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Energy Levels of Light Nuclei
$A = 11$

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Abstract: An evaluation of $A = 11$–12 was published in *Nuclear Physics A*248 (1975), 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 NNDC/TUNL format.

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^{11}He

(Not illustrated)

This nucleus has not been observed: see (1974IR04).

^{11}Li

(Figs. 1 and 4)

^{11}Li has been observed in the bombardment of heavy nuclei by GeV protons. Its mass excess is 40.9 ± 0.1 MeV (1973KL1C). ^{11}Li is bound: E_b for breakup into ^{9}Li + 2n and ^{10}Li + n are 0.2 and 0.3 MeV, respectively [see (1974AJ01) for a discussion of the mass of ^{10}Li]. ^{11}Li has a half-life of 8.5 ± 1 msec (1969KL08), 8.5 ± 0.2 msec (1974RO31): it decays to neutron unstable states of ^{11}Be with $P_n = (61 \pm 7)\%$ (1974RO31) [based on $P_n(^{9}\text{Li}) = 35\%$]. See also (1968TH04, 1970AR27, 1971AR1P), (1968AJ02, 1969GA1G, 1969GA32, 1972CE1A, 1972GA1F, 1972KL1A, 1972TH13, 1972WA07, 1973BR1C, 1973KO1D, 1973VO1D, 1974TH01) and (1971DO1F, 1974IR04, 1974MA1E; theor.).

^{11}Be

(Figs. 1 and 4)

GENERAL: (See also (1968AJ02).)

Model calculations: (1970TA1J, 1973SA30, 1973SP02, 1974IR04).

Special reactions: (1969AR13, 1971AR02, 1972VO06, 1973BA81, 1973KO1D, 1973WI15).

Muon capture (See also reaction 2.): (1967DE1E, 1968DE20, 1969BE41, 1970VA24, 1971BE57, 1973MU1B).

Pion reactions: (1962DY1A, 1971BE85).

Mass of ^{11}Be: The mass excess of ^{11}Be is given as 20.181 ± 0.015 MeV (1965MA54) [based on (1962PU01, 1965RY01)] and as 20.174 ± 0.007 MeV (1970GO11). (1971WA1E) adopt 20.177 ± 0.006 MeV, and so do we. See also (1974TH01).

1. ^{11}Be(β^-)^{11}B $\qquad Q_m = 11.509$

The decay proceeds to ^{11}B*(0, 2.12, 5.02, 6.79, 7.98, 9.87) with $J^\pi = \frac{3}{2}^-$, $\frac{1}{2}^-$, $\frac{3}{2}^-$, $\frac{1}{2}^+$, $\frac{3}{2}^+$ and $\frac{3}{2}^+$, respectively: see Table 11.16 (1971AL07). The half-life is 13.81 ± 0.08 sec (1970AL21). See also (1967FL16, 1968AJ02). The nature of the decay indicates $J = \frac{1}{2}$ or $\frac{3}{2}$, even parity for the ground state of ^{11}Be: see (1971AL07).

Table 11.1: Energy levels of ^{11}Be

E_x (MeV $\pm$ keV)	J^π; T	τ or $\Gamma_{c.m.}$ (keV)	Decay	Reactions
0	$\frac{1}{2}^+$; $\frac{3}{2}$	$\tau_{1/2} = 13.81 \pm 0.08$ sec	β^-	1, 2, 3, 5, 7, 8
0.3198 ± 0.2	$\frac{1}{2}^-$	$\tau_m = 0.18 \pm 0.06$ psec	γ	2, 5
1.785 ± 14	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^+$	$\Gamma = 100 \pm 20$	(n)	2
2.69 ± 20	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^+$	200 ± 20	(n)	2
3.41 ± 20	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^+$	125 ± 20	(n)	2
3.89 ± 20		< 10	(n)	2
3.96 ± 20		15 ± 5	(n)	2
5.25 ± 30		45 ± 10	(n)	2
(5.86)		≈ 300	(n)	2
6.51 ± 50		120 ± 50	(n)	2
6.72 ± 30		40 ± 20	(n)	2
7.03 ± 50		300 ± 100	(n)	2
8.84 ± 50		200 ± 50	(n)	2

2. ^{9}Be(t, p)^{11}Be $\qquad Q_m = -1.167$

Proton groups have been observed to many states of ^{11}Be by (1962PU01: $E_t = 14$ MeV) and (1972AJ01: $E_t = 20$ MeV): see Table 11.2. The first excited state has an excitation energy of 319.8 ± 0.2 keV and $\tau_m = 0.18 \pm 0.06$ psec, corresponding to a very strong E1 transition of 0.33 W.u. (1971HA25). The J^π of ^{11}Be*(0.32) is $\frac{1}{2}^-$, as determined by a study of the yield of 320 keV γ-rays as a function of time in μ^- capture by ^{11}B (1968DE20). The strength of the E1 transition fixes J^π of ^{11}Be$_{g.s.}$ to be $\frac{1}{2}^+$ or $\frac{3}{2}^+$, using the parity information obtained from the nature of the β^- decay of the ground state [see reaction 1]. J^π limits for ^{11}Be*(1.79, 2.69, 3.41) are derived from angular distribution studies (1962PU01, 1964HI08). ^{11}Be*(5.25, 6.72, 8.84) are strongly populated at $E_t = 20$ MeV indicating that these states have a large overlap with ^{9}Be$_{g.s.}$ + two neutrons (1972AJ01). See also (1968AJ02) and (1970AL21, 1971AL07).

3. ^{9}Be(^{6}He, α)^{11}Be $\qquad Q_m = 6.344$

See ^{15}C in (1970AJ04).

4. ^{10}Be(n, γ)^{11}Be $\qquad Q_m = 0.503$

Table 11.2: Levels of ^{11}Be from ^{9}Be(t, p)^{11}Be

E_x (keV) [a]	E_x (keV) [b]	Γ_{lab} (keV) [a]	$\Gamma_{c.m.}$ (keV) [b]	J^π
0	0			$\frac{1}{2}^+$
319.8 ± 0.2 [c]	322 ± 10			$\frac{1}{2}^-$
1780 ± 20	1790 ± 20	110 ± 15	130 ± 25	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^+$
2700 ± 25	2680 ± 30	250 ± 20	250 ± 50	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^+$
3410 ± 25	3410 ± 30	150 ± 20	145 ± 30	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^+$
3890 ± 20	3890 ± 30	< 10	≤ 10	
3960 ± 20	3960 ± 30	< 10	15 ± 5	
	5250 ± 30		45 ± 10	
	(5860)		≈ 300	
	6510 ± 50		120 ± 50	
	6720 ± 30		40 ± 20	
	7030 ± 50		300 ± 100	
	8840 ± 50		200 ± 50	

[a] (1962PU01).
[b] (1972AJ01).
[c] (1971HA25).

The capture cross section is < 1 mb (E.T. Jurney, private communication).

5. ^{10}Be(d, p)^{11}Be $\qquad Q_m = -1.722$

Angular distributions of the p_0 and p_1 groups have been measured at $E_d = 6$ MeV (1970GO11: p_1 only) and 12 MeV (1970AU02): $l_n = 0$ [and therefore $J^\pi = \frac{1}{2}^+$ for ^{11}Be(0)] and 1, $S = 0.73 \pm 0.06$ and 0.63 ± 0.15, respectively (1970AU02). $E_x = 318 \pm 7$ keV for ^{11}Be*(0.32) (1970GO11). See also (1973GO09) and ^{12}B.

6. ^{11}Li(β^-)^{11}Be $\qquad Q_m = 20.7$

See ^{11}Li.

7. ^{11}B(n, p)^{11}Be $Q_{\rm m} = -10.726$

See (1967FL16) and ^{12}B.

8. ^{14}C(^{18}O, ^{21}Ne)^{11}Be $Q_{\rm m} = -12.208$

See (1974BA15).

^{11}B

(Figs. 2 and 4)

GENERAL: (See also (1968AJ02).)

Shell model: (1968GO01, 1970CO1H, 1971BA2Y, 1971NO02, 1972LE1L, 1973HA49, 1973KU03, 1973SA30, 1974ME19).

Cluster and collective models: (1969BA1J, 1970BA1Q, 1971NO02, 1972LE1L, 1973KU03).

Special levels: (1968GO01, 1969HA1G, 1969HA1F, 1970FR1C, 1971NO02, 1972MS01, 1973MA1K, 1973SA30, 1974IR04).

Electromagnetic transitions: (1967WA1C, 1969HA1G, 1969HA1F, 1969WA1C, 1970AL1E, 1972KE36, 1972MU1B, 1972TA21, 1972NA05, 1973HA49, 1973SA30, 1974ME19, 1974MU13).

Astrophysical questions: (1967MI1A, 1972CL1A, 1972KO1E, 1973AU1H, 1973CA1B, 1973CO1B, 1973LA19, 1973RE1G, 1973TI1A, 1973TR1B, 1973WE1D, 1974AU1A, 1974BO1K, 1974JA11, 1974MO1G, 1974RE1A, 1974WO1G).

Special reactions: (1968HA1C, 1968YI01, 1969DA1D, 1969GA18, 1969YI1A, 1971AR02, 1971BA16, 1973KO1D, 1973KU03, 1973LA19, 1973WI15, 1974BA70, 1974BE58, 1974FO22, 1974JA11, 1974LA18, 1975CR01, 1975KU01, 1975PO02).

Muon capture and muon reactions: (1968DE20, 1969BE41, 1969WU1A, 1970FA15, 1970VA24, 1971BE57, 1971BU11, 1971DE2D, 1972BE71, 1972MI15 †).

Pion capture and pion reactions: (1968BO32, 1968GR1C, 1968LO1A, 1968NO1A, 1968NY1A, 1968RI1H, 1968TA1C, 1968WI1B, 1969AG1A, 1969BU1C, 1969MO1E, 1970BA1E, 1970LI1H, 1971BA16, 1971BE85, 1971FA09, 1972HU1A, 1972KA1F, 1972NO1B, 1973AL1D, 1973CH20, 1973JA1J, 1973NY04, 1974HU14, 1974KA07, 1974LE12, 1974TA18).

Kaon reactions: (1972BA09, 1973CH1M).

Other topics: (1968BU1B, 1968GO01, 1968ME13, 1970CO1H, 1971BA2Y, 1972AN05, 1972CA37, 1972LE1L, 1972MU1B, 1972PN1A, 1973CL09, 1973JU2A, 1973KU03, 1973MA48, 1973RO1R, 1974IR04, 1974MO1H, 1974MU13, 1975KU01).

Ground state properties: (1967CO1D, 1967SH14, 1968RO1E, 1969LE1B, 1969PE1D, 1969WU1A, 1971TA1A, 1971ZO03, 1972GL06, 1972LE1L, 1972VA36, 1973CO1P, 1973KU1L, 1973MA1K, 1973SA30, 1973SU1B, 1973SU1C, 1974HA27, 1974ME19, 1974MU13).

$\mu = +2.68864 \pm 0.00007$ nm (1969FU11, 1971SH26);

$Q = 0.0386$ b (1968SC18);

[$Q = 0.04065 \pm 0.00026$ b (1970NE05; theor.)].

† (1972MI15) have observed the γ-decay of ^{11}B*(2.12).

Table 11.3: Energy levels of ^{11}B [a]

E_x in ^{11}B (MeV $\pm$ keV)	J^π; T	τ_m or $\Gamma_{c.m.}$ (keV)	Decay	Reactions
g.s.	$\frac{3}{2}^-$; $\frac{1}{2}$	stable		1, 2, 7, 8, 9, 13, 14, 15, 16, 17, 18, 19, 26, 27, 28, 29, 30, 31, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 64, 65, 66, 67, 68, 69, 70
2.1247 ± 0.4	$\frac{1}{2}^-$	$\Gamma = 0.136 \pm 0.010$ eV	γ	1, 7, 8, 9, 14, 15, 16, 26, 27, 28, 36, 37, 39, 40, 41, 45, 49, 53, 54, 55, 56, 57, 58, 59, 61, 62, 64, 65, 67, 68, 69
4.4451 ± 0.5	$\frac{5}{2}^-$	0.610 ± 0.030 eV	γ	1, 2, 7, 8, 9, 14, 15, 16, 19, 26, 27, 28, 37, 39, 40, 41, 44, 45, 49, 54, 55, 56, 57, 58, 64, 65, 67, 68, 69
5.0207 ± 0.6	$\frac{3}{2}^-$	2.6 ± 0.3 eV	γ	1, 7, 8, 9, 14, 15, 16, 26, 27, 28, 36, 37, 39, 40, 41, 45, 55, 56, 57, 58, 64, 65, 67, 68, 69
6.7429 ± 0.6	$\frac{7}{2}^-$	$\tau_m < 10$ fsec	γ	1, 2, 7, 14, 15, 19, 27, 28, 40, 41, 45, 57, 64, 65, 68, 69
6.7929 ± 1.0	$\frac{1}{2}^+$	< 35 fsec	γ	1, 2, 7, 14, 15, 16, 27, 28, 36, 40, 41, 45, 49, 56, 57, 65, 68
7.2856 ± 1.5	$(\frac{3}{2}, \frac{5}{2})^+$	$\Gamma = 1.1 \pm 0.6$ eV	γ	1, 7, 14, 15, 16, 27, 28, 39, 40, 41, 45, 57
7.9780 ± 1.3	$\frac{3}{2}^+$	$\tau_m < 30$ fsec	γ	1, 14, 16, 27, 36, 41, 57
8.5594 ± 1.9	$\leq \frac{5}{2}^-$	$\Gamma = 1.7 \pm 0.2$ eV	γ	1, 14, 27, 39, 41, 45
8.9202 ± 2.0	$\frac{5}{2}^-$	5.2 ± 0.6 eV	γ, α	1, 2, 14, 19, 27, 39, 41, 64
9.1860 ± 2.0	$\frac{7}{2}^+$	3 eV	γ, α	1, 2, 14, 27, 41, 68
9.2750 ± 2.0	$\frac{5}{2}^+$	7 keV	γ, α	1, 2, 14, 27, 39, 41, 68
9.870 ± 10	$\frac{3}{2}^+$	130 ± 30	α	6, 14, 36
10.26 ± 20	$\frac{3}{2}^-$, $\frac{1}{2}$	150 ± 40	γ, α	2, 6
10.33 ± 20	$(\frac{5}{2}, \frac{7}{2})^-$	70 ± 20	γ, α	2, 6, 16, 27
(10.45 ± 50)		≈ 140	γ, α	2, 41
10.601 ± 10	$\frac{7}{2}^+$	70 ± 10	γ, n, α	2, 6, 25
10.96 ± 50	$\frac{5}{2}^-$	4500	α	6
11.29 ± 30	$\frac{9}{2}^+$	90 ± 50	α	6

Table 11.3: Energy levels of ^{11}B [a] (continued)

E_x in ^{11}B (MeV $\pm$ keV)	J^π; T	τ_m or $\Gamma_{c.m.}$ (keV)	Decay	Reactions
11.49 ± 50			α	6
11.61 ± 50	$\frac{5}{2}^+$	150 ± 50	n, α	3, 6, 20, 25, 41
11.8	$\frac{7}{2}^+$	880	n, α	6, 25
11.88 ± 30		150 ± 50	α	6
11.99 ± 100	$\frac{5}{2}^-$	170	n, α	3, 25
(12.18 ± 40)		230 ± 90	γ, p	18
12.56 ± 30	$\frac{1}{2}^+(\frac{3}{2}^+)$; $T = \frac{3}{2}$	240 ± 50	γ, p, α	6, 16, 18, 38, 44
12.91 ± 20	$\frac{1}{2}^-$; $T = \frac{3}{2}$	240 ± 30	γ, p, α	18, 39, 41, 44, 64
13.03 ± 60		270 ± 50	α	6, 39
13.12	$\frac{9}{2}^-$	425	n, α	3, 20, 25
13.16	$\frac{5}{2}^+$, $\frac{7}{2}^+$	430	n, α	3, 20, 25
14.04 ± 100	$\frac{11}{2}^+$	500 ± 200	n, α	3, 6, 20, 21, 25
14.33 ± 20	$\frac{5}{2}^{(+)}$, $(\frac{3}{2}^-)$; $T = \frac{3}{2}$	250 ± 40	γ, p	18, 44
14.53 ± 50		< 120	n, t, α	3, 6, 20, 21, 24, 25, 44
15.32 ± 100	$(\frac{3}{2}, \frac{5}{2}, \frac{7}{2})^+$; $T = \frac{3}{2}$	635 ± 180	γ, n, p, α	3, 6, 18, 20, 21, 25, 38, 41
15.8 ± 200			n, α	3, 6, 21
16.4 ± 150		broad	n, t, α	3, 24, 25, 41
(16.43 ± 15)		≈ 40	p, d, α	11
17.33		≈ 1000	n, p, d, t, α	11, 24, 25
17.50 ± 50		185 ± 40	γ, n, p, d, α	3, 9, 11, 38
18.37 ± 50	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^+$	260 ± 80	γ, d	9
(19.7)	$(\frac{1}{2})^+$	broad	γ, d	9, 56
21.6			γ, p	38
23.5	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^+$		γ, p	9, 38
25.2 ± 100		broad	γ, n, p	38
27.7			γ, p	38
29.2			γ, p	38

[a] See also Tables 11.4, 11.5 and 11.19.

