

Energy Levels of Light Nuclei $A = 8$

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Abstract: An evaluation of $A = 5-24$ was published in *Nuclear Physics* 11 (1959), p. 1. This version of $A = 8$ 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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⁸Li
(Fig. 7)

GENERAL:

Theory: See (1955LA1D, 1956KU1A, 1957FR1B, 1957KU1B).

1. ⁸Li(β^-)⁸Be $Q_m = 16.001$

The weighted mean of half-lives reported in (1955AJ61) is 0.848 ± 0.004 sec. A value of 0.873 ± 0.013 sec is given by (1958VE20). See also (1958IM1A). The decay is complex: see ⁸Be.

2. ⁶Li(t, p)⁸Li $Q_m = 0.803$
 $Q_0 = 0.790 \pm 0.011$ (1954AL35).

The ground state reaction has been observed by (1952MO19, 1952PE02, 1954AL35, 1955CU1A). (1955CU1A) also reports one event corresponding to the transition to an excited state at 0.7 ± 0.2 MeV.

3. ⁷Li(n, γ)⁸Li $Q_m = 2.035$

The thermal capture cross section is 33 ± 5 mb (1947HU06), 42 ± 10 mb (1956KO1C). At $E_n = 275$ keV, neutron capture is not observed: $\sigma < 0.25$ mb (1956KO1C). Polarization of ⁸Li produced by polarized thermal neutrons has been detected by (1957BU44). See also (1957KU1B, 1958IM1A, 1958SH1A).

4. ⁷Li(n, n)⁷Li $E_b = 2.035$

Cross sections for Li metal and for ⁷Li are reported in (1958HU18: see also (1956GO62, 1957KA1B, 1958BR16)). The thermal cross section is 1.07 ± 0.04 b (C. Hibdon: see (1955HU1B, 1956TH06)).

A pronounced resonance occurs at $E_n = 258$ keV (see Table 8.2). Total cross sections and angular distributions establish that the state has $J = 3^+$, formed by p-waves (1956WI04). A further, broad peak centering at $E_n \approx 5$ MeV may indicate a broad level of ⁸Li at ≈ 6.5 MeV (1958HU18: see also (1956GO62)).

Table 8.1: Energy levels of ${}^8\text{Li}$

E_x in ${}^8\text{Li}$ (MeV)	J^π	$\tau_{1/2}$ or Γ (keV)	Decay	Reactions
0	2^+	$\tau_{1/2} = 0.848 \pm 0.004$ sec	β^-	1, 2, 3, 9, 12, 14, 18
0.975 ± 0.012	$\leq 3^+$		(γ)	2, 9, 18
2.260 ± 0.005	3^+	28	n	4, 9
3.22	$1^{(+)}$	≈ 1000	n	5

Table 8.2: ${}^7\text{Li}(n, n){}^7\text{Li}$ resonance parameters ^a

	(1956WI04)	(1956TH06, 1958HU18)
E_{res} (keV)	256	258 ± 3 ^b
Γ (keV)	32	32 ^c
$\Gamma_n(E_r)$ (keV)	35.8	
γ_n^2 (keV)	351	307
E_λ (keV)	-49	-43
radius (10^{-13} cm)	4.08	4.0
σ_{max} (b)		12.0

^a Energies in the laboratory system.

^b $E_{\text{res}} = 275$ keV, $\sigma_{\text{max}} = 7.0 \pm 0.2$ b (1956GO62).

^c 35 ± 5 keV (1958HU18).

Data on coherent scattering and total cross section for zero-energy neutrons permit two solutions for the two s-wave scattering lengths corresponding to anti-parallel ($J = 1^-$) and parallel ($J = 2^-$) interactions; for the first solution, the interaction is essentially pure $J = 1^-$, for the other, pure $J = 2^-$. Measurement of the interference between the s-wave background and the p-wave (channel spin 2) resonance indicate that the second solution is the correct one, and it is concluded that the splitting between parallel and anti-parallel interactions is about 1.5 MeV (1956TH06). (1956WI04) find, on the other hand, that the observed asymmetries in the angular distributions indicate a nearly statistical ($\frac{5}{3}$) mixture of $J = 1^-$ and 2^- background. Use of scattering in ${}^7\text{Li}$ as a polarization analyzer is discussed by (1956WI1E).

See also (1956BE1D, 1957KH1A).

5. ${}^7\text{Li}(n, n'){}^7\text{Li}^*$

$$E_b = 2.035$$

The excitation function for 0.48-MeV γ -rays shows an abrupt rise from threshold (indicating s-wave formation and emission) and a broad maximum ($\Gamma \approx 1$ MeV) at $E_n = 1.35$ MeV. The rise above threshold indicates the existence of a $J = 1^-$ level, which may be identified with the 1.35-MeV resonance (if a strong d-wave contribution is included). On the other hand, the latter resonance appears to be better described as a $J = 1^+$ level, formed by p-waves. Under this assumption, $E_r(\text{lab}) = 1.45$ MeV, $\Gamma = 1.14$ MeV, with the sum of reduced widths $\theta_{\text{in}}^2 + \theta_{\text{out}}^2 \approx 0.5 \times (3\hbar^2/2MR^2)$. The ratio $\theta_{\text{in}}^2/\theta_{\text{out}}^2 = 0.1$ to 0.4 or 1.0 to 3.0 (1955FR10).

$$6. \text{}^7\text{Li}(n, p)\text{}^7\text{He} \qquad Q_m = -14 \qquad E_b = 2.035$$

Not observed: see ${}^7\text{He}$.

$$7. \text{}^7\text{Li}(n, d)\text{}^6\text{He} \qquad Q_m = -7.779 \qquad E_b = 2.035$$

At $E_n = 14$ MeV, the cross section is 9.8 ± 1.1 mb (1953BA04). See also (1954FR03).

$$8. \text{(a) } \text{}^7\text{Li}(n, t)\text{}^5\text{He} \qquad Q_m = -3.423 \qquad E_b = 2.035$$

$$\text{(b) } \text{}^7\text{Li}(n, t)\text{}^4\text{He} + n \qquad Q_m = -2.466$$

The cross section for reaction (a) is 55 ± 8 mb at $E_n = 14$ MeV (1954FR03). See also (1954MA1E) and (1954BA1B).

$$9. \text{}^7\text{Li}(d, p)\text{}^8\text{Li} \qquad Q_m = -0.192$$

$$Q_0 = -0.183 \pm 0.02 \text{ (1955KH31).}$$

Three proton groups are observed, corresponding to the ground state and to levels at 0.974 ± 0.015 (1955LE24), 0.977 ± 0.02 MeV (1955KH31, 1955KH35) and 2.28 MeV (1955LE24). A search for further levels in the range $E_x = 2.28$ to 8 MeV revealed no levels with $\Gamma < 80$ keV (1958HA10, 1958HA1G). At $E_d = 14$ MeV, the angular distributions of the protons, analyzed by stripping theory, indicate $l_n = 1$ and therefore even parity, $J \leq 3$, for the ground state and the 0.98-MeV level (1955LE24). On the assumption that $J = 2^+$ and 1^+ for the ground state and 0.98-MeV level, respectively, (1957FR1B) calculate $\theta^2 = 0.054$ and 0.028 from the data of (1955LE24). These two levels are presumed to arise from a ${}^{33}\text{P}$ term, with a third component of $J = 0^+$ expected at higher energy (1957FR1B). See also (1955GI1A).

10. ${}^7\text{Li}(t, d){}^8\text{Li}$ $Q_m = -4.224$

Not observed.

11. ${}^7\text{Li}(\alpha, {}^3\text{He}){}^8\text{Li}$ $Q_m = -18.543$

Not observed.

