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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*114 (1968), 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}Li

(Fig. 4)

^{11}Li has been identified in the 5.3 GeV proton bombardment of uranium. It is particle stable (1966PO09). See also (1966GA25, 1967CO1K).

^{11}Be

(Figs. 1 and 4)

GENERAL:

Mass of ^{11}*Be:* The Q-value of the ^{9}Be(t, p)^{11}Be reaction is given as $Q = -1.164 \pm 0.015$ MeV by (1962PU01) (based on ^{12}C(t, p)^{14}C*). This value has been adjusted by (1965RY01) to -1.170 MeV, leading to $M - A$ for ^{11}Be $= 20.181 \pm 0.015$ MeV (relative to ^{12}C) (1965MA54).

See (1960TA07, 1960TA1C, 1961DO03, 1966RO11, 1967DE1V). The ground state of ^{11}Be has even parity (1964AL22).

1. ^{11}Be(β^-)^{11}B $\qquad Q_{\rm m} = 11.513$

The decay proceeds to the ^{11}B states at 0, 2.12, 6.79 and 8.00 MeV ($J^\pi = \frac{3}{2}^-, \frac{1}{2}^-, \frac{3}{2}^+, \frac{3}{2}^+$, respectively); the half-life is 13.68 ± 0.14 sec. The nature of the decay indicates even parity, $J^\pi = \frac{1}{2}^+, \frac{3}{2}^+$ or $\frac{5}{2}^+$ for ^{11}Be$_{\rm g.s.}$ (1961DO03, 1964AL22): see ^{11}B.

2. ^{9}Be(t, p)^{11}Be $\qquad Q_{\rm m} = -1.170$

Proton groups have been observed corresponding to seven states of ^{11}Be: see Table 11.2 (1962PU01). Angular distributions measured at $E_{\rm t} = 6$, 10 and 14 MeV do not show a clear stripping pattern for the ground-state protons. At $E_{\rm t} = 14$ MeV, the distribution of protons corresponding to ^{11}Be*(0.319) exhibits an $L = 2$ pattern indicating $J^\pi = \frac{1}{2}^-, \frac{5}{2}^-$ or $\frac{7}{2}^-$ (1962PU01, 1964HI08). (1960TA07) suggest $J^\pi = \frac{1}{2}^+$ and $\frac{1}{2}^-$ for the ground and first excited states, respectively. The dimensionless reduced widths $\theta^2_{\rm n}$ for $E_{\rm x} = 1.8$, 2.7 and 3.4 MeV indicate $l = 0$, 1 or 2 decay to ^{10}Be + n, $J^\pi = \frac{1}{2}^\pm, \frac{3}{2}^\pm$ or $\frac{5}{2}^+$ (1962PU01). See also (1968HO1F).

3. ^{9}Be(^{6}He, α)^{11}Be $\qquad Q_{\rm m} = 6.343$

Table 11.1: Energy levels of ^{11}Be

E_x (MeV ± keV)	J^π	Γ_{lab} (keV)	Decay	Reactions
0	$\frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+$	$\tau_{1/2} = 13.81 \pm 0.08$ sec	β^-	1, 2, 3, 4
0.319 ± 10	$\frac{1}{2}^-, \frac{5}{2}^-, \frac{7}{2}^-$	< 10	(γ)	2
1.780 ± 20	$\frac{1}{2}^\pm, \frac{3}{2}^\pm, \frac{5}{2}^+$	110 ± 15	(n)	2
2.700 ± 25	$\frac{1}{2}^\pm, \frac{3}{2}^\pm, \frac{5}{2}^+$	250 ± 20	(n)	2
3.410 ± 25	$\frac{1}{2}^\pm, \frac{3}{2}^\pm, \frac{5}{2}^+$	150 ± 20	(n)	2
3.890 ± 20		< 10	(n)	2
3.960 ± 20		< 10	(n)	2

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

E_x (MeV ± keV)	Γ_{lab} (keV)	J^π	θ_n^2 [b]			
			s	p	d	f
0		$\frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+$				
0.319 ± 10	< 10	$\frac{1}{2}^-, \frac{5}{2}^-, \frac{7}{2}^-$				
1.780 ± 20	110 ± 15	$\frac{1}{2}^\pm, \frac{3}{2}^\pm, \frac{5}{2}^+$	0.028	0.051	0.40	10
2.700 ± 25	250 ± 20	$\frac{1}{2}^\pm, \frac{3}{2}^\pm, \frac{5}{2}^+$	0.046	0.080	0.31	3.6
3.410 ± 25	150 ± 20	$\frac{1}{2}^\pm, \frac{3}{2}^\pm, \frac{5}{2}^+$	0.025	0.038	0.073	0.89
3.890 ± 20	< 10					
3.960 ± 20	< 10					

[a] (1962PU01, 1964HI08).

[b] Units of $\hbar^2/\mu R^2$.

See (1967ST21) and ^{15}C.

4. ^{11}B(n, p)^{11}Be $\qquad Q_{\rm m} = -10.731$

At $E_{\rm n} = 14.8$ MeV, σ(nα)/σ(np) $= 10.0 \pm 1.5$ (1958NU40).

5. ^{11}B(γ, π^+)^{11}Be $\qquad Q_{\rm m} = -151.09$

See (1962DY1A, 1963NE07).

^{11}B

(Figs. 2 and 4)

GENERAL:

Shell model: (1956KU1A, 1957KU58, 1960BI07, 1960TA1C, 1961BA1E, 1961BA1F, 1961KO1A, 1961KU1C, 1961TR1B, 1961UM1A, 1964AM1D, 1964NE1E, 1965CO25, 1965FA1B, 1965FA1C, 1966HA18, 1966MA1P, 1967CO32, 1967FA1A, 1968KU1D).

Collective model: (1959BR1E, 1961CL10, 1962CL13, 1964MA1G, 1965NE1B, 1966EL08, 1966MI1F, 1967RI1B, 1968GO01).

Ground state properties: (1962BE1D, 1963BE36, 1964LI14, 1964LI1B, 1964ST1B, 1965HU13, 1966RI12, 1966WI1E, 1967BA78, 1967RH1C, 1967SH05, 1968BA2G).

Other: (1963SE1K, 1964OL1A, 1964TH03, 1966WI1F, 1967BA1E, 1967PO1J).

$\mu = +2.6885$ nm (1965FU1G);

$Q = +0.04$ b (1965FU1G), $+0.0372$ b (1966ST12).

1. ^{6}Li(^{6}Li, p)^{11}B $\qquad Q_{\rm m} = 12.220$

Angular distributions of the protons to ^{11}B states below $E_{\rm x} = 9.3$ MeV have been measured for $E(^{6}$Li$) = 2.4$ to 9.0 MeV (1966KI09). Gamma spectra have been studied at $E(^{6}$Li$) = 2.6$ MeV. Relative populations to ^{11}B levels are reported (1962BE24). See also (1960SH01, 1962BE16, 1963LE09).

Table 11.3: Energy levels of ^{11}B

E_x (Mev ± keV)	J^π	τ_m or Γ (sec) (keV)	Decay	Reactions
g.s.	$\frac{3}{2}^-$	stable		1, 2, 7, 8, 9, 13, 14, 15, 16, 17, 18, 25, 26, 28, 29, 30, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 48, 50, 51, 52, 53, 54
2.1244 ± 0.7 [a]	$\frac{1}{2}^-$	0.122 ± 0.005 eV	γ	1, 7, 8, 9, 14, 15, 16, 25, 26, 29, 30, 34, 35, 36, 39, 42, 43, 45, 46, 52, 53
4.4444 ± 1.4 [a]	$\frac{5}{2}^-$	0.54 ± 0.05 eV	γ	1, 2, 7, 8, 9, 14, 15, 16, 25, 26, 30, 34, 36, 42, 43, 45, 46, 52, 53
5.0189 ± 1.7 [a]	$\frac{3}{2}^-$ $(\frac{1}{2}^-)$	1.73 ± 0.14 eV	γ	1, 7, 8, 9, 14, 15, 16, 25, 26, 30, 34, 36, 42, 43, 45, 46, 52, 53
6.7429 ± 1.8 [a]	$\frac{7}{2}^-$	$\tau_\mathrm{m} < 3 \times 10^{-13}$	γ	1, 2, 7, 14, 15, 25, 26, 34, 36, 42, 43, 45
6.7928 ± 1.8 [a]	$(\frac{1}{2}, \frac{3}{2})^+$	$\tau_\mathrm{m} < 5 \times 10^{-14}$	γ	1, 7, 14, 16, 25, 26, 29, 34, 43
7.296 ± 4	$(\frac{3}{2}, \frac{5}{2})^+$	1.0 ± 0.5 eV	γ	1, 7, 14, 16, 25, 26, 30, 34, 36
7.996 ± 6	$\frac{3}{2}^+$	$\tau_\mathrm{m} < 5 \times 10^{-14}$	γ	1, 7, 14, 16, 25, 29, 34
8.566 ± 4	$\leq \frac{5}{2}^-$	2.0 ± 0.7 eV	γ	1, 7, 14, 25, 34
8.925 ± 4	$\frac{5}{2}^-$	4.0 ± 0.6 eV	γ, α	1, 2, 14, 25, 30, 34, 36
9.185 ± 1	$\frac{7}{2}^+$	3 eV	γ, α	1, 2, 14, 25
9.274 ± 1	$\frac{5}{2}^+$	7 eV	γ, α	1, 2, 14, 25
9.87 ± 20	$\frac{3}{2}^+$	250	α	6, 14, 36
10.25 ± 35	$(\frac{3}{2}^-)$	200	α	6, 14
10.33 ± 15	$\frac{5}{2}^-$ $(\frac{7}{2}^-)$	54 ± 17	α	6, 14, 25
10.595 ± 6	$\frac{7}{2}^+$ $(\frac{5}{2}^+)$	90	α	6, 14
11.0	$\frac{5}{2}^-$ $(\frac{3}{2}^-)$	4500	α	6
11.266 ± 7	$\frac{7}{2}^+$, $\frac{9}{2}^+$	100	α	6, 14
11.462 ± 10		70 ± 30	α	6, 14
11.60 ± 35		150 ± 50	n, α	3, 6
11.884 ± 12	$(\frac{5}{2}^+)$	150 ± 50	n, α	3, 6, 14, 24
12.0 ± 130		≈ 1000	α	6, 14
12.565 ± 12	$(T = \frac{3}{2})$	145 ± 30	α	6, 14, 16
13.02 ± 80	$\frac{1}{2}^-; T = \frac{3}{2}$	358 ± 60		51
13.15 ± 100	$\geq \frac{11}{2}^+$	270 ± 50	n, α	3, 6, 14, 19, 20, 24, 34, 36
14.04 ± 100		500 ± 200	n, α	3, 6, 19, 20, 24

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

E_x (Mev ± keV)	J^π	τ_m or Γ (sec) (keV)	Decay	Reactions
14.563 ± 15		< 120	n, α	3, 6, 14, 20, 24, 36
15.12 ± 100		750	n, α	3, 20, 24
15.80 ± 130		180 ± 100	n, α	3, 6, 20
16.7 ± 300			n, α, d, p, (t)	3, 10, 11, 24
(16.9)			d, p, t	11, 14
17.53 ± 30			n, α, d, p	3, 11, 24
18.3 ± 800	$\frac{1}{2}^+$			41

[a] (1966BR18).

2. ^{7}Li(α, γ)^{11}B $Q_m = 8.664$

Three resonances for capture radiation are reported at $E_\alpha = 401$, 819 and 958 keV, corresponding to ^{11}B levels at 8.92, 9.19 and 9.27 MeV: see Table 11.4. No others appear for $E_\alpha < 2.5$ MeV (1954HE22). See also (1960SI02). Angular distributions and correlations have been studied by (1959JO25, 1962GR07) with the following conclusions:

$\underline{E_x = 9.27\text{ MeV}.}$ The angular distribution of the ground-state transition requires $J^\pi = \frac{3}{2}^\pm$ or $\frac{5}{2}^\pm$. Correlations in the cascades eliminate all but $J^\pi = \frac{5}{2}^+$, formed by p-wave. $\theta^2_\alpha \approx 0.1$. The g.s. radiation is E1, $\Gamma_\gamma = 0.6$ eV [cm].

$\underline{E_x = 4.44\text{ MeV}.}$ The angular distribution in the cascade $9.28 \to 4.44 \to$ g.s. determines $J = \frac{5}{2}$; stripping results give odd parity. The E2/M1 amplitude ratio in the transition to the ground state is $x = -0.2 \pm 0.02$ [1] .

$\underline{E_x = 6.74\text{ MeV}.}$ Angular distributions and branching ratios indicate $J^\pi = \frac{7}{2}^\pm$, with $\frac{7}{2}^-$ favored (and indicated by stripping). The transition $6.74 \to 4.44$ is either pure M1 or pure E2. The branching ratio $6.74 \to$ g.s./$6.74 \to 4.44$ is 1.75 ± 0.1 (1962GR07), 4.9 (1958FE70). See also ^{9}Be(^{3}He, p)^{11}B.

$\underline{E_x = 9.19\text{ MeV}.}$ Angular correlations in the cascade transitions require $J^\pi = \frac{7}{2}^\pm$; the ground-state transition fixes $J^\pi = \frac{7}{2}^+$ formed by f-waves, $\theta^2 = 0.04$, with an M2/E3 amplitude of 0.9 and an E3 strength of 6 to 17 Weisskopf units. See, however, ^{9}Be(^{3}He, p)^{11}B.

$\underline{E_x = 8.93\text{ MeV}.}$ The angular distribution of the ground-state transition yields $J^\pi = \frac{3}{2}^+$ or $\frac{5}{2}^\pm$. Consideration of the transition strength favors $\frac{5}{2}^-$.

[1] The sign and magnitude are in good accord with IPM, if collective enhancement is included (PO66E).