Table 11.4: Electromagnetic transitions in ^{11}B [a]

Initial state	$J^\pi;\ T$	Γ_γ (total) [c] (eV)	Branching ratios (%) to final states						Refs.
			g.s. $\frac{3}{2}^-;\ \frac{1}{2}$	2.12 $\frac{1}{2}^-;\ \frac{1}{2}$	4.45 $\frac{5}{2}^-;\ \frac{1}{2}$	5.02 $\frac{3}{2}^-;\ \frac{1}{2}$	6.74 $\frac{7}{2}^-;\ \frac{1}{2}$	6.70 $(\frac{1}{2}, \frac{3}{2})^+;\ \frac{1}{2}$	
2.12	$\frac{1}{2}^-;\ \frac{1}{2}$	0.136 ± 0.010	100						
4.45	$\frac{5}{2}^-;\ \frac{1}{2}$	0.610 ± 0.030	100 [e]	< 0.5					
			> 97	< 3					(1968BE30)
5.02 [b]	$\frac{3}{2}^-;\ \frac{1}{2}$	2.6 ± 0.3	85 ± 2	15 ± 2	0.3				
			88 ± 2	12 ± 2					(1968EA03)
			88 ± 2.5 [f]	12 ± 2.5 [g]					(1968BE30)
			83 ± 5	17 ± 5					(1971AL07)
6.74 [b,h]	$\frac{7}{2}^-;\ \frac{1}{2}$		70 ± 2	< 3	30 ± 2	< 1			
6.79 [b]	$\frac{1}{2}^+;\ \frac{1}{2}$		71 ± 5	29 ± 5	< 8	< 8			
			66.0 ± 1.5	30.0 ± 1.5	< 0.5	4.1 ± 0.9			(1971AL07)
			67 ± 3	33 ± 3					(1968EA03)
7.29 [c]	$(\frac{3}{2}, \frac{5}{2})^+;\ \frac{1}{2}$	1.1 ± 0.6	87 ± 2	< 1	5.5 ± 1	7.5 ± 1			
7.98 [b]	$\frac{3}{2}^+;\ \frac{1}{2}$		47 ± 2	53 ± 2	< 1	< 1			
			45 ± 2	55 ± 2	< 1.6	< 1.6	< 1.5	< 1.4	(1971AL07)
8.56	$\leq \frac{5}{2}^-;\ \frac{1}{2}$	1.7 ± 0.1	56 ± 2	30 ± 2	5 ± 1	9 ± 1			
			50	30	10	10			(1972NI05)
8.92 [i]	$\frac{5}{2}^-;\ \frac{1}{2}$	5.2 ± 0.6	96		4				(1972NI05)
			93 ± 5		2.3 ± 1				(1962GR07)
			95 ± 1	< 1	4.5 ± 0.5	< 1	< 1	< 1	
9.19	$\frac{7}{2}^+;\ \frac{1}{2}$	≈ 3	0.9 ± 0.3		82.8 ± 2.0		12.8 ± 0.4	< 1.3	(1962GR07)
9.28 [d]	$\frac{5}{2}^+;\ \frac{1}{2}$		19.7 ± 1.0		67.5 ± 2.0		12.8 ± 0.7	< 0.6	(1962GR07)

[a] (1965OL03) except where shown.

[b] See also (1972NI05).

[c] From Table 11.7, corrected for branching to other states.

[d] See Tables 11.6, 11.11, and 11.17 for higher states.

[e] $\delta = -0.19 \pm 0.03$ (1968BE30).

[f] $\delta = 0.03 \pm 0.05$ (1968BE30).

[g] $\delta = -0.05 \pm 0.2$ (1968BE30).

[h] $\delta = -0.45 \pm 0.18$ (1968CO09).

[i] $\delta = -0.11 \pm 0.04$ (1968CO09).

Comments [mainly from (1962GR07, 1965OL03)]

1) *4.45 MeV*. $9.28 \rightarrow 4.45 \rightarrow 0$ angular distribution fixes $J = \frac{5}{2}$. Odd parity determined from direct interaction assignments.

2) *5.02 MeV*. Internal pair correlation permit M1, E2 for the g.s. transition: $J^\pi \leq \frac{7}{2}^-$ (parity from l-assignments). $\tau_{\rm m}$ excludes $\frac{7}{2}$, branch to 2.12, $\frac{5}{2}$. Angular correlation (1968BE30) fixes $\frac{5}{2}^-$.

3) *6.74 MeV*. Internal pairs indicate practically pure E2 g.s. radiation. Angular distributions and branching ratios (and l-assignments) all lead to $\frac{7}{2}^-$.

4) *6.79 MeV*. The allowed β-decay from ^{11}Be indicates $J^\pi \leq \frac{7}{2}^+$ The relatively strong γ-branch to ^{11}B*(21.2) favors $\frac{1}{2}^+$, $\frac{3}{2}^+$. (1968EA03) finds that all γ's from this level are isotropic, suggesting $J^\pi = \frac{1}{2}^+$, but not excluding $\frac{3}{2}^+$.

5) *7.29 MeV*. The g.s. transition is mainly E1, so $J^\pi \leq \frac{5}{2}^+$. The assignment $\frac{1}{2}^+$ is excluded by the strength of $(7.29 \rightarrow 4.45)$.

6) *7.98 MeV*. Transitons to ^{11}B(g.s.) and (2.12) are predominantly E1; thus ^{11}B*(7.98) has even parity, and the odd parity of ^{11}B*(2.12) is confirmed. The transiton to ^{11}B*(2.12) is not isotropic, so $J^\pi = \frac{3}{2}^+$.

7) *8.56 MeV*. Correlation of internal pairs indicate that the g.s. transition is M1 + E2 or E1 + M2, $J^\pi \leq \frac{5}{2}^+$ or $\leq \frac{7}{2}^-$; the lifetime to ^{11}B*(2.12) excludes $\frac{7}{2}^-$. If the level has even parity, the required M2 admixture is excessive. $J^\pi \leq \frac{5}{2}^-$ is favored.

8) *8.92 MeV*. From ^{7}Li(α, γ)^{11}B, $J^\pi = \frac{3}{2}^+$, $\frac{5}{2}^+$, $\frac{5}{2}^-$. The internal pair correlation confirms $\frac{5}{2}^-$. For higher states see comments under individual reactions and (1968AJ02).

Table 11.5: Lifetimes of some ^{11}B states

^{11}B state	$\tau_{\rm m}$ (fsec)	Refs.
2.12	4.8 ± 0.4	Table 11.17
4.45	1.12 ± 0.06	Table 11.17
5.02	0.33 ± 0.03	Table 11.17
6.74	< 300	(1966WA10)
	< 210	(1969TH01)
	< 10	(1969BEYX)
6.79	< 50	(1969BEYX)
	< 35	(1969TH01)
7.29	< 23	(1969TH01)
	0.6 ± 0.3	Table 11.17
7.98	< 66	(1969TH01)
	< 30	(1969BEYX)
8.56	< 60	(1969TH01)
	0.33 ± 0.20	Table 11.17
8.92	0.16 ± 0.03	Table 11.17

1. ^{6}Li(^{6}Li, p)^{11}B $\qquad Q_{\rm m} = 12.218$

Angular distributions of the protons have been reported at $E(^{6}\text{Li}) = 2.0$ MeV (1971PO1D; unpublished: $E_{\rm x} \leq 8.0$ MeV) and 2.4 to 9.0 MeV (1966KI09: $E_{\rm x} < 9.3$ MeV). For γ-spectra see (1962BE24, 1969TH01) and Table 11.4. $\tau_{\rm m}$, measured in this reaction and in reactions 7, 8 and 29 are shown in Table 11.5 (1969TH01).

2. ^{7}Li(α, γ)^{11}B $\qquad Q_{\rm m} = 8.666$

Resonances for capture radiation are displayed in Table 11.6 (1951BE13, 1954HE22, 1967PA19). Angular distributions, branching ratios and correlations have been studied by (1959JO25, 1962GR07): they determine $J^{\pi} = \frac{5}{2}^{-}$, $\frac{7}{2}^{-}$, $\frac{5}{2}^{-}$ or $(\frac{3}{2}^{+})$, $\frac{7}{2}^{+}$ and $\frac{5}{2}^{+}$, respectively for ^{11}B*(4.45, 6.74, 8.92, 9.19, 9.28): see (1968AJ02) for a more complete discussion and Tables 11.4 and 11.6. See also (1969OM1A).

3. ^{7}Li(α, n)^{10}B $\qquad Q_{\rm m} = -2.790$ $\qquad E_{\rm b} = 8.666$

Table 11.6: Resonances in ^{7}Li(α, γ)^{11}B [a]

E_r (keV)	$\Gamma_{c.m.}$ (keV)	^{11}B* (MeV)	J^π	$\omega\Gamma_s$ [d] (eV)	Γ_{γ_0} [e] (eV)	Percentage decay to ^{11}B* [f]			
						0	4.44	6.74	6.79
401 [b]	< 1 [b]	8.921	$(\frac{5}{2})^-$	0.04	[j]	93 ± 5	2.3 ± 1		
819 ± 1 [b]	≈ 3 [g] eV	9.187	$\frac{7}{2}^+$	0.55		0.9 ± 0.3	82.8 ± 2.0	12.8 ± 0.4	< 1.3
958 ± 1 [b]	7 [b]	9.276	$\frac{5}{2}^+$	3.5		19.7 ± 1.0	67.5 ± 2.0	12.8 ± 0.7	< 0.6
2500 ± 20 [c]	433	10.26			17	[h]			
2620 ± 20 [c]	100	10.33			1.0	[h]			
2800 ± 50 [c]	≈ 140 [i]	10.45			$10/2J+1$				
(3040) [c]	90	(10.60)			< 0.2	[h]			

[a] See also Tables 11.4, 11.8, 11.9 and 11.17 and Table 11.4 in (1968AJ02).
[b] (1951BE13). See also (1954HE22).
[c] (1967PA19).
[d] $\omega\Gamma_\gamma\Gamma_\alpha/\Gamma$, in c.m. (1951BE13, 1959JO25). See also (1965OL03).
[e] (1967PA19); based on analysis using $R = 4.9$ fm, $\gamma^2_W = 1.0$ MeV.
[f] (1962GR07). See also Table 11.4.
[g] (1965OL03).
[h] $< 10\%$ to ^{11}B*(2.12) (1967PA19).
[i] Observed width (1967PA19).
[j] See Table 11.17.

Cross section measurements have recently been carried out by (1968MA07) for $E_\alpha = 4.43$ to 5.12 MeV (n_0) and by (1972VA02) for $E_\alpha = 4.5$ to 8.0 MeV (n_0) and 5.7 to 8.0 MeV (n_1). Results from these and previous measurements are displayed in Table 11.7 (1957BI84, 1959GI47, 1963ME08). See also (1968DA1H).

4. ^{7}Li(α, p)^{10}Be $\quad Q_m = -2.5638 \quad E_b = 8.666$

See ^{10}Be in (1974AJ01).

5. ^{7}Li(α, t)^{8}Be $\quad Q_m = -2.5586 \quad E_b = 8.666$

Excitation functions have been measured for $E_\alpha = 14$ to 25 MeV (t_0) and 18 to 25 MeV (t_1): they are essentially smooth (1973VA1A). See also ^{8}Be in (1974AJ01) and (1974KA32; theor.).

Table 11.7: Thresholds and resonances in ^{7}Li(α, n)^{10}B

(1957BI84)		(1959GI47)	(1963ME08)	
E_α (MeV $\pm$ keV)	$\Gamma_{\rm lab}$ (keV)	E_α (MeV $\pm$ keV)	E_α (MeV $\pm$ keV)	$E_{\rm x}$ (MeV $\pm$ keV)
4.379 ± 6 (thresh.)			4.380 ± 20	thresh.
4.7			[4.72]	11.67 ± 100
5.15 ± 80	220	5.15 ± 70 [a]	[5.22] [c]	11.99 ± 100
		(5.64)	5.5	thresh.
		7.15 [b]	7.05 [c]	13.15 ± 100
			[8.44]	14.04 ± 100
			[9.21]	14.53 ± 50
			10.14	15.12 ± 100
			[11.33]	(15.88 ± 200)
			11.90	thresh.
			12.56	(16.7 ± 300)
			13.92	17.53 ± 30
			14.53	thresh.

[a] $J^\pi = \frac{3}{2}^-$ or $\frac{5}{2}^+$, $\Gamma_{\rm n} \approx 20$ keV, $\Gamma_\alpha \approx 300$ keV, formed by $l_{\rm n} = 0$ or 1 (1959GI47) [comparison with ^{10}B(n, α)].

[b] The width of this resonance is large.

[c] The n_0 yield shows the resonances at $E_\alpha \approx 5.2$ and 7.05 MeV: no others are seen in the interval $4.5 < E_\alpha < 8$ MeV (1972VA02).

6. ^{7}Li(α, α)^{7}Li $\qquad E_{\rm b} = 8.666$

The elastic scattering has been studied for $E_\alpha = 1.6$ to 12 MeV (1966CU02), 2.5 to 4.5 MeV (1972BO07), 8.6 to 12.5 MeV and 17.0 to 22.5 MeV (1973KE13) and 12.0 to 18.0 MeV (1970BI1B, 1971BI12). The inelastic scattering, leading to ^{7}Li*(0.48), has been studied at $E_\alpha = 1.6$ to 12 MeV (1966CU02), 1.6 to 3.2 MeV (1967PA19), 2.5 to 4.5 MeV (1972BO07), 5.8 to 6.7 MeV (1975BA06) and 17.0 to 22.5 MeV (1973KE13). See also (1968AJ02) for earlier references.

Observed resonances are displayed in Tables 11.8 and 11.9 (1966CU02, 1967PA19). A weak structure at $E_\alpha \approx 12.7$ MeV and broad structures at $E_\alpha \approx 12$ to 15 MeV are reported by (1970BI1B, 1971BI12): it is not clear whether these correspond to states in ^{11}B. (1973KE13) suggest that the deviations from smooth behavior in the excitation functions are due to the exchange of a triton cluster between two α-particles. See also ^{7}Li in (1974AJ01).

Table 11.8: Structure in ^{7}Li(α, α)^{7}Li and ^{7}Li(α, α')^{7}Li* [a]

E_α [b] (keV)	E_α [c] (keV)	$\Gamma_{\rm c.m.}$ (keV)	$E_{\rm x}$ (MeV $\pm$ keV)
1900 ± 10 [d]		130 ± 30	9.875 ± 10
2480 ± 50		150 ± 40	10.24 ± 50
	2630 ± 30	80 ± 30	10.34 ± 30
3040 ± 10 [d]	3040	70 ± 10	10.601 ± 10
3600 ± 50		≥ 900	10.96 ± 50
	4120 ± 30	90 ± 50	11.29 ± 30
4430 ± 50	4430		11.49 ± 50
4600 ± 50		150 ± 50	11.59 ± 50
5050 ± 30		150 ± 50	11.88 ± 30
	5300 ± 200	≈ 1000	12.0 ± 200
	5500 ± 100	60 ± 50	(12.17 ± 100) [e]
6100 ± 30		150 ± 50	12.55 ± 30
6850 ± 60		270 ± 50	13.03 ± 60
(7200 ± 50) [f]		50 ± 50	(13.25 ± 50) [e]
	7800 ± 100	500 ± 200	(13.63 ± 100) [e]
(8450 ± 200) [g]		500 ± 200	(14.0 ± 200)
(9450 ± 200) [g]		≤ 250	(14.7 ± 200)
	9950 ± 20	500 ± 200	(15.00 ± 20) [e]
(11200 ± 200) [g]			(15.8 ± 200)

[a] (1966CU02), except where shown. See also Table 11.9.

[b] ^{7}Li(α, $\alpha'\gamma$)^{7}Li: σ(total).

[c] ^{7}Li(α, α_0)^{7}Li.

[d] (1967PA19). Other values are 1889 ± 10 (1954LI48), 1910 ± 20 (1957BI84), 1920 ± 30 keV (1966CU02); and 3060 ± 30 (1957BI84), 3032 ± 10 keV (1966CU02).

[e] ^{7}Li(α, n)^{10}B threshold.

[f] Anomaly in angular distribution.

[g] Observed at $\theta = 60°$.

Table 11.9: Resonance parameters in ^{7}Li(α, α)^{7}Li

E_r (MeV)	E_x (MeV)	J^π	$\Gamma_{c.m.}$ [a] (keV)	$\Gamma_{c.m.}$ [b] (keV)	Γ_i/Γ_e [a,e]	Γ_i/Γ_e [b,c]
1.90	9.88	$\frac{3}{2}^+$	250	290	4.0	0.18 [e]
2.50	10.26	$\frac{3}{2}^{(-)}$, $\frac{1}{2}$	200	433	0.04	0.13
2.62	10.33	$\frac{5}{2}^-$, $\frac{7}{2}^-$	100	100	0	0
2.80	10.45			≈ 140		$\ll 1$
3.04	10.60	$\frac{7}{2}^+$	90	90	1.0	0.49
3.54	10.92	$\frac{5}{2}^-$	4500		1.5	
[d]		$\frac{1}{2}^+$	4000		4.6	
4.12	11.29	$\frac{9}{2}^+$	100		0	

[a] (1966CU02): used $R = 6$ fm.

[b] (1967PA19): used $R = 4.9$ fm, $\gamma_W^2 = 1.0$ MeV.

[c] Width ratio: inelastic/elastic.

[d] Broad level in background: E_λ(c.m.) = 1.71. See, however, (1967PA19).

[e] $\Gamma_{\gamma_0} < 0.5$ eV (1967PA19).

7. ^{7}Li(^{6}Li, d)^{11}B $\qquad Q_m = 7.192$

Angular distributions of deuterons have been measured at $E(^{7}\text{Li}) = 3.3$ MeV (1967GA06: $d_0 \rightarrow d_3$) and 3.78 to 5.95 MeV (1967KI03: $d_0 \rightarrow d_3$, d_{4+5}, d_6). For γ-spectra see (1962BE24, 1969TH01) and Table 11.4. For τ_m see Table 11.5 (1969TH01). See also ^{13}C in (1976AJ04).

8. ^{7}Li(^{7}Li, t)^{11}B $\qquad Q_m = 6.199$

Angular distributions have been measured at $E(^{7}\text{Li}) = 2.10$ to 5.75 MeV (1969CA1A: $t_0 \rightarrow t_3$). For τ_m see Table 11.5 (1969TH01). At $E(^{7}\text{Li}) = 79.6$ MeV transitions are observed to several ^{11}B states. $^{11}B_{g.s.}$ is particularly strongly populated: 23 μb/sr, at 7.4° (1974CE06). See also (1974CE1A).

