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Energy Levels of Light Nuclei
$A = 10$

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Abstract: An evaluation of $A = 5$–24 was published in *Nuclear Physics* 11 (1959), p. 1. This version of $A = 10$ differs from the published version in that we have corrected some errors discovered after the article went to press. Figures and introductory tables have been omitted from this manuscript. Reference key numbers have been changed to the TUNL/NNDC format.

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Table of Contents for $A = 10$

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

A. Nuclides: ^{10}Be, ^{10}B, ^{10}C

B. Tables of Recommended Level Energies:

Table 10.1: Energy levels of ^{10}Be

Table 10.4: Energy levels of ^{10}B

Table 10.8: Energy levels of ^{10}C

C. References

D. Figures: ^{10}Be, ^{10}B, ^{10}C

E. Erratum to the Publication: PS or PDF

^{10}Be

(Fig. 12)

GENERAL:

Theory: See (1956KU1A, 1957FR1B, 1958FR1C).

1. ^{10}Be(β^-)^{10}B $\quad Q_{\rm m} = 0.556$

The weighted mean end-point energy is 0.556 ± 0.003 MeV (1951LI26). The mean half-life is $(2.7 \pm 0.4) \times 10^6$ y (1949HU19): $\log ft = 13.65$ (1951FE1A). The spectrum is of the D_2 type (1950WU1A).

2\. (a) ^{7}Li(t, α)^{6}He $\quad Q_{\rm m} = 9.807 \quad E_{\rm b} = 17.246$

(b) ^{7}Li(t, 2n)^{8}Be $\quad Q_{\rm m} = 8.768$

(c) ^{7}Li(t, n)^{9}Be $\quad Q_{\rm m} = 10.435$

(d) ^{7}Li(t, n)^{5}He + ^{4}He $\quad Q_{\rm m} = 7.905$

The neutron yield (elemental Li) at 0° exhibits two broad resonances, at $E_{\rm t} = 0.84$ and 1.70 MeV. The angular distributions are not isotropic (1951CR01). The cross section for reaction (a) has been measured for $E_{\rm t} = 0.6$ to 2.3 MeV ($\theta = 90°$ and $165°$): both the yield of ^{6}He(0) and ^{6}He*(1.71) α-particles show a broad resonance at $E_{\rm t} \approx 1.7$ MeV. At $E_{\rm t} = 1.8$ MeV, $\theta = 90°$, the differential cross section is 2.6 mb/sr for ^{6}He(0) and 8 mb/sr for ^{6}He*(1.71) (1957JA37).

At $E_{\rm t} = 0.24$ MeV the ground state α-particles are distributed as $W(\theta_{\rm c.m.}) = 1 - (0.66 \pm 0.06)\cos^2\theta$, while those corresponding to the 1.7-MeV state of ^{6}He are isotropic within 8%. The formation of the 1.7-MeV state is 8 times more probable than the formation of the ground state. These results indicate p-wave formation of the 0.84-MeV resonance and $J = 2^+$ for the 17.83-MeV state (1952DE1B, 1953CH1A, 1954AL38). See also ^{6}He and (1956MA09).

3\. ^{7}Li(α, p)^{10}Be $\quad Q_{\rm m} = -2.566$

At $E_\alpha = 31.5$ MeV, proton groups are observed leading to the ground and first excited state of ^{10}Be (1956WA29).

4\. ^{9}Be(n, γ)^{10}Be $\quad Q_{\rm m} = 6.812$

Table 10.1: Energy levels of ^{10}Be

E_x in ^{10}Be (MeV)	J^π	Γ (keV) or τ	Decay	Reactions
0	0^+	$\tau_{1/2} = (2.7 \pm 0.4) \times 10^6$ y	β^-	1, 3, 4, 9, 12, 18
3.368 ± 0.009	2^+	$\tau_m < 3.0 \times 10^{-13}$ sec	γ	3, 4, 9
5.959 ± 0.009	1^-	sharp	γ	9
6.178 ± 0.009		sharp		9
6.262 ± 0.009	2^-	sharp	(γ)	9
7.37 ± 0.01	$3^{(+)}$	25 ± 4	n	5, 9
7.54 ± 0.01	2	8 ± 3	n	5, 9
9.27	$(^-)$	≈ 100	n	5, 9
(9.4)	(2^+)	broad	(n)	5, (8)
17.83	(2^+)		n, t, α	2
18.43			n, t, α	2

The thermal capture cross section is 10 ± 1 mb (1958HU18). In addition to the ground-state transition, a 3.41 ± 0.06-MeV γ-ray is observed, attributed to a cascade through the 3.4-MeV state. The intensity of the cascade transition is ≈ 0.25 photon/capture (1953BA18), 0.27 photon/capture (1955GR1E). See also (1953WI1C).

5. ^{9}Be(n, n)^{9}Be $\qquad E_b = 6.812$

The total cross section is constant at 6.04 ± 0.03 b from 0.1 eV to 100 keV (1958HU18): the spin dependent scattering is < 0.003 b (1952PA1A).

In the region $E_n = 0$ to 18 MeV, three resonances are reported at 0.62, 0.81 and 2.73 MeV. The parameters of these resonances are exhibited in Table 10.2.

Angular distributions have been measured for $E_n = 0.54$ to 0.70 MeV by (1955WI25). The patterns are symmetric about 90° in this range, indicating absence of interference between resonance and potential scattering waves of opposite parity. The 0.62-MeV resonance has $J = 3$; a satisfactory fit to the angular distribution is obtained with the assumption of p-wave formation in channel spin 2, with s-wave potential scattering all in channel spin 1. It is observed that the assumption of spin-dependent potential scattering is at variance with observation at thermal energies (see also (1956LA1B)). The possibility of d-wave formation is not excluded. The cross section at the 0.81-MeV resonance is consistent with $J = 2$ (1955WI25). A comparison of reduced widths suggests a close correspondence between ^{10}Be*(7.37), (7.54) and the two ^{10}B levels at 8.89 MeV (1956MA55).

Table 10.2: Resonances in ^{9}Be(n, n)^{9}Be

E_{res} (MeV)	^{10}Be* (MeV)	J^π	l	Γ (keV)	σ (b)	θ_{n}^2 (%)	References
0.62 ± 0.01	7.37	3		30	3.7 [a]	1.7 [d]	(1951BO45)
		$3^{(+)}$	1, (2)	25 ± 4	4.35 [a]		(1955WI25)
					7.75 [b]		(1955HU1B, 1958HU18)
0.81 ± 0.01	7.54	> 0	≥ 1	≤ 11	≈ 1.3 [a]		(1951BO45, 1955HU1B)
		2	1, 2	8 ± 3	5.25 [b]	0.34 [e]	(1955WI25, 1958HU18)
2.73 [c]	9.27	$(^-)$ [f]		100	≈ 4 [b]		(1951BO45)
(2.85)	(9.4)	(2^+) [f]	(1)	(≈ 400)			(1951BO45)

[a] Cross section above background.

[b] Includes background.

[c] The large cross section, peak asymmetry and angular distributions suggest two resonances, a sharp one at 2.73 MeV and a much broader one at ≈ 2.85 MeV (1951BO45, 1958FO46).

[d] Assuming $l = 1$, $R = 4.3 \times 10^{-13}$ cm.

[e] (1956MA55), assuming $l = 1$.

[f] (1958FO46).

Differential elastic scattering cross sections have been measured in the non-resonant regions from $E_{\mathrm{n}} = 0.7$ to 3.0 MeV (1957FO1B, 1958FO46) and analyzed in terms of phase shifts (1957FO1B). For $E_{\mathrm{n}} = 1.0$ to 2.0 MeV, an appreciable p-wave contribution is observed (1958FO46).

The shape of the 2.73-MeV structure suggests that there may actually be two levels involved, at $E_{\mathrm{p}} = 2.73$ MeV, $\Gamma \approx 0.1$ MeV, and a broad state at $E_{\mathrm{p}} = 2.85$ MeV (1951BO45: see, however, the similar situation in ^{10}B (1959MA20)).