Table 11.4: Resonances in ^{7}Li(α, γ)^{11}B [a]

$E_{\rm r}$ [b] (keV)	$\Gamma_{\rm c.m.}$ [b] (keV)	^{11}B* (MeV)	J^{π}	$\omega\Gamma_{\rm s}$ [c] (eV)	Percentage decay [d] to states of ^{11}B* at			
					0	4.44	6.74	6.79
401	< 1	8.919	$(\frac{5}{2})^{-}$	0.04	93 ± 5	2.3 ± 1		
819 ± 1 [e]	≈ 4 [f]	9.185	$\frac{7}{2}^{+}$	0.55	0.9 ± 0.3	82.8 ± 2.0	12.8 ± 0.4	< 1.3
958 ± 1 [e]	7	9.274	$\frac{5}{2}^{+}$	3.5	19.7 ± 1.0	67.5 ± 2.0	12.8 ± 0.7	< 0.6

[a] See also Tables 11.9 and 11.13.

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

[c] $\omega\Gamma_{\gamma}\Gamma_{\alpha}/\Gamma$, in c.m. (1951BE13, 1959JO25). See also (1965OL03).

[d] (1962GR07) $\theta = 55°$; see also (1958FE70, 1959JO25), and Table 11.9.

[e] (1962GR07) find 815, 951 keV; (1957BR18) find 957 ± 2 keV.

[f] $\Gamma \approx 3$ eV (1965OL03).

3. ^{7}Li(α, n)^{10}B $\quad Q_{\rm m} = -2.792 \quad E_{\rm b} = 8.664$

Observed resonances are listed in Table 11.5. Comparison with ^{10}B(n, α)^{7}Li indicates that the resonances at $E_{\alpha} = 5.15$ MeV ($E_{\rm x} = 12.0$ MeV) has $J^{\pi} = \frac{3}{2}^{-}$ or $\frac{5}{2}^{+}$, $\Gamma_{\rm n} \approx 20$ keV, $\Gamma_{\alpha} \approx 300$ keV formed by $l_{\rm n} = 0$ or 1 (1959GI47).

4. ^{7}Li(α, p)^{10}Be $\quad Q_{\rm m} = -2.564 \quad E_{\rm b} = 8.664$

See ^{10}Be in (1966LA04).

5. ^{7}Li(α, t)^{8}Be $\quad Q_{\rm m} = -2.562 \quad E_{\rm b} = 8.664$

See ^{8}Be on (1966LA04).

6. ^{7}Li(α, α)^{7}Li $\quad E_{\rm b} = 8.664$

Elastic scattering has been studied for $E_{\alpha} = 1.6$ to 12 MeV by (1966CU02). The inelastic scattering, leading to ^{7}Li*(0.48) has been studied by (1954HE22: $E_{\alpha} = 1.5$ to 3.5 MeV), (1954LI48: $E_{\alpha} = 1.2$ to 2.8 MeV), (1957BI84: $E_{\alpha} = 1.5$ to 6.0 MeV), (1966CU02: $E_{\alpha} = 1.6$ to 12 MeV); see Table 11.6.

Table 11.5: Thresholds and resonances in ^{7}Li(α, n)^{10}B

(1957BI84)		(1959GI47)	(1963ME08)	
E_α (MeV ± keV)	Γ_{lab} (keV)	E_α (MeV ± keV)	E_α (MeV ± keV)	E_{x} (MeV ± keV)
4.379 ± 6 (thresh.)			4.380 ± 20	thresh.
4.7			[4.72]	11.67 ± 100
5.15 ± 80	220	5.15 ± 70	[5.22]	11.99 ± 100
		(5.64)	5.5	thresh.
		7.15 [a]	7.05	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] The width of this resonance is large.

A detailed fit to the elastic and inelastic data below the first (α, n) threshold, $E_\alpha = 4.38$ MeV, requires at least seven resonances (Table 11.7) (1966CU02). For the 9.87 MeV level, the weakness of the elastic effect eliminates $J = \frac{1}{2}$, while the reduced width in the inelastic channel eliminates $J^\pi = \frac{3}{2}^-$ and $J \geq \frac{5}{2}$; thus $J^\pi = \frac{3}{2}^+$. Of the next two levels, $E_{\text{x}} = 10.25$ and 10.32 MeV, the first influences mainly the inelastic yield, while the second (seen also in ^{10}B(d, p)^{11}B) appears only in the elastic scattering. For the lower, possible assignments are $J = \frac{1}{2}^\pm$, $\frac{3}{2}^\pm$ or $\frac{5}{2}^\pm$, with $\frac{3}{2}^-$ preferred; the upper has $J^\pi = \frac{5}{2}^-$ or $\frac{7}{2}^-$. The narrow level at $E_{\text{x}} = 10.60$ MeV, also seen in ^{9}Be(^{3}He, p)^{11}B shows no effect on elastic scattering at $\theta_{\text{cm}} = 141°$, indicating $l = 3$; $J^\pi = \frac{7}{2}^+$ is preferred, with $J = \frac{5}{2}^+$ possible. A broad maximum in the inelastic cross section at $E_\alpha \approx 3.6$ MeV may indicate a level at $E_{\text{x}} = 11.0$ MeV. An underlying general rise is ascribed to a $J^\pi = \frac{1}{2}^+$ level, with $\Gamma \approx 4.4$ MeV. With this assumption, the elastic yields require $J^\pi = \frac{3}{2}^-$ or $\frac{5}{2}^-$ for the 11.0 MeV level, with $\frac{5}{2}^-$ preferred. The narrow level at $E_\alpha = 4.1$ MeV, $E_{\text{x}} = 11.27$ MeV, appears only weakly in the inelastic cross section; it is seen also in ^{9}Be(^{3}He, p)^{11}B. The elastic scattering indicates $J^\pi = \frac{7}{2}^+$ or $\frac{9}{2}^+$.

Table 11.6: Structure in ^{7}Li(α, α')^{7}Li* and ^{7}Li(α, α)^{7}Li

A		B	C		D			
E_α (keV)	$\Gamma_{\rm cm}$ (keV)	E_α (keV)	E_α (keV)	$\Gamma_{\rm cm}$ (keV)	E_α $^{\rm a}$ (keV)	E_α $^{\rm b}$ (keV)	$\Gamma_{\rm cm}$ (keV)	$E_{\rm x}$ (MeV $\pm$ keV)
1889 ± 10	125 ± 10	1910	1910 ± 20	160	1920 ± 30		130 ± 30	9.89 ± 20
2500 ± 30	≈ 155	2460	2490 ± 50	220	2480 ± 50		150 ± 40	10.24 ± 35
						2630 ± 30	80 ± 30	10.34 ± 20
		3060	3060 ± 30	100	3032 ± 10	3032	70 ± 10	10.595 ± 6
			3600 ± 100	670	3600 ± 50		≥ 900	10.96 ± 35
						4120 ± 30	90 ± 50	11.29 ± 20
					4430 ± 50	4430		(11.49) $^{\rm e}$
					4600 ± 50		150 ± 50	11.59 ± 35
					5050 ± 30		150 ± 50	11.88 ± 20
						5300 ± 200	≈ 1000	12.04 ± 130
						5500 ± 100	60 ± 50	(12.17) $^{\rm e}$
					6100 ± 30		150 ± 50	12.55 ± 20
					6850 ± 60		270 ± 50	13.03 ± 45
					(7200 ± 50) $^{\rm c}$		50 ± 50	(13.25) $^{\rm e}$
						7800 ± 100	500 ± 200	(13.63) $^{\rm e}$
					(8450 ± 200) $^{\rm d}$		500 ± 200	(14.04 ± 130)
					(9450 ± 200) $^{\rm d}$		≤ 250	(14.68 ± 130)
						9950 ± 200	500 ± 200	(15.00) $^{\rm e}$
					(11200 ± 200) $^{\rm d}$		180 ± 100	(15.80 ± 130)

A: (1954LI48): ^{7}Li(α, $\alpha'\gamma$)^{7}Li. B: (1954HE22): ^{7}Li(α, $\alpha'\gamma$)^{7}Li. C: (1957BI84): ^{7}Li(α, $\alpha'\gamma$)^{7}Li. D: (1966CU02): see also Table 11.7.

[a] ^{7}Li(α, $\alpha'\gamma$)^{7}Li: σ(total). [b] ^{7}Li(α, α)^{7}Li. [c] Anomaly in angular distribution. [d] ^{7}Li(α, α')^{7}Li: $\theta = 60°$. [e] ^{7}Li(α, n)^{10}B threshold.

Table 11.7: Resonance parameters in ^{7}Li(α, α)^{7}Li [a]

E_{r} (MeV)	E_{x} (MeV)	J^{π}	$\Gamma_{\mathrm{c.m.}}$ (keV)	$\Gamma_{\mathrm{i}}/\Gamma_{\mathrm{e}}$ [b]
1.88	9.86	$\frac{3}{2}^{+}$	250	4.0
2.50	10.25	$\frac{3}{2}^{-}$	200	0.04
2.60	10.32	$\frac{5}{2}^{-}$	100	0
3.03	10.60	$\frac{7}{2}^{+}$	90	1.0
3.54	11.0	$\frac{5}{2}^{-}$	4500	1.5
[c]		$\frac{1}{2}^{+}$	4000	4.6
4.10	11.27	$\frac{9}{2}^{+}$	100	0

[a] (1966CU02); assignments not unique: see text.

[b] Width ratio: inelastic/elastic.

[c] Broad level in background: E_{λ}(c.m.) $= 1.71$.

Analysis of the structure above $E_{\alpha} = 4.38$ MeV is rendered difficult by the increasing number of open channels. Anomalies observed at $E_{\alpha} = 4.4$, 5.5, 7.2, 7.8 and 9.95 MeV coincide with thresholds in ^{7}Li(α, n)^{10}B* (1966CU02).

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

The lifetimes of ^{11}B*(6.79, 7.30, 8.00) are less than 50 fsec (1967THZX). Gamma spectra indicate that all bound levels are populated at $E(^{6}\mathrm{Li}) = 2.6$ MeV (1962BE24). Angular distributions are not symmetric about $90°$; an α-transfer process is suggested (1961MO02). Angular distributions have also been obtained at $E(^{7}\mathrm{Li}) = 3.78$ to 5.95 MeV for the deuterons to ^{11}B*(0, 2.12, 4.44, 5.02, $6.74 + 6.79$, 7.30) (1967KI03), and at $E(^{7}\mathrm{Li}) = 3.3$ MeV ($^{11}\mathrm{B}^{*} = 0$, 2.12, 4.44, 5.02) (1967GA06). See also (1966RO1E, 1966RO1F).

8. ^{7}Li(^{7}Li, t)^{11}B $\qquad Q_{\mathrm{m}} = 6.197$

Triton-gamma coincidence studies yield the following branching ratios: $^{11}\mathrm{B}^{*}(5.02) \rightarrow$ g.s. (85 ± 5%), $5.02 \rightarrow 2.12$ (15 ± 5%), $5.02 \rightarrow 4.44$ (< 5%), $4.44 \rightarrow$ g.s. (100%), $4.44 \rightarrow 2.12$ (< 5%) (1963CA09): see Table 11.9. The lifetimes of ^{11}B*(6.79, 7.30, 8.00) are less than 0.5 msec (1967THZX). See also (1961MO02, 1962BE24, 1966RO1E, 1966RO1F, 1967WY1B).

Table 11.8: Energy levels of ^{11}B from ^{9}Be(^{3}He, p)^{11}B

(1959HI69, 1963GR20)		(1965MA1E)	(1966BR18)	L [c]
E_x (MeV $\pm$ keV)	Γ (keV)	E_x (MeV $\pm$ keV)	E_x (MeV $\pm$ keV)	
0		0	0	0
2.144 ± 10		2.142 ± 10	2.1243 ± 0.9	0
4.459 [a]		4.454 ± 10	4.4434 ± 1.8	0
5.037 ± 10		5.033 ± 10	5.0187 ± 2.3	0
6.753 ± 10		6.743 ± 10	6.7411 ± 3.0	
6.805 ± 10		6.793 ± 10	6.7909 ± 3.1	1
7.299 ± 10		7.285 ± 10		
7.989 ± 10		8.018 ± 10		
8.567 ± 10		8.560 ± 10		0
8.923 ± 10		8.920 ± 10		0
9.189 ± 10		9.182 ± 10		
9.278 ± 10		9.268 ± 10		
9.87 ± 20	≈ 150			
(10.26)				
10.337 ± 15				
10.594 ± 12				
11.266 ± 7	< 30			
11.462 ± 10				
11.884 ± 12				
11.97				
12.565 ± 12 [b]	145 ± 30			
13.3 ± 100				
14.563 ± 15				

[a] Values up to $E_x = 9.87$ MeV normalized to this group (1959HI69): see (1966BR18).

[b] Possibly $T = \frac{3}{2}$: see text.

[c] Angular momentum transfer (1960HI08).

