Energy Levels of Light Nuclei
$A = 8$

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Abstract: An evaluation of A = 5–10 was published in *Nuclear Physics A*490 (1995), 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. Also, reference key numbers have been changed to the NNDC/TUNL format — see introduction to references for more information.

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^{8}n

(Not illustrated)

^{8}n has not been observed in the interaction of 700 MeV or of 400 GeV protons with uranium: see (79AJ01). See also (87FL1A) and (87SI1E; theor.).

^{8}He

(Figs. 11 and 14)

GENERAL: See also (84AJ01).

Model calculations: (84VA06, 85PO10, 87BL18).

Complex reactions involving ^{8}He: (82AL1C, 83AN13, 85MA13, 85TA1D, 86SA30, 87AR1G, 87BO40, 87KO1Z, 87PE1C, 87TA1F, 88GA10, 88ST06, 88TA1A).

Hypernuclei: (82KA1D, 83DO1B, 84BO1H, 85AH1A, 85IK1A, 86BA1W, 86DA1B, 87MI1A, 87PO1H).

Other topics: (83GL1B, 85AN28, 87AJ1A, 88AJ1B).

Ground-state properties of ^{8}He: (83AN1C, 84FR13, 85SA32, 86HE26, 87BL18, 87HA30, 87SA15, 88JO1C).

Mass of ^{8}He: The atomic mass excess of ^{8}He adopted by us and by (88WA18) is 31598 ± 7 keV. ^{8}He is then stable with respect to decay into $^6\text{He} + 2\text{n}$ by 2.137 MeV. See (79AJ01, 84AJ01).

The interaction nuclear radius of ^{8}He is 2.48 ± 0.03 fm (85TA18, 85TA13) [see also for derived nuclear matter, charge and neutron matter r.m.s. radii].

1. $^8\text{He}(\beta^-)^8\text{Li}$ $\qquad Q_{\text{m}} = 10.652$

The half-life of ^{8}He is 119.0 ± 1.5 msec. The decay takes place $(84 \pm 1)\%$ to ^{8}Li*(0.98) [$\log ft = 4.20$] and $(16 \pm 1)\%$ via the neutron unstable states ^{8}Li*(3.21, 5.4). $(32 \pm 3)\%$ of the emitted neutrons then populate ^{7}Li*(0.48). The decay to ^{8}Li*(3.21, 5.4) suggest $\pi = +$ for ^{8}Li*(3.21) and 0^+ or 1^+ for ^{8}Li*(5.4) (81BJ03). [(BO86Q) suggest $\log ft = 5.0$ for the transition to ^{8}Li*(3.21)]. (86BO41) report β-delayed tritons with a branching ratio of $(0.9 \pm 0.1)\%$. This decay appears to require a 1^+ state in ^{8}Li at 8.8 MeV with a width, $\Gamma_{\text{c.m.}} \simeq 1$ MeV; $\log ft$ is then 4.3 (86BO41). See also (88JO1C).

Table 8.1
Energy levels of ^{8}He

E_x (MeV)	$J^\pi; T$	$\tau_{1/2}$ (msec)	Decay	Reactions
g.s.	$0^+; 2$	119 ± 1.5	β^-	1, 2, 3
2.8 ± 0.4 [a])	$(2^+); 2$			2, 3

[a]) Excited states are calculated at $E_x = 5.83$, 7.92 and 8.18 MeV, with $J^\pi = 2^+$, 1^- and 2^- [$(0+1)\ \hbar\omega$ model space]. In the $(0+2)\ \hbar\omega$ model space the excited states are at 5.69, 9.51 and 11.59 MeV, with $J^\pi = 2^+$, 1^+ and 0^+ (85PO10). See reaction 3 for possible evidence of other states in ^{8}He (BE87DD; prelim.).

2. ^{9}Be(^{7}Li, ^{8}B)^{8}He $\qquad Q_m = -28.264$

At $E(^{7}\text{Li}) = 83$ MeV, $\theta = 10°$, the population of $^{8}\text{He}_{\text{g.s.}}$, an excited state at 2.8 ± 0.4 MeV (presumably $J^\pi = 2^+$) and a structure near $E_x \sim 7$ MeV are reported by (85AL1G). See also (85AL1B, 85AL1H).

3. (a) ^{9}Be(^{9}Be, ^{10}C)^{8}He $\qquad Q_m = -24.602$
   (b) ^{11}B(^{7}Li, ^{10}C)^{8}He $\qquad Q_m = -23.722$

At $E(^{9}\text{Be}) = 106.7$ MeV and at $E(^{11}\text{B}) = 87$ MeV the ground state of ^{8}He is populated. In reaction (a) there is some evidence of a group corresponding to $E_x = 2.6 \pm 0.3$ MeV, $\Gamma = 1.0 \pm 0.5$ MeV, while in reaction (b) excited states are reported at $E_x = 1.3$, 2.6 and 4.0 MeV (± 0.3 MeV). The width of the latter is 0.5 ± 0.3 MeV (BE87DD). See also (88BEYJ).