The elastic scattering in this region changes from being nearly symmetric at 2.4 MeV to being peaked forward at 2.9 MeV. This evidence also suggests two resonances and, together, with the ^{9}Be(n, α)^{6}He results of (1957ST95) probably identifies the broad 2.9-MeV resonance as formed by p-wave neutrons with $J = 2^+$ for ^{10}Be*(9.4) (1958FO46). Polarization measurements at $E_{\mathrm{p}} = 3.1$ MeV indicate interference between a broad $d_{3/2}$ resonance and $s_{1/2}$ hard-sphere scattering (1957MC1B). Other measurements of differential cross sections from $E_{\mathrm{n}} = 0.06$ to 1.80 MeV are reported by (1956LA1B, 1957LA14), from 2.30 to 3.66 MeV by (1953ME1A), at 4.1 MeV by (1955WA27), 7.0 MeV by (1956BE32), and 14.2 MeV by (1957AN52) and (1958NA09). At the higher energies, the neutrons show strong optical-model effects.

The total cross section decreases from 2.14 b at 3.8 MeV to 1.7 b at 8.7 MeV (1955WA27, 1956BE98, 1957BO13, 1958BR16, 1958MA22); see also (1958HU18). At $E_{\mathrm{n}} = 12.7$ MeV, $\sigma_{\mathrm{t}} = 1.60$ b (1953NE01, 1955TA29, 1958BR16) and at $E_{\mathrm{n}} = 14.1$ MeV, $\sigma_{\mathrm{t}} = 1.55$ b (1955TA29), 1.49 ± 0.02 b (1954CO16), 1.53 ± 0.03 b (1952CO41), 1.46 ± 0.03 b (1957KH1A), 1.51 ± 0.02

b (1958BR16). The cross section then decreases monotonically to 1.38 ± 0.03 b at $E_{\mathrm{n}} = 18.0$ MeV (1954CO16). Non-elastic cross sections are given by (1955BE1D, 1955BF01, 1955MA1G, 1955TA29, 1955WA27, 1956BE32, 1956FL1B, 1957RO57, 1958BA03, 1958MA22, 1958MA54, MC58C). See also (1957HU1D), ^{9}Be(n, n′)^{9}Be*, ^{9}Be(n, 2n)^{8}Be and ^{9}Be(n, α)^{6}He. See also (1956HE1D, 1956LA1C, 1957ST1D, 1957ZA1A).

6. (a) ^{9}Be(n, 2n)^{8}Be $\quad Q_{\mathrm{m}} = -1.666 \quad E_{\mathrm{b}} = 6.812$
   (b) ^{9}Be(n, n′)^{9}Be*

The cross section for reaction (a) has been measured for $E_{\mathrm{n}} = 2.6$ to 3.2 MeV. A sharp increase is reported at $E_{\mathrm{n}} = 2.70$ MeV, threshold for process (b): ^{9}Be(n, n′)^{9}Be*(2.4) → n + ^{8}Be; the resonance at $E_{\mathrm{p}} = 2.73$ MeV (see ^{9}Be(n, n)^{9}Be) does not appear (1957FI52: see, however, (1956ED15)). It is suggested that the (n, 2n) reaction mainly proceeds via process (b) in this energy region (1955FO1B, 1957FI52). On the other hand (1958MA22) report evidence from energy spectra that the direct (n, 2n) process occurs for $E_{\mathrm{n}} = 2.6$ to 6 MeV. See ^{9}Be. The absolute cross section σ(n, 2n) rises linearly from 0.1 b at 2.8 MeV to 0.7 b at 3.25 MeV (1957FI52). The $90°$ differential cross section at $E_{\mathrm{n}} = 3.7$ MeV is 39 ± 8 mb/sr (1957HU14, 1958WA05), 27 ± 6 mb/sr (1955FO1B: quoted in (1957HU14)). The cross section for Ra-Be and Po-Be neutrons is 0.37 ± 0.06 b (1956ED15). The average cross section for $E_{\mathrm{n}} = 2$ to 11 MeV is 0.20 ± 0.12 b (1957VA12). At $E_{\mathrm{n}} = 14$ MeV, the cross section is 0.42 ± 0.07 b (1957RO57, 1957ST1C), in agreement with predictions of (1956SA1E) but not of (1953MA1C). (1958AS63) finds $\sigma = 0.54 \pm 0.04$ b at $E_{\mathrm{n}} = 14.1$ MeV. See also (1950HO80, 1952AG1A, 1957DU1B, 1958AN32, 1958BE1E, 1958HO1C).

7. ^{9}Be(n, t)^{7}Li $\quad Q_{\mathrm{m}} = -10.435 \quad E_{\mathrm{b}} = 6.812$

At $E_{\mathrm{n}} = 14$ MeV, σ(n, t) $= 18 \pm 1.5$ mb (1958WY67). See also (1957VA12).

8. ^{9}Be(n, α)^{6}He $\quad Q_{\mathrm{m}} = -0.628 \quad E_{\mathrm{b}} = 6.812$

The cross section for production of ^{6}He has been measured for $E_{\mathrm{n}} = 0.7$ to 4.4 MeV by (1957ST95), for $E_{\mathrm{n}} = 1$ to 6 MeV by (1957VA1D) and for $E_{\mathrm{n}} = 3.3$ to 6.1 MeV by (1955SA1E). (1957ST95) find only a smooth rise to a broad maximum of 104 ± 7 mb at 3.0 MeV, followed by a gradual decrease to 70 mb at 4.4 MeV, possibly to be attributed to competition by ^{9}Be(n, 2n)^{8}Be. No indication of resonance is found at $E_{\mathrm{n}} = 2.7$ MeV. Weak resonances are reported at $E_{\mathrm{n}} = 3.73$ and 4.27 MeV by (1955SA1E). The cross section at $E_{\mathrm{n}} = 14$ MeV is 10 ± 1 mb (1953BA04). See also (1947AL1A, 1957VA12).

Table 10.3: Levels of ^{10}Be from ^{9}Be(d, p)^{10}Be

^{10}Be* [a] (MeV)	Γ [a] (keV)	l_n [c]	l_n [b]	J^π	θ_n^2 [d] (%)
0		1	1	0^+	$5-9$
3.368 ± 0.009		1	1	2^+	1
5.959 ± 0.009		0	0(1)	1^-, (2^-)	15
6.178 ± 0.009					(0.5)
6.262 ± 0.009		0	0(1)	(1^-), 2^-	8
7.37	≈ 25	1		(2^+), 3^+	$1.2-1.4$
			2	$0^-, 1^-, 2^-, 3^-, 4^-$	
7.54	< 10				0.34
9.27 [b]					

[a] (1954JU1C, 1954JU23).

[b] (1958CA12: $E_d = 14.9$ MeV).

[c] (1956GR37: $E_d = 9.0$ MeV).

[d] Computed by (1958ME81) from data of (1951BO45, 1954FU1A, 1956GR37, 1956MA55, and others). See also (1957FR1B).

9. ^{9}Be(d, p)^{10}Be $\qquad Q_m = 4.585$

Levels reported by (1954JU1C, 1954JU23, 1956GR37, 1958CA12) are listed in Table 10.3. At $E_d = 7$ MeV the group corresponding to ^{10}Be*(6.18) is only 5% as intense as that corresponding to ^{10}Be*(6.26). The upper limit to the intensity of other groups is 3% (1954JU23: $\theta = 90°$, $E_d = 5.4 - 7.4$ MeV).

Angular distributions of the protons to ^{10}Be(0) and ^{10}Be*(3.37) have been studied at many energies from $E_d = 1$ to 14.9 MeV: see (1952AJ38, 1954EB02, 1955AJ61, 1955JU10, 1955JU1B, 1956GR37, 1956JU1E, 1956VA17, 1956ZE1A, 1957CO54, 1957JU1A, 1957SM78, 1958CA12, 1958MI93). Except at the lowest energies, the stripping process appears to dominate. At $E_d = 9$ MeV, the ratio of the maximum differential cross sections of the ^{9}Be(d, p)^{10}Be(0) and ^{9}Be(d, n)^{10}B*(1.74) reactions is 1.64 ± 0.25; $\gamma_n^2/\gamma_p^2 = 2.16$ (calculated from stripping theory; predicted value $= 2$) (1956CA1D). See also ^{11}B and (1956GR1D; theor.).