Table 11.9: Gamma decay of ^{11}B levels [a]

E_i (MeV)	J^π_i	τ_m or Γ_γ (sec) (eV)	E_f (MeV)	Branch %	Mult.	χ^2 [b]
2.12	$\frac{1}{2}^-$	0.122 eV [c]	0	100		
4.44	$\frac{5}{2}^-$	0.54 eV [c]	0	100	M1	0.04 [d]
			2.12	< 0.5		
5.02	$(\frac{1}{2}^-)\frac{3}{2}^-$	1.73 eV [c]	0	85 ± 2 [j]	M1 [c]	
			2.12	15 ± 2		
			4.44	< 0.3		
6.74	$\frac{7}{2}^-$	$< 3 \times 10^{-13}$ [e]	0	70 ± 2	E2	0.4
			2.12	< 3		
			4.44	30 ± 2	M1, E2 [g]	
			5.02	< 1		
6.79	$(\frac{1}{2}, \frac{3}{2})^+$	$< 5 \times 10^{-14}$ [f]	0	71 ± 5 [k]		
			2.12	29 ± 5		
			4.44	< 8		
			5.02	< 8		
7.30	$\frac{3}{2}^+, \frac{5}{2}^+$	1.0 eV [c]	0	87 ± 2	E1	0.3
			2.12	< 1		
			4.44	5.5 ± 1		
			5.02	7.5 ± 1		
7.99	$\frac{3}{2}^+$	$< 5 \times 10^{-13}$	0	47 ± 2	E1	0.2
		$< 5 \times 10^{-14}$ [f]	2.12	53 ± 2	E1	0.4
			4.44	< 1		
			5.02	< 1		
8.57	$\leq \frac{5}{2}^{(-)}$	2.0 eV [c]	0	56 ± 2	M1, E2 [c]	
			2.12	30 ± 2		
			4.44	5 ± 1		
			5.02	9 ± 1		
8.93	$\frac{5}{2}^-$	4.0 eV [c]	0	95 ± 1	M1	0.7 [h]
			2.12	< 1		
			4.44	4.5 ± 0.5		
			5.02	< 1		

Table 11.9: Gamma decay of ^{11}B levels [a] (continued)

E_i (MeV)	J_i^π	τ_m or Γ_γ (sec) (eV)	E_f (MeV)	Branch %	Mult.	χ^2 [b]
			6.74	< 1		
			6.79	< 1		
9.19	$\frac{7}{2}^+$	$\Gamma_\gamma = 0.3$ eV	0	0.9 ± 0.3	M2, E3 [i]	
			4.44	82.8 ± 2	E1	
			6.74	12.8 ± 0.4	E1	
			6.79	< 1.3		
9.27	$\frac{5}{2}^+$	$\Gamma_\gamma = 2.3$ eV [g]	0	19.7 ± 1.0	E1	
			4.44	67.5 ± 2.0		
			6.74	12.8 ± 0.7		
			6.79	< 0.6		

[a] From ^{9}Be(^{3}He, p)^{11}B and ^{10}B(d, p)^{11}B (1965OL03 and references therein).

[b] χ^2 = maximum intensity of quadrupole radiation in dipole transitions or of M1 in E2 transitions.

[c] See Table 11.13.

[d] Amplitude E2/M1 = -0.2 ± 0.02 (1962GR07): see (PO66E).

[e] (1966WA10).

[f] (1967THZX).

[g] From ^{7}Li(α, γ)^{11}B (1962GR07). See Table 11.4.

[h] 0.6 % E2 (1962GR07). See also (1966GO12).

[i] Amplitude M2/E3 = 0.9 (1962GR07).

[j] 88 ± 2, 12 ± 2 (1968EA03).

[k] 67 ± 3, 33 ± 3 (1968EA03).

9. ^{9}Be(d, γ)^{11}B $\qquad Q_m = 15.819$

Radiative transitions have been observed to ^{11}B*(0, 2.12, $4.44 + 5.02$). For $E_d = 0.5$ to 1.4 MeV, the intensity ratios are 1:(0.30 ± 0.08):(0.78 ± 0.15). At $E_d = 1.4$ MeV, σ(g.s.) = 4.3 ± 0.8 μb: the g.s. radiation is isotropic at $E_d = 0.7$ and 1.2 MeV (1966ZI01). The 90° differential cross section has been measured for $E_d = 0.5$ to 5.5 MeV for ground state γ-rays: no resonance structure is observed. The peak cross section is about 8 μb. Angular distributions are anisotropic for the higher bombarding energies (1963SU09, 1966SU05, 1966SU1C). See also (1960SU09, 1961SU17).

10. ^{9}Be(d, n)^{10}B $Q_{\rm m} = 4.363$ $E_{\rm b} = 15.819$

The cross section follows the Gamow function for $E_{\rm d} = 70$ to 110 keV (1955RA14). The fast neutron and γ-ray yield rise smoothly to $E_{\rm d} = 1.8$ MeV except for a possible "resonance" at $E_{\rm d} \approx 0.94$ MeV (the fast neutron yield then remains approximately constant to 3 MeV) (1949EV1A, 1955BO1A, 1957SH65, 1960BA46, 1963KO15, 1965SI12). This resonance is observed in the total neutron yield and in the yield of the fast neutrons to each of the first five states of ^{10}B (1957SH65; see however, (1959NE1A)). The polarization angular distributions of the neutrons to ^{10}B*(0, 0.72, 1.74, 2.15) have been measured at $E_{\rm d} = 1.57$, 2.06 and 2.48 MeV (1967MI1F). See also ^{10}B in (1966LA04) and (1965BU10, 1967SC43).

11. (a) ^{9}Be(d, p)^{10}Be $Q_{\rm m} = 4.590$ $E_{\rm b} = 15.819$
(b) ^{9}Be(d, α)^{7}Li $Q_{\rm m} = 7.154$
(c) ^{9}Be(d, t)^{8}Be $Q_{\rm m} = 4.592$
(d) ^{9}Be(d, 2α)^{3}H $Q_{\rm m} = 4.687$
(e) ^{9}Be(d, tn)^{7}Be $Q_{\rm m} = -14.304$

(1952CA19) reports broad maxima in the 90° yield of the ground-state protons at $E_{\rm d} \approx 0.9$, (1.3) and 2.1 MeV (see also (1961IS01)). (1957MC35) observe broad resonances at 1.3 and possibly at 1.8 MeV in the yield of 3.37 MeV γ-rays (from ^{10}Be*) in the range $E_{\rm d} = 1.0$ to 5.6 MeV. No resonances are observed in the yield of 6 MeV γ-rays for $E_{\rm d} = 2.0$ to 5.6 MeV. The yields of protons (at 40°) to the ground state and to the first excited state both decrease slowly and monotonically with energy in the range $E_{\rm d} = 3.8$ to 6.3 MeV (1961RE03, 1961RE04). See also (1962BI11, 1966AM1C, 1967FA03) and (1959AJ76). Polarization of the protons has been studied at $E_{\rm d} = 1$ to 6 (1967BL02), 1.6 (1961VA03), 6 (1960HI09), 7.8 (1962GR14), 7.8, 8.9, 10 and 13.8 (1967SA07), 8.9 (1959HI1E), 10 (1962AL10), 11 (1964PA1E), 13.8 (1962PA12), 15 (1964RE04) and 21 MeV (1963BO1J). See also (1960LU04, 1966MI1E).

The yields of α-particles (reaction (b)) to the ground and first excited states have been measured in the range $E_{\rm d} = 0.5$ to 2.3 MeV. There is no clear indication of resonance structure. The cross sections for the two groups are quite similar but their angular distributions are different over the entire energy range (1962BI11). Yields have also been measured for $E_{\rm d} = 8$ to 12.4 MeV (α_0, α_1) and 9 to 12.4 MeV (α_2) (1966DO1A). See also ^{7}Li in (1966LA04) and (1966AM1C).

The cross section for reaction (c) has been measured for $E_{\rm d} = 0.15$ to 0.62 MeV by (1952DE24), for $E_{\rm d} = 0.6$ to 1.5 MeV by (1955JU10, 1955JU1B), for $E_{\rm d} = 3.8$ to 6.3 MeV by (1961RE03, 1961RE04) and at several energies in the range $E_{\rm d} = 3$ to 19 MeV by (1955HE83). See also (1962BI11, 1966AM1C). The forward yield of tritons shows a peak at $E_{\rm d} = 1.38$ MeV, and possibly, at 0.87 MeV (1955JU10, 1955JU1B, 1958JU38). In the range $E_{\rm d} = 3.8$ to 6.3 MeV, the 40° differential cross section for ground state protons is approximately constant (1961RE03, 1961RE04).

The direct three-body reaction [reaction (d)] does not appear to occur (1953GE01). For reaction (e) see (1955HE83). See also (1962WI15, 1965MA57).

12. ^{9}Be(d, d)^{9}Be $E_b = 15.819$

The differential cross section for elastic scattering has been measured for $E_d = 0.4$ to 1.8 MeV ($\theta = 90^\circ$, 126°, 163.5°). No anomalies were observed (1963RE16: see, however, (1956JU17)). Asymmetries have been measured with polarized deuterons at $E_d = 11.7$ MeV (1966DO1B). See also (1960BU25, 1963NE1H) and ^{9}Be in (1966LA04).

13. ^{9}Be(t, n)^{11}B $Q_m = 9.561$

See (1962SE1A).

14. ^{9}Be(^{3}He, p)^{11}B $Q_m = 10.325$
$Q_0 = 10.344 \pm 0.013$ (1964MA57);
$Q_0 = 10.3221 \pm 0.0023$ (1967OD01).

Proton groups have been observed to 23 states of ^{11}B: see Table 11.8 (1959HI69, 1963GR20, 1966BR18). Angular distributions of many of these protons groups have been observed at $E(^3\mathrm{He}) = 1.0$ to 3.0 MeV (1967CO03), 2 MeV (1963WE08), 4.5 MeV (1959WO53), 5.7 MeV (1959HI69) and 8.8 and 10.2 MeV (1960HI08). Of the first ten groups, seven show stripping patterns: the exceptions are ^{11}B*(6.74, 7.30, 8.00) (1960HI08). The narrow level at $E_x = 12.565$ MeV does not appear in ^{10}B(d, p)^{11}B and may therefore have $T = \frac{3}{2}$ (1963GR20: see, however, ^{7}Li(α, α)^{7}Li). See also (1959AJ76) and ^{12}C.

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 11.9. The following remarks on individual levels derive largely from (1965OL03): see also ^{10}B(d, p)^{11}B.

$\underline{E_x = 9.19\ \text{MeV}.}$ $\Gamma_\gamma/\Gamma = 0.1^{+0.2}_{-0.05}$. From ^{7}Li($\alpha$, γ)^{11}B, $\Gamma_s = 0.275$ eV, $J^\pi = \frac{7}{2}^+$. Then $\Gamma_\alpha = 2.8^{+2.8}_{-1.8}$ eV, $\Gamma_\gamma = 0.3^{+0.1}_{-0.01}$ eV. The ground-state transition of 0.9% is 0.45 E3 and 0.55 M2 leading to M2 and E3 strengths of 0.3 ± 0.1 and 78 ± 26 Weisskopf units, respectively.

$\underline{E_x = 8.93\ \text{MeV}.}$ $\Gamma_\gamma/\Gamma = 1.08 \pm 0.12$. From ^{7}Li($\alpha$, γ)^{11}B, $J^\pi = \frac{3}{2}^+, \frac{5}{2}^+, \frac{5}{2}^-$. The internal pair correlation excludes $J^\pi = \frac{3}{2}^+, \frac{5}{2}^+$, and confirms $\frac{5}{2}^-$. The ground-state transition is then M1 with

0.6% E2. With $\Gamma_{\rm s} = 0.025$ eV, $0.025 \leq \Gamma_\alpha \leq 0.03$ eV, $\Gamma_\gamma \geq 0.15$ eV. See (1966GO12) and ^{11}B(e, e′)^{11}B*.

$\underline{E_{\rm x} = 8.57\ {\rm MeV}.}$ 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. The odd parity assignment agrees with stripping results in the present reaction, but disagrees with the results from ^{10}B(d, p)^{11}B. See ^{11}B(e, e′)^{11}B*.

$\underline{E_{\rm x} = 8.00\ {\rm MeV}.}$ Transitions to ^{11}B$_{\rm g.s.}$ and (2.12) are predominantly E1; thus $E_{\rm x} = 8.00$ MeV has even parity, and the odd parity of ^{11}B*(2.12) is confirmed. The transition to ^{11}B*(2.12) is not isotropic, so $J^\pi = \frac{3}{2}^+$. Comparison of branching ratios with analogous case in ^{11}C suggests some deviation from charge symmetry.

$\underline{E_{\rm x} = 7.30\ {\rm MeV}.}$ 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 $(7.30 \rightarrow 4.44)$.

$\underline{E_{\rm x} = 6.79\ {\rm MeV}.}$ The allowed β-decay from ^{11}Be indicates $J^\pi \leq \frac{7}{2}^+$. The relatively strong γ-branch to ^{11}B*(2.12) 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 $\frac{3}{2}^+$.

$\underline{E_{\rm x} = 6.74\ {\rm MeV}.}$ From ^{7}Li(α, γ)^{11}B, $J = \frac{7}{2}$. Internal pairs indicate practically pure E2 g.s. radiation: $J^\pi = \frac{7}{2}^-$.

$\underline{E_{\rm x} = 5.02\ {\rm MeV}.}$ Stripping work fixes the parity as odd. The internal pair correlations permit M1, E2 for the g.s. transition, $J^\pi \leq \frac{7}{2}^-$; the lifetime $\tau_{\rm m} < 0.5$ psec excludes $J = \frac{7}{2}$. The comparatively strong branch to ^{11}B*(2.12) argues against $J = \frac{5}{2}$, therefore $J^\pi \frac{1}{2}^-$ or $\frac{3}{2}^-$ (1961DO03). Angular correlation studies indicate a $P_2(\cos\theta)$ term of (10 ± 5)%; if this term is real, $J \neq \frac{1}{2}$ (1968EA03).

$\underline{E_{\rm x} = 4.44\ {\rm MeV}.}$ The g.s transition is predominantly M1, consistent with $J^\pi = \frac{5}{2}^-$ (see ^{7}Li(α, γ)^{11}B).

$\underline{E_{\rm x} = 2.12\ {\rm MeV}.}$ The lifetime (4.6 fsec) demands dipole radiation. The E1 transition from ^{11}B*(8.00) requires odd parity; the weakness of the 4.44 $(\frac{5}{2}^-)$ to 2.12 transition leaves only $J^\pi = \frac{1}{2}^-$ (1961DO03).

The properties of the first five levels of ^{11}B are consistent with ascription to p^7; there is evidence that ^{11}B*(8.93) also belongs to p^7, while ^{11}B*(8.57) appears more likely to belong to a higher configuration.