12. ${}^9\text{Be}(\gamma, p){}^8\text{Li}$ $Q_m = -16.885$

See ${}^9\text{Be}$ and (1958CH31).

13. ${}^9\text{Be}(n, d){}^8\text{Li}$ $Q_m = -14.658$

Not observed.

14. ${}^9\text{Be}(p, 2p){}^8\text{Li}$ $Q_m = -16.885$

Production of ${}^8\text{Li}$ at $E_p = 20$ MeV is reported by (1956LE46). At $E_p = 185$ MeV, the summed proton spectrum shows two peaks, corresponding to pickup of protons with binding energies of ≈ 18 and ≈ 26 MeV, respectively. There is some indication of α -particle structure (1958MA1B, 1958TY49).

15. ${}^9\text{Be}(d, {}^3\text{He}){}^8\text{Li}$ $Q_m = -11.409$

See (1954WI25).

16. ${}^9\text{Be}(t, \alpha){}^8\text{Li}$ $Q_m = 2.928$

Not observed.

17. ${}^{10}\text{B}(n, {}^3\text{He}){}^8\text{Li}$ $Q_m = -15.771$

Not observed.

18. ${}^{11}\text{B}(n, \alpha){}^8\text{Li}$ $Q_m = -6.636$

See ${}^{12}\text{B}$.

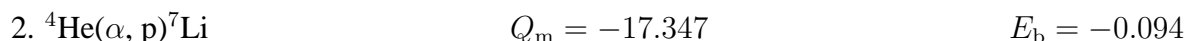
⁸Be
(Fig. 8)

GENERAL:

Theory: See (1955HE1E, 1956KU1A, 1956PE1A, 1957BI1C, 1957FR1B, 1958WI1E).



Recent Q -values are 93.7 ± 0.9 keV (1957CO59: ${}^9\text{Be}(p, d){}^8\text{Be}$), 90 ± 5 keV (1955TR03: ${}^{11}\text{B}(p, \alpha){}^8\text{Be}$): the weighted mean of all measurements is 94.1 ± 0.7 keV (1957VA11). The width of the ground state is 4.5 ± 3 eV (1956RU41: 15% of Wigner limit), ≤ 3.5 eV (1956HE57). The second value leads to $\tau_m \geq 2 \times 10^{-16}$ sec. (Combination of these values places the mean life in the range $\tau_m = 2$ to 4.5×10^{-16} sec.) An upper limit to the mean life is 6×10^{-15} sec (1955TR03). See also (1955AJ61).



See ${}^7\text{Li}$.



Absolute differential cross sections are reported for $E_\alpha = 0.15$ to 3.0 MeV (1956HE57), $E_\alpha = 3.0$ to 5.9 MeV (1956RU41), $E_\alpha = 12.9$ to 21.6 MeV (1953ST52), $E_\alpha = 12.3$ to 22.9 MeV (1956NI20), $E_\alpha = 20$ and 20.4 MeV (1951BR92, 1951MA1B), $E_\alpha = 30$ MeV (1951GR45, 1952GR1A), $E_\alpha = 38.5$ MeV (1957BU13), and $E_\alpha = 44.7$ MeV (1957CO63). See also (1958CH35).

Phase shifts summarizing the work of (1956HE57), (1956RU41) and (1956NI20) are presented in (1956RU41) and (1958NI05). These three sets of data appear to join smoothly, but do not appear to fit well with the data of (1953ST52). For $E_\alpha < 3$ MeV, only the s-wave phase shift is important. A careful survey in the range $146 - 202$ keV reveals no effect of the ground state and places an upper limit of $\Gamma \leq 3.5$ eV on this state (1956HE57): see Table 8.5. Analysis of the 0 to 6 MeV data by effective range theory leads to a value $\Gamma = 4.5 \pm 3$ eV for the ground-state width; $\theta^2 \approx 0.15$ of the Wigner limit (with $R = 5.7 \times 10^{-13}$ cm). Some evidence of shape-dependence is found in this analysis (1956RU41). According to (1958NI05) a good account of the s-wave phase shift below 6 MeV is given by hard-sphere scattering plus resonance scattering from the ground state with a width $\theta^2 = 0.75$ ($R = 4.44 \times 10^{-13}$ cm). There is no indication of other S-states below $E_x = 11.5$ MeV (1958NI05).

Table 8.3: Energy levels of ${}^8\text{Be}$

E_x in ${}^8\text{Be}$ (MeV)	$J^\pi; T$	Γ (MeV)	Decay	Reactions
0	$0^+; 0$	$2.5 \pm 1 \text{ eV}$	α	1, 3, 12, 13, 14, 21, 22, 24, 26, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42
2.90 ^a	$2^+; 0$	1.2 ± 0.3 ^b	α	3, 12, 14, 21, 26, 27, 28, 29, 30, 31, 32, 33, 35, 36, 37, 38, 39, 40
11.7	$4^+; 0$	≈ 6.7	α	3, 12, 21, 27, 28
16.08		0.31	(α)	21, 39, 41
16.67	$(2^+; 1)$	0.19	α	21, 39, 41
(17.6)	$(2^+; 1)$	(< 0.3)	(α)	39
17.64	$1^+; (1)$	$10.7 \pm 0.5 \text{ keV}$	γ, p	14, 16, 21
18.15	$1^+; (0)$	147 keV	γ, p	14, 16, 17, 21
18.9	$(2^-; 0)$	> 0.5	n, p	15, 16, 17, 25
19.1	(3^-)	0.4	γ, p	14, 15, 16
19.22	$3^+; (1)$	0.19	n, p	15, 16
19.9	(2^+)	≈ 0.9	$(\text{n}), \alpha, \text{p}$	15, 20
21.6		≈ 0.8	n, p	15
22.6	$(^+)$	≈ 0.35	$\text{d}, \text{n}, \alpha, \text{p}, \gamma$	5, 6, 10, 14

^a A number of additional states from $E_x = 2$ to 15 MeV have been reported by various observers: see, e.g. ${}^7\text{Li}(\text{d}, \text{n}){}^8\text{Be}$, ${}^{10}\text{B}(\text{d}, \alpha){}^8\text{Be}$, ${}^{11}\text{B}(\text{p}, \alpha){}^8\text{Be}$, ${}^{12}\text{C}(\gamma, \alpha){}^8\text{Be}$ and (1954TIIIC).

^b See Table 8.4.

Table 8.4: Energy and width of first excited state of ${}^8\text{Be}$

E_x (MeV)	Γ (MeV)	Reaction	Reference
2.9	2.0	${}^4\text{He}(\alpha, \alpha){}^4\text{He}$	(1956RU41)
	1.9	${}^7\text{Li}(p, \gamma){}^8\text{Be}$	(1958ME78)
2.95	1.6 ± 0.4	${}^7\text{Be}(d, p){}^8\text{Be}$	(1958SP1A)
3.0 ± 0.1	1.0 ± 0.2	${}^8\text{Li}(\beta^-){}^8\text{Be}$	(1955AJ61) ^a
2.8 ± 0.1	0.8	${}^9\text{Be}(d, t){}^8\text{Be}$	(1955CU16)
2.87 ± 0.06	0.9 ± 0.2 ^b	${}^{10}\text{B}(d, \alpha){}^8\text{Be}$	(1955AJ61) ^a
2.94 ± 0.06	0.84	${}^{11}\text{B}(p, \alpha){}^8\text{Be}$	(1955AJ61) ^a
3.06	0.9	${}^{12}\text{C}(\gamma, \alpha){}^8\text{Be}$	(1955GO59)

^a See also text below reaction 3 in ${}^8\text{Be}$.