9. ^{9}Be(d, γ)^{11}B $\qquad Q_m = 15.8167$

Radiative transitions have been observed to ^{11}B*(0, 2.12, $4.45 + 5.02$) at $E_d = 0.5$ to 1.4 MeV (1966ZI01) and 0.56 to 3.56 MeV (1970BA1R, 1971BA72). The 90° γ_0 differential cross

section has been measured for $E_d = 0.5$ to 5.5 MeV (1963SU09, 1966SU05, 1966SU1C) and 2.9 to 11.9 MeV (1974DE01, 1974DE39). The behavior of the γ_0, γ_1 and γ_{2+3} total cross sections and of the angular distributions of these γ-rays indicate two resonances at $E_d = 1.98 \pm 0.05$ and 3.12 ± 0.05 MeV with $\Gamma_{lab} = 225 \pm 50$ and 320 ± 100 keV, corresponding to ^{11}B*(17.43, 18.37). The higher resonance was not observable in the $\gamma_2 + \gamma_3$ cross section which was not measured beyond $E_d = 2.5$ MeV. The maximum γ_0 cross section observed is 10.1 ± 3.5 μb at $E_d \approx 0.96$ MeV (1971BA72). (1974DE39) observe resonant behavior in the $90°$ γ_0 cross section at $E_d \approx 3.4$ and 9.65 MeV (^{11}B*(18.6, 23.7)) in addition to a wide structure at 4.7 MeV (^{11}B*(19.7)). The angular distributions of γ_0 from ^{11}B*(18.6, 23.7) are typical of E1 transitions. The (d, γ_0) reaction appears to proceed via excitation of the $T = \frac{1}{2}$ component of the giant dipole resonance in ^{11}B.

10. ^{9}Be(d, n)^{10}B $\quad Q_m = 4.3607$ $\quad E_b = 15.8167$

The cross section follows the Gamow function for $E_d = 70$ to 110 keV (1955RA14). The fast neutron and γ-yield rise smoothly to $E_d = 1.8$ MeV except for a possible "resonance" at $E_d \approx 0.94$ MeV. The fast neutron yield then remains approximately constant to 3 MeV: see (1968AJ02) for references. The excitation functions for $n_0 \rightarrow n_4$, and n to ^{10}B*(5.1, 6.57) have been measured for $E_d = 14$ to 16 MeV: no strong fluctuations are observed (1973PA14). Polarization measurements have been reported at $E_d = 0.9$ to 2.5 MeV (1970MI04: $n_0 \rightarrow n_4$), 3.0 to 5.5 MeV (1974TH02: $n_0 \rightarrow n_5$ and n to ^{10}B*(5.1, 6.6)) and 3.0 and 3.5 MeV (1970SP1A, 1971SP1C: $n_0 \rightarrow n_4$). For papers dealing with applications see (1971DA21, 1971EL1B, 1972LU1B, 1973AU1G, 1973WE1T, 1973WE19). See also (1972DA34, 1973SZ07), (1970MI1G; theor.) and ^{10}B in (1974AJ01).

11. (a) ^{9}Be(d, p)^{10}Be $\quad Q_m = 4.5873$ $\quad E_b = 15.8167$
(b) ^{9}Be(d, α)^{7}Li $\quad Q_m = 7.1511$
(c) ^{9}Be(d, t)^{8}Be $\quad Q_m = 4.5925$

Recently measurements of proton yields have been carried out by (1974AN01: 0.3 to 0.9 MeV; p_0, p_1), (1974FR02: 0.6 to 2.7 MeV (p_0), 1.0 to 2.7 MeV (p_1)), (1972AR31: 0.75 to 2.25 MeV; p_0), (1974BO42: 0.9 to 2.5 MeV; p_0, p_1), (1973SA1Q: 0.9 to 3.1 MeV; p_0, p_1) and (1970PO03: 4.5 to 6.0 MeV; p_0, p_1). From these and previous measurements it appears that the p_0 and p_1 yields show a resonance at $E_d = 750 \pm 15$ keV [^{11}B*(16.43)], $\Gamma \approx 40$ keV (1974AN01) and the p_1 yield a resonance at 1.85 MeV [^{11}B*(17.33)], $\Gamma_{c.m.} \approx 1.0$ MeV (1973SA1Q). [The latter is also reported in the yield of 3.37 MeV γ-rays by (1957MC35).] Broad maxima have also been reported at $E_d \approx 0.9$ MeV, (1.3) and 2.1 MeV by (1952CA19: p_0) [see also (1972AR31)] and at 1.3 MeV by (1957MC35: 3.37 MeV γ-ray). (1974FR02) report a broad resonance at $E_d = 1.8$ MeV and a sharp resonance at 2.3 MeV, in the p_1 yield. See also (1968BE1E). Polarization of the protons has been studied at many energies in the range $E_d = 1$ to 21 MeV: see (1968AJ02) for the earlier work and (1968YU01: 7.0 MeV; p_0), (1969CU10: 10.0 MeV; p_0), (1970FI07: 10 and 12 MeV;

p_0, p_1), (1971GR20: 11.8 MeV; p_0), (1971BR44: 12 MeV; p_0), (1972BU26: 12.0 MeV; p_0, p_1), (1968BA19, 1973JO10: 12.3 MeV; p_0, p_1). See also (1967SA06, 1972FI1E, 1973FI1C). See also ^{10}Be in (1974AJ01).

The yields of α-particles, both α_0 and α_1, (reaction (b)) have been measured at $E_d = 0.3$ to 0.9 MeV (1974AN01), 0.5 to 2.3 MeV (1962BI11), 0.6 to 2.0 MeV (1974FR02), 0.9 to 2.2 MeV (1971SA27) and 8 to 12.4 MeV (1966DO1A; also α_2 for $E_d = 9$ to 12.4 MeV). (1974AN01) report a weak indication of the 0.75 MeV resonance, observed in the proton yield, in the α_0 yield. (1962BI11) find no clear indication of resonance structure. See also (1968BE1E, 1973SZ07) and ^{7}Li in (1974AJ01).

The cross section for reaction (c) has been measured for $E_d = 0.15$ to 19 MeV: see (1968AJ02) for the earlier references and (1974AN01: 0.3 to 0.9 MeV; t_0), (1974FR02: 0.6 to 2.0 MeV; t_0), (1974BO42: 0.9 to 2.5 MeV; t_0) and (1973SA1Q: 0.9 to 3.1 MeV; t_0). There is no clear evidence of resonance structure: see, however, (1955JU10, 1955JU1B, 1958JU38). See also ^{8}Be in (1974AJ01).

See also (1973BI1G), (1971EL1B: applied) and (1971KO1Q; theor.).

12. ^{9}Be(d, d)^{9}Be $E_b = 15.8167$

Excitation functions for elastically scattered deuterons have been measured for $E_d = 0.4$ to 1.8 MeV (1963RE16), 1.0 to 2.2 MeV (1972LO05), 1.0 to 2.5 MeV (1968MA1H), 4.5 to 6.0 MeV (1970PO03) and 5.0 to 7.0 MeV (1971DJ02). Polarization measurements involving the d_0 group have been reported at $E_d = 6.3$ MeV (1971DJ02), 11.8 MeV (1971GR20) and 12.6 MeV (1971ZA04). See also (1970VE06, 1971SP1C) and ^{9}Be in (1974AJ01).

13. ^{9}Be(t, n)^{11}B $Q_m = 9.5591$

Angular distributions are reported at $E_t = 1.1$ MeV (1970MAZE; unpublished).

14. ^{9}Be(^{3}He, p)^{11}B $Q_m = 10.3229$

Proton groups have been observed to a number of ^{11}B states: see Table 11.10 (1959HI69, 1966BR18). See also (1970CA28). Angular distributions of many of these proton groups have been studied at $E(^3\text{He}) = 1.0$ to 10.2 MeV: see (1968AJ02) for references and (1973SU07: $E(^3\text{He}) = 0.82$ and 1.10 MeV). L assignments derived from the higher energy work (1960HI08) are also shown in Table 11.10. Gamma ray branching ratios and multipolarities for ^{11}B levels up to $E_x = 9.19$ MeV have been extensively studied by (1958FE70, 1961DO03, 1964AL22, 1965OL03): see Table 11.4 and the discussion in (1968AJ02). Lifetime measurements are shown in Table 11.5 (1969BEYX; abstract). See also (1970OG1A) and (1970LK1A; theor.).

Table 11.10: Energy levels of ^{11}B from ^{9}Be(^{3}He, p)^{11}B [a]

(1959HI69) [b]	(1966BR18)	(1960HI08)
E_x (MeV $\pm$ keV)		L
0	0	0
2.130 ± 10	2.1243 ± 0.9	0
4.445 [c]	4.4434 ± 1.8	0
5.023 ± 10	5.0187 ± 2.3	0
6.739 ± 10	6.7411 ± 3.0	
6.791 ± 10	6.7909 ± 3.1	1
7.285 ± 10		
7.975 ± 10		
8.553 ± 10		0
8.909 ± 10		0
9.175 ± 10		
9.264 ± 10		
9.86 ± 20 [d]		

[a] The previously quoted results of (1963GR20, 1965MA1E) are not displayed here because they have not subsequently been published.

[b] The original results were normalized to the second excited state taken to be at 4.459 MeV. Here they are shown normalized to 4.445 MeV.

[c] (1966BR18).

[d] $\Gamma \approx 150$ keV.

15. ^{9}Be(α, d)^{11}B $\qquad Q_m = -8.031$

Angular distributions have been measured at $E_\alpha = 27.0$ (1975PU01: $d_0 \rightarrow d_6$) and 28.3 MeV (1965KA14: $d_0 \rightarrow d_3$). The predominant L-transfer are $L = 0$, 2; 0 and 0, respectively for ^{11}B*(0, 2.12, 5.02). The angular distribution for ^{11}B*(4.45) is flat (1975PU01). See also (1970OG1A) and (1971BU1K; theor.).

16. (a) ^{9}Be(^{6}Li, α)^{11}B $\qquad Q_m = 14.343$
(b) ^{9}Be(^{6}Li, 2α)^{7}Li $\qquad Q_m = 5.677$
(c) ^{9}Be(^{6}Li, αp)^{10}Be $\qquad Q_m = 3.114$
(d) ^{9}Be(^{6}Li, αt)^{8}Be $\qquad Q_m = 3.119$

Angular distributions have been determined for seven α-groups at $E(^6\text{Li}) = 3$ to 4 MeV: see (1968AJ02). Angular distributions have also been obtained at $E(^6\text{Li}) = 24$ MeV to ^{11}B*(0, 2.12) and to a number of unresolved levels with $E_x \leq 13.2$ MeV (1967CH34, 1968DA20). See also (1970OG1A).

The breakup reactions (reactions (b), (c) and (d)) have been studied at $E(^6\text{Li}) = 3.5$ MeV by (1968JA08): reaction (b) goes mainly via a sequential process involving ^{11}B*(10.3, 11.4, 12.6, 13.16, 13.5). The results for reaction (c) are not conclusive. ^{11}B*(12.6, 13.16) may possibly contribute to reaction (d) (1968JA08).

17. (a) ^{9}Be(^{7}Li, αn)^{11}B $\quad Q_\text{m} = 7.092$
(b) ^{9}Be(^{9}Be, ^{7}Li)^{11}B $\quad Q_\text{m} = -0.880$

For reaction (a) see (1964CA18). For reaction (b) see (1970LK1A; theor.).

18. ^{10}Be(p, γ)^{11}B $\quad Q_\text{m} = 11.229$

The yield of ground state γ-rays has been measured at $90°$ for $E_\text{p} = 0.6$ to 6.3 MeV. Observed resonances are displayed in Table 11.11. The anomaly observed at $E_\text{p} = 1.05$ MeV may not correspond to a state in ^{11}B: it occurs at the threshold for ^{10}B*(0.72) + n. The other four resonances correspond to states in ^{11}B whose energies match well with those of the first four states in ^{11}Be: $T = \frac{3}{2}$. Several known $T = \frac{1}{2}$ states in ^{11}B are not observed in this reaction: see Table 11.3 (1970GO04, 1973GO09).

19. ^{10}B(n, γ)^{11}B $\quad Q_\text{m} = 11.4560$
$Q_0 = 11454.7 \pm 1$ keV (1967RA24);
$Q_0 = 11453 \pm 2$ keV (1967TH05).

The thermal capture cross section is 0.5 ± 0.2 b (1973MU14). For a listing of the observed capture γ-rays see Table 11.12 (1967TH05). The τ_m for ^{11}B*(6.74) is 10^{+12}_{-8} fsec (1969WE07). See also (1973AR1M, 1974AR1K, 1974ST1C) and (1968FO1A; astrophys.).

20. ^{10}B(n, n)^{10}B $\quad E_\text{b} = 11.4560$

The "free" neutron scattering cross section, $\bar{\sigma}_\text{s} = 2.23 \pm 0.06$ b. The coherent scattering amplitude (bound) is $a = +1.4 \pm 0.5$ fm (1973MU14). See also (1969BA1P). The total scattering

Table 11.11: Levels of ^{11}B from the ^{10}Be(p, γ_0))^{11}B reaction (1970GO04)

E_p (MeV ± keV)	E_x (MeV)	$\Gamma_{c.m.}$ (keV)	$(J+\frac{1}{2})(\Gamma_p/\Gamma)\Gamma_{\gamma_0}$ [e] (eV)	Γ_{γ_0} [a,e] (eV)	$\Gamma_{\gamma_1}/\Gamma_{\gamma_0}$	J^π
(1.05 ± 40) [b]	(12.18)	230 ± 90	$3.1^{+2.9}_{-2.0}$			
1.46 ± 30	12.56	230 ± 65	10^{+7}_{-5}	10^{+7}_{-5}	0.25 ± 0.08	$\frac{1}{2}^+(\frac{3}{2}^+)$
1.85 ± 20	12.91	235 ± 27	29 ± 9	29 ± 9 [f]	≤ 0.06	$\frac{1}{2}^-$ [c]
3.41 ± 20	14.33	255 ± 36	29 ± 9	14.5 ± 4.3	≤ 0.1	$\frac{5}{2}^{(+)}(\frac{3}{2}^-)$
4.5 ± 100	15.32	635 ± 180	53^{+34}_{-26} [d]			

[a] These values assume that $J \neq \frac{3}{2}$: see (1970GO04).

[b] See discussion in text.

[c] See Table 11.3.

[d] Assumes that $\sigma_{total} = 4\pi d\sigma/d\Omega\ (90°)$.

[e] Values reported in (1970GO04) are here shown multiplied by 1.7: see (1973GO09).

[f] In the (e, e′) work of (1975KA02) a strong group is observed at $E_x = 13.0 \pm 0.1$ MeV. If it corresponds to the excitation of ^{11}B*(12.91) with $J^\pi = \frac{1}{2}^-$; $T = \frac{3}{2}$, $\Gamma_{\gamma_0} = 36 \pm 7$ eV (1975KA02).

Table 11.12: Neutron capture γ-rays from ^{10}B + n [a]

E_γ (keV)	ΔE_x (keV)	I_γ [b]	Assignment
11447 ± 2 [c]	11453 ± 2	6 ± 1	capt. → g.s.
8916 ± 2	8920 ± 2	15 ± 2	8.92 → g.s.
7006 ± 2	7008 ± 2	54 ± 3	capt. → 4.45
6739 ± 2	6741 ± 2	19 ± 1	6.74 → g.s.
	5020	< 2	5.02 → g.s.
4711 ± 2	4712 ± 2	25 ± 1	capt. → 6.74
4444 ± 2	4445 ± 2	65 ± 3	4.45 → g.s.
2534 ± 2	2534 ± 2	15 ± 2	capt. → 8.92
2295 ± 2	2296 ± 2	10 ± 3	6.74 → 4.45
	2120	< 3	2.12 → g.s.

[a] (1967TH05).

[b] Photons/100 captures.

[c] $\Gamma_\gamma = 0.01$ eV (1957BA18).

Table 11.13: Resonances in ^{10}B + n [a]

^{10}B(n, n′γ)^{10}B (1960DA08)		^{10}B(n, α)^{7}Li (1961DA16)		Yield of	^{11}B* (MeV)
E_{res} (MeV)	Γ (keV)	E_{res} (MeV)	Γ (keV)		
		0.23 [b]		σ_t, α	11.66
		0.53	140	α_0, α_1	11.94
1.93	260	1.86 [e]	570	σ_t [c], α_0, α_1, t	13.2
(2.6)	broad	2.79	530	σ_t [c], α_0, α_1	14.0
3.31	370	3.43	< 120	α_0, t	14.57
4.1		4.1	800	σ_t [c], α_0, α_1	15.2
4.73		[d]			15.75
		5.7	broad	α_0, t	16.6
		6.4	broad	α_0, t	17.3

[a] See also Table 11.14.

[b] (1951BO45, 1966MO09, 1970NE03).

[c] (1951BO45).

[d] (1961FO07).

[e] $J^\pi \geq \frac{11}{2}^+$ (1961DA16). See, however, Table 11.14.

cross section is constant at 2.23 ± 0.06 b for $E_n = 0.7$ to 10 keV and then rises to 2.97 b at $E_n = 127$ keV (1970AS10).

Total cross section measurements in the range $E_n = 10$ to 500 keV confirm the broad maximum near $E_n = 0.23$ MeV, originally suggested by (1951BO45) and also observed in the (n, α) cross section (1966MO09). At higher energies the total cross section shows broad maxima at $E_n = 1.9$ and 2.8 MeV (1951BO45) and at 4.3 MeV (1961FO07): see Table 11.13. In the range $E_n = 5.5$ to 16 MeV σ_{tot} is constant at 1.5 b (1961FO07).

Polarization measurements (0.075 to 2.2 MeV and 2.63 MeV) and measurements of differential cross sections (0.075 to 4.4 MeV) by (1971LA10, 1973CO05, 1973HA2G, 1973HA64) have been analyzed using R-matrix calculations: the results are shown in Table 11.14. They are consistent with results from ^{10}B(n, n′γ) and ^{7}Li(α, n).