See also (1960EL1C, 1961EL1A, 1962WE1C, 1963VA16, 1966WA1C).

15. ^{9}Be(α, d)^{11}B $\qquad Q_{\rm m} = -8.028$

At $E_\alpha = 28.3$ MeV, differential cross sections have been measured ($\theta = 15°$ to $47°$) for the deuteron groups to ^{11}B*(0, 2.12, 4.44, 5.02) (1965KA14). See also (1955RA41, 1962WE1C, 1967ZE1A).

16. ^{9}Be(^{6}Li, α)^{11}B $Q_{\rm m} = 14.347$

Angular distributions and total cross sections have been determined for seven α-groups. In the range $E(^{6}\text{Li}) = 3$ to 4 MeV, the distributions change only slowly. A direct interaction mechanism is suggested (1961EL1A, 1961HO19, 1961LE01, 1961LE09, 1961RU1B, 1966SA04). Gamma raditation has been studied by (1963NO02, 1964CA18). Evidence of participation of a level near $E_{\rm x} = 12.5$ MeV is reported by (1961CO33, 1961LE08). See also (1963BA1T, 1966BA1T, 1966RO1E, 1966RO1F, 1966RO1H).

17. (a) ^{9}Be(^{7}Li, αn)^{11}B $Q_{\rm m} = 7.094$
(b) ^{9}Be(^{14}N, ^{12}C)^{11}B $Q_{\rm m} = 5.547$

For reaction (a) see (1964CA18). For reaction (b) see (1964BO1M).

18. ^{10}B(n, γ)^{11}B $Q_{\rm m} = 11.456$

The thermal neutron capture cross section is 0.5 ± 0.2 b. The direct ground-state decay has $\Gamma_{\gamma} = 0.01$ eV (1957BA18). See also (1959AJ76).

19. ^{10}B(n, n)^{10}B $E_{\rm b} = 11.456$

The thermal scattering cross section (bound) for B is 4.4 ± 0.2 bn (1958HU18). The coherent scattering amplitude (bound) for ^{10}B is $a = +1.4 \pm 1.5$ fm. Combined with the potential scattering amplitude of 5.0 fm (derived from (1955WI25)), this low value indicates a resonance level above the neutron binding energy (1965DO14, 1966DO11). According to (1960BI04) the total cross section $\sigma_{\rm s} + \sigma_{\rm n,\alpha}$ fits the expression $\sigma = 2.43 + 642/E^{1/2}$ up to 70 keV; the $1/\nu$ term is ascribed to $\sigma_{\rm n,\alpha}$ and $\sigma_{\rm s}$ is taken to be 2.43 b: see also (1964ST25, 1965MO1J). Elastic scattering differential cross sections at $E_{\rm n} = 0.55$, 1.0 and 1.5 MeV are analyzed in terms of phase shifts by (1955WI25): only s-waves appear at $E_{\rm n} = 0.55$ MeV.

The total cross section (including $\sigma_{\rm n,\alpha}$) shows broad maxima at $E_{\rm n} = 1.9$ and 2.8 MeV (1951BO45) and at 4.3 MeV (1961FO07); an additional peak at $E_{\rm n} = 0.2$ MeV may be indicated (1951BO45). Above $E_{\rm n} = 5.5$ MeV, $\sigma_{\rm tot}$ is constant at 1.5 b to 16 MeV (1961FO07, 1964ST25). Polarization and differential cross sections have been measured for 70 energies in the range $E_{\rm n} = 0.075$ to 2.25 MeV. The polarization is nearly constant for $E_{\rm n} = 0.5$ to 2.25 MeV and shows no appreciable effect of the resonance at $E_{\rm n} = 1.9$ MeV. Most of the width of this resonance appears to be in the α-channel (1967LA1N). See also (1959MA1C, 1960AN14, 1966AG1A, 1967CI1B) and (1959AJ76).

Table 11.10: Resonances in $^{10}\mathrm{B} + \mathrm{n}$ [a]

^{10}B(n, n′γ)^{10}B (1960DA08)		^{10}B(n, α)^{7}Li (1961DA16)			^{11}B* (MeV)
E_{res} (MeV)	Γ (keV)	E_{res} (MeV)	Γ (keV)	Yield of	
					11.67 [a]
		0.53	140	α_0, α_1	11.94
1.93	260	1.86	570	α_0, α_1, t	13.18
(2.6)	broad	2.79	530	α_0, α_1	13.99
3.31	370	3.43	< 120	α_0, t	14.52
4.1		4.1	800	α_0, α_1	15.2
4.73					15.75
		5.7	broad	α_0, t	16.7
		6.4	broad	α_0, t	17.3

[a] $E_{\mathrm{res}} = 0.230$ MeV (1966MO09).

20. ^{10}B(n, n′)^{10}B* $E_{\mathrm{b}} = 11.456$

The yield of 0.7 MeV γ-rays has been studied from threshold to $E_{\mathrm{n}} = 5.2$ MeV: resonances are observed at $E_{\mathrm{n}} = 1.93$, (2.6), 3.31, 4.1 and 4.73 MeV (see Table 11.10) (1960DA08). See also (1964ST25) and (1963GL1F, 1963GO1M).

21. ^{10}B(n, p)^{10}Be $Q_{\mathrm{m}} = 0.228$ $E_{\mathrm{b}} = 11.456$

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

22. ^{10}B(n, d)^{9}Be $Q_{\mathrm{m}} = -4.363$ $E_{\mathrm{b}} = 11.456$

See (1954RI15). See also (1963GO1M).

23. ^{10}B(n, t)^{8}Be $Q_{\mathrm{m}} = 0.229$ $E_{\mathrm{b}} = 11.456$

The ^{10}B(n, t)^{4}He^{4}He cross section has been measured for $E_{\rm n} = 1.4$ to 8.2 MeV by (1961DA16). Fluctuations in the cross section are observed at some of the resonant energies in the ^{10}B(n, α) reaction: see Table 11.10. See also (1964ST25, 1966JE1B).

24. ^{10}B(n, α)^{7}Li $\quad Q_{\rm m} = 2.792 \quad E_{\rm b} = 11.456$

The "recommended" value of the thermal isotropic absorption cross section is 3837 ± 10 b (1964ST25), which includes recent determinations by (1963PR11: 3837 ± 9 b; (1961ME02): $3843 {\pm} 17$ b; (1960SA13, 1961SA02): $3838 {\pm} 11$ b; (1960SC15): $3848 {\pm} 38$ b). See also (1964AL05, 1965WY01). The cross section follows the $1/\nu$ law from 4 meV to 500 keV (1964ST25, 1965MO1J, 1966CO1K, 1967CO1N) except for a weak resonance at $E_{\rm n} = 230$ keV (1966MO09). There appears to be some discrepancy between reported values of $\sigma_{\rm abs}$ and σ(n, α) (1966MO09).

Observed resonances are listed in Table 11.10 (1951PE18, 1957BI84, 1961DA16). Comparison of σ(n, α) and σ(n, n), at the $E_{\rm n} = 0.53$ MeV resonance indicates $J^\pi = \frac{1}{2}^+, \frac{3}{2}^\pm$, or $\frac{5}{2}^\pm$. For the $E_{\rm n} = 1.86$ MeV resonance, the minimum spin assignment consistent with the observed cross section is $J^\pi = \frac{11}{2}^+$ (1961DA16). The ratio of ground-state to excited state transitions varies monotonically with energy although the 0.53 MeV resonance appears to influence the cross-section ratio to some extent: see (1959AJ76, 1960YO02, 1963MA39, 1965MA65). Recent determinations of the branching ratio for thermal neutrons yield (6.50 ± 0.03)% (see (1966TO01)), (6.70 ± 0.2)% (1966MA2P) for the ground state function. At $E_{\rm n} = 0.16$ MeV, the ratio is (8.4 ± 0.5)% (1966MA2P).

See also (1957SE1B, 1961BE24, 1961MA1F).

25. ^{10}B(d, p)^{11}B $\quad Q_{\rm m} = 9.231$

Proton groups reported by (1951VA1A, 1953EL12, 1961JA23, 1966BR18) are listed in Table 11.11. Angular distributions have been studied at many energies: see (1959AJ76) and (1960HA08: 0.17 to 0.25 MeV), (1957SJ66: 0.8 MeV), (1961RE01: 1.2 MeV), (1959GO69, 1960GO14: 1.25 MeV), (1967PO01: 1.75 to 3.0 MeV), (1965LE1B: 2 to 12 MeV), (1961PU1B: 3.0 MeV), (1960GO11, 1960GO25: 4.6 MeV), (1963MO07: 6 MeV), (1960BI08: 7.8 MeV), (1958ZE01: 8.1, 9.2, 10 MeV), (1962HI07: 10.1 MeV), (1960TA27: 11.4 MeV), (1967MO1Q: 12 MeV), (1965BA31: 13.5 MeV), (1961ZE02: 12.5, 15.5, 18.5, 21.5 MeV) and (1962SL04: 28 MeV).

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 (1957WI26, 1958EV01, 1958HE47, 1961LE1F). 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 ($a/K \approx 4.0$) (1956KU1A, 1960BI08, 1965OL03). There is some disagreement about the parities of ^{11}B*(8.57, 8.93): see ^{9}Be(^{3}He, p)^{11}B and (1966GO12, 1967PO01). The levels at 9.19 and 9.28 MeV, $J^\pi = \frac{7}{2}^+$ and $\frac{5}{2}^+$, respectively, show strong $l = 0$ stripping and are ascribed to capture of a 2s neutron by ^{10}B (1960BI07, 1960BI08, 1967PO01). See also (1960MA32, 1964BA1G, 1967BA2J, 1967MO1N, 1967ST1H).

Table 11.11: ^{11}B levels from ^{10}B(d, p)^{11}B

E_x (MeV $\pm$ keV)		E_x (MeV $\pm$ keV)		$(2J+1)\theta^2$	l_n	$(2J+1)\theta^2$
(1951VA1A, 1953EL12)	(1961JA23)	(1966BR18)	l_n	(1962HI07)		(1960BI08)
0	0	0	1	0.120	1	1.00
2.140 ± 14 [d]	2.128 ± 10	2.1246 ± 1.1				0.09
4.464 ± 14 [d]	4.449 ± 8	4.4458 ± 2.1	1	0.048		0.46
5.039 ± 14 [d]	5.023 ± 8	5.0192 ± 2.4	(1)	(0.010)		0.11
6.765 ± 13 [a,d]		6.7439 ± 2.2	1	0.210 [c]	1	1.72
6.815 ± 13 [a,d]		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 [b]						

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

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

[c] See also (1967PO01).

[d] Corrected by (1966BR18).

Studies of (p, γ) correlations are reported by (1959CR1A, 1959GA05, 1959GO69, 1960CR1A, 1960GO11, 1960GO14, 1960GO25, 1961RE01, 1965OL03, 1966GO1N: see also (1959AJ76)). The principal results are exhibited in Table 11.9 and are discussed in reaction 14.

(1963GR20: $E_d = 10.0$ MeV) report that the 11.27 MeV state is populated in this reaction while the narrow 12.57 MeV state observed in ^{9}Be(^{3}He, p)^{11}B is not seen. This suggests $T = \frac{1}{2}$ and $\frac{3}{2}$, respectively, for these two states. See, however, ^{7}Li(α, α)^{7}Li.

See also (1959BO1C, 1959BU1F, 1959HO1D, 1959LE1B, 1959TO1A, 1960BI1B, 1960NE1C, 1961BU16, 1961TE02, 1961ZE03, 1962ME1B, 1963GL1C, 1963MO1E, 1963SM05, 1963TA1A, 1963TA1C, 1964MA57, 1965BA31, 1965ST1E, 1966BA1X, 1966BA2R, 1967SC1K) and ^{12}C.

Polarization studies are reported by (1958HE47, 1959HI1E, 1960ER1A, 1960TA27, 1961ZI02, 1962PA12, 1962TA13, 1962ZI01, 1963BO1J, 1963ER1A, 1964BE08, 1964PA1E, 1965SZ01, 1965ZI1A, 1966BA2V).

26. ^{10}B(t, d)^{11}B $\qquad Q_m = 5.199$

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 (1963HO19, 1963KN02, 1967BI1E) and ^{13}C in (1970AJ04).

27. ^{10}B(α, ^{3}He)^{11}B $Q_{\rm m} = -9.122$

Not reported.

28. ^{10}B(^{14}N, ^{13}N)^{11}B $Q_{\rm m} = 0.903$

See (1963TO1D, 1963TO1E, 1966CO27, 1966GA04, 1967CO1T).

29. ^{11}Be(β^-)^{11}B $Q_{\rm m} = 11.513$

The decay properties of ^{11}Be are exhibited in Table 11.12. The transition energy to the ground state is $E_{\beta_{\rm (max)}} = 11.48 \pm 0.15$ MeV; $\tau_{1/2} = 13.57 \pm 0.15$ sec, $\log ft = 6.77$ (1958AL96, 1959WI49), $\tau_{1/2} = 14.1 \pm 0.3$ sec (1958NU40). The small ft values of the transitions to the $\frac{3}{2}^+$ states at 6.79 and 8.00 MeV indicate even parity [$J = \frac{1}{2}$, $\frac{3}{2}$ or $\frac{5}{2}$] for the ground state of ^{11}Be (1961DO03, 1964AL22).

30. ^{11}B(γ, γ)^{11}B

Mean gamma widths of low-lying levels obtained by resonance scattering and transmission studies are listed in Table 11.13. M1 transition strengths calculated in intermediate coupling are given by (1965CO25).