The 3.37-MeV level has $J = 2^+$, established by the (p, γ) correlation ($J \geq 2$), the stripping pattern ($J \leq 3^+$) and the internal pair formation coefficient (E1, M1 or E2): see (1955AJ61, 1958CH1A). Detailed study of the (p, γ) correlation at $E_d = 2.5$ to 3.9 MeV confirms this assignment and fixes the channel spin mixture (for capture of $l = 1$ neutrons) as 10% $J_c = 1$, 90% $J_c = 2$. This mixture is just that expected in pure L-S coupling for a $^{3}P_2$ state (1957CO54). Similar results are reported at $E_d = 7.7$ MeV by (1958PA1C). The gamma-ray energy is 3351 ± 27 (1953MA1A), 3400 ± 30 (1957MC35), 3360 ± 30 keV (1958ME81). Comparison of the γ-energy at $E_{\rm d} = 3.2$ MeV with recoils in vacuum and recoils stopped in Ta reveals no effect on the Doppler shift and sets an upper limit of 3.0×10^{-13} sec on the mean lifetime. A value of 0.4 to 1.0×10^{-12} sec is expected for a single-particle E2 transition (1959KO1B). It thus appears that shifts of some $20 - 30$ keV should be subtracted from the observed γ-energies.

From the stripping pattern, the 5.96-MeV level is assigned $J = 1^-$ or 2^- (Table 10.3). A gamma ray of energy 5.98 ± 0.04 (1953MA1A), 6.035 ± 0.04 (1955BE81, 1957MC35), 6.01 ± 0.06 MeV (1958ME81) is assigned to this level, as is another, of energy 2.54 ± 0.04 MeV (1958ME81: ^{10}Be*(5.96 $\rightarrow$ 3.37)). The fact that the cascade and direct transitions are roughly comparable in intensity fixes $J = 1^-$ (1958ME81).

The 6.26-MeV level ($J = 1^-$ or 2^-) appears to decay only to the 3.37-MeV level: the absence of the ground state transition indicates $J = 2^-$ (1958ME81). The 7.37-MeV level presents some difficulty. From stripping results $l_{\rm n} = 1$, $J = 2^+, 3^+$ (see, however, (1958CA12)); from ^{9}Be(n, n), $J = 3$ and $l_{\rm n} = 1$, possibly 2. The reduced width appears to be nearly the same as that of the 3.37-MeV level and $J = 2^+$ is suggested. Shell-model calculations indicate a vanishing width if $J = 3^+$ (1956GR37, 1957FR1B). The polarization of ground-state protons has been studied by (1958HI74). See also (1956GE1A, 1956TU1A, 1957HA1F).

10. ^{9}Be(t, d)^{10}Be $\quad Q_{\rm m} = 0.553$

Not reported.

11. ^{9}Be(α, ^{3}He)^{10}Be $\quad Q_{\rm m} = -13.766$

Not reported.

12. ^{10}B(n, p)^{10}Be $\quad Q_{\rm m} = 0.227$

See (1948EG1A, 1955JA18).

13. ^{10}B(t, ^{3}He)^{10}Be $\quad Q_{\rm m} = -0.538$

Not reported.

14. ^{11}B(n, d)^{10}Be $\quad Q_{\rm m} = -9.010$

Not reported.

15. ^{11}B(p, 2p)^{10}Be $Q_{\mathrm{m}} = -11.237$

See (1958MA1B, 1958TY49).

16. ^{11}B(d, ^{3}He)^{10}Be $Q_{\mathrm{m}} = -5.743$

Not reported.

17. ^{11}B(t, α)^{10}Be $Q_{\mathrm{m}} = 8.576$

Not reported.

18. ^{13}C(n, α)^{10}Be $Q_{\mathrm{m}} = -3.843$

See ^{14}C.

^{10}B

(Fig. 13)

GENERAL:

Theory: See (1955FR1F, 1956KU1A, 1957FR1B, 1957GR1D, 1957KU58, 1958FR1C, 1958KU1C, 1959WA16).

1. ^{6}Li(α, γ)^{10}B $\qquad Q_{\rm m} = 4.459$

Five resonances are observed in the range $E_{\alpha} = 0.5$ to 2.6 MeV, corresponding to ^{10}B*($4.76 - 6.06$ MeV): see Table 10.5. No other resonances appear for $E_{\alpha} < 3.8$ MeV (^{10}B*(6.74)) (1957ME27).

The 4.76-MeV state decays mainly to ^{10}B*(0.7). The angular distribution of γ-rays indicates $J = 2^{+}$, with a ratio E2/M1 $= 1.8$ (1957ME27), E2/M1 $= 0.68$; $J = 3^{+}$ is possible, but unlikely (1957WA07). The strength of the E2 radiation is ≈ 0.01 eV, several times the single-particle value (1957ME27). The relative weakness of the M1 transition may reflect the predicted inhibition of such transitions for $T_{\rm z} = 0$, $\Delta T = 0$ transitions (1958MO17). The weakness of the ground-state radiation is puzzling (1953WI32). Observation of γ-decay in ^{9}Be(d, n)^{10}B suggests $\Gamma_{\gamma} \approx \Gamma_{\alpha}$ (1958ME81).

The 5.11-MeV level was not observed by (1954JO09) who estimated $\omega\Gamma_{\rm s} < 0.02$ eV ($\Gamma_{\rm s} = \Gamma_{\alpha}\Gamma_{\gamma}/\Gamma_{\alpha} + \Gamma_{\gamma}$). According to (1957ME27), $\omega\Gamma_{\rm s} = 0.1$ eV. The angular distribution admits $J = 2^{+}$ and 4^{-} as possible assignments; $J = 3^{+}$ is possible but unlikely. The earlier suggested assignment $J = 2^{-}$ appears to be excluded. On the other hand, (1958ME81) observe that the angular distribution can be accounted for by $J = 2^{-}$ if E1 radiation is strongly inhibited, i.e. if $T = 0$. See ^{9}Be(d, n)^{10}B and ^{9}Be(p, γ)^{10}B.

Angular distributions of gamma radiation from the 5.16-MeV level admit $J = 1^{+}$ or 2^{+}; 1^{-} and 2^{-} are possible, but unlikely (1957ME27). Observation of a γ-decay in ^{9}Be(d, n)^{10}B strongly supports the suggestion that $\Gamma_{\alpha} \approx \Gamma_{\gamma}$ and that the reported width is largely experimental (1958ME81). In this case, the assignment $T = 1$ is indicated (1954JO09, 1959WA16). See also (1957KU58; theor.).

For the 5.92-MeV level, $J = 2^{\pm}$, 3^{+} and 4^{+} are possible. Only $J = 4^{+}$ gives a satisfactory account of the angular distribution from the 6.02-MeV level. The ratio E2/M1 $= 9.0$ (1957ME27).

2. (a) ^{6}Li(α, p)^{9}Be $\qquad Q_{\rm m} = -2.125 \qquad E_{\rm b} = 4.459$
   (b) ^{6}Li(α, d)^{8}Be $\qquad Q_{\rm m} = -1.565$

See (1956WA29).