^b $\theta^2 \approx 2$ (1953TR04).

The d-wave phase shift first becomes appreciable near $E_\alpha = 2.5$ MeV (1956HE57) and appears to pass through resonance at 6.0 MeV (1956RU41). The g-wave shift rises continuously from $E_\alpha = 11$ to 23 MeV; a broad ${}^8\text{Be}$ level is indicated at $E_x = 11.7$ MeV (1956NI20, 1958NI05). The course of the phase shifts appears to be consistent with a simple two-body interaction with an attractive potential near $R \approx 5 \times 10^{-13}$ cm and a repulsive core at a smaller radius; some dependence of the well shape on l is required (1951HA1B, 1956HE1B, 1956RU41, 1958NI05, 1958VA1B). A detailed comparison with the model of (1951HA1B) is made by (1958NI05). At 38.5 MeV, the s and d phase shifts are large, while the δ_4 , δ_6 and δ_8 phase shifts are small. These results are consistent with 0^+ and 2^+ states near 19 MeV (see ${}^7\text{Li}(p, \alpha){}^4\text{He}$) and are not inconsistent with a 4^+ state at ≈ 11 MeV (1957BU13). See also (1955AJ61), (1956HA1C, 1958MC1C; theor.) and (1954SN1A).

$$4. {}^6\text{Li}(d, \gamma){}^8\text{Be} \quad Q_m = 22.279$$

Not observed: see (1953SA1A, 1954SI07).

$$5. \text{(a) } {}^6\text{Li}(d, n){}^7\text{Be} \quad Q_m = 3.380 \quad E_b = 22.279$$

$$\text{(b) } {}^6\text{Li}(d, n){}^4\text{He} + {}^3\text{He} \quad Q_m = 1.796$$

The excitation curve has been measured for $E_d = 0.06$ to 5.5 MeV (1952BA1A, 1954HI34, 1956NE13, 1957SL01). A broad s-wave resonance is indicated at $E_d = 0.41$ MeV, $\Gamma = 0.45$

Table 8.5: Levels of ${}^8\text{Be}$ from ${}^4\text{He}(\alpha, \alpha){}^4\text{He}$ ^a

E_x (MeV)	J^π	$\Gamma_{\text{c.m.}}$	R (10^{-13} cm)	θ^2 ($3\hbar^2/2MR^2$)
0	0^+	2.5 ± 1 eV	5.7	0.15
			4.44	0.75
2.9	2^+	2.0 MeV	5.0	0.7
			3.5	0.4
11.8	4^+	6.7 MeV	4.44	1.3

^a From (1956HE57, 1956RU41, 1958NI05). Double entries indicate alternative solutions.

MeV (1952BA1A, 1956NE13). At this energy the neutron yield to the 0.43-MeV state of ${}^7\text{Be}$ is isotropic, while at $E_d = 600$ keV and above, the angular distributions indicate a strong admixture of stripping process (1956NE13). A sharp resonance at $E_d = 2.12$ MeV is reported by (1952BA1A). However, (1957SL01) find that the forward cross section rises from ≈ 22 mb/sr at $E_d = 1.1$ MeV to ≈ 57 mb/sr at 5.5 MeV without sharp resonances. This is confirmed by (1954BU1B) who reports no appreciable change in slope at $E_d \approx 1.8$ MeV and suggests that the increase in neutron yield observed by (1952BA1A) might have been due to oxygen contamination.

The ratio of 430-keV γ -radiation from this reaction and 477-keV γ -radiation from the mirror reaction, ${}^6\text{Li}(d, p){}^7\text{Li}$, has been measured for $E_d = 0.2$ to 1.8 MeV. This ratio, which measures Γ_n/Γ_p , rises from 1.1 to about 1.13 at $E_d = 0.45$ MeV, falling to 0.98 at $E_d = 1.8$ MeV. The theoretical ratio, assuming charge symmetry, rises from 0.96 at low energy to 0.98 at $E_d = 1.8$ MeV. It is concluded that the predictions of charge independence are borne out within 15%, and that the slight deviation observed may be connected with the resonance near $E_d = 0.45$ MeV (1957WI24). See also (1954HI34).

$$6. \text{ (a) } {}^6\text{Li}(d, p){}^7\text{Li} \quad Q_m = 5.027 \quad E_b = 22.279$$

$$\text{ (b) } {}^6\text{Li}(d, p){}^4\text{He} + {}^3\text{H} \quad Q_m = 2.561$$

Cross sections and angular distributions have been measured for $E_d = 30$ keV to 3 MeV by (1950KR1A, 1953SA1A: see (1950WH02, 1954NI1A, 1957JA37)). A broad maximum near $E_d = 1.0$ MeV is interpreted by (1950WH02) as indicating a level at $E_d = 0.4$ MeV, $\Gamma \approx 0.5$ MeV. The angular distributions at $E_d > 1$ MeV indicate stripping effects, with $l_n = 1$ (1954NI1A). See also the discussion of the work of (1957WI24) in the preceding section. See also (1955AJ61).

$$7. {}^6\text{Li}(d, d){}^6\text{Li} \quad E_b = 22.279$$

See ${}^6\text{Li}$.

$$8. \text{{}^6\text{Li}(d, t)\text{{}^5\text{Li}} \quad Q_m = 0.765 \quad E_b = 22.279$$

The cross section for tritium production rises rapidly to 190 mb at 1 MeV, then more slowly to 290 mb near 4 MeV. There is evidence of deviation from isotropy near 0.4 MeV ([1955MA20](#)). See also ${}^5\text{Li}$.

$$9. \text{{}^6\text{Li}(d, \text{{}^3\text{He}})\text{{}^5\text{He}} \quad Q_m = 0.839 \quad E_b = 22.279$$

See ${}^5\text{He}$.

$$10. \text{{}^6\text{Li}(d, \alpha)\text{{}^4\text{He}} \quad Q_m = 22.373 \quad E_b = 22.279$$

Cross sections have been measured for $E_d = 30$ keV to 1.6 MeV ([1953SA1A](#): see ([1950WH02](#), [1954HI34](#), [1957JA37](#))). A broad maximum is observed at $E_d = 0.6$ MeV which is interpreted in terms of a resonance at $E_d = 0.35$ MeV, $\Gamma \approx 0.5$ MeV ([1950WH02](#): see, however, ([1954HI34](#))). See also ([1956PO1A](#)), ([1956SA1B](#); theor.) and ([1952AJ38](#)).

$$11. \text{{}^6\text{Li}(t, n)\text{{}^4\text{He}} + \text{{}^4\text{He}} \quad Q_m = 16.115$$

See ([1952CU1B](#)).

$$12. \text{{}^6\text{Li}(\text{{}^3\text{He}, p)\text{{}^8\text{Be}} \quad Q_m = 16.786$$

At $E(\text{{}^3\text{He}}) = 1.25$ MeV, proton groups are observed to the ground state, the 2.9-MeV state and possibly to a state at ≈ 12.3 MeV ($\Gamma \approx 2$ MeV, intensity $\approx 6\%$ of 2.9-MeV transition). It is suggested that the 12.3-MeV state may be that observed in ${}^4\text{He}(\alpha, \alpha){}^4\text{He}$. No other states are observed with $E_x \lesssim 14$ MeV. The upper limits on the intensities of groups leading to such states are 1% (of 2.9-MeV transition) for sharp states and 3% for levels 1 MeV wide ([1956MO19](#)). These results are confirmed by ([1956SC01](#)) at $E(\text{{}^3\text{He}}) = 1.5$ and 2 MeV: no group of width $\lesssim 1$ MeV appears for $E_x < 14$ MeV with an intensity as much as 2% of the ${}^8\text{Be}^*(2.9)$ group. See also ([1953KU24](#), [1955AL57](#)).