From a threshold determination, (1965SC04) finds $E_{\rm x} = 2124 \pm 3$ keV for the first excited state. (1959HA1J) report $(2J+1)\,\Gamma_\gamma = 0.6 \pm 0.1$ eV for ^{11}B*(9.19): see, however, ^{7}Li(α, γ)^{11}B. Resonance scattering from levels st 4.4, 5.0, 7.3 and 8.8 MeV is reported by (1962SE02). See also (1959FA1A, 1960BO23, 1960RE05, 1962BO17, 1964LO1C, 1967LO1B).

31. ^{11}B(γ, n)^{10}B $Q_{\rm m} = -11.456$

The cross section shows many peaks in the range $E_\gamma = 12$ to 28 MeV. The integrated cross section to 29 MeV is 68.6 ± 4 MeV · mb (1965HA19). See also (1961BA1D, 1963CO1D).

Table 11.12: Beta decay of ^{11}Be (1958AL96, 1959WI49, 1964AL22)

^{11}B* (MeV)	J^{π} [a]	% betas	log ft	E_{γ} (MeV $\pm$ keV)	% gammas [b]
0	$\frac{3}{2}^-$	61	6.78		
2.12	$\frac{1}{2}^-$	29	6.68	2.121 ± 10	32
4.44	$\frac{5}{2}^-$	≤ 0.2	≥ 8.2		
5.02	$\frac{3}{2}^-, (\frac{1}{2}^-)$	≤ 0.2	≥ 8.2		
6.74	$\frac{7}{2}^-$		≥ 6.9		
6.79	$(\frac{1}{2}, \frac{3}{2})^+$	6.5	5.92	6.792 ± 6	4.4
				4.64 ± 20	2.1
7.30	$(\frac{3}{2}, \frac{5}{2})^+$	≤ 1.5	≥ 6.4		
8.00	$\frac{3}{2}^+$	4.1	5.55	7.97 ± 30	1.7
				5.86 ± 40	2.4
8.57	$\leq \frac{5}{2}^-$	≤ 0.3	≥ 6.3		
8.93	$\frac{5}{2}^-$	≤ 0.15	≥ 6.3		

[a] Assignments from summary Table 11.3.

[b] Relative to all β-transitions.

32. (a) ^{11}B(γ, p)^{10}Be $\quad Q_{\rm m} = -11.228$
    (b) ^{11}B(γ, d)^{9}Be $\quad Q_{\rm m} = -15.819$

See (1961DO08, 1962CH26, 1962LI13, 1962VO1C, 1963KI1C) for reaction (a), and (1962CH26, 1962VO1C, 1963BA1K) for reaction (b).

33. (a) ^{11}B(γ, t)^{4}He + ^{4}He $\quad Q_{\rm m} = -11.132$
    (b) ^{11}B(γ, α)^{7}Li $\quad Q_{\rm m} = -8.664$

See (1955AJ61, 1959AJ76, 1962VO1C).

34. ^{11}B(e, e)^{11}B

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, suggests a $j - j$

Table 11.13: Gamma widths from ^{11}B(γ, γ)^{11}B and ^{11}B(e, e′)^{11}B* [e]

E_x (MeV)	J^π	Γ_γ to g.s. (eV)	Reaction	Ref.
2.12	$\frac{1}{2}^-$	0.14 ± 0.018	$\gamma\gamma$	(1958ME79)
		0.22 ± 0.06 [c]	$\gamma\gamma$	(1963VA10)
		0.11 ± 0.04	$\gamma\gamma$	(1964BO22)
		0.137 ± 0.020	$\gamma\gamma$	(1965KE05)
		0.114 ± 0.005	$\gamma\gamma$	(1965SC04)
		0.130 ± 0.031 [a,c]	$\gamma\gamma$	(1965HA1K)
		0.16 ± 0.02	ee	(1966KO08)
		0.17 ± 0.034	ee	(1962ED02)
		0.122 ± 0.005		mean
4.44	$\frac{5}{2}^-$	0.56 ± 0.08	$\gamma\gamma$	(1958RA14)
		0.43 ± 0.095	$\gamma\gamma$	(1959CO95)
		0.500 ± 0.200 [a,c]	$\gamma\gamma$	(1965HA1K)
		0.60 ± 0.2 [c]	ee	(1966KO08)
		1.1 ± 0.4 [c]	ee	(1962ED02)
		0.60 ± 0.09 (M1) $+ 0.016 \pm 0.002$ (E2)	ee	(1967SP02)
		0.54 ± 0.05		mean
5.02	$\frac{3}{2}^-$	1.1 ± 0.2 [d]	$\gamma\gamma$	(1959CO95)
		0.500 ± 0.200 [a]	$\gamma\gamma$	(1965HA1K)
		2.4 ± 0.8	ee	(1966KO08)
		3.7 ± 1.5	ee	(1962ED02)
		1.73 ± 0.14 (M1) < 0.0034 (E2)	ee	(1967SP02)
7.3	$(\frac{5}{2}^-)$	1.0 ± 0.5	ee	(1962ED02)
8.56	$(\frac{3}{2})^-$	0.72 ± 0.30 (M1) 0.40 ± 0.10 (E2)	ee	(1966SP02)
8.93	$\frac{5}{2}^-$	4.0 ± 0.6 (M1) [b]	ee	(1966SP02)

[a] Preliminary values.

[b] See also (1962ED02, 1966KO08) for higher levels.

[c] Omitted from mean.

[d] See (1967SP02).

[e] See also Table 11.9.

coupling scheme for $^{11}B_{\rm g.s.}$ (1966RA29). The quadrupole contribution to the elastic form factor is best accounted for by the undeformed shell model, $Q = 3.72$ (±20%) b, r(r.m.s.) $= 2.42$ fm (1966IS1A, 1966ST12). See also (1963GO04, 1963GU1A, 1965GO1K, 1965GR18, 1965RA1C, 1965VA1G).

Ground-state transition widths for various excited states determined by inelastic scattering are listed in Table 11.13 (1962ED02, 1966KO08, 1966SP02, 1967SP02). For ^{11}B*(8.57), the dependence of the transition probability on q^2 indicates an E2-M1 mixture: hence the parity is odd, $J \leq \frac{5}{2}$. The observed γ-width if ^{11}B*(8.93) implies $\Gamma_\alpha = 0.03$ eV (compare ^{9}Be(^{3}He, p)^{11}B (1966SP02)). See also (1962BA1D, 1964BR1N, 1966RI1G, 1967KA1A, 1967LE1E).

35. ^{11}B(n, n′)^{11}B*

See (1955GR18, 1961LI04, 1962TE05, 1963OP1A, 1966FR18).

36. (a) ^{11}B(p, p′)^{11}B*
(b) ^{11}B(p, 2p)^{10}Be $\qquad Q_{\rm m} = -11.228$

Study of the pair line spectrum of the 2.12 MeV γ-ray establishes that there is no parity change between the ground and first excited states: therefore the parity of the excited state is odd (1963WI01; see also (1962GO09, 1963SC33)). The 2.12 MeV excited state decays by emission of a 2.134 ± 0.005 MeV γ-ray (1957MC35): it exhibits $< 2.0 \times 10^{-3}$ part of circular polarization; this observation places an upper limit of $F^2 \lesssim 1 \times 10^{-7}$ for the intensity of the parity non-conserving part of the wave function (1958WI41).

At $E_{\rm p} = 185$ MeV, proton groups are observed to ^{11}B levels at 2.2 ± 0.1, 4.5 ± 0.1, 5.1 ± 0.15, 6.8 ± 0.1 (probably corresponds to ^{11}B*(6.74)), 7.4 ± 0.3, 8.95 ± 0.15, ≈ 9.8, 10.5 ± 0.2, 11.9 ± 0.2, 13.0 ± 0.2 ($\Gamma \approx 0.4$ MeV) and 14.5 ± 0.4 MeV (1965HA17). The state at $E_{\rm x} = 6.79$ MeV is not reported by (1965HA17) or by (1964NE06). Assuming that the (p, p′) transitions involve mainly E2, Γ(E2↓) is 22 ± 9 meV for ^{11}B*(4.44) and 90 ± 40 meV, for ^{11}B*(6.74) (1964JA03). See also (1965JA1A).

See also (1959EG1C, 1959JO43) for polarization studies; (1961KO08, 1962KI02, 1965HU10) for angular distributions at $E_{\rm p} = 5.8$ to 7.5 MeV and (1959EG20, 1959TO1A, 1961CL09, 1962CL13).

For reaction (b) see (1964LI1D, 1964TI02, 1966JA1A, 1967JA1E, 1968JA1G) and ^{10}Be in (1966LA04).

37. ^{11}B(d, d)^{11}B

The angular distribution of elastically scattered deuterons has been determined at $E_{\rm d} = 11.8$ MeV and analyzed by the optical model (1967FI07). See (1955KH35, 1962SL03, 1965GA02).

38. ^{11}B(t, t)^{11}B

Angular distributions of elastically scattered tritons hasve been measured at $E_t = 1.75$ and 2.10 MeV. Optical model fits have been made (1968HE1N).

39. ^{11}B(^{3}He, ^{6}Li)^{8}Be $Q_m = 4.566$

Angular distributions observed at $E(^3\text{He}) = 3.0$ and 5.2 MeV suggest a cluster pick-up mechanism, indicating a substantial (^{8}Be + t) configuration in ^{11}B (1967YO02).

40. ^{11}B(α, α)^{11}B

At $E_\alpha = 28.5$ MeV, angular distributions are obtained for the elastic α-particles and the inelastic α's corresponding to ^{11}B*(2.12, 4.44, 5.02, $6.74 + 6.79$, 7.30, 8.57) (1967NA06). See also (1964ST1K, 1966GE12).

41. (a) ^{11}B(^{11}B, ^{11}B)^{11}B
(b) ^{11}B(^{16}O, ^{16}O)^{11}B

For reaction (a), see (1967GU1A). For reaction (b) see (1966OE1A).

42. ^{11}C(β^+)^{11}B $Q_m = 1.981$

See ^{11}C.

43. (a) ^{12}C(γ, p)^{11}B $Q_m = -15.957$
(b) ^{12}C(e, e$'$p)^{11}B $Q_m = -15.957$

For reaction (a) see (1962PA08, 1963WA18, 1965AL02, 1966PA05). For reaction (b) see (1962DO1A, 1962PA08, 1965AM1B, 1965CO1E). See also ^{12}C.

44. ^{12}C(p, 2p)^{11}B $Q_m = -15.957$

In the summed proton spectrum, gross structure is observed corresponding to $Q = -15.6 \pm 0.6$ and -34.3 ± 0.8 MeV corresponding to $^{11}B_{g.s.}$ and an excited state with $J^{\pi} = \frac{1}{2}^{+}$ at $E_x = 18.3$ MeV (ejection of p- and s-protons, respectively) (1965RI1A, 1966TY01). See also (1958MA1B, 1958TY49, 1960GO1M, 1961PU1A, 1962GA09, 1962GA23, 1962GO1P, 1965BE1E, 1965CO1E, 1966BE1B, 1966WA12). A high resolution experiment shows groups corresponding to ^{11}B*(0, 2.12, 4.44, 5.02, 6.79) (1965PU02, 1967PU01). The angular correlation and energy distribution of the protons emitted at $E_p = 45.5$ MeV have been measured by (1967RI08) and compared with distorted-wave t-matrix approximation theory.

See also (1960GO16, 1961CL09, 1961GA14, 1962CO17, 1962VA1G, 1963CL1B, 1963GR1G, 1963RI1B, 1964BO1L, 1966YU1A, 1967YU02; expt.) and (1960RI1B, 1962BA1J, 1962CL13, 1962DI1A, 1962IN1A, 1963BE42, 1963CL07, 1963YU1A, 1964BA1C, 1965YU1B, 1966LI1E, 1966NG1B, 1967JA1E; theor.).

45. ^{12}C(n, d)^{11}B $\qquad Q_m = -13.732$

See (1962AU1A, 1966ME03, 1967ME11).

46. ^{12}C(d, ^{3}He)^{11}B $\qquad Q_m = -10.463$

Angular distributions with DWBA indicate $l = 1$ pickup for ^{11}B*(0, 2.0, 4.8). No $l = 3$ fit is possible for the $\frac{5}{2}^{-}$ and $\frac{7}{2}^{-}$ states [^{11}B*(4.3, 6.5)], suggesting a double process involving ^{12}C (2^{+}) as an intermediate stage (1966CH1K). The ground-state angular distribution has also been determined at $E_d = 82$ MeV (1967AR21). At $E_d = 28.5$ MeV, the cross sections for the (d, ^{3}He) and (d, t) reactions to the mirror ground states ^{11}B and ^{11}C are the same (1966DE1C). See also (1965PE17, 1967FI1G).

47. ^{12}C(t, α)^{11}B $\qquad Q_m = 3.858$

Angular distirbutions of the α-particles to the ground and first excited states of ^{11}B have been measured at $E_t = 1$ to 2 MeV (1962GU01), 10.1 MeV (1962PU01) and 13 MeV (1965AJ01). At the two higher energies, the angular distributions of the α-particles to the 4.44 and 5.02 MeV states have also been determined. Ground state angular distributions have been measured at 18 energies between $E_t = 1.5$ and 3.2 MeV (1966SE1D, 1968SE1F). See also (1960MU07, 1961HO1F, 1962NE1D, 1963NI04, 1964BE1K, 1965HO1C, 1965NE1B).

48. ^{12}C(^{12}C, ^{13}N)^{11}B $\qquad Q_m = -14.013$

See (1967VO1D, 1967WI04).

49. ^{12}C(^{14}N, ^{15}O)^{11}B $Q_{\rm m} = -8.664$

See (1966PO1B, 1967BI06).

50. ^{13}C(n, t)^{11}B $Q_{\rm m} = -12.422$

This reaction has not been reported.

51. ^{13}C(p, ^{3}He)^{11}B $Q_{\rm m} = -13.185$

At $E_{\rm p} = 43.7$ MeV, ^{3}He particles are observed corresponding to a $T = \frac{3}{2}$ state in ^{11}B: $E_{\rm x} = 13.02 \pm 0.08$ MeV ($\Gamma = 358 \pm 60$ keV); $L = 0$ $(J = \frac{1}{2}^{-})$ (1966MA2N). See also ^{11}C.