Elastic scattering differential cross sections are also reported at $E_n = 7.02$ and 7.55 MeV (1969HO1G) and at 9.72 MeV (1970CO12). See also (1969MA39, 1970PO1E), (1967IR1A, 1972LA1F) and (1966AG1A, 1967BE1F; theor.).

21. ^{10}B(n, n′)^{10}B* $E_b = 11.4560$

The yield of 0.7 MeV γ-rays has been studied from threshold to $E_{\rm n} = 5.2$ MeV: observed resonances are displayed in Table 11.13 (1960DA08). See also (1970NE03). Inelastic scattering cross sections for formation of various ^{10}B states have been measured by (1970NE03: $E_{\rm n} = 1.45$ to 4.90 MeV, and 14.8 MeV), (1969HO1G: $E_{\rm n} = 7.02$ and 7.55 MeV) and (1970CO12: $E_{\rm n} = 9.72$ MeV). See also ^{10}B in (1974AJ01) and (1969RO1F).

22. ^{10}B(n, p)^{10}Be $\quad Q_{\rm m} = 0.2266 \quad E_{\rm b} = 11.4560$

The thermal cross section is < 0.2 b (1973MU14). See also ^{9}Be in (1974AJ01) and (1970NE03).

23. ^{10}B(n, d)^{9}Be $\quad Q_{\rm m} = -4.3607 \quad E_{\rm b} = 11.4560$

See ^{9}Be in (1974AJ01).

24. (a) ^{10}B(n, t)^{8}Be $\quad Q_{\rm m} = 0.2318 \quad E_{\rm b} = 11.4560$
(b) ^{10}B(n, t)^{4}He^{4}He $\quad Q_{\rm m} = 0.3237$

The cross section for reaction (b) has been measured for $E_{\rm n} = 1.4$ to 8.2 MeV by (1961DA16). Fluctuations are observed at some of the resonant energies in the ^{10}B(n, α) reaction: see Table 11.13. See also (1968ST1D) and (1969AN25, 1971AN1M).

25. ^{10}B(n, α)^{7}Li $\quad Q_{\rm m} = 2.790 \quad E_{\rm b} = 11.4560$

The "recommended" value of the thermal isotropic absorption cross section is 3837 ± 9 b (1973MU14). See also (1970ME1F). The ground state branching for thermal neutrons is $6.308 \pm 0.006\%$ (1967DE15). See also (1968MA07), and (1968AJ02) for earlier references. The cross section for $E_{\rm n} = 10$ eV to 200 keV is given by the expression

$$13.837/\sqrt{E} - 0.312 - 1.014 \times 10^{-2}\sqrt{E} + \frac{2.809\times10^{5}}{\sqrt{E}[(170.3-E)^2+2.243\times10^{4}]}\text{b (1970SO1A).}$$

The cross section for the (n, α_0) reaction has been calculated by (1968MA07) from that for the ^{7}Li(α, n) reaction: $E_{\rm n} = 30$ to 516 keV.

The α_1 cross section has been measured for $E_{\rm n} = 47$ keV to 4.9 MeV and at 14.8 MeV (1970NE03): the cross section is substantially higher than that reported by (1961DA16). Observed resonances are displayed in Tables 11.13 and 11.14 (1961DA16).

Table 11.14: R-matrix analysis of resonant states in ^{10}B + n [a]

E_n (MeV)	E_x (MeV)	J^π	l_n	Γ_n	Γ_{α_0}	Γ_{α_1}	$\Gamma_{c.m.}$ (keV)
				(c.m., MeV)			
	10.60	$\frac{7}{2}^+$	0		0.030	0.070	100
0.17	11.61	$\frac{5}{2}^+$	0	0.004	0.296	0.0	300
0.37	11.79	$\frac{7}{2}^+$	0	0.770	0.001	0.113	884
0.53	11.94	$\frac{5}{2}^-$	1	0.031	0.080	0.090	201
1.83	13.12	$\frac{9}{2}^-$	1	0.100	0.275	0.050	425
1.88	13.16	$\frac{5}{2}^+, \frac{7}{2}^+$	2	0.080	0.200	0.150	430
2.82	14.02	$\frac{11}{2}^+$	2	0.800	0.045	0.010	855
4.2	15.3	$(\frac{3}{2}, \frac{5}{2}, \frac{7}{2})^+$	2	0.500	0.100	0.100	700

[a] (1971LA10, 1972HA04, 1973CO05, 1973HA64): analysis based on polarization and differential cross-section measurements of the elastic scattering, and on results from ^{10}B(n, α_0) and (n, α_1). The analysis used a two-level, four-channel R-matrix formalism with a non-diagonal background R^0 matrix: see (1973HA64). This analysis does not include ^{11}B*(14.53) because the resonance is weak, narrow and almost entirely in the α-channel (1973CO05). See also Table 11.13.

Other recent measurements include those by (1969BO03) at $E_n = 30$ to 800 keV (relative cross sections for α_0 and α_1) and by (1969AN25) at 14.4 MeV (cross section for formation of $\alpha_0 + \alpha_1$, α_2). (1972HA04) have calculated differential cross sections for α_0 and α_1 based on R-matrix parameters derived from neutron elastic scattering, polarization measurements and (n, α) data. See also (1974HA1W, 1975HA1G; theor.). See also ^{7}Li in (1974AJ01), (1968GI1D, 1968GU1B, 1968ST1D, 1970DE1H, 1972LA1F, 1975FR1B), (1964FO1A; astrophys.) and (1968MO1D, 1968PA1E, 1973FA1M, 1973LI1E; applied).

26. ^{10}B(p, π^+)^{11}B $\qquad Q_m = -128.895$

Angular distributions for proton capture to ^{11}B*(0, 2.15 ± 0.10) have been measured at $E_p = 185$ MeV. The population of ^{11}B*($4.45 + 5.02$) and of unresolved higher states is also observed but an attempt to observe $T = \frac{3}{2}$ analogue states in ^{11}B and ^{11}N (the latter populated via (p, π^-)) was unsuccessful (1974DA27).

27. ^{10}B(d, p)^{11}B $\qquad Q_m = 9.2314$

Proton groups reported by (1951VA1A, 1953EL12, 1961JA23, 1966BR18) are listed in Table 11.15. Angular distributions have been studied at many energies in the range $E_{\rm d} = 0.17$ to 28 MeV [see (1968AJ02) for a listing of the earlier references] and (1970HU1B: 0.35 MeV; $p_0 \rightarrow p_3$, p_{4+5}, p_6, p_7), (1973CO18: 0.67 to 2.32 MeV; p_{4+5}), (1970PO03: 4.5 to 5.5 MeV; $p_0 \rightarrow p_3$) and (1967GO27: 13.6 MeV; p_0). The lowest five levels are formed by $l_{\rm n} = 1$ except for ^{11}B*(2.12) which appears to involve a spin-flip process. They are presumed to comprise the set $\frac{3}{2}^-$, $\frac{1}{2}^-$, $\frac{5}{2}^-$, $\frac{3}{2}^-$, $\frac{7}{2}^-$ expected as the lowest p^7 levels $(a/K \approx 4.0)$. ^{11}B*(9.19, 9.28) [$J^\pi = \frac{7}{2}^+$ and $\frac{5}{2}^+$, respectively] show strong $l = 0$ stripping and are ascribed to capture of a 2s neutron by ^{10}B: see (1968AJ02) for a listing of all the relevant references. The probability $p_{3/2}$ for transfer of a neutron with angular momentum $\frac{3}{2}$ has been determined for the p_0 group using vector polarized deuterons with $E_{\rm d} = 10$ and 12 MeV, and compared with shell model calculations of (1965CO25, 1967CO32), (1970FI07; and see also (1967SC29)).

Studies of pγ correlations are discussed in reaction 14 of (1968AJ02) and displayed in Table 11.4 of this paper.

See also ^{12}C, (1967CO30, 1967SP09, 1973BR24), (1973FO02) and (1969BO1F, 1969DO08, 1970DE35, 1970DO07, 1970DO13; theor.).

28. ^{10}B(t, d)^{11}B $\qquad Q_{\rm m} = 5.1984$

At $E_{\rm d} = 5.5$ MeV, deuteron groups are observed to the ground state of ^{11}B and to states at $E_{\rm x} = 2.126$, 4.449, 5.027, 6.769, 6.806 and 7.301 MeV (± 10 keV). All the angular distributions appear to be characteristic of $l_{\rm n} = 1$ (1961BA10). See also ^{13}C in (1976AJ04).

29. ^{10}B(α, ^{3}He)^{11}B $\qquad Q_{\rm m} = -9.1225$

Angular distributions have been measured at $E_\alpha = 56$ MeV for the ground state transitions in this, and in the analog (α, t) reactions: the average ratio of the (α, ^{3}He) to the (α, t) differential cross sections is 1.2 ± 0.1 (1968GA1C, 1969GA11).

30. (a) ^{10}B(^{6}Li, ^{5}Li)^{11}B $\qquad Q_{\rm m} = 5.79$

(b) ^{10}B(^{7}Li, ^{6}Li)^{11}B $\qquad Q_{\rm m} = 4.205$

See (1969TH01) for reaction (a) and (1974KO1G) for reaction (b).

31. ^{10}B(^{14}N, ^{13}N)^{11}B $\qquad Q_{\rm m} = 0.902$

Table 11.15: ^{11}B levels from ^{10}B(d, p)^{11}B

(1951VA1A, 1953EL12)	(1961JA23)	(1966BR18)	l_n	(1962HI07)	l_n	(1960BI08)
E_x (MeV ± keV)		E_x (MeV ± keV)		$(2J+1)\theta^2$		$(2J+1)\theta^2$
0	0	0	1	0.120	1	1.00
2.140 ± 14 [a]	2.128 ± 10	2.1246 ± 1.1				0.09
4.464 ± 14 [a]	4.449 ± 8	4.4458 ± 2.1	1	0.048		0.46
5.039 ± 14 [a]	5.023 ± 8	5.0192 ± 2.4	(1)	(0.010)		0.11
6.765 ± 13 [a,b]		6.7439 ± 2.2	1	0.210	1	1.72
6.815 ± 13 [a,b]		6.7938 ± 2.2				
7.298 ± 6			(2?)	(0.022)		
7.987 ± 9					isotropic	
8.568 ± 5	8.565 ± 10		(2?)		2	
8.927 ± 5	8.926 ± 10		1	0.186	0, 2	
9.191 ± 5	9.190 ± 10		0	0.242	0	
9.276 ± 5	9.278 ± 10		0	0.175	0	
10.32 ± 20 [c]						

[a] Corrected by (1966BR18).

[b] 6.752 ± 6, 6.804 ± 6: see (1964AL22).

[c] $\Gamma = 54 \pm 17$ keV (1953EL12).

See (1968GA03) and (1968GO1K, 1970GO1B, 1970SC1G, 1973MC17, 1973OS03; theor.) and (1968AJ02).

32. ^{10}B(^{15}N, ^{14}N)^{11}B $\quad Q_m = 0.622$

Not reported.

33. ^{10}B(^{16}O, ^{15}O)^{11}B $\quad Q_m = -4.213$

See (1968OK06).

34. ^{10}B(^{18}O, ^{17}O)^{11}B $\quad Q_m = 3.409$

The angular distribution has been measured at $E(^{18}\mathrm{O}) = 20$ and 24 MeV (1971KN05). See also (1974SW04).

35. ^{10}B(^{19}F, ^{18}F)^{11}B $\qquad Q_\mathrm{m} = 1.025$

The angular distribution has been measured at $E(^{19}\mathrm{F}) = 20$ and 24 MeV (1971KN05). See also (1968GA03) and (1970GO1B; theor.).

36. ^{11}Be(β^-)^{11}B $\qquad Q_\mathrm{m} = 11.509$

^{11}Be decays to ^{11}B*(0, 2.12, 5.02, 6.79, 7.98, 9.87): see Table 11.16 for the parameters of the observed β and γ transitions (1971AL07). Delayed α-particles are also observed with a total I_α of 3.0%/decay. These α-particles are not observed to be in coincidence with 478 keV γ-rays [upper limit = 5% for $E_\alpha > 0.3$ MeV], suggesting that they result from the decay of ^{11}B*(9.87) to $^{7}\mathrm{Li}_{\mathrm{g.s.}}$ (1971AL07). The half-life of ^{11}Be is 13.81 ± 0.08 sec (1970AL21). See also (1968AJ02) and (1974AL11).

37. ^{11}B(γ, γ)^{11}B

Mean gamma widths of low-lying states obtained by resonance scattering and transmission studies are listed in Table 11.17 (1958ME79, 1958RA14, 1959CO95, 1964BO22, 1965KE05, 1968CR07, 1973SA21, 1974LE1K). See also (1974WE1R) and (1968AJ02).

38. (a) ^{11}B(γ, n)^{10}B $\qquad Q_\mathrm{m} = -11.4560$
(b) ^{11}B(γ, p)^{10}Be $\qquad Q_\mathrm{m} = -11.2294$
(c) ^{11}B(γ, d)^{9}Be $\qquad Q_\mathrm{m} = -15.8167$
(d) ^{11}B(γ, t)^{4}He + ^{4}He $\qquad Q_\mathrm{m} = -11.1323$
(e) ^{11}B(γ, α)^{7}Li $\qquad Q_\mathrm{m} = -8.666$

The giant dipole resonance is shown to consist mainly of $T = \frac{1}{2}$ states in the lower energy region and of $T = \frac{3}{2}$ states in the higher energy region by observing the decay to states in ^{10}B and ^{10}Be (reactions (a) and (b)) (1971PA10). Absolute measurements of the ^{11}B(γ, all n) cross section from threshold to 28 MeV have been carried out by (1973HU09, 1973HU1D): the cross section exhibits a maximum at $E_\gamma = 25.2 \pm 0.1$ MeV ($\sigma \approx 8$ mb) in addition to some weaker structure. The integrated cross section from threshold to 27.6 MeV is 0.37 ± 0.04 in units of 60 NZ/A.

Table 11.16: Beta decay of ^{11}Be (1971AL07) [a]

^{11}B* [b] (keV)	J^π [c]	I_β (%)	log ft	E_γ (keV)	I_γ [d] (%)	Transition to ^{11}B*
g.s.	$\frac{3}{2}^-$	57 ± 3	6.81 ± 0.02			
2125.0 ± 0.7	$\frac{1}{2}^-$	29 ± 3	6.68 ± 0.04	2124.8 ± 0.7	33 ± 3	g.s.
4445	$\frac{5}{2}^-$	< 0.06	> 10.9 [e]			
5020.1 ± 1.7	$\frac{3}{2}^-$	0.28 ± 0.11	7.94 ± 0.14	5019.3 ± 1.7	0.47 ± 0.09	g.s.
				2893.1 ± 0.8	0.093 ± 0.028	2125
6742.7 ± 1.8 [g]	$\frac{7}{2}^-$	< 0.08				
6792.6 ± 1.8	$\frac{1}{2}^+$	6.8 ± 0.8	5.91 ± 0.05	6790.5 ± 1.8	4.51 ± 0.69	g.s.
				4666.3 ± 1.8	2.00 ± 0.28	2125
				1772.2 ± 0.7	0.28 ± 0.06	5020
7286	$(\frac{3}{2}, \frac{5}{2})^+$	< 0.16				
7978.1 ± 1.9	$\frac{3}{2}^+$	3.9 ± 0.5	5.58 ± 0.05	7974.7 ± 1.9	1.74 ± 0.30	g.s.
				5851.8 ± 1.9	2.13 ± 0.34	2125
8559	$\leq \frac{5}{2}^-$	< 0.06	> 7.0			
8920	$\frac{5}{2}^-$	< 0.02	> 8.5 [e]			
9870	$\frac{3}{2}^+$	3.0 ± 0.7 [f]	4.03 ± 0.15 [f]			

[a] See also Table 11.12 in (1968AJ02).

[b] When errors are indicated the excitation energies are determined in this experiment from the measured E_γ.

[c] From Table 11.3.

[d] Intensity in % per β-decay, normalized to 33 ± 3% for the 2.13 MeV γ-intensity.

[e] log $f_1 t$. Q_0 assumed to be 11.506 ± 0.007 MeV.

[f] Assuming that the breakup of ^{11}B*(9.87) is solely to ^{7}Li$_{\rm g.s.}$. If the inelasticity for the breakup of ^{11}B*(9.87) is that suggested by (1966CU02), then the β-branch is 15 ± 3.5%, log $ft = 3.33 \pm 0.15$, and the β branches to the other ^{11}B states have to be recalculated: see (1971AL07).

[g] Energy derived from $E_{\rm x}$ of ^{11}B*(6.79) and known ΔE of 4th and 5th states (1970BR23) [49.9 keV].

Table 11.17: Gamma widths from ^{11}B(γ, γ)^{11}B and ^{11}B(e, e)^{11}B [a]

E_x (MeV)	J^π	Γ_{γ_0} (eV)	Reaction	Refs.
2.12 [b]	$\frac{1}{2}^-$	0.14 ± 0.018	$\gamma\gamma$	(1958ME79)
		0.11 ± 0.04	$\gamma\gamma$	(1964BO22)
		0.137 ± 0.020	$\gamma\gamma$	(1965KE05)
		0.12 ± 0.02	$\gamma\gamma$	(1968CR07)
		0.23 ± 0.09	$\gamma\gamma$	(1973SA21)
		0.14 ± 0.04	ee	(1975KA02)
		0.17 ± 0.034	ee	(1962ED02)
		0.136 ± 0.010		mean
4.45	$\frac{5}{2}^-$	0.56 ± 0.08	$\gamma\gamma$	(1958RA14)
		0.43 ± 0.095	$\gamma\gamma$	(1959CO95)
		0.53 ± 0.21	$\gamma\gamma$	(1973SA21)
		0.615 ± 0.037	$\gamma\gamma$	(1974LE1K)
		0.73 ± 0.07 (M1)+ 0.020 ± 0.002 (E2)	ee	(1975KA02)
		0.60 ± 0.09 (M1)+ 0.016 ± 0.002 (E2)	ee	(1967SP02)
		0.610 ± 0.030		mean
5.02 [e]	$\frac{3}{2}^-$	1.1 ± 0.2 [d]	$\gamma\gamma$	(1959CO95)
		2.4 ± 0.8	ee	(1966KO08)
		3.7 ± 1.5	ee	(1962ED02)
		1.73 ± 0.14 (M1) < 0.0034 (E2)	ee	(1967SP02)
		2.12 ± 0.21	ee	(1975KA02)
7.29	$(\frac{3}{2}, \frac{5}{2})^+$	1.0 ± 0.5	ee	(1962ED02)
8.56	$\leq \frac{5}{2}^-$	0.73 ± 0.07 (M1) 0.23 ± 0.03 (E2)	ee	(1975KA02) [f]
8.92	$\frac{5}{2}^-$	4.0 ± 0.6 (M1)	ee	(1966SP02)
		4.93 ± 0.50	ee	(1975KA02)

[a] See also Tables 11.4 and 11.5.