$$13. \text{}^6\text{Li}(\alpha, d)\text{}^8\text{Be} \quad Q_m = -1.565$$

This reaction has been observed at $E_\alpha = 31.5$ MeV (1956WA29).

$$14. \text{}^7\text{Li}(p, \gamma)\text{}^8\text{Be} \quad E_b = 17.253$$

The cross section has been studied from $E_p = 30$ keV (1957JA37) to 7.7 MeV. Resonances are observed at $E_p = 0.44, 1.03$ and 2.1 MeV: see Table 8.6. There is no further structure up to 5 MeV (1952BA1B). The radiation comprises two components, one from the ground-state transition, with $E_\gamma = 17.2 + \frac{7}{8} E_p$ and the other from the transition to the 2.9-MeV broad excited state, with $E_\gamma \approx 14.3 + \frac{7}{8} E_p$. Both are resonant at the 0.44-MeV resonance, but only the lower energy transition shows the 2.1-MeV resonance (1957NE1A). The intensity ratio of the higher to the lower-energy radiation increases from 0.5 at $E_p = 0.2$ MeV to 1.7 at $E_p = 0.44$ MeV and falls to 1.0 at $E_p = 0.6$ MeV (1956CA1A: $\theta = 90^\circ$). Between $E_p = 1.0$ and 3.5 MeV the ratio is constant within 30% at $\frac{2}{3}$ (1955WI1D, 1957NE1A). Evidence for a component at ≈ 12 MeV is discussed by (1953TI1C: see also (1955CA19)). A broad resonance appears near $E_p = 5.8$ MeV probably corresponding to the “giant” (γ, p) resonance, $E_x = 22.3$ MeV (1959GE33).

The angular distributions of both γ -rays show small deviations from isotropy at the $E_p = 0.44$ MeV resonance and exhibit strong interference effects nearby. The observed distribution of the 17.6-MeV radiation at resonance is consistent with p-wave formation if the channel spin ratio $\chi \equiv \sigma(1)/\sigma(2) = \frac{1}{4}$: this ratio implies an intermediate coupling with $a/K = 2$ to 3 (1958NE17: see also (1950DE1A, 1957FR1B)). Angular distributions in the range $E_p = 0.9$ to 1.2 MeV are reported by (1954KR06) and $0^\circ/90^\circ$ cross sections for $E_p = 1.5$ to 3.5 MeV by (1957NE1A). The latter observations indicate that some process other than direct s-wave capture is responsible for the background between resonances (1954WI1A, 1957NE1A).

A study of (γ - α) coincidences at $E_p = 0.45$ MeV yields an angular correlation which rules out the assignment $J = 0^+$ to the 2.9-MeV ^8Be level and indicates that the 14.7-MeV γ -radiation contains a mixture of E2 and M1 radiation (1956BO1H: see also (1954DE1D)). The alpha spectra, taken singly (1956LA1A) and in coincidence with γ -rays (1958ME78) show no evidence of weakly excited levels reported by (1954IN1A: see also (1955TI1B)). In the work of (1958ME78), the 2.9-MeV level appears to have a width of 1.9 MeV; compare (1950BU1B). There is some evidence for a broad level near $E_x = 10$ MeV (1956LA1A).

See also (1955RI1A, 1956PO1A) and (1957FR1B, 1957KU58; theor.).

$$15. \text{}^7\text{Li}(p, n)\text{}^7\text{Be} \quad Q_m = -1.646 \quad E_b = 17.253$$

The cross section has been studied from the threshold at $E_p = 1.8811$ MeV (see ^7Be) to 10 MeV (1957BO1F, 1957JA37, 1957KA1C: see also (1958TA03)). Resonances are indicated at $E_p = 1.93, 2.25, (3.0)$ and 5.0 MeV (see Table 8.7). Absolute cross sections are given by

Table 8.6: Resonances in ${}^7\text{Li}(p, \gamma){}^8\text{Be}$

E_r (keV)	Γ_{lab} (keV)	${}^8\text{Be}^*$ (MeV)	References
441.4 ± 0.5	12	17.64	(1948BO1A, 1949FO18)
441.5 ± 0.5	12.2 ± 0.5		(1952HU1C)
441.2 ± 0.6	12 ± 1		(1955BU1A, 1956BU27)
1030 ± 5^a	168^a	18.15	(1954KR06)
2000			(1954PR1A)
2100	400		(1955SW1A)
2130	400	19.1	(1957NE1A)

^a From ${}^7\text{Li}(p, p){}^7\text{Li}$ (1949FO18).

^b See also Table 8.7.

(1948TA16) and (1958MA07): see also (1959MA20: footnote 14). Angular distributions in the range $E_p = 2.0$ to 2.5 MeV show strong $(\cos \theta)$ terms, suggesting interference of states of opposite parity (1948BR1A, 1948TA16). (1954AD1A) has shown that the behavior in this region can be accounted for by ascribing the 2.25-MeV resonance to p-wave formation, with $J = 3^+$ and $\gamma_p^2 = \gamma_n^2 = 0.8 \times 10^{-13}$ MeV-cm (presumably the $T = 1$ analogue of ${}^8\text{Li}^*(2.28)$), and assuming a background due to s-wave, $J = 1^-$ and 2^- , levels of undetermined location. According to (1957NE1A), a better account of the cross section below 2.4 MeV is obtained with the $J = 3^+$ level assumed to have $\gamma_n^2/\gamma_p^2 = 5.5$ and a single s-wave $J = 2^-$ level at $E_p = 1.9$ MeV, with $\gamma_n^2/\gamma_p^2 = 5.5$. With this large ratio the low energy cross section can be accounted for in detail and can be made to agree with that derived from the inverse reaction ${}^7\text{Be}(n, p){}^7\text{Li}$ (1957NE1A, 1958MA07: see also (1955HA34)). [It is of interest to note that a similar apparent deviation from charge independence occurs in ${}^{10}\text{B}(\alpha, n){}^{13}\text{N}$ and ${}^{10}\text{B}(\alpha, p){}^{13}\text{C}$ (see ${}^{14}\text{N}$). On the other hand, see ${}^6\text{Li}(d, p){}^7\text{Li}$ and ${}^6\text{Li}(d, n){}^7\text{Be}$.] Using the stacked-foil method, (1957KA1C) report structure in the excitation function corresponding to ${}^8\text{Be}$ levels at 21.5, 22.5, 23.85, (24.9) and (25.6) MeV. At $E_p = 10$ MeV, the cross section for production of ${}^7\text{Be}$ is 120 ± 20 mb (1957KA1C), 100 ± 20 mb (1957BO1F).

The relative intensity of the low-energy neutrons (to ${}^7\text{Be}^*(0.43)$) to the high-energy (ground state) neutrons varies with energy: see Table 8.8. In the range $E_p = 2.5$ to 2.9 MeV, the low-energy neutrons are practically isotropic (c.m. system). From the shape of the excitation function, (1955BA1L) conclude that the reaction to ${}^7\text{Be}^*$ proceeds by s-wave protons in and s-wave neutrons out.

It is pointed out by (1954AD1A) that the existence of the $J = 3^+$ level, apparently well separated from the other components $J = 1^+$ and 2^+ which can be formed with channel spin 2, indicates a strong spin-orbit interaction, which should lead to polarization of the neutrons and scattered protons. Polarization measurements are reported by (1954AD1A, 1954WI42, 1955OK1A, 1956WIIE, 1958CL98, 1958CR85, 1958ST28). See also (1957RO1C, 1958GI15).