Table 10.4: Energy levels of ^{10}B

E_x in ^{10}B (MeV)	$J^\pi; T$	Γ (keV) or τ_m	Decay	Reactions
0	3^+; 0	stable	–	4, 10, 13, 16, 17, 20, 21, 23
0.7174 ± 0.001	1^+; 0	$(9.6 \pm 0.6) \times 10^{-10}$ sec	γ	4, 5, 10, 11, 15, 16, 17, 18, 19, 23
1.739 ± 0.005	0^+; 1		γ	4, 5, 10, 11, 16, 19
2.152 ± 0.005	1^+; 0		γ	5, 10, 11, 15, 16, 17, 23
3.583 ± 0.005	2^+; 0		γ	5, 10, 16, 17
4.771 ± 0.005	(2^+); 0	< 10	α, γ	1, 10, 16
5.105 ± 0.007	$(2^-$; 0)	1.2	α, γ	1, 10, 16
5.159 ± 0.007	$(1^+$, 2^+; 1)	< 0.5	α, γ	1, 10, 16
(5.37 ± 0.04)				10
5.58 ± 0.04				10
5.92 ± 0.02	$(2^\pm$, 3^+, $4^+)$	12 ± 3	α, γ	1, 10
6.02 ± 0.01	4^+	< 1	α, γ	1, 10
6.16 ± 0.02		< 20		10
6.40 ± 0.03		< 100		10
6.57 ± 0.02		≈ 30		10
(6.77 ± 0.04)				10
6.88 ± 0.01	1^-; 0	145	p, γ, d, α	5, 7, 9
(7.01)			p, d	9
(7.20)			p, d, α	9
7.47	2^+	≈ 80	p	7
7.48 ± 0.01	2^-; 1	80 ± 3	p, γ, d, α	5, 7, (9)
7.56 ± 0.01	0^+; (1)	3.5 ± 0.5	p, γ	5, 7
7.78	2^-	≈ 360	p, (γ), d, α	5, 7, 9
(8.07)		≈ 350	p, d	9
(8.66)		≈ 220	p, d	9
8.89 ± 0.01	2^+; 1	36 ± 2	p, γ, α_2	5, 7, 9
8.89 ± 0.01	$(3^+$; 1)	84 ± 6	p, n	6, 7
9.7	; (1)	≈ 650	p, n, α_2	6, 9
10.7	$(^+$; 1)	≈ 450	p, γ, n, α_2	5, 6, 9

3. (a) ^{7}Li(^{3}He, p)^{9}Be $Q_{\rm m} = 11.200$ $E_{\rm b} = 17.784$
(b) ^{7}Li(^{3}He, d)^{8}Be $Q_{\rm m} = 11.759$
(c) ^{7}Li(^{3}He, α)^{6}Li $Q_{\rm m} = 13.325$

See ^{6}Li, ^{8}Be and ^{9}Be.

4. ^{7}Li(α, n)^{10}B $Q_{\rm m} = -2.793$
$Q_0 = -2.788 \pm 0.004$ (1957BI84: neutron threshold).

Thresholds for production of slow neutrons are observed at $E_\alpha = 4.379 \pm 0.006$ MeV (^{10}B(0)) and $E_\alpha = 5.51$ MeV (^{10}B*(0.71)) (1957BI84). Thresholds at $E_\alpha = 4.45$, 5.64, 6.49 and 7.15 MeV are reported by (1956RO06): ^{10}B*(0, 0.76, 1.30, 1.72). At $E_\alpha = 8.16$ MeV, neutron groups corresponding to ^{10}B*(0, 0.72, 1.32, 1.71) are reported. It is noted that the 1.3-MeV level is not observed in any other reaction (1956RO06). See also (1957NE1B).

5. ^{9}Be(p, γ)^{10}B $Q_{\rm m} = 6.585$

Observed resonances are listed in Table 10.6. An earlier reported resonance at 0.49 MeV is not confirmed (1955LO1A, 1956CL69). Cross sections from $E_{\rm p} = 30$ to 250 keV are reported by (1953SA1A: see (1957JA37)).

The $E_{\rm p} = 0.33$-MeV resonance (^{10}B*(6.89)) has been the object of considerable study. The proton width indicates s-wave formation (1956WI16); the isotropy of the radiation is consistent with this assignment (1955CA25, 1956CL69). Of the possibilities $J = 1^-$ or 2^-, the latter appears to be excluded by the strength of the transition to ^{10}B*(1.74, $J = 0^+$; $T = 1$) (1956WI16). The angular correlation in the cascade ^{10}B*($6.89 \rightarrow 0.7 \rightarrow$ g.s.) is consistent with $J = 1^-$(E1)1^+(E2)3^+ (1957BI75). The strong E1 transition to ^{10}B*(1.74) and the large deuteron width indicate $T = 0$ for the 6.89-MeV level. On the other hand, the transitions to ^{10}B*(0.7, 2.1) are nearly as strong, and would appear to require a $T = 1$ admixture of the order of 20%. Such a large admixture might be ascribed to a neighboring $J = 1^-$; $T = 1$ state of the same parentage (^{9}Be + s-wave proton) (see, however, (1957BA1J)). The strong M1 transition to ^{10}B*(5.11) and the absence of the E1 transition to ^{10}B*(5.16) present some difficulty (1956WI16). According to (1959ME1C) however, the observed transition is not to ^{10}B*(5.11) but rather to ^{10}B*(5.16); also this transition is not strongly resonant in this region. The 6.2, 5.2 and 4.7-MeV γ-rays all show the same resonance, excluding the possibility that two states may be involved. The ground-state transition shows only a monotonic rise, attributable partly to direct capture and partly to the tail of the 993-keV resonance (1958ED16). The angular correlation of 1.0 and 0.7-MeV γ-rays is consistent with $J = 1^+$ or 2^+ for ^{10}B*(0.7) (1955CA25).

For $E_{\rm p} = 380$ to 460 keV (thick target), a $2 - 4$ % anisotropy is observed in the high energy radiation ($E_\gamma > 3$ MeV). At $E_{\rm p} = 600$ keV, (thick target), the cascade ^{10}B*($6.9 \rightarrow 3.58 \rightarrow 0.7 \rightarrow$

Table 10.5: Levels of ^{10}B from ^{6}Li(α, γ)^{10}B (1957ME27)

$E_{\rm res}$ (keV)	$E_{\rm x}$ (MeV)	$\Gamma_{\rm lab}$ (keV)	E_{γ} [a] (MeV)	(%)	$\omega\Gamma_{\rm s}$ [b] (eV)	J^{π}
500 ± 25 [c]	4.759		4.76	8 [d]		2^+, (3^+)
			4.05	92	0.05 [e]	
1085	5.110	2 [f]	5.1	96	0.10	(2^+), (4^-), (2^-)
			4.4	4	0.005	
1175 [g]	5.164	< 0.8 [f]	5.16	7	0.04	1^+, 2^+
			4.44	29	0.15	
			3.01	64	0.32	
2435	5.920	20	5.9	100		$2^{\pm}$, 3^+, 4^+
2605	6.022	< 1.5 [f]	6.0	100		4^+

[a] Primary radiation: see Fig. 14.

[b] $\Gamma_{\rm s} \equiv \Gamma_{\alpha}\Gamma_{\gamma}/(\Gamma_{\alpha} + \Gamma_{\gamma})$.

[c] (1953WI32, 1954JO09).

[d] (1957ME27); (1957WA07) finds $< 3\%$.

[e] (1957WA07).

[f] S.S. Hanna, private communication: see (1958ME81).

[g] (1954JO09) give 1183 ± 5, $\omega\Gamma_{\rm s} \approx 1$ eV, $J = 2^+$; $T = 1$; (1953WI32) give branching fractions 5 : 25 : 70.

g.s.) is observed, with an intensity of 0.35 that of the $(6.9 \rightarrow 1.74)$ cascade. It is suggested that the intensity of this transition implies a strong $T = 1$ admixture in ^{10}B*(3.58) (1957BI75).

The broad resonance at 0.99 MeV ($E_{\rm x} = 7.48$ MeV) is also believed to be formed by s-waves. The angular distribution of the γ-radiation suggests dominant s-wave formation with some d-wave contribution (1949DE1A, 1953PA22); see, however, (1956MO90). The resonance is located at 993 ± 2 (1953HO1C: $\Gamma = 88 \pm 3$ keV), 989.5 ± 1.4 keV (1956HU1B: $\Gamma = 91 \pm 5$ keV). Assuming $J = 2$, $\Gamma_{\gamma} = 23$ eV (1953HO1C). The strength of the transition to the ground state indicates E1, $T = 1$ (1953WI1B): again, as in the 6.89-MeV level, a considerable contamination is required, since ^{9}Be(p, d)^{8}Be and ^{9}Be(p, α)^{6}Li are also resonant. Study of the angular correlation of internal conversion pairs indicates about equal contributions of E1 and E3 or M2 transitions (1954DE1D). It is suggested by (1956MO90) that the observed transitions actually arise from two levels at 980 keV, ($J = 2^+$) and 993 keV, with ($J = 2^-$): see ^{9}Be(p, p)^{9}Be.