52. ^{13}C(d, α)^{11}B $Q_{\rm m} = 5.168$

Angular distributions of ground-state α-particles have been determined at $E_{\rm d} = 3.3$ to 4.2 MeV (1963MA24), 10 to 12 MeV (1967CU1A). Alpha groups corresponding to the states at 2.12, 4.44 and 6.79 MeV have been observed by (1951LI29, 1953SP1A). The γ-decay of the 4.44 (1955BE62, 1958RA13) and 5.02 MeV states (1963AL21) is also reported. See also (1959EL43, 1965NE10, 1966KL06, 1966KL1E, 1966KL1F) and ^{15}N in (1970AJ04).

53. ^{14}C(p, α)^{11}B $Q_{\rm m} = -0.784$

Angular distributions of the α-particles to the first four states of ^{11}B have been determined at $E_{\rm p} = 18$ MeV (1962BR34). See also (1967EL1D).

54. ^{14}N(n, α)^{11}B $Q_{\rm m} = -0.157$

See (1958DO63, 1959GA14, 1959HA13, 1963MO04, 1963SE08, 1964MO1D, 1966CS1B, 1966MA2M, 1967MO21) and ^{15}N in (1970AJ04).

^{11}C

(Figs. 3 and 4)

GENERAL:

Shell model: (1956KU1A, 1957KU58, 1960TA1C, 1961KU1C, 1965FA1C).

Collective model: (1966EL08).

Ground-state properties: (1963BE36, 1964ST1B, 1967SH05).

Other: (1962DY1A, 1964RE1B, 1967AU1B, 1967DE1V, 1967FA1A, 1967NE1D, 1967PO1J, 1968DI1B).

$$Q = (+)0.0308 \pm 0.0006 \text{ b (1963KO1G, 1964HA46);}$$

$$\mu = (-)1.027 \pm 0.010 \text{ nm (1963KO1G, 1964HA46);}$$

$$J = \tfrac{3}{2} \text{ (1961SN01).}$$

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

The mean value of reported half-lives is 20.34 ± 0.04 min (see Table 11.15); $ft = 3882$. The ratio of K-capture of positron emission is (0.19 ± 0.03)% (1957SC29), $(0.230^{+0.014}_{-0.011})$% (1967CA09). See also (1965GA1D, 1966MI1F, 1967AM1H).

2. (a) ^{6}Li(^{6}Li, n)^{11}C $\qquad Q_\mathrm{m} = 9.457$
   (b) ^{7}Li(^{6}Li, 2n)^{11}C $\qquad Q_\mathrm{m} = 2.204$

At $E(^6\mathrm{Li}) = 4.1$ MeV, neutron groups have been observed to the first seven excited states and to the 8.42 MeV state. Associated γ-rays were used for the stop triggering of the time-of-flight system. The group to the 8.4 MeV state had an intensity ≈ 10% of that to the highest bound state at $E_\mathrm{x} = 7.5$ MeV suggesting a small Γ_α for the 8.42 MeV state (compare ^{12}C(^{3}He, α)^{11}C). No evidence for the γ-decay of the 8.11 MeV state was found (1966BA2U). See also (1957NO17, 1960NO1A, 1962BE16, 1962BE24).

3. ^{9}Be(^{3}He, n)^{11}C $\qquad Q_\mathrm{m} = 7.562$

Reported neutron groups are listed in Table 11.16. Angular distributions and excitation func-

Table 11.14: Energy levels of ^{11}C

E_x in ^{11}C (MeV ± keV)	$J^\pi; T$	τ (psec) or Γ (keV) (keV)	Decay	Reactions
0	$\frac{3}{2}^-$	$\tau_{1/2} = 20.39 \pm 0.06$ min	β^-	1, 2, 3, 11, 12, 13, 14, 15, 16, 17, 18, 19, 21, 22, 23, 24, 26
1.995 ± 3	$\frac{1}{2}^-$		γ	2, 3, 11, 13, 16, 20, 22, 25
4.305 ± 6	$\frac{5}{2}^-$	$\tau_m < 0.5$ psec	γ	2, 3, 11, 13, 16, 22, 25
4.794 ± 6	$\frac{3}{2}^-$	< 0.5	γ	2, 3, 11, 13, 16, 20, 22, 25
6.339 ± 5	$\frac{1}{2}^+$	< 0.11	γ	2, 3, 11, 13, 16, 22
6.480 ± 6	$\frac{7}{2}^-$	< 0.25	γ	2, 3, 13, 16, 22
6.906 ± 4	$\frac{5}{2}^+$	< 0.16	γ	2, 3, 11, 13, 20, 22
7.509 ± 6	$\frac{3}{2}^+$	< 0.5	γ	2, 3, 11, 13, 22
8.107 ± 3	$\leq \frac{5}{2}^-$		(γ)	3, 11, 13, 22
8.420 ± 4	$\frac{5}{2}^-$	Γ_α small	γ	2, 11, 13, 22
8.652 ± 4	$+$			11
8.694 ± 4	$(+)$			11
9.731 ± 5	$(\frac{5}{2}^+)$	$\Gamma = 450 \pm 50$ keV	γ, p, α_0	4, 10, 11
10.086 ± 5	$\frac{7}{2}^+$	≈ 200	p, α_0, α_1	6, 10, 11
10.682 ± 5	$\frac{9}{2}^+$	200 ± 30	p, α_0, α_1	6, 10, 11
(10.801 ± 5)			p, α_1	10
(11.032 ± 5)			p, α_1	10
11.45 ± 10		370	p, α_1	10, 11
(11.957 ± 7)			p, α_1	10, 11
12.45 ± 80	$\frac{1}{2}^-; T = \frac{3}{2}$	560 ± 60		24
12.65 ± 20	$(\frac{7}{2}^+)$	370	γ, p, α_0, α_1	4, 7, 10
13.33			p, α_0, α_1	10
13.90 ± 20		≈ 400	p	7
14.07 ± 20		broad	n, p, (α_0, α_1)	5, 10
14.76 ± 40		broad	n, p, α_1	5, 10
15.35 ± 50		broad	n, p, α_1	5, 10
15.60 ± 50		broad	n, p	5
≈ 16		≈ 3200	(n), p	7

Table 11.15: Half-life of ^{11}C

$\tau_{1/2}$ (min)	Ref.
20.35 ± 0.08	(1941SM11)
20.50 ± 0.6	(1941SO01)
20.0 ± 0.1	(1951DI12)
20.74 ± 0.10	(1953KU08)
20.26 ± 0.1	(1955BA63)
20.8 ± 0.2	(1957PR53)
20.11 ± 0.13	(1958AR15)
20.34 ± 0.04	Weighted mean

tions have been studied in the range $E(^3\text{He}) = 1.3$ to 10 MeV by (1961DU1B, 1963DU12, 1963VA16, 1965DI06, 1965TO06, 1966AD1D: see (1966WE1B, 1968OK1D)). In the middle range of these energies, the reaction is dominated by direct interaction, but it is not clear whether two-particle stripping or knock-on processes are involved. Large back angle cross sections are unexplained by DWBA (1965TO06). At 10 MeV, the distributions are consistent with a predominant role for the two-nucleon stripping process. The contribution of the knock-on process appears to be small (1968OK1D).

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 11.17, ^{10}B(d, n)^{11}C and ^{12}C(^{3}He, $\alpha\gamma$)^{11}C. The following remarks on individual levels derive largely from (1965OL03, 1965RO07):

Transitions to $^{11}\text{C}_\text{g.s.}$ and (2.0) are predominantly E1, fixing the parity of ^{11}C*(7.51) as even and that of ^{11}C*(2.0) as odd. The transition to ^{11}C*(2.0) is not isotropic, so $J \neq \frac{1}{2}$; $J^\pi = \frac{3}{2}^+$ or $\frac{5}{2}^+$ are possible, but if ^{11}C*(2.0) is $\frac{1}{2}^-$, $J^\pi = \frac{5}{2}^+$ is eliminated (see also ^{12}C(^{3}He, α)^{11}C). The relatively large strength of the cascade transition is difficult to understand, and comparison with ^{11}B*(8.00) suggests some deviation from charge symmetry (1965OL03, 1965RO07).

$\underline{E_\text{x} = 6.91\text{ MeV}}$. The g.s transition is predominantly E1 so $J^\pi \leq \frac{5}{2}^+$ (1965OL03). Branching ratios favor $J = \frac{3}{2}$ or $\frac{5}{2}$ (1965RO07): $J = \frac{5}{2}$ from ^{12}C(^{3}He, α)^{11}C. The analogue is presumably ^{11}B*(7.30) (1965OL03). $\tau_\text{m} < 0.16$ psec (1966WA10).

$\underline{E_\text{x} = 6.48\text{ MeV}}$. The E2 character of the g.s. transition indicates $J^\pi \leq \frac{7}{2}^-$; $J = \frac{7}{2}$ from ^{12}C(^{3}He, α)^{11}C. This level is weakly populated in ^{9}Be(^{3}He, n)^{11}C. The analogue is presumably ^{11}B*(6.74). $\tau_\text{m} < 0.25$ psec (1966WA10). See also (1966GO12).

$\underline{E_\text{x} = 6.34\text{ MeV}}$. The g.s. transition is predominantly E1 so $J^\pi \leq \frac{5}{2}^+$ (1965OL03). Relative transition strengths are consistent with $J = \frac{1}{2}$ or $\frac{3}{2}$ with the assumption that ^{11}B*(6.79) is the mirror level (1965RO07). $\tau_\text{m} < 0.11$ psec (1966WA10). $J^\pi = \frac{1}{2}^+$ from ^{12}C(^{3}He, α)^{11}C.

Table 11.16: ^{11}C levels from ^{9}Be(^{3}He, n)^{11}C

(1963VA16)	(1965TO06)			(1965RO07)	(1968MC1C)
E_x [a]	E_x [a]	L	J^π	E_x [a]	E_x [a]
0	0	$0+2$	$\leq \frac{5}{2}^-$		-0.010 ± 18
2.01 ± 30	1.97 ± 30	$(0)+2$			1.968 ± 13
4.29 ± 20	4.25 ± 30	$(0)+2$			4.304 ± 10
4.79 ± 20	4.76 ± 30	$0+2$	$\leq \frac{5}{2}^-$		4.797 ± 9
6.39 ± 20	6.37 ± 30 [b]	$1+3$		6.37 ± 100 [b]	6.338 ± 6
					6.480 ± 6
6.88 ± 20	6.89 ± 30	weak		6.93 ± 80	6.909 ± 5
	7.48 ± 30	weak		7.50 ± 50	7.516 ± 6
	8.10 ± 30	0	$\leq \frac{5}{2}^-$		8.108 ± 4
					8.418 ± 5
					8.651 ± 4
					8.694 ± 4

[a] E_x given in MeV ± keV.

[b] Probably unresolved doublet: the higher component is only weakly populated if at all.

$\underline{E_x = 4.79 \text{ MeV}.}$ Stripping results indicate odd parity, $J \leq \frac{5}{2}^-$ (1965TO06), consistent with the observed M1, E2 nature of the g.s. transition. The strength of the transition to ^{11}C*(2.0) argues against $J > \frac{5}{2}$. $J = \frac{3}{2}$ from ^{12}C(^{3}He, α)^{11}C.

$\underline{E_x = 4.31 \text{ MeV}.}$ The M1 g.s. transition indicates $J^\pi \leq \frac{5}{2}^-$. $J = \frac{5}{2}$ from ^{12}C(^{3}He, α)^{11}C.

$\underline{E_x = 2.00 \text{ MeV}.}$ The E1 transition from ^{11}C*(7.50) fixes the parity as odd, $J^\pi \leq \frac{7}{2}^-$. $J^\pi = \frac{1}{2}^-$ is fixed from ^{12}C(^{3}He, α)^{11}C.

See also (1959LI1D, 1962SE1A, 1963MA1K, 1964BR13, 1966WA1C, 1967BA1E, 1967BO1D).

4. ^{10}B(p, γ)^{11}C $\qquad Q_m = 8.693$

In the range $E_p = 0.7$ to 4.7 MeV, two broad resonances are reported at 1.14 and ≈ 4.4 MeV: see Table 11.18 (1954DA20, 1955BA22, 1956CH20, 1957HU79, 1962OP03). At the $E_p = 1.14$ MeV resonance ($E_x = 9.73$ MeV), capture γ-rays are observed corresponding to the direct ground-state transition (relative intensity 1.0 ± 0.2) and to cascades via the states at 6.48 (0.3), 4.31 (0.18 ± 0.02) and 2.00 MeV (0.05), with $(2J+1)\Gamma_\gamma = 10$, 1.8 and 3 eV for the ground state transition and the cascades through the 6.48 and 4.31 MeV states, respectively (1961JA11). The

6.48 MeV state decays $\approx \frac{1}{3}$ of the time via a cascade through the 4.31 MeV state (1961JA11). The 4.31 MeV state goes by direct ground-state decay ($> 98\%$) while the 4.79 MeV state decays in ($15 \pm 5\%$) of the cases via the 2.0 MeV state ($E_\gamma = (2.72 \pm 0.08) + (2.05 \pm 0.08)$ MeV) (1961DO03). See Table 11.17.