[b] See also (1963VA10, 1966KO08, 1974LE1K).

[c] See also (1962ED02, 1966KO08). (This footnote is not labeled in the table.)

[d] See (1967SP02).

[e] See also (1974LE1K).

[f] See also (1966SP02).

The results are consistent with the photoabsorption cross section proceeding via $T = \frac{1}{2}$ at lower energies (1973HU09). This is also the picture derived from the (γ, d_0) cross section (reaction (c)): it peaks at ≈ 19 MeV, lower than it would if $T = \frac{3}{2}$ states were involved (1974DE01). See also (1968KA1D, 1969MU10, 1971KA70, 1972SL1B) and (1970HA28).

The cross section for (γ, n) shows many peaks in the range $E_\gamma = 12$ to 28 MeV (1965HA19). (1969SO06, 1970SO03) report resonances at $E_\gamma = 12.4$, 13.1, 13.65, 14.75, 15.1, 15.5, 15.85, 16.2, 16.5, 16.9, 17.5, (20.2), 21.6, 23.2, (24.5), 25.5, 27.7 and 29.2 MeV in the (γ, p) cross section. [See (1970SO03) also for Γ_γ and J^π for the states below 18 MeV (mainly $\frac{5}{2}^+$), and for an evaluation of the structure reported by (1965HA19).] See also (1972BU1J, 1973SP02) and (1971DU11; theor.). For reactions (d) and (e) see (1959AJ76).

39. (a) ^{11}B(e, e)^{11}B
(b) ^{11}B(e, ep)^{10}Be $\qquad Q_\mathrm{m} = -11.229$

The charge-scattering radius is 1.55 fm (1959ME24). Magnetic elastic scattering at $\theta = 180°$ shows strong M3 effects: the derived ratio of static M3/M1, 2.9 ± 0.2 fm^2, suggesting a j-j coupling scheme for $^{11}B_{g.s.}$ (1966RA29). The quadrupole contribution to the elastic form factor is best accounted for by the undeformed shell model, $Q = 3.72$ ($\pm 20\%$) fm^2, r(r.m.s.) $= 2.42$ fm (1966IS1A, 1966ST12). The excitation of ^{11}B*(2.1, 4.4, 5.0, 8.6, 8.9) has been studied by (1975KA02: $E_\mathrm{e} = 52$ to 90 MeV). (1973FL1A) report the excitation of ^{11}B*(7.30, 9.27) at the same E_e. The giant resonance region, centered at ≈ 18 MeV, is characterized by a lack of prominent features except for a pronounced peak at $E_\mathrm{x} = 13.0 \pm 0.1$ MeV (mixed M1-E2) and a broad transverse group at $E_\mathrm{x} = 15.5$ MeV (1975KA02).

Ground state transition widths for various excited states are listed in Table 11.17 (1962ED02, 1966KO08, 1966SP02, 1967SP02, 1975KA02). For reaction (b) see (1971VL01, 1972VL1A) and ^{10}Be in (1974AJ01). See also (1968AJ02), (1971RI1E), (1968GO1J, 1972THZF), (1968JA1D, 1969VI02, 1973DO01, 1973GA19, 1973RO11, 1973SP02; theor.).

40. ^{11}B(n, n′)^{11}B*

Angular distributions of neutrons have been measured at $E_\mathrm{n} = 7.55$ MeV (1969HO1G: $n_0 \rightarrow n_2$), 9.72 MeV (1970CO12: $n_0 \rightarrow n_3$, n_{4+5}) and 14.1 MeV (1970AL08: $n_0 \rightarrow n_3$, n_{4+5}, n_6). For branching ratios see Table 11.4 (1972NI05). See also ^{12}B, (1968AL1E, 1970PO1E) and (1968CA1A, 1969WA11, 1971MI12, 1971OT03, 1974BI07; theor.).

41. (a) ^{11}B(p, p′)^{11}B*
(b) ^{11}B(p, 2p)^{10}Be $\qquad Q_\mathrm{m} = -11.229$

Observed proton groups are displayed in Table 11.18 (1969SU03, 1971BR41, 1974KA15). Angular distributions have been measured at $E_p = 12$ to 21.5 MeV (1972TH1C), 30.3 MeV (1969KA15: $p_0 \rightarrow p_2$), 100 MeV (1970HO07: $p_0 \rightarrow p_3$), 155 MeV (1968GE04: $p_0 \rightarrow p_3$, p_{4+5}) and 185 MeV (1969SU03: $p_0 \rightarrow p_2$ and p to ^{11}B*(8.56, 8.92)). For an angular correlation experiment see (1970HU01). See also (1968AJ02), (1970TH1F, 1973CA1H), (1969WA11, 1971LO05, 1973KA04; theor.) and ^{12}C. For reaction (b) see ^{10}Be in (1974AJ01). The spectroscopic factors for the (t + ^{8}Be) and (α + ^{7}Li) cluster structures in ^{11}B [as determined from a study of the ^{11}B(p, α)^{6}Li reaction] are ≈ 0.77 and ≈ 0.02, respectively (1972DE01, 1972DE02).

42. ^{11}B(d, d)^{11}B

The elastic scattering has been studied at $E_d = 5.5$ MeV (1971HIZF) and 11.8 MeV (1967FI07). See also (1968VE11, 1968VE1C, 1970VE06, 1971TA1E) and (1969VE09, 1970EL16; theor.).

43. ^{11}B(t, t)^{11}B

The elastic scattering has been studied at $E_t = 1.8$ and 2.1 MeV (1969HE08, 1969SI12).

44. (a) ^{11}B(^{3}He, ^{3}He)^{11}B
(b) ^{11}B(^{3}He, ^{6}He)^{8}Be $\qquad Q_m = 4.570$

The elastic scattering has been studied at $E(^3\text{He}) = 8$, 10, 12, 15 and 18 MeV (1969MI15, 1969PA11), 14 MeV (1970NU02) and 18.3, 20.6 and 27.2 MeV (1972BU30), and 74 MeV (1974AS06: also ^{11}B*(4.45)). A coupled channel analysis of the 74 MeV results suggests a quadrupole deformation $\beta_2 = +0.43$ or -0.50 for ^{11}B (1974AS06). At $E(^3\text{He}) = 29.8$ MeV a number of ^{11}B states are populated, including suggested $T = \frac{3}{2}$ states [see Table 11.19] with $E_x = 12.51 \pm 0.05$, 12.98 ± 0.09 and 14.40 ± 0.05 MeV, with $\Gamma_{c.m.} = 260 \pm 50$, 390 ± 120 and 220 ± 50 keV, respectively. There is a weak indication also of a state at $E_x = 14.51$ MeV (1971WA21). See also (1969AD1C, 1970BA1P, 1970DU07). For reaction (b) see (1972YO02).

45. (a) ^{11}B(α, α)^{11}B
(b) ^{11}B(α, 2α)^{7}Li $\qquad Q_m = -8.666$

Angular distributions have been reported at $E_\alpha = 28.3$ MeV (1965KO1A: $\alpha_0 \rightarrow \alpha_3$, α_{4+5}, α_6), 28.4 and 29.0 MeV (1968KA24: α_0) and 28.5 MeV (1967NA06: $\alpha_0 \rightarrow \alpha_3$, α_{4+5}, α_6, α_8). For reaction (b) see (1969FU09).

Table 11.18: States of ^{11}B from ^{11}B(p, p′)^{11}B* and ^{13}C(d, α)^{11}B

(1969SU03) [a,d]	(1971BR41) [a]	(1974KA15) [a]	(1970BR23) [b]	(1969SU03)	
	E_x (keV)			B(M1)↑ [e]	B(E2)↑ [f]
0		0	0		
2130 ± 30		2124.7 ± 0.5	2125.4 ± 1.4	0.55 [c]	3.4 ± 0.8
4450 ± 30	4445.3 [c]	4445.2 ± 0.5	4444.5 ± 1.6	0.71 ± 0.12	16.9 [c]
5030 ± 50	5020.0 [c]	5021.1 ± 0.6	5020.2 ± 1.9	0.67 ± 0.12	1.4 ± 0.7
6700 ± 60	6743.4 [c]	6743.0 ± 0.7	6745.82 ± 3.4		10.0 ± 1.5
	6792.6 ± 1.6		6795 ± 3.0		
	7285.6 ± 1.5				
	7978.0 ± 1.7				
8520 ± 70	8559.4 ± 1.9			0.27 ± 0.06	4.1 ± 0.8
8910 ± 60	8920.2 ± 2.0			0.86 ± 0.14	1.0 ± 0.5
	9185.0 ± 2.0				
	9274.4 ± 2.0				
10450 ± 150					
11650 ± 150					
12850 ± 100					
15200 ± 150					
16400 ± 150					

[a] ^{11}B(p, p′)^{11}B*.

[b] ^{13}C(d, α)^{11}B.

[c] Values in this column normalized to this value.

[d] See also (1965HA17).

[e] See discussion of validity of these numbers in (1969SU03).

[f] Other experiments show that the $2.12 \rightarrow 0$ transition is 100 % M1.

46. ^{11}B(^{6}Li, ^{6}Li)^{11}B

The elastic scattering has been measured at $E(^{6}\text{Li}) = 28$ MeV (1972BA52) and analyzed by the optical model.

47. ^{11}B(^{9}Be, ^{9}Be)^{11}B

See (1970LK1A; theor.).

48. (a) ^{11}B(^{10}B, ^{10}B)^{11}B
(b) ^{11}B(^{11}B, ^{11}B)^{11}B

See (1975HI1D), and (1967GU1A) for reaction (b).

49. ^{11}B(^{12}C, ^{12}C)^{11}B

The elastic scattering has been studied at $E(^{11}\text{B}) = 28$ MeV (1969VO07, 1969VO10), at $E(^{12}\text{C}) = 15$, 17, 20 and 24 MeV (1974BO15), and at $E(^{12}\text{C}) = 87$ MeV (1971LI11). The population of ^{11}B*(2.12, 4.45, 6.79) and of ^{12}C*(0, 4.43) has also been reported: see (1969VO07). See also (1974DA1P) and (DE63Y, 1970AN1D; theor.).

50. ^{11}B(^{14}N, ^{14}N)^{11}B

The elastic scattering has been investigated at $E(^{14}\text{N}) = 41$, 77 and 113 MeV (1971LI11).

51. ^{11}B(^{16}O, ^{16}O)^{11}B

The elastic scattering has been studied at $E(^{16}\text{O}) = 14.5$ to 27.5 MeV (1968OK1B) and 27, 30, 32.5, 35 and 60 MeV (1969VO10, 1972SC03, 1974KO1P). See also (1969BR1D, 1971BO1V) and (1970SC1G, 1974DE17; theor.).

52. ^{11}C(β^+)^{11}B $\qquad Q_{\text{m}} = 1.982$

Table 11.19: Possible $T = \frac{3}{2}$ states in ^{11}B [a]

Reaction	E_x (MeV $\pm$ keV)	$\Gamma_{c.m.}$ (keV)	Refs.
^{10}Be(p, γ)^{11}B	12.56 ± 30	230 ± 65	(1970GO04)
^{11}B(^{3}He, ^{3}He)^{11}B*	12.51 ± 50	260 ± 50	(1971WA21)
	12.56 ± 30	240 ± 50	"best"
^{10}Be(p, γ)^{11}B	12.91 ± 20	235 ± 27	(1970GO04)
^{11}B(^{3}He, ^{3}He)^{11}B*	12.98 ± 90	390 ± 120	(1971WA21)
^{13}C(p, ^{3}He)^{11}B	12.94 ± 50	350 ± 50	(1968CO26)
^{13}C(p, ^{3}He)^{11}B	12.91 ± 30	260 ± 50	(1974BE20)
	12.91 ± 20	240 ± 30	"best"
^{10}Be(p, γ)^{11}B	14.33 ± 20	255 ± 36	(1970GO04)
^{11}B(^{3}He, ^{3}He)^{11}B*	14.40 ± 50	220 ± 50	(1971WA21)
	14.33 ± 20	250 ± 40	"best"
^{10}Be(p, γ)^{11}B	15.32 ± 100	635 ± 180	(1970GO04)

[a] These states have also been seen in other reactions: see Table 11.3. The parameters shown in that table reflect all the pertinent data. See also Table 11.22 for $T = \frac{3}{2}$ states in ^{11}C.

See ^{11}C.

53. ^{12}C(γ, p)^{11}B $\qquad Q_m = -15.9572$

The fraction of transitions to the ground and to excited states of ^{11}B [and to ^{11}C states reached in the (γ, n) reaction] has been measured at $E_{bs} = 24.5$, 27, 33 and 42 MeV: the ground state is predominantly populated. The population of analog states in the (γ, n) and (γ, p) reactions are similar: see ^{11}C (1970ME17). See also the discussions in (1973DI1C, 1973SP03, 1974DI17) and in ^{12}C. Angular distributions of the p_{0+1} and the $p_{2+3+4+5}$ groups have been measured by (1974FI17: $E_\gamma = 60$, 80, 100 MeV). See also (1968FR12) and (1970MU1D, 1971BI01, 1973MS01, 1973MS02; theor.).

54. ^{12}C(e, ep)^{11}B $\qquad Q_m = -15.9572$

At $E_e = 497$ MeV the excitation of ^{11}B*(0, 2.1, 5.) has been observed by Auriol *et al.* (see (1972RA1E)). See also (1967AM1A), ^{12}C and (1968BO1D, 1968CI1B, 1968WA1D, 1969BA1F, 1972BE59, 1974HA14; theor.).

55. ^{12}C(n, d)^{11}B $Q_{\rm m} = -13.7325$

Angular distributions have been measured at $E_{\rm n} = 56$ MeV for the deuterons to ^{11}B*(0, 2.12, $4.45 + 5.02$) (1974KI1A).

56. ^{12}C(p, 2p)^{11}B $Q_{\rm m} = -15.9572$

Gross structure is seen in the summed proton spectrum with $Q = -15.6 \pm 0.6$ and -34.3 ± 0.8 MeV (1965RI1A, 1966TY01), -15.0 ± 0.5 and -35.5 ± 1.0 MeV (1971LA16), corresponding to $^{11}B_{g.s.}$ and an excited state with $J^\pi = \frac{1}{2}^+$ at $E_{\rm x} \approx 19.5$ MeV (ejection of p- and s-protons, respectively). High resolution experiments show groups corresponding to ^{11}B*(0, 2.12, 4.45, 5.02, 6.79) (1965PU02, 1967PU01, 1974ST1R). See also (1969EP01, 1971HA61, 1971HO03, 1972PU1A), (1968AJ02, 1969RU1A, 1973JA01), (1967KO1B, 1969MC13, 1970KA01, 1971YO1E, 1972KO13, 1972LI1J, 1972ST33, 1973GU18, 1973GU1D; theor.) and ^{12}C.

57. ^{12}C(d, ^{3}He)^{11}B $Q_{\rm m} = -10.4634$

Angular distributions of ^{3}He ions have been measured at $E_{\rm d} = 20$, 24, 28 MeV (1971IN1C; unpublished: to ^{11}B*(0, 2.12, 4.45, 5.02, $6.74 + 6.79$, 7.29, 7.98)), 28 MeV (1968GA13: to g.s.), 28 and 50 MeV (1968DU01: ^{11}B*(0, 6.74)), 28.5 MeV (1966DE1C: to g.s.), 52 MeV (1968HI01: to ^{11}B*(0, 2.12, 4.45, 5.02, $6.74 + 6.79$, 7.29)) and 80 MeV (1974AS04: to ^{11}B*(0, 4.45)). A coupled channels Born approximation analysis gives good agreement with the angular distributions: a positive β_2 is suggested by the results (1974AS04): see, however, (1974KU17). See also (1969KA1A, 1973WA1E, 1974DI1A) and (1969TA1D, 1973ST16, 1974ST18; theor.).

58. ^{12}C(t, α)^{11}B $Q_{\rm m} = 3.8574$

Angular distributions of the α-particles to ^{11}B*(0, 2.12) have been measured at $E_{\rm t} = 1$ to 2 MeV (1962GU01), 1.11 to 3.40 MeV (1969ET01), 10.1 MeV (1962PU01) and 13 MeV (1965AJ01; also α_2, α_3). Electromagnetic transitions have been studied by (1968BE30): see Table 11.4 (1968BE30) confirm $J = \frac{3}{2}$ for ^{11}B*(5.02). See also (1969AR1B) and (1969NA1C; theor.).

59. ^{12}C(^{10}B, ^{11}C)^{11}B $Q_{\rm m} = -7.266$

This reaction has been studied at $E(^{10}\mathrm{B}) = 100$ MeV: $^{11}\mathrm{B}_{\mathrm{g.s.}}$ is much more strongly excited than ^{11}B*(2.12) (1973YO1C, 1973YO1D). The ratios of the yields $^{11}\mathrm{B}_{\mathrm{g.s.}}/^{11}\mathrm{C}_{\mathrm{g.s.}}$ and ^{11}B*(2.12)/^{11}C*(2.00) have been studied at 100 MeV. They differ from 1 by a few percent at certain angles: the deviations are more pronounced for the first excited states (1974HA1V).