16. ${}^7\text{Li}(p, p){}^7\text{Li}$

$$E_b = 17.253$$

Absolute differential scattering cross sections are reported for $E_p = 0.4$ to 1.4 MeV (1953WA27), $E_p = 1.4$ to 3.0 MeV (1956MA12), and $E_p = 14.5, 20.0$ and 31.5 MeV (1956KI54). Anomalies appear at $E_p = 0.44, 1.03, 1.88, 2.1$ and 2.5 MeV (see Table 8.7). Both the 0.44- and the 1.03-MeV resonances are ascribed to p-waves, $J = 1^+$, with channel spins 1 and 2 in a ratio of 1 to 5 (1953CH1A, 1953LI1A, 1955LI1B: compare ${}^7\text{Li}(p, \gamma){}^8\text{Be}$).

The anomaly at $E_p = 1.88$ MeV coincides with the ${}^7\text{Li}(p, n){}^7\text{Be}$ threshold and is ascribed to the abrupt change in total width of a broad (2^- ?) resonance when neutron emission becomes possible (1956MA12, 1957NE1A). The observed structure at $2.0 - 2.25$ MeV may reflect interference of the p-wave 2.25-MeV ($J = 3^+$) resonance with one at $E_p = 2.1$ MeV, also formed by p-waves (1956MA12). Preliminary results of a phase shift analysis suggest, on the other hand, interference between a $J = 3^-$ level at $E_p = 2.1$ MeV with a 2^- level at $E_p = 1.9$ MeV, and interference of the 3^+ level at $E_p = 2.25$ MeV with a broad 1^+ level near 3 MeV (J. Olness quoted in (1957NE1A)).

17. (a) ${}^7\text{Li}(p, p'){}^7\text{Li}^*$

$$E_b = 17.253$$

(b) ${}^7\text{Li}(p, p'\gamma){}^7\text{Li}$

A pronounced resonance appears in the yield of inelastically scattered protons (1951BR10, 1954MO04) and 0.48-MeV γ -rays (1954KR06) at $E_p = 1.030 \pm 0.005$ MeV, $\Gamma = 168$ keV. The angular distribution of the protons is approximately isotropic at resonance, $\sigma = 42$ mb, and asymmetric above it, consistent with an s- or p-wave resonance interfering with a non-resonant wave of opposite parity (1954MO04: see also (1955LI1B)).

The yield of 480-keV radiation rises smoothly from $E_p = 1.5$ to 3.0 MeV except for a pronounced cusp at 1.881 MeV (1955HA34, 1957NE1A). Analysis of the excitation function suggests that the inelastic process is enhanced by the $J = 2^-$ level at 1930 keV and that the cusp results from the sudden increase in the total width when neutron emission becomes possible (1957NE1A). See also (1951BA79).

18. ${}^7\text{Li}(p, d){}^6\text{Li}$

$$Q_m = -5.026$$

$$E_b = 17.253$$

See ${}^6\text{Li}$.

19. ${}^7\text{Li}(p, t){}^5\text{Li}$

$$Q_m = -4.261$$

$$E_b = 17.253$$

See ${}^5\text{Li}$.

Table 8.7: Levels in ^8Be from $^7\text{Li} + p$

E_{res} (keV)	$^8\text{Be}^*$ (MeV)	Γ_{lab} (keV)	l_p	$J^\pi; T$	θ_p^2	$^7\text{Li}(p, \gamma)^8\text{Be}$		$^7\text{Li}(p, n)^7\text{Be}$			$^7\text{Li}(p, p')^7\text{Li}^*$ $\Gamma_{p'}$ (keV)	References
						σ_{res} (mb)	$\omega\Gamma_\gamma$ (eV)	l_n	γ_n^2/γ_p^2	θ_n^2		
441.5	17.64	12.2	1	$1^+; 1$	0.064	6.0	9.4				0	(1949FO18, 1952HU1C)
1030	18.15	168	1	$1^+; (0)$		res.	2				≈ 6	(1949FO18, 1951BR10, 1954KR06, 1954MO04)
1900	18.94	> 500	0	2^-		non res.						(1957NE1A, 1958MA07)
2100	19.1	400	2(1)	(3^-)		res.		0	4.5 ^b	> 0.3	res.	(1957NE1A)
2250	19.22	220	1	$3^+; (1)$	0.04	(non res.)					small	(1957NE1A)
(≈ 3000)	(19.9)	> 1000	(1)	(1^+)				1	5.5 ^c	[0.2]	small	(1957NE1A) ^d
≈ 3000	19.9 ^a	≈ 1000	(1)	(2^+)						(res.)		(1957NE1A, 1958MA07) ^d
5000	21.6	≈ 900								res. ^e		(1951BL1A, 1952BA1B, 1959GI47)

^a $^7\text{Li}(p, \alpha)^4\text{He}$.

^b 5.2 ± 0.3 (1958MA07); $\Gamma_n = \Gamma_p$ at $E_p = 1.93$ to 1.97 MeV.

^c 5.2 ; $\gamma_n^2 = 2.9 \times 10^{-13}$ MeV-cm (1958MA07), $\Gamma_n = \Gamma_p$.

^d See also (1955MA84).

^e (1959GI47) find $E_{\text{res}} \approx 5.0 \pm 0.5$ MeV, $\Gamma \approx 0.9$ MeV, $\sigma \approx 140$ mb, $J \geq 3$ (if single resonance).

Table 8.8: Relative yield of neutrons to $^7\text{Be}^*(0.43)$ and $^7\text{Be}(0)$

E_p (MeV)	$\theta(\text{lab})$	$I_{0.43}/I_0$ (%)	References
2.40	all	0.18 ± 0.06	(1955MA84)
2.5	all	2.5 ^a	(1955BA1K, 1955BA1L)
2.75	30°	9 ± 1.5	(1950JO57)
2.89	30°	10.5 ± 1	(1950JO57)
3.0		8 ^a	(1955BA1K, 1955BA1L)
3.66	30°	12 ± 1	(1950JO57)
3.9 – 5.4		≈ 10	(1954CR1A)
5.0	20° – 90°	52.5	(1950GR1A)

^a See curve in (1955BA1K).

20. $^7\text{Li}(p, \alpha)^4\text{He}$

$$Q_m = 17.347$$

$$E_b = 17.253$$

The cross section, which has been measured to 3.8 MeV, exhibits a broad maximum at $E_p = 3$ MeV which is interpreted in terms of a level ≈ 1 MeV wide, with $J = 2^+$, at $E_p \approx 3$ MeV, and a several-MeV broad level of $J = 0^+$, underlying the region: see (1948HE1A, 1948HE1B, 1948IN1A, 1953SA1A, 1957JA37). Absolute differential cross sections are reported by (1958FR03) for $E_p = 1.0$ to 1.5 MeV: at 1.01 MeV, $d\sigma/d\omega$ (lab, 90°) = 0.67 mb/sr, see also (1956MA12). Differential cross sections have also been measured at $E_p = 15.0$ and 18.5 MeV; there are indications of a triton pickup process at these energies (1957MA1F). See also $^4\text{He}(\alpha, p)^7\text{Li}$, (1955AJ61, 1955RI1A, 1956BA1E, 1956CR47, 1958BU38).

