC29). See also (1957BR18, 1957KA1C).

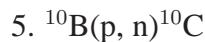2. (a) ^{6}Li(^{6}Li, n)^{11}C $\qquad\qquad\qquad Q_\mathrm{m} = 9.462$

   (b) ^{7}Li(^{6}Li, 2n)^{11}C $\qquad\qquad\quad Q_\mathrm{m} = 2.209$

   See (1957NO17).

3. ^{9}Be(^{3}He, n)^{11}C $\qquad\qquad\qquad\qquad Q_\mathrm{m} = 7.565$
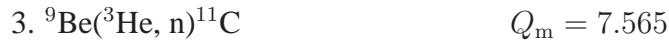
   See (1952PO27, 1953KU08, 1954MO1E).

4. ^{10}B(p, γ)^{11}C $\qquad\qquad\qquad\qquad Q_\mathrm{m} = 8.700$

For $E_\mathrm{p} = 0.7$ to 3 MeV, the main capture radiation is to the ground state. Weaker radiations, $\approx$ 5%, with $E_\gamma \approx 4.2$ and 5.8 MeV suggest a cascade through the 4.23 MeV level (1956CH20, 1957HU79). Two broad resonances are reported at 1.14 and ≈ 4.4 MeV: see Table 11.9 (1954DA20, 1955BA22, 1955HA01, 1956CH20, 1957HU79). The angular distribution at the first resonance is $1 + 0.5\cos^2\theta$. Using $\sigma_\alpha = 16$ mb/sr, (1956CH20) find $\omega\Gamma_\mathrm{p} \approx 40$ keV, $\Gamma_\alpha \approx 500$ keV, $\omega\Gamma_\gamma = 10$ eV, consistent with M1 radiation. The angular distribution and the gamma-ray width appear to rule out all $J \leq \frac{7}{2}$ except $J = \frac{5}{2}^-$ (1956CH20); see, however, ^{10}B(p, α)^{7}Be (1956CR07). The cross section increases rapidly in the range $E_\mathrm{p} = 2.2$ to 2.7 MeV, but there is no indication of a previously reported 2.4 MeV resonance (see (1954DA20, 1955BA22, 1957HU79)). See also (1955AJ61, 1955WI1E) and (1957JA37).

Table 11.8: Energy levels of ^{11}C

E_x (MeV $\pm$ keV)	J^π	τ (min) or Γ (keV)	Decay	Reactions
0	$(\frac{3}{2}^-)$	$\tau_{1/2} = 20.45 \pm 0.06$	β^+	1, 2, 3, 4, 11, 14, 15, 17, 18, 19, 20, 21, 23, 24
1.99 ± 20	$(\frac{3}{2}^- \rightarrow \frac{9}{2}^-)$		γ	11, 12, 15, 21
4.26 ± 30	$(\frac{3}{2}^- \rightarrow \frac{9}{2}^-)$		γ	4, 11
4.75 ± 30	$(\frac{3}{2}^- \rightarrow \frac{9}{2}^-)$		γ	11
6.50 ± 20			γ	11
6.77 ± 40			(γ)	11
7.40 ± 40			γ	11
8.108 ± 8				11
8.431 ± 8				11
8.661 ± 8				11
8.98 ± 30				11
(9.13 ± 20)				11
(9.28 ± 30)				11
9.74 ± 10	$(\frac{3}{2}^-)$	450	γ, p, α	4, 6, 10, 11
10.09 ± 10	$(\frac{7}{2}^+)$	200	p, α	6, 10, 11
$(10.69 \pm 20$)				11
10.89 ± 20				11
(11.26 ± 20)				11
(11.52 ± 20)				11
12.3		≈ 500	γ, p, α	4, 10
13.8 ± 200			p, α	10
(15.7 ± 200)			(p, α)	10

5. ^{10}B(p, n)^{10}C $\qquad\qquad Q_m = -4.56 \qquad\qquad E_b = 8.700$

The cross section is ≤ 1.4 mb at $E_p = 5.35$ MeV, ≤ 2 mb at $E_p = 5.51$ MeV (1959GI47). See (1958MA1F, 1958TA03) and ^{10}C.