60. ^{12}C(^{12}C, ^{13}N)^{11}B $\qquad Q_{\mathrm{m}} = -14.014$

The angular distribution involving the ground state transitions has been measured at $E(^{12}\mathrm{C}) = 114$ MeV (1974AN36). See also (1967WI04, 1969BR1G).

61. ^{12}C(^{14}N, ^{15}O)^{11}B $\qquad Q_{\mathrm{m}} = -8.665$

See (1966PO1B, 1967BI06, 1967VO1A, 1974AN36). See also (1969BR1D, 1973SC1J) and ^{15}O in (1976AJ04).

62. ^{12}C(^{19}F, ^{20}Ne)^{11}B $\qquad Q_{\mathrm{m}} = -3.112$

At $E(^{19}\mathrm{F}) = 40$, 60 and 68.8 MeV angular distributions involving $^{20}\mathrm{Ne}_{\mathrm{g.s.}} + ^{11}\mathrm{B}_{\mathrm{g.s.}}$, $^{20}\mathrm{Ne}^{*}_{1.63} + ^{11}\mathrm{B}_{\mathrm{g.s.}}$ and $^{20}\mathrm{Ne}_{\mathrm{g.s.}} + ^{11}\mathrm{B}^{*}_{2.12}$ ($E = 68.8$ MeV only) have been measured by (1972SC03). See also (1969VO1D, 1970VO1F) and (1972BO21; theor.).

63. ^{13}C(n, t)^{11}B $\qquad Q_{\mathrm{m}} = -12.4214$

Not reported.

64. ^{13}C(p, ^{3}He)^{11}B $\qquad Q_{\mathrm{m}} = -13.1852$

At $E_{\mathrm{p}} = 50.5$ MeV, in addition to ^{11}B*(0, 2.12, 4.45, 5.02, 6.74, 8.92), a state is observed at $E_{\mathrm{x}} = 12.94 \pm 0.05$ MeV, $\Gamma = 350 \pm 50$ keV. Comparison of the angular distributions of the ^{3}He and of the tritons [in the analog reaction] at $E_{\mathrm{p}} = 43.7$ and 50.5 MeV lead to the assignments $J^{\pi} = \frac{1}{2}^{-}$; $T = \frac{3}{2}$ for this state and for ^{11}C*(12.50): the strong proton and the weak α-decay are consistent with this assignment (1968CO26). The $T = \frac{3}{2}$ state is also observed at $E_{\mathrm{p}} = 40$ MeV by (1974BE20): $E_{\mathrm{x}} = 12.91 \pm 0.03$ MeV, $\Gamma = 260 \pm 50$ keV. ^{11}B*(12.55, 14.33) reported by (1970GO04) in the ^{10}Be(p, γ)^{11}B reaction are not observed by (1974BE20): see Table 11.19. Angular distributions have been measured to ^{11}B*(0, 2.12, 4.45, 5.02) at $E_{\mathrm{p}} = 26.9$ to 43.1 MeV (1975MI01) and at 43.7 and 49.6 MeV (1968FL02). See also (1969SC1F).

65. ^{13}C(d, α)^{11}B $Q_{\rm m} = 5.1686$

Observed proton groups are displayed in Table 11.18 (1970BR23). Angular distributions are reported at $E_{\rm d} = 0.41$ to 0.81 MeV (1971PU01: α_0, α_1), 1.0 to 2.7 MeV (1970LI1E: α_0, α_1), 1.4 MeV (1966KL1A: α_0), 3.3 to 4.2 MeV (1963MA24: α_0), 6.8 MeV (1968DE26: $\alpha_0 \rightarrow \alpha_3$), 11.7 MeV (1969CU08: $\alpha_0 \rightarrow \alpha_3$) and 12.1, 13.3 and 14.1 MeV (1970KL04: $\alpha_0 \rightarrow \alpha_3$). See also (1968AJ02), (1967SP09, 1968CO04, 1971LI1K) and ^{15}N.

66. ^{13}C(^{17}O, ^{19}F)^{11}B $Q_{\rm m} = -4.864$

See (1974CH1Q).

67. ^{14}C(p, α)^{11}B $Q_{\rm m} = -0.7837$

Angular distributions of the $\alpha_0 \rightarrow \alpha_3$ groups have been measured at $E_{\rm p} = 18$ MeV (1962BR34).

68. (a) ^{14}N(n, α)^{11}B $Q_{\rm m} = -0.1574$
(b) ^{14}N(n, 2α)^{7}Li $Q_{\rm m} = -8.823$

Angular distributions for the α_0 and α_1 groups have been measured at $E_{\rm n} = 4.9$ MeV (1973KI1G), 14.1 MeV (1968BA30 [also α_{2+3}], 1968HS03 [also α_2, α_3, α_{4+5}], 1968MA11, 1973BO26), 14.8 to 18.8 MeV (1971SA31) and 14.9 MeV (1968LE11). See also (1969DI1B, 1970DI1A, 1974TU1A). The angular distribution of the 2.12 MeV γ-ray ($E_\gamma = 2118 \pm 5$ keV) is isotropic; that for the 4.4 MeV γ-ray shows a weak anisotropy. Both γ-rays are Doppler broadened: $\tau_{\rm m} < 100$ fsec [see Table 11.5] (1972NY02). See also (1971NY03) and ^{15}N in (1976AJ04).

At $E_{\rm n} = 14.1$ and 15.7 MeV various states of ^{11}B with $8.9 < E_{\rm x} < 14.5$ MeV appear to be involved in the sequential decay to ^{7}Li. Angular correlation results are consistent with $J^\pi = \frac{7}{2}$ and $\frac{5}{2}$ for ^{11}B*(9.19, 9.28), respectively (1971SC16).

69. ^{15}N(α, ^{8}Be)^{11}B $Q_{\rm m} = -11.083$

At $E_\alpha = 72.5$ MeV, the excitation of ^{11}B*(0, 2.12, 4.45, 5.02, 6.74) is reported (1974WO1D).

70. ^{19}F(^{12}C, ^{20}Ne)^{11}B $Q_{\rm m} = -3.112$

See (1971BO1V).

^{11}C

(Figs. 3 and 4)

GENERAL: (See also (1968AJ02).)

Shell model: (1972LE1L, 1973HA49, 1973SA30, 1974ME19).

Cluster and collective model: (1972LE1L).

Special levels: (1969HA1G, 1969HA1F, 1972MS01, 1973SA30, 1974IR04).

Electromagnetic transitions: (1967WA1C, 1969HA1F, 1969HA1G, 1969WA1C, 1973HA49, 1973SA30, 1974ME19).

Astrophysical questions: (1970BA1M, 1972KO1E, 1973LA19).

Special reactions: (1968BE1F, 1968HA1C, 1968MO1C, 1968NO07, 1969GA18, 1969HI1A, 1969YI1A, 1970KR1C, 1971AR02, 1971BA16, 1971BI22, 1971EP02, 1971MO1H, 1973CO1V, 1973JO07, 1973LA19, 1973PH1B, 1973SK01, 1973VA12, 1973WE1N, 1974DI16, 1974HA61).

Applied topics: (1974PE04).

Pion capture and pion reactions: (1968DA1G, 1968NY1A, 1970LI1H, 1971BL02, 1972KA1F, 1972NO1B, 1972SE13, 1973AL1D, 1973AL1E, 1973AR1B, 1973CH20, 1973HO43, 1973JA1J, 1974AM01, 1974MI11).

Other topics: (1968BU1B, 1970SH1C, 1972AB14, 1972AN05, 1972CA37, 1972LE1L, 1973RO1R, 1974IR04).

Ground state properties: (1967CO1D, 1967SH14, 1968RO1E, 1969FU11, 1969PE1D, 1971TA1A, 1971ZO03, 1972LE1L, 1972VA36, 1973CO1P, 1973MA1K, 1973SA30, 1974ME19).

$\mu = -0.964 \pm 0.001$ nm (1969WO03);

$\mu = \pm 0.997$ nm (1968SC18);

$\mu = -0.964 \pm 0.001$ nm (1973CO1P); see also (1971SH26);

$Q = \pm 0.0322$ b (1968SC18).

1. ^{11}C(β^+)^{11}B $\qquad Q_{\rm m} = 1.982$

The half-life of ^{11}C is 20.40 ± 0.04 min (1969AW02). [The weighted mean value of previously reported half-lives is 20.34 ± 0.04 min: see Table 11.15 in (1968AJ02).] $\log ft = 3.591 \pm 0.002$ (B. Zimmerman, private communication). Relativistic corrections to the $\log ft$ value are considered by (1970ST04). The ratio of K-capture to positron emission is $(0.230^{+0.014}_{-0.011})$% (1967CA09). See also (1957SC29, 1969BE09, 1970BE66, 1972CH1G, 1973HO43), (1968FI02) and (1969LE1D, 1969SU15, 1970DA21, 1970KO41, 1971VA1C, 1973EM1B, 1973MU1D, 1973WI04, 1973WI11, 1974LE1G, 1974ME19, 1974WI1M; theor.).

Table 11.20: Energy levels of ^{11}C [a]

E_x in ^{11}C (MeV $\pm$ keV)	J^π; T	τ or $\Gamma_{c.m.}$ (keV)	Decay	Reactions
g.s.	$\frac{3}{2}^-$; $\frac{1}{2}$	$\tau_{1/2} = 20.40 \pm 0.04$ min	β^+	1, 2, 4, 5, 12, 14, 15, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 35, 36
2.0000 ± 0.5	$\frac{1}{2}^-$	$\tau_m < 0.5$ psec	γ	2, 4, 5, 12, 14, 17, 21, 22, 23, 26, 28, 29, 30, 31, 32, 33
4.3188 ± 1.2	$\frac{5}{2}^-$	< 0.14 psec	γ	2, 4, 5, 12, 14, 17, 21, 23, 26, 28, 32
4.8042 ± 1.2	$\frac{3}{2}^-$	< 0.5 psec	γ	2, 4, 12, 14, 17, 21, 23, 26, 28, 32
6.3392 ± 1.4	$\frac{1}{2}^+$	< 0.11 psec	γ	2, 4, 12, 14, 17, 21, 28
6.4782 ± 1.3	$\frac{7}{2}^-$	< 0.25 psec	γ	2, 4, 5, 12, 14, 17, 21, 23, 26, 28, 32
6.9048 ± 1.4	$\frac{5}{2}^+$	< 69 fsec	γ	2, 4, 12, 14, 17, 23, 26, 28, 32
7.4997 ± 1.5	$\frac{3}{2}^+$	< 91 fsec	γ	2, 4, 12, 14, 17, 26, 28, 32
8.1045 ± 1.7	$\frac{3}{2}^-$		(γ)	4, 12, 14, 17, 26, 28
8.425 ± 8	$\frac{5}{2}^-$		γ	2, 4, 12, 14, 17, 26, 28
8.655 ± 8	$\frac{7}{2}^+$	$\Gamma \ll 9$ keV	(γ)	12, 14, 17, 26
8.701 ± 20	$\frac{5}{2}^+$	15 ± 1		12, 14, 26
9.732 ± 5	$(\frac{5}{2}^+)$	450 ± 50	γ, p, α	5, 7, 11, 26
10.084 ± 5	$\frac{7}{2}^+$	≈ 230	p, α	7, 11, 14, 26
10.680 ± 5	$\frac{9}{2}^+$	200 ± 30	p, α	7, 11, 12, 26
(10.799 ± 5)			p, α	7, 11
11.030 ± 5	$T = \frac{1}{2}$	300 ± 60	p, α	7, 11, 26, 32
11.44 ± 10		360	p, α	7, 11, 26
11.954 ± 7			p, α	7, 11
(12.16 ± 40)	$(T = \frac{3}{2})$	270 ± 50	p	4, 8, 22
12.4	$\pi = -$	$1 - 2$ MeV	γ, p	5
12.50 ± 30	$\frac{1}{2}^-$; $\frac{3}{2}$	490 ± 40	p, α	4, 8, 22, 32
12.65 ± 20	$(\frac{7}{2}^+)$	360	p, ^{3}He, α	7, 8, 10, 11
(13.01)			γ, p	5

Table 11.20: Energy levels of ^{11}C [a] (continued)

E_x in ^{11}C (MeV ± keV)	J^π; T	τ or $\Gamma_{c.m.}$ (keV)	Decay	Reactions
13.33 ± 60		270 ± 80		32
13.4		1100 ± 100	p, α	7, 11
13.90 ± 20	$(T = \frac{3}{2})$	200 ± 100	p	4, 8, 22, 32
14.07 ± 20		135 ± 50	n, p	6, 7, 32
14.76 ± 40		≈ 450	n, p, ^{3}He	6, 8, 10
15.35 ± 50	$\pi = -$	broad	γ, n, p	5, 6, 8
15.59 ± 50		≈ 450	n, p	6, 8
16.7	$\pi = -$	800 ± 100	γ, p	5
(18.2)			γ, p	5

[a] See also Table 11.21.

2. (a) ^{6}Li(^{6}Li, n)^{11}C $\quad Q_m = 9.453$
   (b) ^{7}Li(^{6}Li, 2n)^{11}C $\quad Q_m = 2.203$
   (c) ^{7}Li(^{7}Li, 3n)^{11}C $\quad Q_m = -5.048$

At $E(^6\text{Li}) = 4.1$ MeV (reaction (a)) angular distributions have been obtained for the neutrons to ^{11}C*(2.00, 4.32, 4.80, 6.34 + 6.48, 6.90, 7.50). In addition, n-γ coincidences via ^{11}C*(8.43) [and a 8.43 MeV γ-ray] are reported. ^{11}C*(8.10) was not observed (1967BA53). See also (1969GU1D). The lifetimes, τ_m, for ^{11}C*(4.32, 6.90, 7.50) are < 140, < 69 and < 91 fsec, respectively. The upper limits for τ_m of ^{11}C*(6.34, 6.48) [which were unresolved] are 0.5 psec. The ground state transition from ^{11}C*(7.50) has $E_\gamma = 7505 \pm 8$ keV (1969TH01). For reaction (b) see (1968AJ02). For reaction (c) see (1974CE06).

3. ^{7}Be(α, γ)^{11}C $\quad Q_m = 7.545$

See (1972PA1C, 1975FO19).

4. ^{9}Be(^{3}He, n)^{11}C $\quad Q_m = 7.558$

Reported neutron groups are listed in Table 11.16 of (1968AJ02). Angular distributions have

Table 11.21: Gamma decay of ^{11}C levels

E_i (MeV)	J_i^π	τ_m [b] (psec)	E_f (MeV)	Branch [a] (%)	Mult. [a]	Branch [c] (%)	X [c]
2.00	$\frac{1}{2}^-$	< 0.5	0	100			
4.32	$\frac{5}{2}^-$	< 0.5	0	100	M1	100	$+0.17 \pm 0.03$ [g]
		< 0.14 [h]	2.00	< 2		< 2	
4.80	$\frac{3}{2}^-$	< 0.5	0	83 ± 4	M1	86 ± 2 [f]	[e]
			2.00	17 ± 4		14 ± 2 [f]	[e]
6.34	$\frac{1}{2}^+$	< 0.11	0	65 ± 3	E1	68 ± 3	
			2.00	35 ± 3		32 ± 3 [d]	
			4.32			< 7	
			4.80	< 4		< 3	
6.48	$\frac{7}{2}^-$	< 0.25	0	89 ± 2	E2	88 ± 2	-0.01 ± 0.06
			2.00	< 2		< 4	
			4.32	11 ± 2		12 ± 2	
			4.80			< 2	
6.90	$\frac{5}{2}^+$	< 0.16	0	89 ± 3	E1	91 ± 2	0.02 ± 0.03
		< 0.07 [h]	2.00	< 2		< 1	
			4.32	11 ± 3		4.5 ± 1	
			4.80	< 3		4.5 ± 1	
			6.34	< 5			
			6.48	< 5			
7.50	$\frac{3}{2}^+$	< 0.5	0	36 ± 2	E1	37 ± 3	-0.04 ± 0.04
		< 0.09 [h]	2.00	64 ± 2	E1	63 ± 8	0 ± 0.03
			4.32	< 3		< 1	
			4.80	< 3		< 1	
			6.34	< 3			
			6.48	< 3			
			6.90	< 4			
9.73 [i]	$(\frac{5}{2}^+)$		0	65 ± 15			
			2.00	3			
			4.32	12 ± 2			
			6.48	20			

[a] From ^{9}Be(^{3}He, n)^{11}C and ^{10}B(d, n)^{11}C (1965OL03): includes earlier measurements, except for ^{11}C*(9.73): see footnote [i].

[b] (1966WA10).

[c] (1968EA03): ^{12}C(^{3}He, α)^{11}C: $X \equiv$ amplitude ratio of $(L+1)/L$.

[d] The cascade is through ^{11}C*(2.0) and not ^{11}C*(4.3) (1968EA03).

[e] See ^{12}C(^{3}He, α)^{11}C.

[f] 86 ± 3, 14 ± 3% (1966GA19); 84 ± 3, 16 ± 3% (1967BL22).

[g] $+0.16$ $(-0.02, +0.06)$ (1966GA19); 0.13 ± 0.04 (1967BL22).

[h] (1969TH01).

[i] (1961JA11): ^{10}B(p, γ)^{11}C.

been studied in the range $E(^{3}\text{He}) = 1.3$ to 10 MeV: see (1968AJ02) for the earlier references and (1969DE1F, 1971DE2C: $E(^{3}\text{He}) = 4.0$ MeV), (1969HO1F: 4.25 and 6.2 MeV), (1974FU11: 10.5 and 13.0 MeV). The dominant L-values from the angular distributions reported by (1974FU11) are 0 for ^{11}C*(0, 8.10), 1 for ^{11}C*(6.34, 7.50), 2 for ^{11}C*(2.00, 4.32, 4.80, 6.48, 8.43) and 3 for ^{11}C*(6.90). Neutron groups to $T = \frac{3}{2}$ states have been reported by (1971WA21) [$E_{\text{x}} = 12.17 \pm 0.05$ and 12.55 ± 0.05 MeV] and by (1969BR30) [$E_{\text{x}} = 12.5 \pm 0.1$, 13.7 ± 0.1 and 14.7 ± 0.1 MeV]: see Table 11.22.