21. $^7\text{Li}(d, n)^8\text{Be}$

$$Q_m = 15.026$$

Table 8.9: Slow neutron thresholds in ${}^7\text{Li}(d, n){}^8\text{Be}$ (1957SL01)

E_d (MeV)	$\Gamma_{c.m.}$ (MeV)	${}^8\text{Be}^*$ (MeV)
1.35	0.31	16.08
2.10	0.19	16.67
3.32	< 0.02	17.61
4.08	0.23	18.20

A careful study of the neutron spectrum at $E_d = 2$ MeV at several angles reveals only two distinct groups, corresponding to ${}^8\text{Be}(0)$ and ${}^8\text{Be}^*(2.9)$. No other levels below $E_x = 10$ MeV appear in this work: upper limits for groups leading to levels near $E_x = 4$ to 5 MeV and $E_x = 7.5$ MeV are 10% and 20%, respectively, of the ground state group. Angular distributions of the ground state and 3-MeV state neutrons exhibit $l_p = 1$ stripping patterns at forward angles (1954TR1A, 1955TR1B). Other workers have reported neutron groups corresponding to levels at 2.2, 2.9, 4.1, 5.1 and 7.6 MeV: see for instance, (1953TR1B, 1954RE1A, 1955BE1D, 1955GI1B, 1955IH1A, 1955IH1B), as well as states at 10 MeV (1941RI1A), 11.1 and 14.7 MeV (1950WH1B).

Thresholds for slow neutron production indicate ${}^8\text{Be}$ levels at 16.08, 16.67, 17.61 and 18.20 MeV (1954BO79, 1957SL01) (see Table 8.9). It is suggested that the 16.67-MeV level is the lowest $T = 1$ level of ${}^8\text{Be}$, and that the levels at 17.61 and 18.20 MeV correspond to those seen in $({}^7\text{Li} + p)$ at $E_p = 0.44$ and 1.03 MeV (1954BO79). A search for nuclear pairs from possible pair-emitting states of ${}^8\text{Be}$ yielded an upper limit of 2×10^{-5} mb at $E_d = 0.33$ MeV for excitation of such states in the range $E_x = 5.0$ to 8.5 MeV (1955BE62). See also (1955CA1A, 1955CA1C, 1955PE1C, 1956BO1F, 1956BO43, 1956CA1B, 1956RI37, 1957CA14).

22. ${}^7\text{Li}({}^3\text{He}, d){}^8\text{Be}$ $Q_m = 11.759$

See (1954MO92) and (1955AL57).

23. ${}^7\text{Li}(\alpha, t){}^8\text{Be}$ $Q_m = -2.560$

Not observed.

24. ${}^7\text{Li}({}^7\text{Li}, {}^6\text{He}){}^8\text{Be}$ $Q_m = 7.247$

See (1957NO17).

25. (a) ${}^7\text{Be}(n, p){}^7\text{Li}$	$Q_m = 1.646$	$E_b = 18.899$
(b) ${}^7\text{Be}(n, \alpha){}^4\text{He}$	$Q_m = 18.993$	

At thermal energies, the (n, p) cross section is $(5.1 \pm 0.6) \times 10^4$ b (1955HA34) while the (n, α) cross section is < 25 mb (1958SE08). These observations are consistent with the odd parity of ${}^7\text{Be}$. Less than 10% of transitions involve ${}^7\text{Li}^*(0.48)$. Comparison of the (n, p) cross section with the cross section for ${}^7\text{Li}(p, n){}^7\text{Be}$ gives evidence for an $l = 0$ level in ${}^8\text{Be}$ within 20 keV below the neutron threshold, with $\Gamma < 30$ keV (1955HA34). See, however, (1957NE1A, 1958MA07), and see also (1954AD1A). Comparison of the thermal cross section with the (p, n) cross section observed in the inverse reaction supports the assignment $J = \frac{3}{2}$ for ${}^7\text{Be}_{\text{g.s.}}$ (1957NE1A).

26. ${}^7\text{Be}(d, p){}^8\text{Be}$	$Q_m = 16.672$
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At $E_d = 0.85$ MeV, $\theta = 30^\circ, 90^\circ$ and 270° , proton groups are observed corresponding to ${}^8\text{Be}_{\text{g.s.}}$ and the broad level, $E_x = 2.95$ MeV, $\Gamma = 1.6 \pm 0.4$ MeV. No other prominent groups appear for $E_x < 5.8$ MeV (1958SP1A).

27. ${}^8\text{Li}(\beta^-){}^8\text{Be}$	$Q_m = 16.001$
	$Q_0 = 15.94 \pm 0.08$ (1958VE20).

The observed β -spectrum closely matches the mean of reported α -spectra (1955FR29) for $E_\beta > 3$ MeV and is consistent with 89% branching via ${}^8\text{Be}^*(2.9)$, with $\log ft = 5.67$ and 11% to higher states, possibly ${}^8\text{Be}^*(11.7)$, $\log ft = 4.6$. Less than 1% of transitions involve ${}^8\text{Be}_{\text{g.s.}}$: $\log ft > 8$ (1958VE20: see also (1955AJ61)). Upper limits to transitions to sharp states in ${}^8\text{Be}$ with $E_x = 2, 4$ and 6 MeV are, respectively, 2.5, 1 and 0.5% (1955FR29: see also (1956AR21)).

The α - β angular correlation is isotropic within a few per cent for all β -energies: see (1955AJ61). It is pointed out by (1955MO1A) that a small, $\approx 0.5\%$, anisotropy may be expected at high β -energies because of the increased importance of $l = 1$ and 2 emission, even in an allowed transition. Anisotropy in the β -decay from partially oriented ${}^8\text{Li}$ nuclei is reported by (1957BU44: see also (1958SH1A)). The distribution of recoil momenta and the neutrino-recoil correlation establish that the decay is at least 90% Gamow-Teller and that the Gamow-Teller portion is at least 90% axial vector in character. The observations also require $J = 2^+$ for the ${}^8\text{Li}$ ground state (1958BA1E, 1958LA07, 1958LA08: see also (1958MO1D)). An upper limit of 0.2 ± 0.1 % is reported by (1956TA07) on the number of disintegrations leading to 4.9-MeV γ -radiation: see also (1953BU35). See also (1955GI1A) and (1955JA1C, 1955LA1D; theor.).

28. ${}^8\text{B}(\beta^+){}^8\text{Be}$	$Q_m = 17.978$
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The observed positron spectrum matches the ${}^8\text{Li}$ - ${}^8\text{B}$ α -spectra for $E_{\beta^+} > 6$ MeV. About 80% of transitions involve ${}^8\text{Be}^*(2.9)$, $\log ft = 5.72$, with $\approx 19\%$ to higher states, possibly ${}^8\text{Be}^*(11.7)$, $\log ft = 4.6$. Less than 5% go to ${}^8\text{Be}_{\text{g.s.}}$, $\log ft > 7.3$ (1958VE20). See (1950AL57, 1952KI1A, 1954GI1A). See also (1955GI1A).

$$\begin{aligned} 29. \text{ (a) } {}^9\text{Be}(\gamma, n){}^8\text{Be} & \quad Q_m = -1.667 \\ \text{ (b) } {}^9\text{Be}(n, 2n){}^8\text{Be} & \quad Q_m = -1.667 \\ & \quad Q_0 = -1.664 \pm 0.004 \text{ (1956CO56)}. \end{aligned}$$

At $E_\gamma = 6$ MeV, most of the transitions are to the 2.9-MeV state (1954CA1A). See also ${}^9\text{Be}$ and (1956CO56). For reaction (b), see ${}^9\text{Be}$ and ${}^{10}\text{Be}$.

$$30. {}^9\text{Be}(p, d){}^8\text{Be} \quad Q_m = 0.560$$

Angular distributions of ground-state deuterons are remarkably similar for $E_p = 5, 10, 16.5$ and 22 MeV and show strong contributions from the pickup process (1951HA1A, 1953CO1C, 1955SU1A, 1956RA32, 1956RE04, 1956SU1A, 1958SU14). The significance of this result, which is not consistent with the simple Butler theory, is discussed by (1955DA1D, 1956GL25: see also (1955DA1E, 1955SA1D, 1956DA1D, 1956KO1B, 1957GR1C). At $E_p = 16.5$ MeV, the distribution is consistent with $l_n = 1$, $R_0 = 3.0 \times 10^{-13}$ cm, and $\theta^2 = 0.024$ for ${}^8\text{Be}(0)+n$ (1956RE04). At higher energies, the distributions appear to be affected by pickup from within the nuclear volume (1956BE14, 1956SE1A). For $E_p = 31$ and 95 MeV, unresolved ${}^8\text{Be}$ states near 17 MeV appear, possibly representing pickup of a 1s neutron in ${}^9\text{Be}$ (1956BE14, 1956SE1A: see ${}^9\text{Be}$).