The narrow 7.56-MeV level [$E_{\rm p} = 1085 \pm 2$ keV (1953HO1C), 1083.7 ± 0.7 keV, $\Gamma = 3.8 \pm 0.5$ keV (1956HU1B)] decays mainly to the 0.7-MeV state (1953HO1C: $\Gamma_{\gamma} = 6.0$ eV assuming $J = 0$). The angular distributions of these γ-rays and the subsequent 0.7-MeV γ-rays are isotropic, consistent with $J = 0$ (1953PA22). From $E_{\rm p} = 1.1$ MeV to the neutron threshold at 2.06 MeV, no further structure is observed except a possible broad level tailing off from 1.15 to 1.55 MeV (1955KI1B): see ^{9}Be(p, d)^{8}Be and ^{9}Be(p, p)^{9}Be.

The excitation curve for $E_\gamma > 6$ MeV shows a pronounced resonance at $E_{\rm p} = 2.567 \pm 0.003$ MeV, and another, ≈ 0.5 MeV wide, superimposed on a general rise, at $E_{\rm p} = 4.72 \pm 0.01$ MeV. At the 2.6-MeV resonance, the capture radiation appears to proceed predominantly to the 0.7-MeV state (1953MA1A). It would appear from the width that this resonance corresponds to the ^{9}Be(p, $\alpha\gamma$)^{6}Li resonance, $J = 2^+$, and not to the ^{9}Be(p, n)^{9}B resonance, $J = 3^+$, at the same energy (see (1956MA55)).

6. ^{9}Be(p, n)^{9}B $\qquad Q_{\rm m} = -1.854 \qquad E_{\rm b} = 6.585$

Resonances in the neutron yield occur at $E_{\rm p} = 2.56$, 4.70 and (4.90) MeV (1952HA10, 1955MA84, 1956MA55, 1959GI47, 1959MA20); see (1957JA37) and Table 10.6. A broad maximum ($\theta = 90°$) near $E_{\rm p} = 3.5$ MeV suggests an additional ^{10}B state at 9.7 MeV with $\Gamma \approx 0.7$ MeV (1956MA55, 1959MA20). Angular distributions are nearly isotropic near $E_{\rm p} = 2.56$ MeV but show marked structure at higher energies (1956MA55). The excitation function for ground-state neutrons ($\rm n_0$) does not show the resonance at 4.9 MeV. If this peak represents neutrons leading to ^{9}B*(2.3), it may arise from the tail of the $E_{\rm p} = 3.5$-MeV resonance rather than from a new level. A continuous distribution of neutrons, observed for $E_{\rm p} > 4.5$ MeV, is attributed to excitation of ^{9}Be*(2.4) followed by breakup via ^{8}Be*(2.9) (1959MA20).

Table 10.6: Resonances in ^{9}Be + p [r]

$E_{\rm p}$ (keV)	$E_{\rm x}$ (MeV)	$\Gamma_{\rm lab}$ (keV)	$l_{\rm p}$	Product [a]	E_γ (MeV)	Final State	Γ_γ (eV)	$J^\pi; T$
330 [b]	6.88	160	0	γ, α, d, p	(6.9)	g.s.	0 [d]	$1^-; 0$
					6.2	0.7	1.0	
					5.2	1.7	2.6	
					4.7	2.1	0.52	
					(1.7)	(5.1)	(0.61) [o]	
(470) [e]	(7.01)			d, p				
(680) [e]	(7.20)			α, d, p				
980 ± 10 [f]	7.467	90	1	p				$2^+;$
991 ± 1.4 [g]	7.477	89 ± 3 [g]	0	γ, α, d, p	7.5	g.s.	23 [i]	$2^-; 1$
					(6.8)	0.7	≤ 1.7	
					(5.8)	1.7	≤ 0.4	

Table 10.6: Resonances in $^{9}\mathrm{Be} + \mathrm{p}$ [r] (continued)

$E_{\rm p}$ (keV)	$E_{\rm x}$ (MeV)	$\Gamma_{\rm lab}$ (keV)	$l_{\rm p}$	Product [a]	E_{γ} (MeV)	Final State	Γ_{γ} (eV)	$J^{\pi}; T$
					(5.4)	2.1	≤ 0.7	
1083.7 ± 0.7 [j]	7.561	3.8 ± 0.5	1 [h]	γ, p	6.9	0.7	6.0 [i]	0^{+}; (1) [h,p]
					5.4	2.1	≤ 0.3	
					(2.5)	5.1	≈ 0.9 [s]	
1330 [k]	7.78	≈ 400 [h]	0	p, (γ), d, α				2^{-};
1650 [q]	8.07	≈ 400		p, d				
2300 [q]	8.66	≈ 250		p, d				
2567 ± 3 [j]	8.895	40 ± 2	1	p, α_2, γ	(8.1) [l]	0.7		2^{+}; 1
				(α_0n)				
2567 ± 3	8.895	93 ± 7 [n]	(1)	p, n				(3^{+}; 1) [a]
(3500) [n]	9.7	≈ 700		p, n, α_2				(; 1)
4600 [n]	10.7	≈ 500		p, n, γ, α_2				($^{+}$; 1)

$E_{\rm p}$ (keV)	$\frac{\Gamma_{\rm p}\ (\mathrm{keV})}{\theta^2_{\rm p}}$	$\frac{\Gamma_{\rm d}\ (\mathrm{keV})}{\theta^2_{\rm d}}$	$\frac{\Gamma_{\alpha}\ (\mathrm{keV})}{\theta^2_{\alpha}}$	$\frac{\Gamma_{\alpha_2}\ (\mathrm{keV})\ [a]}{\theta^2_{\alpha_2}}$	$\frac{\Gamma_{\rm n}\ (\mathrm{keV})}{\theta^2_{\rm n}}$
330 [b]	$\frac{25\ [c]}{0.15}$	$\frac{59}{0.12}$	$\frac{57}{0.013}$	0	0
(470) [e]				0	0
(680) [e]				0	0
980 ± 10 [f]	$\frac{80\ [h]}{0.07}$	$\frac{\leq 10\ [r]}{\leq 0.02}$	$\frac{\leq 10\ [r]}{< 0.005}$	0	0
991 ± 1.4 [g]	$\frac{60\ [h]}{0.06}$	$\frac{\approx 15\ [r]}{0.008}$	$\frac{\approx 15\ [r]}{0.004}$	0	0
1083.7 ± 0.7 [j]	3.8 [h]			0	0
1330 [k]	$\frac{260\ [h]}{0.15}$	$\frac{\leq 70\ [r]}{\leq 0.03}$	$\frac{\leq 70\ [r]}{\leq 0.016}$	0	0
1650 [q]					
2300 [q]					
2567 ± 3 [j]	$\frac{[16]\ [l]}{0.0016}$	$\frac{< 13.5\ [m]}{< 5 \times 10^{-3}}$	$\frac{0.08 - 4.0\ [m]}{10^{-5} - 10^{-3}}$	$\frac{[20]\ [l]}{0.33}$	$\frac{[4]\ [l]}{0.0016}$
2567 ± 3	$\frac{}{0.013}$			(0)	$\frac{}{0.013}$
(3500) [n]					
4600 [n]					

[a] "α_2" to ^{6}Li*(3.58), $J = 0^+$; $T = 1$.

[b] Removal of s-wave penetration factor gives $E_{\rm res} = 307$ keV, $\Gamma = 160$ keV (1955LO1A).

[c] (1956WI16). (1956MO90) finds 48/0.5, 47/0.4, 62/0.05 with a factor of 2 uncertainty.

[d] (1956CL69). (1955CA25) report relative intensities 15 : 40 : 100 : 45 for the first four and $\Gamma_\gamma = 5$ eV for the 5.1-MeV radiation; however, the ground-state transition appears to be non-resonant (1955LO1A, 1956CL69, 1958ED16). See also (1957BI75).

[e] (1949TH05, 1951NE03)

[f] (1956DE33, 1956MO90).

[g] (1953HO1C, HU55).