Gamma branching ratios and multipolarities for ^{11}C levels up to $E_{\text{x}} = 7.5$ MeV have been studied by (1965OL03, 1965RO07): see Table 11.21. Together with evidence from reactions 12 and 27 they lead to assignments of $J^{\pi} = \frac{1}{2}^{-}$, $\frac{5}{2}^{-}$, $\frac{3}{2}^{-}$, $\frac{1}{2}^{+}$, $\frac{7}{2}^{-}$, $\frac{5}{2}^{+}$ and $\frac{3}{2}^{+}$, respectively for ^{11}C*(2.00, 4.32, 4.80, 6.34, 6.48, 6.90, 7.50): see (1965OL03, 1965RO07) and reaction 3 in (1968AJ02) for a summary of the evidence concerning these assignments.

See also (1973SU07), (1968NE1A, 1970EL17, 1970MA38) and ^{12}C.

5. ^{10}B(p, γ)^{11}C $\qquad Q_{\text{m}} = 8.691$

A broad resonance is reported at $E_{\text{p}} = 1.15$ MeV: see Table 11.23 (1956CH20, 1957HU79, 1967PA19). Capture γ-rays are observed corresponding to the ground state transition and to cascades via ^{11}C*(2.00, 4.32, 6.48): see Table 11.21 (1961JA11). See also (1961DO03).

The 90° yield of γ_0 has been measured for $E_{\text{p}} = 2.6$ to 17 MeV and angular distributions have been obtained for $E_{\text{p}} = 2.8$ to 14 MeV. The excitation function is consistent with the giant resonance centered at $E_{\text{x}} \approx 16$ MeV. In addition to weak structures at $E_{\text{p}} = 4.75$ MeV and 10.5 MeV, there are three major peaks at $E_{\text{p}} = 4.1$, 7.0 and 8.8 MeV ($\Gamma = 1 - 2$ MeV) [$E_{\text{x}} = 12.4$, 15.0, 16.7 MeV]. At ^{11}C*(12.4), the γ_0 angular distribution is essentially isotropic: $\Gamma_{\text{p}}\Gamma_{\gamma}/\Gamma \approx 200$ eV, $\Gamma_{\gamma} \approx 5$ keV (assuming $\Gamma_{\text{p}} \approx 10$ keV). The $E_{\text{p}} = 4.1$ MeV resonance is probably part of the E1 giant resonance and is formed by s-wave capture. At the two higher resonances, the angular distributions are characteristic of E1 giant resonances in light nuclei. The ^{10}B(p, γ_1) cross section is small for $E_{\text{p}} = 2.6$ to 17 MeV (1970KU09). See also (1973SU1E) and (1973HA1X, 1973SP02; theor.). The lifetimes of ^{11}C*(4.32, 6.49), $\tau_{\text{m}} < 20$ fsec (1969ROZT; abstract).

Table 11.22: Possible $T = \frac{3}{2}$ states in ^{11}C [a]

Reaction	E_x (MeV)	$\Gamma_{c.m.}$ (keV)	Refs.
^{9}Be(^{3}He, n)^{11}C	12.17 ± 0.05	200 ± 100	(1971WA21)
^{10}B(p, p$_2$)^{10}B**	12.20 ± 0.10		(1971WA21)
^{11}B(^{3}He, t)^{11}C	12.15 ± 0.05	290 ± 50	(1971WA21)
	12.16 ± 0.04 [b]	270 ± 50	mean
^{9}Be(^{3}He, n)^{11}C	12.55 ± 0.05	350 ± 100	(1971WA21)
^{9}Be(^{3}He, n)^{11}C	12.5 ± 0.1		(1969BR30)
^{10}B(p, p$_2$)^{10}B**	12.45 ± 0.10	400 ± 100	(1971WA21)
^{11}B(^{3}He, t)^{11}C	12.57 ± 0.07	370 ± 90	(1971WA21)
^{13}C(p, t)^{11}C	12.47 ± 0.06	550 ± 50	(1968CO26)
^{13}C(p, t)^{11}C	12.48 ± 0.04	540 ± 60	(1974BE20)
	12.50 ± 0.03	490 ± 40	mean
^{9}Be(^{3}He, n)^{11}C	13.7 ± 0.1		(1969BR30)
^{11}B(^{3}He, t)^{11}C	13.92 ± 0.05	260 ± 50	(1971WA21) [a]

[a] See also Table 11.19 for $T = \frac{3}{2}$ states in ^{11}B.

[b] See, however, reaction 32 (1974BE20).

6. ^{10}B(p, n)^{10}C $\qquad Q_m = -4.433 \qquad E_b = 8.691$

The total (p, n) cross section has been measured to $E_p = 10.6$ MeV: broad maxima are observed at $E_p = 5.92 \pm 0.02$, 6.68 ± 0.04, 7.33 ± 0.05 and 7.60 ± 0.05 MeV (see Table 11.23) (1963EA01). The cross section for formation of ^{10}C$_{g.s.}$ measured up to 12 MeV shows similar behavior to 8 MeV. At $E_p \approx 8$ MeV, a sharp maximum is observed. The cross section for production of 3.35 MeV γ-rays (from ^{10}C*) does not appear to show structure for $E_p = 8.5$ to 12 MeV (1966SE03). See also (1973ZW1A; theor.) and ^{10}C in (1974AJ01).

7. ^{10}B(p, p)^{10}B $\qquad E_b = 8.691$

Below $E_p = 0.7$ MeV, the scattering can be explained in terms of pure s-wave potential scattering but the possibility of a state near $E_p = 0.27$ MeV ($E_x = 8.95$ MeV) cannot be excluded. The elastic scattering then shows two conspicuous anomalies at $E_p = 1.50 \pm 0.02$ MeV and at 2.18 MeV [$E_x = 10.05$ and 10.67 MeV] with $J^\pi = \frac{7}{2}^+$ and $\frac{9}{2}^+$: see Tables 11.23 and 11.24 (1960OV1A, 1962OV02: $E_p = 0.15$ to 3.0 MeV). The elastic scattering has also been studied

recently by (1970BO17: $E_p = 3$ to 10.5 MeV), and (1969WA11: $E_p = 5.0$ to 13.4 MeV; optical model analyses). (1969WA11) report a single broad resonance at $E_p \approx 5$ MeV, while (1970BO17) report seven resonances in the corresponding energy interval, in addition to resonances at $E_p = 3.6$ and 4.4 MeV. See also (1962AN11). The depolarization parameter D has been measured for polarized protons with $E_p = 25$ MeV (1974BI1F) and 50 MeV (1970BA05). See also (1970BE1B) and (1973ZW1A, 1974GU13; theor.).

8. ^{10}B(p, p′)^{10}B* $E_b = 8.691$

The yield of γ_1 [from ^{10}B*(0.72)] rises monotonically from $E_p = 1.5$ to 4.1 MeV (1952DA05, 1954DA20, 1957HU79, 1964BE31) and then shows resonance behavior at $E_p = 4.35$ and 5.73 MeV (1962OP03: see Table 11.23). For $E_p = 6$ to 12 MeV, the cross section for γ_1 shows several sharp maxima superposed on a broad maximum ($\Gamma \approx 2.5$ MeV) at $E_p \approx 7.2$ MeV (1966SE03). [The cross section below $E_p = 10$ MeV appears to be in error: see (1969WA23).] Yields of five other γ-rays involved in the decay of ^{10}B*(1.74, 2.16, 3.59, 5.18) have also been measured by (1966SE03) in the range $E_p = 4$ to 12 MeV.

Yield curves for inelastically scattered protons have been measured at $E_p = 5.0$ to 16.4 MeV (p_1, p_2, p_3), 6.6 to 16.4 MeV (p_4), 8.9 to 16.4 MeV (p_5) and 10.9 to 16.4 MeV (p to ^{10}B*(6.03)): the principal feature for all groups, except that to ^{10}B*(6.03), is a structure at $E_p \approx 7.5$ MeV, $\Gamma \approx 4$ MeV. In addition narrower structures are observed, including three at $E_p = 5.75$, 6.90 and 7.80 MeV (± 0.2 MeV) with widths of ≈ 500 keV (1969WA23). It had previously been suggested by (1966SE03) that the formation of $T = 1$ states was relatively suppressed in this reaction. (1969WA23) find that the isotopic spin effect disappears when a correction factor $(2J_f+1)$ is included. Excitation curves for the p_1, p_2 and p_3 groups have been measured for $E_p = 3.5$ to 5.0 MeV. Possible resonances are observed in the p_2 yield [to the $T = 1$ state ^{10}B*(1.74)] corresponding to the first $T = \frac{3}{2}$ states at $E_x = 12.16$ and 12.50 MeV [see Table 11.22]: these do not occur in the yield of p_1 and p_3 (1971WA21).

9. ^{10}B(p, d)^{9}B $Q_m = -6.211$ $E_b = 8.691$

Polarization measurements have been carried out at $E_p = 49.6$ MeV for the deuterons to ^{9}B*(0, 2.36) (1971SQ02). See also ^{9}B in (1974AJ01).

10. ^{10}B(p, ^{3}He)^{8}Be $Q_m = -0.532$ $E_b = 8.691$

The ground-state yield shows slight maxima at energies similar to those in the (p, α) yield in the range $E_p = 4$ to 10 MeV. However, the angular distributions do not vary strongly over the region and it is suggested that a direct interaction mechanism dominates (1963JE01). (1966SE03) report two strong maxima at $E_p \approx 4.5$ and 6.5 MeV. See also ^{8}Be in (1974AJ01).

Table 11.23: Resonances in ^{10}B + p [a]

E_{res} (MeV ± keV)	E_x (MeV)	J^π	Γ_{lab} (keV)	Decay	Refs.
1.145 ± 5	9.732	$(\frac{5}{2}^+)$	500 ± 50	γ, p_0, α_0	(1951BR10, 1956CH20, 1956CR07, 1957HU79, 1967PA19)
1.533 ± 5	10.084	$\frac{7}{2}^+$	≈ 250	p_0, α_0, α_1	(1951BR10, 1956AL23, 1956CH20, 1956CR07, 1957HU79, 1962OV02)
2.189 ± 5	10.680	$\frac{9}{2}^+$	220 ± 30	p_0, α_0, α_1	(1962OV02, 1964BE31, 1964JE01)
2.320 ± 5	(10.799)			p_0, α_1	(1964BE31)
2.574 ± 5	(11.030)			p_0, α_1	(1964BE31)
3.03 ± 10	11.44		400	p_0, α_0, α_1	(1962OP03, 1964JE01)
3.592 ± 7	11.954			p_0, α_1	(1964BE31, 1970BO17)
3.9 ± 100	12.20	$T = \frac{3}{2}$		p_2	(1971WA21)
4.1 ± 100	12.45	$T = \frac{3}{2}$	440 ± 100	p_2	(1971WA21)
4.1 [b,c]	12.4	$\pi = -$	$1 - 2$ MeV	γ_0	(1970KU09)
4.36 ± 20	12.65	$(\frac{7}{2}^+)$	400	p, α_0, α_1, ^{3}He	(1962OP03, 1964JE01, 1966SE03, 1970BO17)
(4.75)	(13.01)			γ_0	(1970KU09)
5.2	13.4		1200 ± 100	p_0, α_0, α_1	(1962OP03, 1964JE01, 1966SE03, 1969WA11, 1970BO17)
5.73 ± 20	13.90		≈ 500	p	(1962OP03, 1969WA23, 1970BO17)
5.92 ± 20	14.07		broad	n, p_0	(1963EA01, 1964JE01, 1966SE03, 1970BO17)
6.68 ± 40	14.76		≈ 500	n, p, ^{3}He	(1963EA01, 1964JE01, 1966SE03, 1969WA23, 1970BO17)
7.33 ± 50 [c]	15.35	$\pi = -$	broad	γ_0, n, p	(1963EA01, 1966SE03, 1969WA23, 1970KU09)
7.60 ± 50	15.59		≈ 500	n, p	(1963EA01, 1969WA23, 1970BO17)
8.8 [c]	16.7	$\pi = -$	900 ± 100	γ_0	(1970BO17, 1970KU09)
(10.5)	(18.2)			γ_0	(1970KU09)

[a] See also Table 11.24.

[b] $\Gamma_p\Gamma_\gamma/\Gamma \approx 200$ eV (1970KU09).

[c] Probably part of the E1 giant resonance (1970KU09).

Table 11.24: Level parameters for ^{10}B(p, p)^{10}B and ^{10}B(p, α)^{7}Be [a]

E_r (MeV)	E_x (MeV)	J^π	Γ_p (MeV)	Γ_{α_0} (MeV)	Γ_{α_1} (MeV)	θ^2_p	$\theta^2_{\alpha_0}$	$\theta^2_{\alpha_1}$
1.17 [b]	9.75	$(\frac{5}{2}^+)$	0.045	0.255				
1.50 [c]	10.05	$\frac{7}{2}^+$	0.090	0.100	0.060	0.02	0.26	0.35
2.18 [c]	10.67	$\frac{9}{2}^+$	0.100	0.100		0.17	0.11	
4.36 [d]	12.65	$(\frac{7}{2}^+)$	0.20	0.15	0.05	0.02	0.29	0.08

[a] See also Table 11.23.

[b] (1956CR07, 1962OV02).

[c] (1962OV02).

[d] (1964JE01).

11. ^{10}B(p, α)^{7}Be $\quad Q_m = 1.1462 \quad E_b = 8.691$

The total cross section for this reaction has been measured for $E_p = 60$ to 180 keV by (1972SZ02): the extrapolated cross section at the Gamow energy, taken to be 19.1 keV, is $\approx 10^{-12}$ b.

The parameters of observed resonances are displayed in Tables 11.23 and 11.24. The ground state (α_0) α-particles exhibit broad resonances at $E_p = 1.17$, 1.53, 2.18, 3.0, 4.4, 5.1 and 6.3 MeV (see (1962OV02, 1964JE01) and (1959AJ76)). Alpha particles to the 0.43 MeV ^{7}Be state (α_1) and 0.43 MeV γ-rays exhibit all but the 1.2 MeV resonance (see (1962OP03, 1964BE31, 1964JE01, 1966SE03) and (1959AJ76)). Weak resonances are also reported at 2.32, 2.57 and 3.59 MeV (1964BE31). A broad maximum dominates the region from $E_p = 4$ MeV to about 7.5 MeV (1966SE03). See also (1968HA1B), (1973ZW1A; theor.) and (1974PE1C; applied).

12. ^{10}B(d, n)^{11}C $\quad Q_m = 6.467$

Angular distribution measurements have recently been reported at $E_d = 0.5$ to 0.8 MeV (1969CH04: n to ^{11}C*(6.35 + 6.49)), 5.8 MeV (1970BO34: see Table 11.25) and 11.8 MeV (1971MU18: n_0). See also (1969JO1F). For recent angular correlation measurements see (1972TH14, 1973PA1N). A great deal of work had previously been done on this reaction: see (1959AJ76, 1968AJ02 [particularly Table 11.20]) for a discussion of the earlier work. Information on the γ-decay of ^{11}C states has been summarized by (1965OL03) and is incorporated in Table 11.21.

Table 11.25 summarizes results obtained in this reaction and in the (^{3}He, d) reaction (1955MA76, 1963OV02, 1970BO34). See also (1967CO30, 1973BR24) and ^{12}C.

Table 11.25: Energy levels of ^{11}C from ^{10}B(d, n)^{11}C and ^{10}B(^{3}He, d)^{11}C

E_x (MeV $\pm$ keV)	J^π	l [f]	l [g]	$S_{d,n}$ [g]	$S_{^3He,d}$ [g]	l [i]	$S_{^3He,d}$ [i]
0	$\frac{3}{2}^-$	1	1	1.12	0.88	1	1.09
2.0006 ± 0.9 [a]	$\frac{1}{2}^-$	(1)	(1)	(0.18)	(0.036)		
			(3)		≤ 0.09	(3)	< 0.40
4.322 ± 10 [b]	$\frac{5}{2}^-$	1	1	0.27	0.20	1	0.17, 0.19
4.808 ± 10 [b]	$\frac{3}{2}^-$	1	1	< 0.02		(1)	< 0.08
						(3)	< 0.35
6.345 ± 10 [b]	$\frac{1}{2}^+$		2		0.07	2	0.08
6.476 ± 10 [b]	$\frac{7}{2}^-$	1	1	0.86	0.56	1	0.73, 0.79
6.903 ± 10 [b]	$\frac{5}{2}^+$	(1)				2	0.06
						0	< 0.04
7.498 ± 10 [b]	$\frac{3}{2}^+$					2	0.08
8.107 ± 10 [b]	$\frac{3}{2}^-$ [k]					1	0.07
8.425 ± 8 [c]	$\frac{5}{2}^-$	1	1	0.65	0.46	1	0.73, 0.79
8.655 ± 8 [c, d]	$\frac{5}{2}^+$	0	0	<u>0.84</u>	0.45		
			2	0.8	<u>0.32</u>		
	$\frac{7}{2}^+$ [j]		0	<u>0.63</u>	0.33	2	0.41
			2	0.6	<u>0.24</u>	0	< 0.34
8.701 ± 20 [d]	$\frac{5}{2}^+$ [j]	(0)	0	<u>0.40</u>	0.14	0	< 0.8
			2	≤ 0.2	0.13		
	$\frac{7}{2}^+$		0	<u>0.30</u>	0.11		
			2	≤ 0.15	0.10		
10.08 [h]							
10.68 [d, e]		(0, 2)					

[a] (^{3}He, d): (1970BR23).
[b] (^{3}He, d): (1961HI08).
[c] (d, n): neutron threshold measurements (1955MA76); based on Q_m.
[d] (d, n): observed by time-of-flight technique (1963OV02).
[e] $\Gamma \approx 200$ keV (1963OV02).
[f] From (d, n) work summarized in Table 11.20 of (1968AJ02).
[g] From (1970BO34): $S_{d,n}$ obtained at $E_d = 5.8$ MeV, $S_{^3He,d}$ obtained at $E(^3He) = 11.0$ MeV [both $\pm$30%]. When $S_{d,n}$ and $S_{^3He,d}$ differ appreciably, the more reliable value is underlined.
[h] See (1971CO07).
[i] From $E(^3He) = 21$ MeV work of (1971CO07); when two values are shown for $S_{^3He,d}$, they are in order of descending j.
[j] Value determined by (1973FO02).
[k] See (1970FO05).