Table 11.17: 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	100			
4.31	$\frac{5}{2}^-$	< 0.5	0	100	M1	100	$+0.17 \pm 0.03$ [g]
			2.0	< 2		< 2	
4.79	$\frac{3}{2}^-$	< 0.5	0	83 ± 4	M1	86 ± 2 [f]	[e]
			2.0	17 ± 4		14 ± 2 [f]	[e]
6.34	$\frac{1}{2}^+$	< 0.11	0	65 ± 3	E1	68 ± 3	
			2.0	35 ± 3		32 ± 3 [d]	
			4.3			< 7	
			4.8	< 4		< 3	
6.48	$\frac{7}{2}^-$	< 0.25	0	89 ± 2	E2	88 ± 2	-0.01 ± 0.06
			2.0	< 2		< 4	
			4.3	11 ± 2		12 ± 2	
			4.8			< 2	
6.91	$\frac{5}{2}^+$	< 0.16	0	89 ± 3	E1	91 ± 2	0.02 ± 0.03
			2.0	< 2		< 1	
			4.3	11 ± 3		4.5 ± 1	
			4.8	< 3		4.5 ± 1	
			6.3	< 5			
			6.5	< 5			
7.51	$\frac{3}{2}^+$	< 0.5	0	36 ± 2	E1	37 ± 3	-0.04 ± 0.04
			2.0	64 ± 2	E1	63 ± 8	0 ± 0.03
			4.3	< 3		< 1	
			4.8	< 3		< 1	
			6.3	< 3			
			6.5	< 3			
			6.9	< 4			

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

[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).

5. ^{10}B(p, n)^{10}C $\quad Q_{\rm m} = -4.432 \quad E_{\rm b} = 8.693$

$E_{\rm thresh.} = 4880.1 \pm 2.0$ keV; $Q_0 = -4432.8 \pm 1.8$ keV (1966FR09). This result is 44 keV lower than the value used by (1965MA54), and considerably more accurate. We adopt $(M-A)$ ^{10}C $=$ 15702.6 ± 2.0 keV for the present review.

The total (p, n) cross section has been measured to $E_{\rm p} = 10.6$ MeV by (1963EA01): broad maxima are observed at $E_{\rm p} = 5.92 \pm 0.02$, 6.68 ± 0.04, 7.33 ± 0.05 and 7.60 ± 0.05 MeV (see Table 11.18). The cross section for formation of ^{10}C$_{\rm g.s.}$ measured up to $E_{\rm p} = 12$ MeV, shows similar behavior to 8 MeV. At $E_{\rm p} \approx 8$ 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 $E_{\rm p} = 8.5$ to 12 MeV (1966SE03). See also (1959AJ76, 1963VA1C, 1965VA23).

6. ^{10}B(p, p)^{10}B $\quad E_{\rm b} = 8.693$

The elastic scattering shows two conspicuous anomalies, at $E_{\rm p} = 1.50 \pm 0.02$ MeV and at 2.18 MeV, corresponding to states at $E_{\rm x} = 10.06$ and 10.68 MeV with $J^\pi = \frac{7}{2}^+$ and $\frac{9}{2}^+$ (see Tables 11.18 and 11.19). Below $E_{\rm p} = 0.7$ MeV, the scattering can be explained in terms of pure s-wave potential scattering but the possibility of a state near $E_{\rm p} = 0.270$ MeV ($E_{\rm x} = 8.95$ MeV) cannot be excluded (1960OV1A, 1962OV02: $E_{\rm p} = 0.15$ to 3.0 MeV). (1962OV02) also report evidence for a state formed by s-wave protons near $E_{\rm p} = 2.8$ MeV. On the other hand (1962AN11) who have studied scattering to $E_{\rm p} = 3.5$ MeV interpret the data as indicating a resonance above $E_{\rm p} = 3.5$ MeV. See also (1951BR10, 1961RO05, 1966JA1F).

7. ^{10}B(p, p′)^{10}B* $\quad E_{\rm b} = 8.693$

The yield of 0.71 MeV radiation, from ^{10}B*, rises monotonically from $E_{\rm p} = 1.5$ to 4.1 MeV (1952DA05, 1954DA20, 1957HU79, 1964BE31), and then shows resonance behavior at $E_{\rm p} = 4.35 \pm 0.02$ MeV and 5.73 ± 0.02 MeV (1962OP03: see Table 11.18). For $E_{\rm p} = 6$ to 12 MeV, the

Table 11.18: Resonances in ^{10}B + p [a]

$E_{\rm res}$ (MeV $\pm$ keV)	$E_{\rm x}$ (MeV)	J^π	$\Gamma_{\rm lab}$ (keV)	Decay	Refs.
1.145 ± 5	9.731	$(\frac{5}{2}^+)$	500 ± 50	γ, p, α_0	(1951BR10, 1955HA01, 1956CH20, 1956CR07, 1957HU79)
1.533 ± 5	10.086	$\frac{7}{2}^+$	≈ 250	p, α_0, α_1	(1951BR10, 1956AL23, 1956CH20, 1956CR07, 1957HU79, 1962OV02)
2.189 ± 5	10.682	$\frac{9}{2}^+$	220 ± 30	p, α_0, α_1	(1962OV02, 1964BE31, 1964JE01)
2.320 ± 5	10.801			p, α_1	(1964BE31)
2.574 ± 5	11.032			p, α_1	(1964BE31)
3.03 ± 10	11.45		400	p, α_0, α_1	(1962OP03, 1964JE01)
3.592 ± 7	11.957			p, α_1	(1964BE31)
4.36 ± 20	12.65	$(\frac{7}{2}^+)$	400	γ, p, α_0, α_1, ^{3}He	(1962OP03, 1964JE01, 1966SE03)
5.10	13.33			p, α_0, α_1	(1962OP03, 1964JE01, 1966SE03)
5.73 ± 20	13.90		≈ 500	p	(1962OP03)
5.92 ± 20	14.07		broad	n, p_0, (α_0, α_1)	(1963EA01, 1964JE01, 1966SE03)
6.68 ± 40	14.76		broad	n, p, (^{3}He), α_1	(1963EA01, 1964JE01, 1966SE03)
7.33 ± 50	15.35		≈ 2500	n, p, (α_1)	(1963EA01, 1966SE03)
7.60 ± 50	15.60		broad	n, p	(1963EA01)
8 [b]	16		≈ 3500	(n), p	(1966SE03)

[a] See also Table 11.19.

[b] See reaction 7. This broad state may be a giant resonance in the $(\alpha + \alpha + {\rm d} + {\rm p})$ system.

Table 11.19: 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)	$\Gamma_{\alpha 0}$ (MeV)	$\Gamma_{\alpha 1}$ (MeV)	θ^2_p	$\theta^2_{\alpha 0}$	$\theta^2_{\alpha 1}$
1.17 [b]	9.76	$(\frac{5}{2}^+)$	0.045	0.255				
1.50 [c]	10.06	$\frac{7}{2}^+$	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 11.18.

[b] (1956CR07, 1962OV02).

[c] (1962OV02).

[d] (1964JE01).

cross section shows several sharp maxima superposed on a broad maximum ($\Gamma \approx 2.5$ MeV) at $E_p \approx 7.2$ MeV (1966SE03). (1966SE03) have also measured the yields of the 1.02 (^{10}B*(1.7) $\rightarrow$ ^{10}B*(0.7)), 1.43 (^{10}B*(2.1) $\rightarrow$ ^{10}B*(0.7) and ^{10}B*(3.6) $\rightarrow$ ^{10}B*(2.2)), 2.86 (^{10}B*(3.6) $\rightarrow$ ^{10}B*(0.7)) and 4.44 ^{10}B*(5.16) $\rightarrow$ ^{10}B*(0.7)) MeV gamma rays for $E_p = 4$ to 12 MeV. The yields of both the 2.15 and 3.58 MeV states of ^{10}B show a broad resonance, about 4 MeV wide, centered at $E_p \approx 8$ MeV, with some fine structure superimposed. The yields of the 1.74 and 5.16 MeV states show this resonance weakly or not at all (this is also true of the neutrons in reaction 6). For the groups that show the broad resonance, the maximum cross sections vary from 20 to 160 mb and tend to increase with increasing Q. For the groups that do not show the broad resonance, the cross sections are all below 5 mb and reach their maxima in the 7–12 MeV region. The weak reactions are those in which the residual nucleus is left in a $T = 1$ state. This is explained in terms of an $\alpha + \alpha + \mathrm{d} + \mathrm{p}$ character for the broad resonance. This suggests a significant ($\alpha + \alpha +$ d) cluster structure for the ^{10}B ground state as well as for the first few low-lying states of ^{10}B (1966SE03, 1967WA1L).

8. ^{10}B(p, d)^{9}B $\quad Q_m = -6.213 \quad E_b = 8.693$

See ^{9}B IN (1966LA04).

9. ^{10}B(p, ^{3}He)^{8}Be $\quad Q_m = -0.534 \quad E_b = 8.693$

The ground-state yield has been obtained for $E_p = 4$ to 10 MeV ($\theta = 50°, 90°$). There are slight maxima at similar energies to those in the (p, α) yield. However, the angular distributions do not vary strongly over the region covered and it is suggested that a direct interaction mechanism dominates (1963JE01). (1966SE03) report two strong maxima at $E_{\rm p} \approx 4.5$ and 6.5 MeV.

10. ^{10}B(p, α)^{7}Be $Q_{\rm m} = 1.148$ $E_{\rm b} = 8.693$

The parameters of observed resonances are displayed in Tables 11.18 and 11.19. The ground state (α_0) α-particles exhibit broad resonances at $E_{\rm p} = 1.17$, 1.53, 2.18, 3.0, 4.4, 5.1 and 6.3 MeV (1959AJ76, 1962OV02, 1964JE01). 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 (1959AJ76, 1962OP03, 1964BE31, 1964JE01, 1966SE03). Weak resonances are also reported at 2.32, 2.57 and 3.59 MeV (1964BE31). A broad maximum dominates the region from $E_{\rm p} = 4$ MeV to about 7.5 MeV (1966SE03). See also discussion under reaction 6, and (1963VA1C).

11. ^{10}B(d, n)^{11}C $Q_{\rm m} = 6.468$

Neutron spectra have been studied by (1959AJ76), (1952JO10, 1956CE1B, 1956CE73, 1956GR54, 1956MA83, 1957GR50, 1959NE1A, 1960MC1C, 1963OV02, 1965SI13) and others. Angular distributions, γ spectra and (n-γ) correlations are reported by (1960FE13, 1960MC1C, 1960NE17, 1961JA12, 1962FR06, 1963BR1H, 1965OL03, 1966AD1D), (1966GO12, 1966RU01, 1966WE1B, 1967DI01) and (1959AJ76). The principal results are exhibited in Table 11.20.

DWBA fits to the ground-state distribution are reported by (1967DI01: $E_{\rm d} = 5$ to 7.6 MeV). At $E_{\rm d} = 7.6$ and 9.0 MeV, the angular distributions corresponding to the first four levels match the PWBA $l = 1$ patterns moderately well, although the ^{11}C*(2.0) level is relatively weak (1956CE1B, 1956CE73: 7.6 MeV) and (1956MA83: 9 MeV). For $E_{\rm d} = 1$ to 4 MeV, levels at $E_{\rm x} = 6.48$, 8.43 and 8.66 MeV show good patterns; ^{11}C*(2.0, 4.3, 4.8, 6.34, 6.91) are quite weak (1960FE13, 1960NE17, 1965SI13: $E_{\rm d} = 5$ to 8 MeV) and (1961JA12). The ^{11}C*(2.0) is believed to have $J^{\pi} = \frac{1}{2}^{-}$ and is presumably formed by an exchange or spin-flip mechanism (1963AU1A). In $j - j$ coupling, it is expected that only the levels $(\frac{3}{2})_{\rm I}$, $(\frac{7}{2})_{\rm I}$ and $(\frac{5}{2})_{\rm II}$ will show large stripping widths: these are presumably ^{11}C*(0, 6.48, 8.42) (1960BI08, 1960MA32, 1961JA12).

Information on the gamma decay of levels up to ^{11}C*(7.50) has been summarized by (1965OL03) and is incorporated in Table 11.17. See also (1966GO12).

Neutron threshold measurements indicate levels at 8.103, 8.426 and 8.656 MeV (1955MA76: ± 8 keV; based on $Q_{\rm m}$). (1963OV02) has investigated this region with time-of-flight techniques and finds that two levels exist near $E_{\rm x} = 8.7$ MeV, at $E_{\rm x} = 8.657$ and 8.702 MeV. A broad level is located at $E_{\rm x} = 10.69$ MeV ($\Gamma \approx 200$ keV) but no evidence is found for other levels reported above $E_{\rm x} = 8.7$ MeV. The doublet appears to correspond to the s-particle doublet in ^{11}B*(9.19, 9.28) (1963OV02).

See also (1959BR75, 1959BU1F, 1960FE01, 1963MO07, 1965MA1K, 1966GO1N, 1966RO1X, 1967SC1K) and ^{12}C.

Table 11.20: Levels of ^{11}C from ^{10}B(d, n)^{11}C

E_x (MeV $\pm$ keV)	J^{π} [f]	l	$(2J+1)\theta^2$ [a]	$(2J+1)\theta^2$ [b]	Refs. [c]
0	$\frac{3}{2}^-$	1	(4)	4	(1956MA83, 1967DI01)
1.94 ± 50	$\frac{1}{2}^-$	(1)	weak		(1956MA83, 1960NE17)
4.260 ± 21 [d]	$\frac{5}{2}^-$	1	(2.8)	1.2	(1960MC1C, 1960NE17)
4.749 ± 17 [d]	$\frac{3}{2}^-$	1	(0.9)	0.54	(1955SA1B, 1960NE17, 1962FR06, 1966RU01)
6.34	$(\frac{1}{2})^+$				(1961JA12)
6.487 ± 14 [d]	$\frac{7}{2}^-$	1	7.5		(1955BE81, 1955SA1B, 1960FE13, 1960MC1C, 1960NE17, 1962FR06, 1963BR1H, 1966RU01)
6.91 ± 20 [e]	$\frac{5}{2}^+$	(1)	(0.9)		(1962FR06)
7.40 ± 40	$\frac{3}{2}^+$				(1955SA1B)
8.103 ± 8	$(\leq \frac{5}{2}^-)$				(1955MA76)
8.426 ± 8	$-$	1	2.9		(1955MA76)
8.656 ± 8	$+$	0	10.3		(1955MA76, 1963OV02)
8.702 ± 20	$(+)$	(0)			(1963OV02)
(8.97 ± 20)					(1957GR50)
(9.13 ± 20)					(1952JO10)
(9.28 ± 30)					(1956CE1B, 1956CE73)
(9.69 ± 30)					(1956CE1B, 1956CE73)
(10.09 ± 20)					(1957GR50)
10.69	$(+)$	(0, 2)			(1963OV02)
(10.89 ± 20)					(1957GR50)
(11.26 ± 20)					(1956CE1B, 1956CE73)
(11.52 ± 20)					(1956CE1B, 1956CE73)

[a] (1961JA12); $E_d = 1$ to 4 MeV: relative values.