[h] (1956MO90).

[i] (1953HO1C).

[j] (1952HA10, 1956HU1B).

[k] (1955KI1B, 1956MO90, 1956WE37).

[l] (1953MA1A, 1954MA26).

[m] (1956WE37): based on $\Gamma_{\rm p} = 7$ keV.

[n] (1956MA55, 1959GI47, 1959MA20).

[o] (1959ME1C) find that this transition peoceeds to the 5.16-MeV level, and is mainly non-resonant.

[p] (1959WA16).

[q] (1956WE37): see (1958ME81).

[r] See a similar table in (1958ME81).

[s] Meyerhof and Tanner (1959ME1C) find this transition is resonant and proceeds mainly to ^{10}B*(5.16). The large width suggests E1 or M1 radiation.

The 2.56-MeV resonance is believed to be distinct from the resonance observed at the same energy in ^{9}Be(p, $\alpha\gamma$)^{6}Li, because of its greater width (93 keV vs. 38 keV). Estimates of the reduced proton and neutron widths agree well with the known parameters of the 7.37 MeV, $J = 3^+$; $T = 1$ state of ^{10}Be. Assignment of $J = 3^+$ to the ^{10}B state accounts for the absence of ^{9}Be (p, $\alpha\gamma$)^{6}Li γ-rays at this resonance (1956MA55). See also (1957ST1D, 1958MA1F, 1958TA03).

7. ^{9}Be(p, p)^{9}Be $\qquad E_{\rm b} = 6.585$

For $E_{\rm p} = 0.22$ to 0.78 MeV, the elastic scattering is adequately described by s-wave formation of a broad level at $E_{\rm p} = 330$ keV, $J = 1^-$ or 2^-. For $J = 1^-$, $\Gamma_{\rm p}/\Gamma = 0.30$ (1956MO90).

In the range $E_{\rm p} = 0.8$ to 1.6 MeV, attempts to fit the scattering data with s-waves are only moderately successful. That the major contribution at the 980-keV state is s-wave is indicated by the existence of interference minima at all angles near $E_{\rm p} = 1$ MeV. Inclusion of d-waves, $J = 2^-$, does not improve the fit. The best account of the behavior of the cross section in this region is obtained with the assumption of two s-wave resonances, $J = 2^-$, at $E_{\rm res} = 998$ and 1330 keV, $\Gamma_{\rm p}/\Gamma = 0.65 \pm 0.15$, $\Gamma(998) = 150 \pm 50$ keV, $\Gamma(1330) = 400 \pm 100$ keV, $\theta^2_{\rm p} \approx 0.006$ and 0.15, respectively, superposed on a p-wave, $J = 2^+$ resonance at 980 keV (see below). There is also some hint of a higher s-wave, $J = 1^-$, resonance (1956MO90). (1956DE33) also finds that the $E_{\rm p} = 998$ keV level is formed by s-waves, with $\Gamma = 90$ keV, $\Gamma_{\rm p}/\Gamma = 0.7$. The scattering near 1.1 MeV requires a broad p-wave resonance at 1.1 MeV, $\Gamma = 200$ keV, $\Gamma_{\rm p}/\Gamma$ small (1956DE33).

At the 1084-keV resonance (^{10}B*(7.56)), the smallness of the scattering anomaly indicates $J = 0$. Absence of interference at $\theta = 90°$ suggests $l = 1$, hence $J = 0^+$. A satisfactory fit is obtained with the inclusion of a p-wave, 2^+, state in the background. The 2^+ state appears to be formed with channel spin 1, $\Gamma_{\rm p}/\Gamma \approx 0.9$ and to be located within a few hundred keV below 1084 keV. A fit to the data near 1 MeV gives $E_{\rm res} = 980 \pm 10$ keV, $\Gamma = 90$ keV, $\theta^2_{\rm p} \approx 0.07$ (1956MO90). A scattering anomaly has also been observed at $E_{\rm p} \approx 2.56$ MeV. This anomaly increases in the backward direction indicating p-wave formation of a level at 8.89 MeV with $J \geq 2$, $\Gamma_{\rm p}$ large (1956DE33).

Recent work on differential cross sections has been done in the range $E_{\rm p} = 5.4$ to 31.5 MeV by (1952BR52, 1953WRZZ, 1956DA03, 1956KI54, 1956KL55, 1956RA32). See also (1955GR12, 1955HI1B, 1958BR24) and ^{9}Be.

8. ^{9}Be(p, t)^{7}Be $\qquad Q_{\rm m} = -12.081 \qquad E_{\rm b} = 6.585$

See (1954CO02).

9. (a) ^{9}Be(p, d)^{8}Be $\qquad Q_{\rm m} = 0.560 \qquad E_{\rm b} = 6.585$
(b) ^{9}Be(p, α)^{6}Li $\qquad Q_{\rm m} = 2.125$

Excitation functions and angular distributions have been studied for $E_{\rm p} = 0.3$ to 1.3 MeV by (1949TH05, 1951NE03, 1956MO90) and for $E_{\rm p} = 0.8$ to 3.0 MeV by (1956WE37). Observed resonances are listed in Table 10.6. Angular distributions at the 330-keV resonance are isotropic, consistent with s-wave formation (1956MO90). Proton and deuteron reduced widths for this resonance are evidently quite large, while the α-width is some 10 times smaller (1956MO90, 1956WI16). For $E_{\rm p} > 500$ keV, the distributions show strong interference terms, implying contributions from states of both parities (1951NE03, 1956WE37). It is noted by (1956MO90) that the states appearing in ^{9}Be(p, p)^{9}Be are not sufficient to account for this interference, and an additional p-wave state near $E_{\rm p} \approx 700$ keV offers a plausible solution; see also (1958ME81). Above $E_{\rm p} = 1.8$ MeV, pronounced pickup is evident in the (p, d) reaction (1956WE37).

A pronounced maximum occurs in the integrated cross section for both reactions at $E_{\rm p} = 930$ keV, $\Gamma = 130 \pm 30$ keV, presumably due to the $J = 2^-$; $T = 1$ resonance seen in ^{9}Be(p, γ)^{10}B and ^{9}Be(p, p)^{9}Be at $E_{\rm p} = 991$ keV. The reason for the energy shift is not clear. An appreciable $T = 0$ contamination is required; this may be due to the 1330-keV, $J = 2^-$, resonance which appears in the (p, d), (p, α), (p, p) and possibly (p, γ) yields (1956WE37).

The 7.56-MeV state is not resonant for (p, α) or (p, d); this observation is consistent with its $J = 0^+$ character. Broad, weak maxima occur in the total (p, d) cross section at $E_{\rm p} = 1.25$, 1.64 and 2.3 MeV; the 90° (p, α) cross section shows maxima at $E_{\rm p} = 1.25$, and ≈ 2.0 MeV with a small anomaly at $E_{\rm p} = 2.56$ MeV, $\Gamma = 40 \pm 10$ keV. The $E_{\rm p} = 1.25$-MeV structure is probably associated with the $E_{\rm p} = 1.33$-MeV resonance in ^{9}Be(p, p)^{9}Be, while the 2.56-MeV anomaly is clearly connected with the strong resonance at that energy seen in ^{9}Be(p, $\alpha\gamma$)^{6}Li ($J = 2^+$; $T = 1$). An upper limit to the deuteron width at this resonance is $\Gamma_{\rm d} = 13.5$ keV, $\theta^2 = 4.5 \times 10^{-3}$. For α_0 particles, $0.08 < \Gamma_\alpha < 4.0$ keV, $2.2 \times 10^{-5} < \theta^2_\alpha < 1.1 \times 10^{-3}$ (1956WE37). For the (p, $\alpha_2\gamma$) reaction, the resonance occurs at 2.562 ± 0.006 MeV, $\Gamma = 38 \pm 3$ keV, $\theta^2_{\rm n} + \theta^2_{\rm p} = 0.0032$ (1954MA1C, 1956MA55: $\Gamma = 41 \pm 2$ keV). From the fact that this state (^{10}B*(8.89)) decays primarily to the $J = 0^+$; $T = 1$ state of ^{6}Li (3.58 MeV) it is concluded that it has $T = 1$ (1954MA1C, 1954MA26). The observed cross section requires $J \geq 2$, while the width requires $J \leq 2$. For $J = 2$, $\theta^2_{\alpha_2} = 0.19$ or 0.33, $\theta^2_{\rm n} = 0.0016$ (1954MA26). This resonance is presumed to be distinct from the ^{9}Be(p, n)^{9}B resonance which occurs at the same energy (1956MA55). A further resonance for ^{6}Li*(3.6) γ-rays appears at $E_{\rm p} = 4.49$ MeV, and a broad rise near $E_{\rm p} = 3.5$ MeV, observed in ^{9}Be(p, n)^{9}B, seem also to be found here. It is suggested that these states have $T = 1$ and correspond to ^{10}Be*(9.27) and ^{10}Be*(9.4) (1959MA20).