13. ^{10}B(t, 2n)^{11}C $\qquad Q_{\rm m} = 0.209$

See (1961RO21).

14. ^{10}B(^{3}He, d)^{11}C $\qquad Q_{\rm m} = 3.198$

Angular distributions have been measured recently at $E(^{3}\text{He}) = 1.38$ MeV (1970BE1F: d_0), 11.0 MeV (1970BO34: see Table 11.25), 18.0 MeV (1973FO02: deuterons to ^{11}C*(8.66, 8.70)) and 21.0 MeV (1970FO05, 1971CO07: see Table 11.25). Table 11.25 displays also the spectroscopic factors derived from this reaction and from the (d, n) reaction.

The study of the angular distributions of the deuterons to ^{11}C*(8.66, 8.70) shows that these levels are the analogs, respectively, of ^{11}B*(9.19, 9.28) whose J^{π} are $\frac{7}{2}^{+}$ and $\frac{5}{2}^{+}$ [the ^{11}B states were studied in the (d, p) reaction]: $\Gamma_{\rm c.m.}$ are $\ll 9$ keV and 15 ± 1 keV, respectively, for ^{11}C*(8.66, 8.70) (1973FO02).

Singlet deuteron emission has been studied at $E(^{3}\text{He}) = 8$, 10 and 11 MeV by (1970BO07).

15. ^{10}B(α, t)^{11}C $\qquad Q_{\rm m} = -11.123$

Angular distributions have been measured at $E_{\alpha} = 46$ MeV (1969FO1C; abstract; for tritons to ^{11}C states with $E_{\rm x} \leq 8.1$ MeV) and at 56 MeV (1968GA1C, 1969GA11; t_0).

16. ^{10}B(^{6}Li, ^{5}He)^{11}C $\qquad Q_{\rm m} = 4.10$

See (1957NO17).

17. ^{10}B(^{7}Li, ^{6}He)^{11}C $\qquad Q_{\rm m} = -1.287$

Angular distributions of ^{6}He ions corresponding to the transition to $^{11}\text{C}_{\rm g.s.}$ have been measured at $E(^{7}\text{Li}) = 3.0$, 3.5 and 3.8 MeV (1968ST12). At $E(^{7}\text{Li}) = 24$ MeV, the population of ^{11}C*(0, 2.00, 4.32, 4.80, $6.34 + 6.48$, 6.90, 7.50, 8.10, 8.43, 8.66) is reported (1974KO1G).

18. ^{10}B(^{14}N, ^{13}C)^{11}C $\qquad Q_{\rm m} = 1.141$

See (1968BU1B, 1969BR1D, 1970GO1B) and (1968AJ02).

19. ^{10}B(^{16}O, ^{15}N)^{11}C $\quad Q_{\rm m} = -3.436$

See (1968OK06).

20. ^{10}B(^{19}F, ^{18}O)^{11}C $\quad Q_{\rm m} = 0.699$

See (1968GA03).

21. ^{11}B(p, n)^{11}C $\quad Q_{\rm m} = -2.765$

Neutron groups have been observed to ^{11}C*(0, 2.008, 4.320, 4.806, 6.330, 6.481) (± 20 keV) (1965OV01). See also (1970CL01). Angular distributions of the n_0 group have been measured at many energies up to $E_{\rm p} = 18.5$ MeV [see (1968AJ02)] and at 30.5 and 49.5 MeV (1970CL01: also n_1 and $n_2 + n_3$). See also (1969MO32, 1973GO1V), (1969BA1N; astrophys. considerations) and ^{12}C.

22. ^{11}B(^{3}He, t)^{11}C $\quad Q_{\rm m} = -2.001$

Angular distributions of t_0 and t_1 have been measured at $E(^3\text{He}) = 10$ MeV (1967CR04) and 14 MeV (1970NU02). See also (1969OP1A, 1970OP1B). At $E(^3\text{He}) = 26$ MeV the known states of ^{11}C below $E_{\rm x} = 11$ MeV are populated and triton groups are also observed to states, assumed to be $T = \frac{3}{2}$, at $E_{\rm x} = 12.15$, 12.57 and 13.92 MeV [see Table 11.22] and, possibly, 14.15 MeV (1971WA21). See also (1968BR23).

23. ^{11}B(^{6}Li, ^{6}He)^{11}C $\quad Q_{\rm m} = -5.492$

At $E(^6\text{Li}) = 30$ MeV, ^{6}He groups are observed corresponding to ^{11}C*(0, 2.00, 4.32, 4.80, 6.48, 6.90) and the angular distribution to $^{11}C_{\rm g.s.}$ is reported (1972LE1P).

24. ^{12}C(γ, n)^{11}C $\quad Q_{\rm m} = -18.722$

The fraction of transitions to the ground and to excited states of ^{11}C [and to ^{11}B states reached in the (γ, p) reaction] has been measured at $E_{\rm bs} = 24.5$, 27, 33 and 42 MeV: the ground state is predominantly populated. The population of analog states in the (γ, n) and (γ, p) reactions are

similar. And a significant decay strength is found to the positive parity states with $6 < E_x < 8$ MeV. In general the main contribution to the strength of the transitions to the various excited states of ^{11}B, ^{11}C lies in rather localized energy bands in ^{12}C which are a few MeV wide (1970ME17). See also the discussion in (1973DI1C, 1973SP03). See also (1969DE12, 1973GL1C, 1974SC23), (1970MU1D, 1971BI01, 1973MS01, 1973MS02; theor.) and ^{12}C.

25. (a) ^{12}C(e, en)^{11}C $Q_m = -18.722$
(b) ^{12}C(π^+, πN)^{11}C $Q_m = -18.722$
^{12}C(π^-, π^-n)^{11}C
(c) ^{12}C(n, 2n)^{11}C $Q_m = -18.722$
(d) ^{12}C(p, pn)^{11}C $Q_m = -18.722$

For reaction (a) see (1969BA1F; theor.) and ^{12}C. For reaction (b) see (1973HO43). See also (1970LI1H) and the "*Pion capture and pion reactions*" section in ^{12}C. For reaction (c) see ^{13}C. For reaction (d) see (1968DE22, 1968PA05, 1969PO01) and ^{12}C.

26. ^{12}C(p, d)^{11}C $Q_m = -16.497$

Angular distributions have been recently measured at $E_p = 55$ MeV (1974SH1N: d_0, d_1, d_{2+3}), 100 MeV (1968LE01, 1969LI01: d_0, d_1, d_{2+3}, d_{4+5+6}), 155.6 MeV (1969BA05: d to ^{11}C*(0, 2.0, 4.3, 4.8, 6.7, 8.0, 11.0)), 185 MeV (1971KA56: see Table 11.26) and 700 MeV (1973TH1A, 1974BA58: $d_0 \rightarrow d_4$, d_6). The broad peak at $E_x = 15 \pm 0.7$ MeV and the weak [≈ 7 MeV broad] structure at $E_x = 18-23$ MeV reported by (1969BA05) are not observed by (1971KA56). See also (1969SU02, 1973FA10). For a listing of earlier angular distribution measurements [$E_p = 19$ to 60 MeV] see (1968AJ02). See also (1968TI1A, 1972RO1K, 1974KI1A) and (1968JA1D, 1969DO08, 1969TO1A, 1970BA1N, 1971LO28 [pion], 1971MC15, 1972ST33, 1973TA27, 1974IN07; theor.).

27. ^{12}C(d, t)^{11}C $Q_m = -12.464$

At $E_d = 28$ MeV the t_0 angular distribution has been measured and a detailed comparison has been made with the results from the mirror reaction ^{12}C(d, ^{3}He)^{11}B (1966DE1C, 1968GA13). Angular distributions of the t_0 group have also been measured at $E_d = 20.0$, 24.0 and 28.0 MeV by (1971IN1C; unpublished thesis): at the highest energy angular distributions of several triton groups to excited states of ^{11}C are also reported. See also (1971BO50; theor.) and (1968AJ02).

28. ^{12}C(^{3}He, α)^{11}C $Q_m = 1.857$

Table 11.26: Levels of ^{11}C from ^{12}C(p, d)^{11}C [a]

E_x (MeV $\pm$ keV)	J^π [c]	S_{rel}
0	$\frac{3}{2}^-$	100
1.9997 ± 0.5 [b]	$\frac{1}{2}^-$	17.4
4.30 ± 50	$\frac{5}{2}^-$	< 0.06
4.80 ± 50	$\frac{3}{2}^-$	9.7
(6.34)	$\frac{1}{2}^+$	< 0.03
6.49 ± 50	$\frac{7}{2}^-$	0.6
6.92 ± 50	$\frac{5}{2}^+$	0.7
7.53 ± 50	$\frac{3}{2}^+$	0.4
8.13 ± 50	$\frac{3}{2}^-$	0.7
8.43 ± 50	$\frac{5}{2}^-$	0.08
8.67 ± 80	$\frac{7}{2}^+ + \frac{5}{2}^+$	
9.3 ± 100		
9.7 ± 100	$(\frac{5}{2}^+)$	
10.1 ± 200	$\frac{7}{2}^+$	
10.7 ± 200	$\frac{9}{2}^+$	
11.0 ± 100		
11.5 ± 200		

[a] (1971KA56): $E_p = 185$ MeV.

[b] (1974NO07).

[c] From Table 11.20.

Angular distributions have been measured at many energies. Recent experiments are reported at $E(^3\text{He}) = 9.5$, 10.5 and 11.5 MeV (1970BO34), 13.9 MeV (1968OB01: $\alpha_0 \rightarrow \alpha_3$), 16, 17 and 18 MeV (1970GR08), 19.1, 27.1 and 35.7 MeV (1968AR12), 24 and 28 MeV (1973FU02), 24.0, 29.2, 34.7 and 39.6 MeV (1974YA10: α_0, α_1, α_2), 35.6 MeV (1970FO05: α_0 and α to ^{11}C*(8.10, 8.43)), 42 MeV (1973SI11: $\alpha_0 \rightarrow \alpha_4$), 44.8 MeV (1966BA13: α_0) and 217 MeV (1974GE09: α_0, α_1, α_2, α_3). See Table 11.27 for a display of the results and (1968AJ02) for a summary of the extensive earlier work. For discussions of the reaction mechanisms see, e.g. (1970BO34, 1973FU02).

Alpha-γ correlations have been studied for $E(^3\text{He}) = 4.7$ to 12 MeV: see, in particular, (1968EA03). Their results are summarized in Table 11.21 and are discussed in detail in reaction 22 (1968AJ02). A measurement of the linear polarization of the 2.00 MeV γ-ray (together with knowledge of the τ_m) fixes $J^\pi = \frac{1}{2}^-$ for ^{11}C*(2.00) (1968BL09). See also (1970CA28,

Table 11.27: Levels of ^{11}C from ^{12}C(^{3}He, α)^{11}C [a]

E_x (MeV ± keV)	l [d]	S_{rel}		
		$E(^3\text{He}) = 16$ MeV [f]	24 MeV [g]	28 MeV [g]
0	1	1	1	1
1.999 ± 4 [b]	1	0.10	≤ 0.6	≤ 0.6
4.3188 ± 1.2 [c]	3	0.057	(0.04)	(0.06)
4.8042 ± 1.2 [c]	1	0.11	0.22	0.22
6.3392 ± 1.4 [c]	0	0.003 [h]	≤ 0.07	≤ 0.07
6.4782 ± 1.3 [c]	3	0.11 [h]	0.06	(0.06)
6.9048 ± 1.4 [c]	2	0.018	(0.15)	(0.17)
7.4997 ± 1.5 [c]	2	0.006 [h]	(0.07)	(0.09)
8.1045 ± 1.7 [c]	1 [e]	0.017 [h,i]		
8.43	3 [e]	0.034 [h,j]		

[a] See Table 11.21 for γ-decay work (1968EA03).
[b] (1968EA03).
[c] (1970BR23).
[d] (1970BO34). See also (1968AR12, 1970GR08).
[e] (1970FO05).
[f] (1970GR08).
[g] (1973FU02).
[h] At $E(^3\text{He}) = 18$ MeV.
[i] Assuming $J^\pi = \frac{3}{2}^-$.
[j] Assuming $J^\pi = \frac{5}{2}^-$.

1970JA1E), (1969DO08, 1972WE1F, 1974DO15; theor.) and ^{15}O in (1976AJ04).

29. ^{12}C(^{6}Li, ^{7}Li)^{11}C $\quad Q_m = -11.471$

At $E(^6\text{Li}) = 36$ MeV the angular distributions involving $^7\text{Li}_{\text{g.s.}} + {}^{11}\text{C}_{\text{g.s.}}$ and $^7\text{Li}^*_{0.48} + {}^{11}\text{C}^*_{2.00}$ have been studied by (1973SC26).

30. (a) ^{12}C(^{10}B, ^{11}B)^{11}C $\quad Q_m = -7.266$
(b) ^{12}C(^{12}C, ^{13}C)^{11}C $\quad Q_m = -13.775$

Reaction (a) has been observed at $E(^{10}\mathrm{B}) = 100$ MeV: $^{11}\mathrm{C}_{\mathrm{g.s.}}$ is much more strongly populated than ^{11}C*(2.00) (1973YO1C, 1973YO1D). See also reaction 58 in ^{11}B (1974HA1V). The angular distribution involving the ground state transitions has been measured for reaction (b) at $E(^{12}\mathrm{C}) = 114$ MeV (1974AN36).

31. ^{12}C(^{14}N, ^{15}N)^{11}C $\qquad Q_{\mathrm{m}} = -7.888$

See (1967BI06, 1974AN36). See also (1967VO1A, 1969BR1D, 1973SC1J) and ^{15}N in (1976AJ04).

32. ^{13}C(p, t)^{11}C $\qquad Q_{\mathrm{m}} = -15.186$

At $E_{\mathrm{p}} = 43.7$ to 50.5 MeV angular distributions of the tritons have been studied to ^{11}C*(0, 2.00, 4.32, 4.80, 6.48, 6.90, 7.50) and to a $T = \frac{3}{2}$ state at $E_{\mathrm{x}} = 12.47$ MeV [see Table 11.22] whose J^{π} is determined to be $\frac{1}{2}^{-}$ [it is thus the mirror of ^{11}Be*(0.32)] (1968CO26, 1968FL02). The state decays primarily by p $\rightarrow$ ^{10}B*(1.74). Alpha decay to $^{7}\mathrm{Be}^{*}_{\mathrm{g.s.}+0.4}$ is also observed (1968CO26). Angular distributions have also been measured for $E_{\mathrm{p}} = 26.9$ to 43.1 MeV (1975MI01: $\mathrm{t}_0 \rightarrow \mathrm{t}_3$). At $E_{\mathrm{p}} = 46.7$ MeV the $T = \frac{3}{2}$ state is also observed by (1974BE20) who, in addition, report the population of states with $E_{\mathrm{x}} = 11.03 \pm 0.03$, 13.33 ± 0.06, 13.90 ± 0.04 and 14.07 ± 0.04 MeV [$\Gamma = 300 \pm 60$, 270 ± 80, 150 ± 50 and 135 ± 50 keV, respectively]. However, the $T = \frac{3}{2}$ state at $E_{\mathrm{x}} = 12.16$ MeV reported by (1971WA21) in reactions 4, 8 and 22 is not observed by (1974BE20). See also (1969SC1F) and (1971KA04; theor.).

33. ^{14}N(p, α)^{11}C $\qquad Q_{\mathrm{m}} = -2.922$

Angular distributions have been reported at $E_{\mathrm{p}} = 4.99$ to 5.55 MeV (1969WE02: α_0), 6.0 to 9.0 MeV (1968SH11: α_0) and 7.53, 8.03, 9.54 and 10.54 MeV (1970ME30: α_0, α_1) and 20.5 to 44.3 MeV (1974PI05: α_0, α_1). See also (1972MA21), (1968AJ02) and ^{15}O in (1976AJ04).

34. ^{16}O(γ, nα)^{11}C $\qquad Q_{\mathrm{m}} = -25.884$

See (1968AJ02).

35. ^{16}O(p, ^{6}Li)^{11}C $\qquad Q_{\mathrm{m}} = -22.185$

See (1969HO1H).

36. ^{16}O(α, ^{9}Be)^{11}C $\qquad Q_{\rm m} = -24.310$

At $E_\alpha = 42$ MeV, the angular distribution involving the transition to $^{9}\mathrm{Be}_{\rm g.s.} + {}^{11}\mathrm{C}_{\rm g.s.}$ has been measured (1972RU03).

^{11}N

(Fig. 4)

The ^{14}N(^{3}He, ^{6}He)^{11}N reaction has been studied at $E(^{3}\mathrm{He}) = 70$ MeV (1974BE20). A ^{6}He group is observed which corresponds to a state in ^{11}N with an atomic mass excess of 25.23 ± 0.10 MeV and $\Gamma = 740 \pm 100$ keV. The cross section for forming this state is 0.5 μb/sr at 10°. The observed state is interpreted as being the $J^\pi = \frac{1}{2}^-$ mirror of ^{11}Be*(0.32) because of its width; the $\frac{1}{2}^+$ mirror of $^{11}\mathrm{Be}_{\rm g.s.}$ would be expected to be much broader (1974BE20). The ^{11}N state is unbound with respect to decay into $^{10}\mathrm{C} + \mathrm{p}$ by 2.31 MeV. See also (1968AJ02, 1969LO1B, 1970WA1G, 1974IR04).

^{11}O

(Not illustrated)

This nucleus has not been observed: see (1972WA07, 1974IR04).

^{11}F

(Not illustrated)

This nucleus has not been observed: see (1974IR04).

References

(Closed 31 January 1975)

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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