At $E_p = 7.4$ MeV, a search for ${}^8\text{Be}$ levels revealed only the ground-state and the 2.9-MeV state in the range $E_x = 0$ to 6.5 MeV (1956CA1C). See also (1954FI1A, 1955GI1A, 1956ST30, 1957BE49) and (1955LA1C; theor.).

$$\begin{aligned} 31. \text{ (a) } {}^9\text{Be}(d, t){}^8\text{Be} & \quad Q_m = 4.592 \\ \text{ (b) } {}^9\text{Be}(d, t){}^4\text{He} & \quad Q_m = 4.686 \end{aligned}$$

At $E_d \approx 1.2$ and 3.5 MeV, the ground and first excited states are observed: see (1952CU1A, 1953CU1B, 1953GE01, 1956GE1A, 1956JU1D). For the first excited state, (1955CU16) finds $E_x = 2.8 \pm 0.1$ MeV, $\Gamma = 0.8$ MeV. At $E_d = 0.5$ MeV ($\theta = 60^\circ$ and 90°), there is no evidence for excited states of ${}^8\text{Be}$ with $E_x = 3.4$ to 4.8 MeV: the upper limit to the intensity of the corresponding groups is 2% of the 2.9-MeV group (1956GE1A). At $E_d = 14.8$ MeV ($\theta = 15^\circ$), there is no evidence for states with $E_x = 7.1$ to 15.4 MeV (1956CA1C).

Recent studies of the angular distribution of ground-state tritons for $E_d = 0.1$ to 15 MeV have been reported by (1955JU10, 1955JU1B, 1956HA90, 1957SM1A: see also (1955AJ61)). Below $E_d \approx 0.5$ MeV, the tritons show strong backward peaking, suggestive of interference of compound nucleus states of opposite parity (1957SM1A: see ^{11}B). At high energies, the reaction proceeds mainly by pickup, with $l_n = 1$ (1956HA90). See also (1955DA1E; theor.), (1957HA1F) and ^9Be .

$$32. \ ^9\text{Be}(^3\text{He}, \alpha)^8\text{Be} \quad Q_m = 18.911$$

At $E(^3\text{He}) = 0.90$ MeV, the ground (weak) and 2.9-MeV (strong) states are observed: see (1955AJ61).

$$33. \ ^{10}\text{B}(\gamma, d)^8\text{Be} \quad Q_m = -6.025$$

^8Be states up to $E_x = 10$ MeV are reported to be involved in this reaction: see (1954TI1C, 1955AJ61, 1955TI1A).

$$34. \ ^{10}\text{B}(n, t)^8\text{Be} \quad Q_m = 0.234$$

See (1951PE1B, 1954RI15, 1955JA18, 1956FR18, 1957TI1A) and ^{11}B .

$$35. \ ^{10}\text{B}(p, ^3\text{He})^8\text{Be} \quad Q_m = -0.532$$

See (1952CR30, 1955RE16).

$$36. \ (a) \ ^{10}\text{B}(d, \alpha)^8\text{Be} \quad Q_m = 17.819$$

$$(b) \ ^{10}\text{B}(d, \alpha)^4\text{He}^4\text{He} \quad Q_m = 17.913$$

All observers agree that transitions occur to the ground state and a state at $E_x \approx 2.87 \pm 0.06$ MeV, $\Gamma = 0.93 \pm 0.15$ MeV, (weighted mean of (1951WH1A, 1953CU1C, 1953TR04)). However, there is conflicting evidence on whether other states with $E_x < 15$ MeV are involved in this reaction. (1954CU1A) report additional states at (4), 5.1 and 7.5 MeV (see also (1955AJ61)). However, (1953TR04: $E_d = 0.6$ to 1.07 MeV) report no other low lying states; (1956BO1J: $E_d = 5$ MeV, $\theta = 50^\circ$ and 90°) have not observed any other states below $E_x = 9$ MeV; (1955HO48: $E_d = 1.4$ to 3.2 MeV, several angles) find no evidence for excited states other than the 2.9-MeV level below

$E_x \approx 10$ MeV; and (1956KA1A, 1958KA31: $E_d = 1.7$ MeV) find no groups corresponding to ^8Be states with $E_x = 9.8$ to 14.8 MeV above the continuum attributed to $^{10}\text{B}(d, \alpha)^4\text{He}^4\text{He}$.

The observed α -spectrum corresponding to the 2.9-MeV level may be reasonably well accounted for by the Breit-Wigner formula with $l_\alpha = 2$, $E_\lambda = 5.29$ MeV, $\gamma_\alpha^2 = 13.4 \times 10^{-13}$ MeV-cm, $R = 4.48 \times 10^{-13}$ cm [$\theta^2 \approx 2$] (1953TR04).

$$\begin{aligned} 37. \text{ (a) } & ^{11}\text{B}(\gamma, t)^8\text{Be} & Q_m &= -11.230 \\ & \text{(b) } & ^{11}\text{B}(\gamma, t)^4\text{He}^4\text{He} & Q_m &= -11.136 \end{aligned}$$

These reactions have been observed in boron-loaded photoplates. Six states of ^8Be below $E_x = 5$ MeV are reported to be involved in reaction (a) (1953ER1A). See also (1955TI1A).

$$38. \ ^{11}\text{B}(p, \alpha)^8\text{Be} \quad Q_m = 8.582$$

Alpha-particle groups corresponding to the ground state and to the 2.9-MeV state are reported; $E_x = 2.94 \pm 0.06$ MeV, $\Gamma = 0.84$ MeV (1951LI1B, 1953BE61: see (1955AJ61)). Excitation of several additional levels is reported by (1953GL1A); however, a careful search by (1955HO48) reveals no evidence for any levels with $E_x < 7$ MeV except the ground state and that at 2.9 MeV.

The alpha particles leading to the ground state are strongly anisotropic at the $E_p = 163$ -keV resonance ($^{12}\text{C}^* = 16.11$, $J = 2^+$; $T = 1$); it is thus unlikely that $J = 2$ (1952TH1B). The directional correlation of successively emitted α -particles at $E_p = 163$ keV indicates isotropic breakup of $^8\text{Be}(0)$ and hence $J = 0$, with $J = 2$ excluded. From the angle between the α -particles resulting from the breakup, $Q = 90 \pm 5$ keV is obtained; the half-life is $< 4 \times 10^{-15}$ sec (1955TR03). The angular correlation of alpha particles leading to the 2.9-MeV state with those resulting from the subsequent breakup is consistent with $J = 2^+$ for the 2.9-MeV state (1955GE1A). Certain peculiarities in the relative yields of ground state and 2.9-MeV excited state α -particles suggest that the latter level may have a significant $T = 1$ admixture: see (1953BE61, 1955HO48).