Table 11.9: Resonances in ^{10}B(p, γ)^{11}C, ^{10}B(p, p)^{10}B, ^{10}B(p, α_0)^{7}Be and ^{10}B(p, $\alpha_1\gamma$)^{7}Be

Reaction	E_{res} (MeV)	Γ_{lab} (keV)	σ	E_{x} (MeV)	J^π	Refs.
^{10}B(p, γ)^{11}C	1.146 ± 0.005	414 ± 20	$5.5 \pm 2.8\ \mu$b	9.74		(1957HU79)
^{10}B(p, γ)^{11}C	1.135 ± 0.015	540 ± 40	$3.5 \pm 1.0\ \mu$b		$(\frac{5}{2}^-)$	(1956CH20)
^{10}B(p, γ)^{11}C	1.21		$7.5 \pm 3.8\ \mu$b			(1954DA20)
^{10}B(p, γ)^{11}C	1.18 ± 0.04	570 ± 20				(1955HA01)
^{10}B(p, α_0)^{7}Be	1.15		205 ± 40 mb			(1951BR10)
^{10}B(p, p)^{10}B	(1.15)					(1951BR10)
^{10}B(p, α_0)^{7}Be	1.1	> 330			$(\frac{5}{2}^+)$	(1956AL23)
^{10}B(p, α_0)^{7}Be	1.17	300	210 ± 40 mb		$\frac{3}{2}^-$	(1956CR07)
^{10}B(p, $\alpha_1\gamma$)^{7}Be	1.533 ± 0.005	220	80 ± 40 mb	10.09		(1957HU79)
^{10}B(p, $\alpha_1\gamma$)^{7}Be	1.5	250	100 ± 20 mb		$\frac{7}{2}^+$	(1956CR07)
^{10}B(p, α_0)^{7}Be	1.5	250	230 ± 40 mb		$\frac{7}{2}^+$	(1956CR07)
^{10}B(p, $\alpha_1\gamma$)^{7}Be	1.52	250	140 ± 30 mb 210 ± 70 mb			(1951BR10, 1954DA20)
^{10}B(p, α_0)^{7}Be	1.5		140 ± 30 mb			(1951BR10)
^{10}B(p, p)^{10}B	(1.5)					(1951BR10)
^{10}B(p, $\alpha_1\gamma$)^{7}Be	1.53		210 ± 50 mb			(1956CH20)
^{10}B(p, α_0)^{7}Be	1.5	≈ 230			$(\frac{5}{2}^-)$	(1956AL23)
^{10}B(p, γ)^{11}C	≈ 4	≈ 500		12.3		(1955BA22)
^{10}B(p, α)^{7}Be	≈ 4					(1957KA1C)
^{10}B(p, α)^{7}Be	5.6			13.8		(1957KA1C)
^{10}B(p, α)^{7}Be	(7.8)			(15.7)		(1957KA1C)

6. ^{10}B(p, p)^{10}B $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ $E_{\text{b}} = 8.700$

The elastic scattering cross section at $\theta = 138°$ rises from nearly the Rutherford value for $E_{\text{p}} < 0.9$ MeV to 4 times Rutherford at $E_{\text{p}} = 1.6$ MeV. Anomalies are observed at $E_{\text{p}} = 1.15$ and 1.5 MeV (1951BR10). See Table 11.9.