10. ^{9}Be(d, n)^{10}B $\qquad Q_{\rm m} = 4.358$

Neutron groups are observed corresponding to ^{10}B states listed in Table 10.7: see (1951AJ1A, 1952PR1A, 1953PR1A, 1955GE1B, 1955GR1D, 1957MU1D, 1957NE1C, 1957SH65, 1958GE04, 1958NE38). Thresholds for slow neutron production corresponding to ^{10}B states from 4.77 to 6.57 MeV are reported by (1954BO79). Indications of a state at 2.8 MeV are reported by (1953DY1A, 1954RE1A, 1958GE04). Angular distributions to the low states have been studied at many energies from $E_{\rm d} = 0.5$ to 3.4 MeV: see (1952AJ22, 1952PR1A, 1953PR1A, 1955GE1B, 1955GR1D, 1957NE1C, 1957SH65). The data show evidence both for stripping and compound nucleus formation with more evidence of the former in the higher energy work: the ground state and the first four excited states have $J \leq 3$ and even parity, and one or both of the 5.1-MeV levels have $J = 1^-$ or 2^- (1952AJ22). It is of interest that the 3.6-MeV state shows a well developed stripping pattern even at the lowest bombarding energies. According to (1958SA17, 1959NE1A), however, the character changes drastically at $E_{\rm d} = 1.5$ to 2 MeV, suggesting some contribution of “heavy particle” stripping. The group leading to the 0.72-MeV state also shows this effect. See also (1956MA1N; theor.). Absolute reduced widths for several levels have been estimated by (1958ME81) using published cross section data: see Table 10.7.

The mean lifetime of the 0.72-MeV state is $(7 \pm 2) \times 10^{-10}$ sec (1953TH14), $(8.5 \pm 2.0) \times 10^{-10}$ sec (1956SE08), $(11.8 \pm 3.3) \times 10^{-10}$ sec (1958GO47, 1958KN1B), $(9.6 \pm 1.0) \times 10^{-10}$ sec (1958DA11); compare with ^{10}B(p, p$'$)^{10}B*. The γ-ray energy is 716.6 ± 1 keV (1949RA02). The 1.74-MeV state ($J = 0^+$; $T = 1$) decays via the 0.7-MeV state: $E_\gamma = 1022 \pm 2$ keV (1949RA02). The ground-state transition is $< 10\%$ (1951AL1B). See also (1954SH1A).

The 2.1-MeV state decays directly to the ground state and via cascades through the 0.72 and 1.74-MeV levels; $E_\gamma = 2151 \pm 16$, 1433 ± 5, 413.5 ± 1 keV; the intensities are in ratio 1.2 : 2.5 : 1.2 (1949RA02). The relative contribution of the 1400-keV γ-ray is uncertain since this radiation also arises from the transition $3.58 \rightarrow 2.1$ (1954SH1A). The relative strength of the low energy,

Table 10.7: Levels of ^{10}B from ^{9}Be(d, n)^{10}B [a], ^{10}B(p, p′)^{10}B* [h] and ^{10}B(d, d′)^{10}B* [h]

^{10}B* (MeV)	l_p [a]	J^π	θ^2_p [a] (%)	Γ_γ (eV) to final state at E_x [d]			
				0	0.7	1.7	2.1
0	1	3^+	≈ 1.7				
0.717 [h]	1	1^+	≈ 3.5	[10^{-4}] [e]			
1.739	1	0^+	≈ 2.5	$< 7\%$ [f]	100%		
2.152	1	1^+		30% [g]	[40%]	30%	
3.583	1	2^+	≈ 0.7	20% [g]	60%	0	(20%)
4.771 [c]	(1)	2^+	≈ 0.3	(0.005) [d]	(0.055)		
5.105 [b,c]	(0)	(2^-)	≈ 1.3	0.06 [d]	0.003		≤ 0.012
5.159 [b,c]	(1)	(2^+)	(0.5)	(0.04) [d]	(0.18)		(0.39)
(5.37)							
5.58							
(5.72)							
5.93 [c]	(1)	(3^+)	≈ 0.5	100%			
6.06 [b,c]		4^+		100%			
6.16 [b,c]							
6.43 [c]							
6.57 [c]							
(6.77)							

[a] (1952AJ22, 1958ME81).

[b] Not resolved in neutron groups.

[c] Observed as slow neutron thresholds (1954BO79).

[d] (1958ME81): see also Table 10.5 (^{6}Li(α, γ)^{10}B).

[e] (1953TH14, 1956SE08).

[f] (1957MC35).

[g] (1949RA02, 1954SH1A, 1957MC35).

[h] Energies of first seven excited states are from (1953BO70, 1953BR1A); probable errors are ±5 keV for first five, and ±7 keV for the 5.11 and 5.16-MeV states. For more precise values for the 0.7-MeV state, see text under reaction 10 in ^{10}B.

$2.1 \rightarrow 1.7$ MeV, transition is attributed to a strong inhibition of the M1, $\Delta T = 0$ transition from ^{10}B*(2.1 to 0.7) (1958MO17: see also (1957KU58)). For the 3.58-MeV level. the ground state transition is about $\frac{1}{3}$ as intense as that to the 0.7-MeV state (1949RA1B: see also (1957MC35, 1958CH1A)). The transition $(3.58 \rightarrow 2.1)$ also occurs (1954SH1A). The angular correlation $(2.86 \rightarrow 0.7)$ is consistent with $J = 1^+$ or 2^+ for the 3.6-MeV level; $J = 0$, 3 are excluded. For $J = 2^+$, acceptable schemes are 2 (0.93 M1 $+ 0.07$ E2)1(E2)3 or 2(E2)1(E2)3 (1956SH94). A spin 1^+ assignment would permit a strong M1 transition to the $J = 0^+$; $T = 0$ state at 1.74 MeV (1958MO17).

The fact that gamma radiation is observed in competition with α-decay from the 4.77 and 5.16-MeV levels suggests that $\Gamma_\gamma \approx \Gamma_\alpha$ for these two states. No radiation is observed from the 5.11, 5.93, or 6.06-MeV levels in ^{9}Be(d, n)^{10}B (1958ME81: see also (1959NE1A)). No gamma rays of energy 6.5 to 8.0 MeV are observed with intensity $>$ 5% of the 6.0-MeV, ^{10}Be radiation (1955BE81: $E_\mathrm{d} = 3.85$ MeV). The ratio of $5.16 \rightarrow$ g.s. to $5.16 \rightarrow 0.7$ radiation is $1 : 2$ (1955BE81: see, however, (1957MC35)).

At $E_\mathrm{d} = 9$ MeV, the ratio of the maximum differential cross sections of the ^{9}Be(d, p)^{10}Be and ^{9}Be(d, n)^{10}B reactions to the first $T = 1$ states leads to a ratio of reduced widths of 2.16 (calculated from stripping theory; predicted value from charge independence: 2) (1956CA1D). See also (1956BA1F, 1956BO1F, 1956BO43, 1956DE1D, 1956GO1H, 1957GR1A, 1958BE03).