[b] (1956CE1B, 1956CE73, 1960MA32); $E_d = 7.55$ MeV: relative values.

[c] (1952JO10) lists 12 levels, (1956CE1B, 1956CE73) lists 17, (1961JA12) lists 11: see also (1959AJ76).

[d] (1959NE1A) and references therein.

[e] (1961JA12).

[f] J^{π} from Table 11.17.

12. ^{10}B(t, 2n)^{11}C $\quad Q_{\rm m} = 0.211$

See (1961RO21).

13. ^{10}B(^{3}He, d)^{11}C $\quad Q_{\rm m} = 3.199$

$Q_0 = 3.226 \pm 0.010$ (1964MA57).

Angular distributions of the neutrons to the ground state of ^{11}C and to the first five excited states have been analyzed by stripping theory [(1961HI08: $E(^3{\rm He}) = 9.84$ MeV) and (1965PA10: $E(^3{\rm He}) = 3.5$ to 10 MeV)] and the excitation energies of nine states have been determined (1961HI08): see Table 11.21.

Table 11.21: Energy levels of ^{11}C from ^{10}B(^{3}He, d)^{11}C and ^{11}B(p, n)^{11}C

(1961HI08) [a]			(1965OV01) [d]
$E_{\rm x}$ (MeV ± keV)	l	$\theta^2_{\rm p}$ [b]	$E_{\rm x}$ (MeV ± keV)
0	1	0.019	0
2.002 ± 10 [c]	[c]		2.008 ± 20
4.322 ± 10	1	0.009	4.320 ± 20
4.808 ± 10	(1)	(0.006)	4.806 ± 20
6.345 ± 10			6.330 ± 20
6.476 ± 10	1	0.033	6.481 ± 20
6.903 ± 10			
7.498 ± 10			
8.107 ± 10			
8.42			

[a] ^{10}B(^{3}He, d): $E(^3{\rm He}) = 9.84$ MeV.

[b] Values based on known J^π of states.

[c] (1960FO01) find $E_{\rm x} = 1.990 \pm 0.005$ MeV, $l = 1$.

[d] ^{11}B(p, n)^{11}C; time-of-flight.

See also (1959AL96, 1960FO01, 1960SP08, 1962BR10).

14. ^{10}B(α, t)^{11}C $\quad Q_{\rm m} = -11.121$

The tritons corresponding to the ground state have been observed at $E_\alpha = 43$ MeV (1967DE1K).

15. (a) ^{10}B(^{6}Li, ^{5}He)^{11}C $\qquad Q_\mathrm{m} = 4.038$
(b) ^{10}B(^{14}N, ^{13}C)^{11}C $\qquad Q_\mathrm{m} = 1.143$

For reaction (a) see (1957NO17). For reaction (b) see (1962NE01, 1963TO1E, 1966GA04).

16. ^{11}B(p, n)^{11}C $\qquad Q_\mathrm{m} = -2.763$

$$E_\mathrm{thresh.} = 3.0164 \pm 0.0015 \text{ (1961BE13)};$$
$$E_\mathrm{thresh.} = 3.019 \pm 0.004 \text{ (1959BR06)}.$$

Neutron groups have been observed to ^{11}C$_\mathrm{g.s.}$ and to the first excited states: see Table 11.21 (1965OV01). Angular distributions of the ground-state neutrons have been studied at many energies up to $E_\mathrm{p} = 18.5$ MeV (1960HI04, 1961AL07, 1964AN1B, 1964SA1D, 1964ST1C, 1965WA04). See also (1956AJ22, 1961GO13, 1961TA12, 1963PA1E, 1964BA16, 1965VA23, 1966UN1A) and ^{12}C.

17. ^{11}B(^{3}He, t)^{11}C $\qquad Q_\mathrm{m} = -1.999$
$Q_0 = -2.0023 \pm 0.0012$ (1965GO05).

The ground-state tritons have been observed at $E(^3\mathrm{He}) = 4.8$ to 5.0 MeV, dσ/d$\Omega \approx 0.26$ mb/sr (1965GO05). Angular distributions of t$_0$ and t$_1$ have been obtained at $E(^3\mathrm{He}) = 10$ MeV (1967CR04).

18. ^{12}C(γ, n)^{11}C $\qquad Q_\mathrm{m} = -18.720$

See (1963FU05, 1967FI1E) and ^{12}C.

19. (a) ^{12}C(n, 2n)^{11}C $\qquad Q_\mathrm{m} = -18.720$
(b) ^{12}C(p, pn)^{11}C $\qquad Q_\mathrm{m} = -18.720$

For reaction (a) see ^{13}C in (1970AJ04). For reaction (b) see ^{13}N in (1970AJ04) and (1962AU1A, 1962BA1A, 1962GU10, 1966PA08).

20. ^{12}C(p, d)^{11}C $Q_{\rm m} = -16.495$

At $E_{\rm p} = 155$ MeV, deuteron groups have been observed to the ground state and to excited states of ^{11}C at 2.0 ± 0.1, 4.9 ± 0.1 and (7.0 ± 0.2) MeV (1962RA01, 1963BA1R, 1963RA01, 1967BA2L). See also (1965DE1A, 1965KE02, 1965PU02, 1965VE1B). Angular distributions have been measured at $E_{\rm p} = 19 - 20$ MeV (1962WA31), 27.5 MeV (1967GL01), 30 MeV (1967CH15), 31.1 and 33.5 MeV (1967GR1M), 36 MeV (1965KE02), 40 MeV (1963KA26, 1966SH1A), 45 MeV (1966MA2B), 54.9 MeV (1968TA1P), and 60 MeV (1965IS06). For spectroscopic factors, see (1967BA2L). See also (1956SE1A, 1959GR1B, 1960RA12, 1961CL09, 1962BE1H, 1963CL07, 1963IS1B, 1963MA1J, 1964JA1C, 1964SH07, 1965GL1E, 1967HO1M, 1967TO1D).

21. ^{12}C(d, t)^{11}C $Q_{\rm m} = -12.462$

Ten states of ^{11}C have been observed at $E_{\rm d} = 50$ MeV. The angular distributions are identical with those seen in the mirror reaction ^{12}C(d, ^{3}He)^{11}B to analogue states (1966CH1K): see ^{11}B. At $E_{\rm d} = 28.5$ MeV the (d, t) and (d, ^{3}He) cross sections to the ground states of the mirror nuclei ^{11}C and ^{11}B are equal (1966DE1C). See also (1959VL23, 1967FI1G), and ^{14}N in (1970AJ04).

22. ^{12}C(^{3}He, α)^{11}C $Q_{\rm m} = 1.858$
$Q_0 = 1.856 \pm 0.012$ (1960HI07).

Angular distributions of alpha particles to the ground state have been observed at $E(^{3}{\rm He}) = 1.8$ to 5.4 MeV (1964KU05), 2.4 to 4.5 MeV (1963LU05), 4.8 to 5.9 MeV (1966BL01), 8.5 to 10.0 MeV (1966SC22), 6.0, 8.8, 9.4 and 10.1 MeV (1960HI07), 16 to 18 MeV (1967GR1L, 1967GR1N), 24.8 MeV (1967HA21), 26 to 33 MeV (1963PA1G), and 26 MeV (1966DA1H). The α_1 distributions (to the 2 MeV state) have been investigated at $E(^{3}{\rm He}) = 4.2$, 4.9, 5.6, 6.0, 8.8, 9.4, 10.1, 16 to 18 MeV (1960HI07, 1964KU05, 1966BL01, 1967GR1L, 1968GR1G). Angular distributions at the higher energies are consistent with $l_{\rm n} = 1$ for both α_0 and α_1 (1960HI07). See also (1966SC22). The energy of the first excited state is $E_{\rm x} = 1.990 \pm 0.010$ (1959PO61), 2.000 ± 0.010 (1960HI07), 1.999 ± 0.004 MeV (1968EA03). See also (1961CA1D, 1962AG01, 1962CA29, 1962GA17, 1962WE1C, 1963PA15, 1964BE1K, 1965GR1R). See also ^{15}O in (1970AJ04) and (1966HA1Q, 1967BR1N).

Studies of $\alpha - \gamma$ correlations have been carried out by (1965WA06: $E(^{3}{\rm He}) = 4.7$ MeV), (1965NE06, 1965SC1D: $E(^{3}{\rm He}) = 5.1$ MeV), (1967BL22: $E(^{3}{\rm He}) = 9$ MeV), (1966GA19:

$E(^3\text{He}) = 10$ MeV), and (1968EA03: $E(^3\text{He}) = 6$ to 12 MeV) with the following results (1968EA03) (see also ^{9}Be(^{3}He, n)^{11}C and Table 11.17):

$\underline{E_x = 8.42\text{ MeV}.}$ This level is unbound $\Gamma_\gamma/\Gamma = 0.2 \pm 0.1$.

$\underline{E_x = 8.11\text{ MeV}.}$ $\Gamma_\gamma/\Gamma < 0.04$; $J^\pi \leq (\frac{5}{2}^-)$ from ^{9}Be(^{3}He, n)^{11}C (Table 11.16).

$\underline{E_x = 7.51\text{ MeV}.}$ For the ground-state transition, the $\alpha - \gamma$ correlation permits $J = \frac{3}{2}$ or $\frac{5}{2}$. With the $J = \frac{5}{2}$ assignment, an unreasonable M2 enhancement is required, therefore $J^\pi = \frac{3}{2}^+$ and $x(\equiv (L+1)/L$ amplitude$) = -0.04 \pm 0.04$ (1968EA03). The correlation in the cascade transition excludes $J^\pi = \frac{3}{2}^-$ for ^{11}C*(2.0) and indicates $J^\pi = \frac{1}{2}^-$, $x = 0.0 \pm 0.03$ (1968EA03).

$\underline{E_x = 6.91\text{ MeV}.}$ The correlation analysis gives $J = \frac{5}{2}$, $x = 0.02 \pm 0.03$; $J = \frac{1}{2}$ and $\frac{3}{2}$ are eliminated.

$\underline{E_x = 6.48\text{ MeV}.}$ Analysis of $\alpha - \gamma$ correlation gives $J = \frac{7}{2}$, $x = -0.01 \pm 0.06$.

$\underline{E_x = 6.34\text{ MeV}.}$ The cascade transition is via ^{11}C*(2.0) and not ^{11}C*(4.31). From ^{9}Be(^{3}He, n)^{11}C, $J^\pi = \frac{1}{2}^+$ or $\frac{3}{2}^+$. For $J^\pi = \frac{3}{2}^+$ correlation analysis requires an excessive M2 admixture. The angular distribution of α's at $E(^3\text{He}) = 11.0$ MeV gives an $l = 0$ pattern: $J^\pi = \frac{1}{2}^+$.

$\underline{E_x = 4.79\text{ MeV}.}$ The decay is to $^{11}\text{C}_{\text{g.s.}}$ and (2.0). With $J^\pi = \frac{1}{2}^-$ for ^{11}C*(2.0), the correlation analysis eliminates $J^\pi = \frac{5}{2}^-$ and $\frac{1}{2}^-$ and gives for $J^\pi = \frac{3}{2}^-$, x(g.s.) $= -(0.04 \pm 0.04)$ or $-(3.28 \pm 0.49)$, and $x(4.8 \to 2.0) = +(0.03 \pm 0.05)$ or $+(1.60 \pm 0.12)$. See also (1966GA19, 1967BL22).

$\underline{E_x = 4.31\text{ MeV}.}$ Analysis of angular correlations gives $J = \frac{5}{2}$, $x = 0.17 \pm 0.03$. See also (1966GA19, 1967BL22).

$\underline{E_x = 2.00\text{ MeV}.}$ Stripping results give $l_n = 1$, $J^\pi = \frac{1}{2}^-$ or $\frac{3}{2}^-$. The $\alpha - \gamma$ correlation is isotropic (1965NE06, 1965WA06). The cascade from ^{11}C*(7.51) excludes $J^\pi = \frac{3}{2}^-$. See also (1967BL22).

23. ^{12}C(^{14}N, ^{15}N)^{11}C $\quad Q_m = -7.885$

See (1966PO1B, 1967BI06).

24. ^{13}C(p, t)^{11}C $\quad Q_m = -15.185$

At $E_p = 43.7$ MeV, a triton group was observed corresponding to a $T = \frac{3}{2}$ state at $E_x = 12.45 \pm 0.08$ MeV, $\Gamma = 566 \pm 60$ keV, $J^\pi = \frac{1}{2}^-$ (1966MA2N). See also (1968TA1V).

25. ^{14}N(p, α)^{11}C $\quad Q_m = -2.920$

At $E_p = 38$ MeV angular distributions have been obtained for α_0, α_1, $\alpha_2 + \alpha_3$ (1968GA1N). See also (1961CL09, 1962MA1L, 1963BR14) and ^{15}O in (1970AJ04).

26. ^{16}O(γ, nα)^{11}C $Q_m = -25.881$

See (1955AJ61) and (1962BI09).

^{11}N

(Not illustrated)

See (1960GO1B, 1966KE16).

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(Closed 15 December 1967)

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