7. ^{10}B(p, p')^{10}B* $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ $E_{\text{b}} = 8.700$

The yield of 0.71 MeV radiation, from the first excited state of ^{10}B, rises monotonically from $E_p = 1.5$ to 2.7 MeV (1952DA05, 1954DA20, 1957HU79). At $E_p = 2.7$ MeV the cross section is 11 ± 5 mb (1957HU79). Above $E_p = 2.4$ MeV, weak ($\approx 1\%$) γ-rays of 1.00 ± 0.04 MeV ($1.74 \rightarrow 0.71$ transition in ^{10}B) and 2.12 ± 0.06 MeV ($2.14 \rightarrow$ g.s. transition) are observed (1957HU79). See also (1952CR30), (1956CH20) and (1957JA37).

8. ^{10}B(p, d)^{9}B $Q_m = -6.212$ $E_b = 8.700$

   See ^{9}B.

9. ^{10}B(p, ^{3}He)^{8}Be $Q_m = -0.532$ $E_b = 8.700$

   See ^{8}Be.

10. ^{10}B(p, α)^{7}Be $Q_m = 1.147$ $E_b = 8.700$

The excitation function is a smooth exponential from $E_p = 60$ to 200 keV (1955BA1M). Excitation functions have been studied up to 3 MeV (see (1957JA37)). Using the stacked foil method, (1957KA1C) report structure in the excitation function corresponding to ^{11}C levels at 12.3, 13.8 ± 0.2 and 15.7 ± 0.2 MeV. The ground state α-particles (α_0) exhibit broad resonances at $E_p = 1.17$ and 1.53 MeV superposed on a continuous isotropic background (1951BR10, 1956AL23, 1956CR07). Alpha particles to the 0.43 MeV ^{7}Be state (α_1) and 0.43 MeV γ-rays show only the resonance at $E_p = 1.53$ MeV (1951BR10, 1954DA20, 1956CH20, 1956CR07, 1957HU79). A summary of the evidence on the (^{10}B + p) resonances is given in Tables 11.9 and 11.10.

The reaction cross section for α_0 at the $E_p = 1.17$ MeV resonance requires $J \geq \frac{3}{2}$. The angular distribution is isotropic, except for small terms attributed to interference, restricting the choice to $\frac{5}{2}^+, \frac{7}{2}^+, \frac{3}{2}^-$. The absence of α_1 suggests $\frac{3}{2}^-, \frac{5}{2}^+$ as most likely; $\frac{3}{2}^-$ would agree with the mirror level in ^{11}B (1956CR07: see Table 11.10).

At the $E_p = 1.5$ MeV resonance, the angular distribution of α_0 has the form $1 - 0.53\cos^2\theta$. Between resonances, coefficient of odd order Legendre polynomials show a sharp peak, indicating that the two levels have opposite parity. The α_1 distribution at $E_p = 1.5$ MeV also shows interference effects. From the reaction cross section at $E_p = 1.5$ MeV, $J \geq \frac{5}{2}$. The most satisfactory account of the α_0 and α_1 angular distributions is given with the assumption of $J = \frac{7}{2}^+$, formed by s- and d-waves. The assumption $J = \frac{5}{2}^+, \frac{5}{2}^-$ for the 1.17 and 1.5 MeV resonances is excluded (1956CR07: see Table 11.10).

At $E_p = 1.2$ MeV the (non-resonant) 430 keV γ-rays are isotropic $\pm 2\%$ (1956CH20). See also (1955WI1E).

Table 11.10: Resonance parameters for ^{10}B(p, α)^{7}Be (1956CR07)

E_{res} (MeV)	J^π	Γ (keV)	Γ_{p} (keV)	Γ_{α_0} (keV)	Γ_{α_1} (keV)	θ_{p}^2 (%)	$\theta_{\alpha_0}^2$ (%)	$\theta_{\alpha_1}^2$ (%)
1.17	$\frac{3}{2}^-$	300	75 [a,c]	225	non res	0.8	8	
			225 [a]	75		2.5	2.7	
1.53 [b]	$\frac{7}{2}^+$	250	1600 [a]	56	34	13	15.7	20.3
			90 [a]	100	60	9	32	42

[a] Alternative solutions.