11. ^{9}Be(^{3}He, d)^{10}B $\quad Q_\mathrm{m} = 1.091$

At $E(^3\mathrm{He}) = 2.1$ MeV, gamma-rays from the 0.72-MeV state have been observed (1957FE1B). At $E(^3\mathrm{He}) = 5.7$ MeV, deuteron groups are observed to the ground state of ^{10}B and to levels at 0.724 ± 0.010, 1.751 ± 0.010, and 2.163 ± 0.010 MeV (S. Hinds and R. Middleton, private communication). The angular distributions follow quite closely the $l_\mathrm{p} = 1$ stripping patterns.

12. ^{9}Be(α, t)^{10}B $\quad Q_\mathrm{m} = -13.228$

Not reported.

13. ^{10}Be(β^-)^{10}B $\quad Q_\mathrm{m} = 0.556$

See ^{10}Be.

14. (a) ^{10}B(γ, d)^{4}He + ^{4}He $\quad Q_\mathrm{m} = -5.930$
(b) ^{10}B(γ, α)^{6}Li $\quad Q_\mathrm{m} = -4.459$
(c) ^{10}B(γ, np)^{4}He + ^{4}He $\quad Q_\mathrm{m} = -8.157$
(d) ^{10}B(γ, p)^{9}Be $\quad Q_\mathrm{m} = -6.585$

In the range $E_\gamma = 10$ to 30 MeV, reaction (a) proceeds almost entirely through excited states of ^{8}Be: transitions via $(\alpha + \mathrm{d})$-emitting states of ^{6}Li apparently do not occur. Reaction (b) is said to proceed via the ground state and γ-emitting states of ^{6}Li at 1.1 and 2.2 MeV (1953ER1A) (there is no evidence for a state at 1.1 MeV in any other reaction: see (1952AJ38) and (1955AJ61)). For reaction (d) see (1956GO1F, 1956GO1G, 1957BA1H).

15. ^{10}B(n, n′)^{10}B*

At $E_\mathrm{n} = 2.56$ MeV, a 717 ± 7 keV γ-ray is observed (1956DA23).

16. ^{10}B(p, p′)^{10}B*

The first seven excited states have been accurately located by inelastic scattering: see Table 10.7 (1953BO70, 1953BR1A). The energy of the first state is given as 717 ± 5 keV (1953BO70), 719 ± 1.6 keV (1952CR30) and 718 ± 5 keV (1954DA20: γ-radiation). The mean life of this state is $(10.5 \pm 1.0) \times 10^{-10}$ sec (1957BL02), $(9.0 \pm 1) \times 10^{-10}$ sec (1958HO97). This lifetime is about a factor of 10 shorted than that calculated on the shell model with reasonable values of the radius and intermediate coupling parameter (1957BL02: see, however, (1957FR1B, 1957KU58); see also ^{9}Be(d, n)^{10}B).

At $E_\mathrm{p} > 3$ MeV, gamma rays of energy 710 ± 15, 1023 ± 5, 1438 ± 5, and 2120 ± 60 keV are observed (1957HU79, 1957MC35). An upper limit of 7% is found for direct transitions from ^{10}B*(1.74 $\rightarrow$ g.s.) (1957MC35). At $E_\mathrm{p} > 4.5$ MeV, additional radiations at 2860 ± 10 and 3560 ± 50 keV (Doppler corrected) are observed, with intensity ratio 2.9. Shell model calculations would predict a ratio of 0.67 to 0.5 (1957MC35: see also (1957KU58)).

17. ^{10}B(d, d′)^{10}B*

Deuteron groups corresponding to the ground state and to states at 0.7, 2.1, and 3.6 MeV are reported by (1953BO70): see Table 10.7. The absence of deuteron groups corresponding to the 1.74-MeV state is strong evidence of its $T = 1$ character.

18. ^{10}B(α, α')^{10}B*

See (1956BO25).

19. ^{10}C(β^+)^{10}B $\qquad Q_\mathrm{m} = 3.78$

The half-life is 19.1 ± 0.8 sec (1949SH25); E_{β^+}(max) $= 2.2 \pm 0.1$ MeV. The β^+-decay is to the first two excited states of ^{10}B: relative transition probabilities to the 0.72-, 1.74- and 2.15-MeV levels are $98.4/1.65 \pm 2/< 0.1$ (1953SH38): $\log ft$ using E_β(max) $= 2.04$ and 1.02 MeV (from $Q_{\rm m}$ above) are 3.2 and 3.7. The gamma decay of the first two excited states of ^{10}B is observed: $E_\gamma = 723 \pm 15$ and 1033 ± 30 keV (1953SH38). See also (1953KO1B), (1957FR1B) and (1958GE33).

20. ^{11}B(γ, n)^{10}B $\quad Q_{\rm m} = -11.464$

See (1951SH63).

21. ^{11}B(p, d)^{10}B $\quad Q_{\rm m} = -9.237$

At $E_{\rm p} = 18.9$ MeV, the ground state deuteron angular distributions indicate $l_{\rm n} = 1$ (1956RE04).

22. (a) ^{11}B(d, t)^{10}B $\quad Q_{\rm m} = -5.205$
(b) ^{11}B(^{3}He, α)^{10}B $\quad Q_{\rm m} = 9.114$
(c) ^{12}C(n, t)^{10}B $\quad Q_{\rm m} = -18.937$
(c) ^{12}C(p, ^{3}He)^{10}B $\quad Q_{\rm m} = -19.702$

These reactions have not been reported.

23. ^{12}C(d, α)^{10}B $\quad Q_{\rm m} = -1.351$
$Q_0 = -1.39 \pm 0.02$ (1957EL12).

At $E_{\rm d} = 8.9$ MeV, α-groups have been observed corresponding to the ground state of ^{10}B and to excited states at 0.72 ± 0.02 and 2.14 ± 0.02 MeV. No α-group was observed to the $T = 1$, 1.74-MeV state (1957EL12). See also (1951AS1A) and (1953SP1A).

24. ^{13}C(p, α)^{10}B $\quad Q_{\rm m} = -4.070$

Not reported.

Table 10.8: Energy levels of ^{10}C

$E_{\rm x}$ in ^{10}C (MeV)	J^{π}	Γ or $\tau_{1/2}$	Decay	Reactions
0	(0^+)	19.1 ± 0.8 sec	β^+	1, 2
3.34 ± 0.2				2
(5.1)		broad or unresolved		2

25. ^{14}N(γ, α)^{10}B $\qquad Q_{\rm m} = -11.615$

See (1953MI31), (1955RA1E) and (1956LI05).

Arguments supporting the J^{π} assignments for the first five excited states of ^{10}B are presented in reaction 20 in ^{10}B in (1955AJ61). The assignment of the 4.77-MeV state now appears to be $J = 2^+$ (see ^{6}Li(α, γ)^{10}B).

^{10}C

(Fig. 15)

Mass of ^{10}*C*: The mass difference ^{10}C-^{10}B is given as 3.84 ± 0.1 MeV from β-end-point measurements (1953SH38), and as 3.57 ± 0.2 MeV (1954AJ32) from the ^{10}B(p, n)^{10}C Q-value. The weighted mean of these two results yields a mass excess for ^{10}C of 18.79 ± 0.09 MeV, using the Wapstra (1955WA1A) value for the mass of ^{10}B.

1. ^{10}C(β^+)^{10}B $\qquad Q_{\rm m} = 3.78$

The decay is complex. See ^{10}B.

2. ^{10}B(p, n)^{10}C $\qquad Q_{\rm m} = -4.56$

At $E_{\rm p} = 17.2$ MeV, neutron groups are observed corresponding to the ground state ($Q_0 = -4.35 \pm 0.2$ MeV), to an excited state at 3.34 ± 0.2 MeV, and possibly to wide or unresolved levels at $E_{\rm x} \approx 5.1$ MeV (1954AJ32). The slow neutron threshold for the ground state of ^{10}C has not been observed up to $E_{\rm p} = 6$ MeV in preliminary measurements by (1955BA22). The neutron threshold measurement reported in (1955AJ61) has been withdrawn: (T.W. Bonner, private communication).

Two other reactions leading to ^{10}C have not been observed: ^{10}B(^{3}He, t)^{10}C ($Q_{\rm m} = -3.80$) and ^{12}C(p, t)^{10}C ($Q_{\rm m} = -23.50$).

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(Closed December 01, 1958)

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