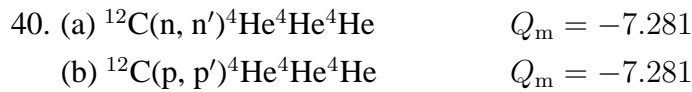
Nuclear pairs have been reported with $E(\pi) = 7$ MeV (1951PH1B); see, however, (1955BE62). See also (1955TI1B).

$$39. \ ^{12}\text{C}(\gamma, \alpha)^8\text{Be} \quad Q_m = -7.375$$

For $E_\gamma < 40$ MeV, the reaction involves mainly states of ^8Be at 0, 2.9, (4.1) (16.5 ± 0.2 ; $\Gamma < 0.4$), 16.8 ± 0.2 ($\Gamma < 0.3$), 17.6 ± 0.2 ($\Gamma < 0.3$) MeV, with indications of further states near 6, 10 and 15 MeV. There is no evidence for three-body reactions in this work (1955GO59). Evidence for levels at 3.2, 4.0, (7.5) and 9.0 MeV is reported by (1955GL1A: see also (1954TI1C)). The

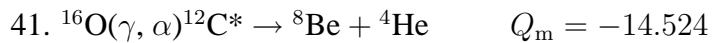
ground state decay energy is given as 87 ± 8 keV; for the first excited state, $E_x = 3.06$ MeV, $\Gamma = 0.9$ MeV (1955GO59). The excitation function is characterized by a number of resonances, suggesting that the process takes place via definite energy levels of ^{12}C (see ^{12}C); the principal types of levels involved being $J = 1^-$; $T = 1$, (E1 absorption) and $J = 2^+$; $T = 0, 1$ (E2) (1955GO59: see also (1953GE1B, 1955TI1A, 1957MU1C)). For $E_\gamma < 25$ MeV, the reaction proceeds mainly to $^8\text{Be}(0)$ and $^8\text{Be}^*(2.9)$; angular correlations indicate $J = 0$ and $J = 2$, respectively for these states. Wide variations in the branching ratio with energy are attributed to differences in isobaric spin impurities, estimated as 0.05×10^{-3} for the ground state, and $\geq 10^{-3}$ for $^8\text{Be}^*(2.9)$.

For $E_\gamma > 26$ MeV the reaction changes radically, now involving the 17 to 18 MeV states of ^8Be , with E1 absorption. The fact that these levels are so strongly excited in this manner suggests that they have $T = 1$. Angular distributions indicate $J = 2$ for $^8\text{Be}^*(16.8)$ and $J = 2$ (or possibly 0) for $^8\text{Be}^*(17.6)$. It is noted that the latter level cannot be identified with the well-known 17.63-MeV, $J = 1^+$ level (see $^7\text{Li} + \text{p}$) (1955GO59: see, however, (1953WA27)). Excitation of proton-emitting levels near $E_x = 18$ and 22 MeV is reported by (1956LI05). See also (1953GU1A, 1955HA1D, 1955TI1A).



Reaction (a) has been studied for $E_n = 12.3$ to 20.1 MeV by (1955FR35) who find evidence for transitions through the ground state and the 2.9-MeV level. See also (1955AJ61) and ^{12}C .

Reaction (b) at $E_p = 29$ MeV appears to proceed predominantly through the ground state and the 2.9-MeV level. It is not clear whether higher levels in ^8Be are involved (1955NE18). See also (1955CU1C, 1956SA1C, 1956SA1D, 1957JA1B).



At $E_\gamma \approx 22$ MeV, the reaction appears to proceed mainly via the 9.6 and 10.8-MeV states of ^{12}C to the ground state of ^8Be . For $E_\gamma > 24$ MeV, transitions through the 15(?) and 16-MeV $T = 1$ state(s) of ^{12}C , to the 2.9-MeV state of ^8Be appear to dominate: see (1955AJ61) and (1955HA1D, 1955TI1A, 1956DA1C).



At $E_p = 29$ MeV, more than half the transitions are through the ground state of ^8Be ; there is no evidence for participation of any excited states of ^8Be (1955KO1A). See also (1957JA1B).

Table 8.10: Energy levels of ${}^8\text{B}$

E_x in ${}^8\text{B}$ (MeV)	J^π	$\tau_{1/2}$ or Γ (MeV)	Decay	Reactions
0	$(2^+, 3^+)$	$\tau_{1/2} = 0.77 \pm 0.01$ sec	β^+	1, 2, 3, 4
$(0.6 \pm 0.1)^a$		0.15 ± 0.1		2
$(0.80 \pm 0.05)^a$		0.05 ± 0.03		2

^a Note added in proof: See, however, (1959FA02).

${}^8\text{B}$
(Fig. 9)

Mass of ${}^8\text{B}$: The mass excess of ${}^8\text{B}$ is 25.287 ± 0.008 MeV, from the threshold energy of the ${}^6\text{Li}({}^3\text{He}, n){}^8\text{B}$ reaction.

1. ${}^8\text{B}(\beta^+){}^8\text{Be}$ $Q_m = 17.978$
 $Q_0 = 17.91 \pm 0.12$ MeV (1958VE20).

The half-life of ${}^8\text{B}$ is 0.78 ± 0.01 sec (1958DU78), 0.61 ± 0.11 sec (1952SH44), 0.65 ± 0.1 sec (1950AL57), 0.75 ± 0.02 sec (1958VE20). The decay proceeds mainly to the 2.9-MeV state of ${}^8\text{Be}$, $\log ft = 5.72$ (1958VE20). See also (1958DU78) and ${}^8\text{Be}$.

2. ${}^6\text{Li}({}^3\text{He}, n){}^8\text{B}$ $Q_m = -1.976$

The threshold has been observed, both in production of slow neutrons and of ${}^8\text{B}$ positron activity, at $E({}^3\text{He}) = 2.9661 \pm 0.0017$ MeV, yielding a mass excess of 25.287 ± 0.008 MeV. ${}^8\text{B}$ is then stable with respect to ${}^7\text{Be} + {}^1\text{H}$ by 138 ± 9 keV. Two additional thresholds ¹ for slow neutron production are reported, in the range $E({}^3\text{He}) = 2.9$ to 6.0 MeV, at 3.9 ± 0.1 and 4.16 ± 0.05 MeV which may correspond to excited states of ${}^8\text{B}$ at $E_x = 0.6 \pm 0.1$ MeV ($\Gamma = 0.2 \pm 0.1$ MeV) and 0.80 ± 0.05 MeV ($\Gamma = 0.07 \pm 0.04$ MeV). It is pointed out that the existence of two low-lying levels in ${}^8\text{B}$ would be rather surprising in view of the level structure of ${}^8\text{Li}$ (1958DU78).

3. (a) ${}^9\text{Be}(p, 2n){}^8\text{B}$ $Q_m = -20.418$
 (b) ${}^{10}\text{B}(p, t){}^8\text{B}$ $Q_m = -18.528$
 (c) ${}^{12}\text{C}(p, n\alpha){}^8\text{B}$ $Q_m = -26.136$

¹ Note added in proof: See, however, (1959FA02).

See (1950AL57).

4. (a) $^{10}\text{B}(\gamma, 2\text{n})^8\text{B}$ $Q_{\text{m}} = -27.002$
(b) $^{11}\text{B}(\gamma, 3\text{n})^8\text{B}$ $Q_{\text{m}} = -38.456$
(c) $^{12}\text{C}(\gamma, \text{p}3\text{n})^8\text{B}$ $Q_{\text{m}} = -54.423$

See (1952SH44).

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(Closed December 01, 1958)

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

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