[b] (1957HU79).

[c] Compare ^{10}B(p, γ)^{11}C.

11. ^{10}B(d, n)^{11}C $Q_{\text{m}} = 6.473$

Level information derived from studies of the neutron groups is displayed in Table 11.11 (1952JO10, 1954PA29, 1956CE1B, 1956CE73, 1956GR54, 1956MA83, 1957GR50, 1958MC1E, 1959NE1A). See also (1953GI05, 1954BU06, 1956BO1F). A search for possible doublet structure at $E_{\text{x}} = 6.50$ MeV revealed no other level in this neighborhood. A group with relative intensity $\frac{1}{10}$ would have been seen if the separation were as much as 40 keV (1959NE1A: $E_{\text{d}} = 1.5$ MeV, $\theta = 60°$).

Neutron threshold measurements indicate levels in ^{11}C at 8.108, 8.431, and 8.661 MeV (1955MA76: ± 0.008 MeV). Gamma-ray measurements indicate lines with $E_\gamma = 4.75 \pm 0.03$ MeV (1955SA1B), 5.35 ± 0.05 MeV (1955SA1B: from ^{11}C*(7.4 $\rightarrow$ 2.0)), and 6.50 ± 0.03 (1955BE81: Doppler corrected), 6.52 ± 0.05 MeV (1955SA1B). Gamma rays of energy 6.5, 4.3, and ≈ 2.0 MeV are observed in coincidence with neutrons leading to ^{11}C*(6.50). In coincidence with neutrons to ^{11}C*(4.26 and 4.75, unresolved) are $E_\gamma = 4.28, \approx 2.3, \approx 2.0$ MeV (1958MC1E). See also (1957BI78).

12. ^{10}B(^{3}He, d)^{11}C $Q_{\text{m}} = 3.206$

At $E(^3\text{He}) = 2$ MeV, deuterons have been observed in coincidence with a 2.0 ± 0.1 MeV γ-ray (1957GO1B).

13. ^{10}B(α, t)^{11}C $Q_{\text{m}} = -11.113$

Not reported.

Table 11.11: Levels of ^{11}C from ^{10}B(d, n)^{11}C

$E_{\rm x}$ (MeV $\pm$ keV)	$l_{\rm p}$	J^π	References
0	1	$\frac{3}{2}^- \to \frac{9}{2}^-$ [a]	(1954PA29, 1956CE1B, 1956CE73, 1956MA83)
1.94 ± 50	1	$\frac{3}{2}^- \to \frac{9}{2}^-$ [a,b]	(1952JO10, 1954PA29, 1956CE1B, 1956CE73, 1956GR54, 1956MA83)
4.26 ± 30	1	$\frac{3}{2}^- \to \frac{9}{2}^-$	(1952JO10, 1954PA29, 1956CE1B, 1956CE73, 1956GR54, 1958MC1E, 1959NE1A)
4.75 ± 30	1	$\frac{3}{2}^- \to \frac{9}{2}^-$	(1952JO10, 1955SA1B, 1956CE1B, 1956CE73, 1956GR54, 1959NE1A)
6.50 ± 20	[c]		(1952JO10, 1955BE81, 1955SA1B, 1956CE1B, 1956CE73, 1958MC1E, 1959NE1A)
6.77 ± 40	[c]		(1952JO10, 1956CE1B, 1956CE73)
7.40 ± 40			(1952JO10, 1956CE1B, 1956CE73)
8.108 ± 8			(1952JO10, 1955MA76, 1956CE1B, 1956CE73)
8.431 ± 10	[d]		(1952JO10, 1955MA76, 1956CE1B, 1956CE73)
8.661 ± 10	[d]		(1952JO10, 1955MA76, 1956CE1B, 1956CE73)
8.97 ± 20			(1952JO10, 1956CE1B, 1956CE73, 1957GR50)
(9.13 ± 20)			(1952JO10)
(9.28 ± 30)			(1956CE1B, 1956CE73)
9.69 ± 30			(1956CE1B, 1956CE73)
10.09 ± 20			(1956CE1B, 1956CE73, 1957GR50)
(10.69 ± 20)			(1956CE1B, 1956CE73, 1957GR50)
10.89 ± 20 [e]			(1956CE1B, 1956CE73, 1957GR50)

[a] $(2J + 1)\gamma^2 = 2.1 \times 10^{-19}$ and 0.8×10^{-19} erg $\cdot$ cm for ^{11}B*(0, 2.1), respectively (1956MA83): $\theta_{\rm n}^2 = 0.02$ and 0.016.
[b] J probably $\frac{1}{2}^-$: see ^{10}B(d, p)^{11}B.
[c] $l_{\rm p} = 1$ for unresolved groups at $E_{\rm x} \approx 6.6$ MeV (1956MA83).
[d] $l_{\rm p} = 1$ for unresolved groups at $E_{\rm x} \approx 8.5$ MeV (1956MA83). (1957GR50) reports $l_{\rm n} = 0$.
[e] Neutron groups are also reported to $E_{\rm x} = (11.26 \pm 0.02)$ and (11.52 ± 0.02) MeV (1956CE1B, 1956CE73).

14. ^{10}B(^{6}Li, ^{5}He)^{11}C $Q_{\rm m} = 4.045$

See (1957NO17).

15. ^{11}B(p, n)^{11}C $Q_{\rm m} = -2.764$
     $Q_0 = -2.83^{+0.08}_{-0.05}$ (1956AJ22).

At $E_{\rm p} = 7.03$ MeV, groups are observed corresponding to the ground state and to a state at 2.01 ± 0.06 MeV. The intensity of the ground-state group is ≈ 2.5 times that of the ^{11}C*(2.0) group at the four angles studied; $I(0°)/I(20°) \approx 2.5$ for both groups. An appreciable number of low-energy (< 1.5 MeV) neutrons of undetermined origin is reported (1956AJ22). See also (1955MA84, 1958GO77).

16. ^{11}B(^{3}He, t)^{11}C $Q_m = -1.999$

Not reported.

17. ^{12}C(n, 2n)^{11}C $Q_m = -18.722$

See ^{13}C.

18. ^{12}C(γ, n)^{11}C $Q_m = -18.722$

See ^{12}C.

19. ^{12}C(p, d)^{11}C $Q_m = -16.495$

See (1952BR52, 1956GR1E, 1956WE1B).

20. ^{12}C(d, t)^{11}C $Q_m = -12.463$

See (1956WE1B) and ^{14}N.

21. ^{12}C(^{3}He, α)^{11}C $Q_m = 1.856$

At $E(^3$He$) = 1.3$ and 2.0 MeV, no 1.9 MeV γ-radiation (from ^{11}C*(2.0)) is observed by (1957BR18). The energy of the first excited state is 1.990 ± 0.010 MeV (1959PO61). See also (1952FR1A, 1952PO27, 1953KU08, 1958WE1E).

22. ^{13}C(p, t)^{11}C $Q_m = -15.183$

Not reported.

23. ^{14}N(p, α)^{11}C $Q_m = -2.916$

See ^{15}O.

24. ^{16}O(γ, nα)^{11}C $Q_m = -25.870$

See (1955AJ61).

References

(Closed 1 December 1958)

References are arranged and designated by the year of publication followed by the first two letters of the first-mentioned author's name and then by two additional characters. Most of the references appear in the National Nuclear Data Center files (Nuclear Science References Database) and have NNDC key numbers. Otherwise, TUNL key numbers were assigned with the last two characters of the form 1A, 1B, etc. In response to many requests for more informative citations, we have, when possible, included up to ten authors per paper and added the authors' initials.

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