^{8}Li

(Figs. 11 and 14)

GENERAL: See also (84AJ01).

Nuclear models: (83KU17, 83SH38, 84MO1H, 84RE1B, 84VA06, 88WO04).

Special states: (82PO12, 83KU17, 84RE1B, 84VA06, 86XU02).

Electromagnetic transitions: (83KU17).

Astrophysics: (87MA2C).

Complex reactions involving ^{8}Li: (83FR1A, 83GU1A, 83OL1A, 83WI1A, 84GR08, 84HI1A, 84LA27, 85JA1B, 85MA02, 85MA13, 85MO17, 86AV1B, CS86C, 86GO1G, 86HA1B, 86MA19, 86MO1C, 86NA1D, 86SA30, 86SI1B, 86WE1C, 86XU02, 87BA39, 87BE1F, 87BL13, 87CH26, 87DE37, 87GR11, 87JA06, 87LY04, 87TA1F, 87WA09, 88AU1A, 88BL09, 88CA06, 88KI05, 88LI1A, 88RU01, 88ST06, 88TA1A).

Polarization of ^{8}Li: (84KO25, 86HA1P, 86NO1C, 86NO1D, 87NO04).

Applications: (85HA40, 86NO1C, 87NO04).

Reactions involving pions and other mesons: (83HA45, 86CE04, 86GO1G).

Hypernuclei: (82KA1D, 82MO1B, 83MO1C, 83SH1E, 84AS1D, 84CH1G, 84MI1C, 84MI1E, 84SH1J, 84ZH1B, 85MO1F, 86AN1R, 86DA1B, 86YA1F, 87MI1A, 87PO1H, 87YA1M, 88TA1B).

Other topics: (85AN28).

Ground state of ^{8}Li: (83ANZQ, 85AN28, 85SA32, 86GL1A, AR87H, 87HA30, 87VA26, 88JO1C, 88PO1E, 88VA03, 88WO04).

$J = 2$: see (74AJ01)

$\mu = +1.65335 \pm 0.00035$ n.m.: see (78LEZA)

$Q = 24 \pm 2$ mb: see (79AJ01).

The interaction nuclear radius of ^{8}Li is 2.36 ± 0.02 fm (85TA18) [see also for derived nuclear matter, charge and neutron matter r.m.s. radii].

1. ^{8}Li(β^{-})^{8}Be $\qquad Q_{\mathrm{m}} = 16.0039$

The β^{-} decay is to the broad 2^{+} first-excited state of ^{8}Be, which then breaks up into 2α [see reaction 24 in ^{8}Be]. The half-life is 838 ± 6 msec [see (84AJ01)]; $\log ft = 5.4$ (86WA01).

Table 8.2
Energy levels of ^{8}Li [a]

E_x (MeV ± keV)	J^π; T	τ or $\Gamma_{c.m.}$ (keV)	Decay	Reactions
g.s.	2^+; 1	$\tau_{1/2} = 838 \pm 6$ ms	β^-	1, 2, 3, 7, 8, 9, 11, 12, 13, 14, 15, 17, 18
0.9808 ± 0.1	1^+; 1	$\tau_m = 12 \pm 4$ fs	γ	2, 7, 8, 10, 11, 12, 13, 17, 18
2.255 ± 3	3^+; 1	$\Gamma = 33 \pm 6$ keV	γ, n	2, 3, 4, 7, 11, 12, 13
3.21	1^+; 1	~ 1000	n	5, 10
5.4	$(0, 1)^+$; 1	~ 650	n	5, 10
6.1 ± 100	(3); 1	~ 1000	n	4
6.53 ± 20	4^+; 1	35 ± 15	n	2, 4, 7, 12, 13
7.1 ± 100		~ 400	n	4
(8)	(1^+)	~ 1000	t	10
(9)		~ 6000		11
10.8222 ± 5.5	0^+; 2	< 12		16

[a]) For additional states see reaction 4.

2. ^{6}Li(t, p)^{8}Li $\qquad Q_m = 0.801$

Angular distributions have been obtained at $E_t = 23$ MeV for the proton groups to ^{8}Li*(0, 0.98, 2.26, 6.54 ± 0.03); $\Gamma_{c.m.}$ for ^{8}Li*(2.26, 6.54) are 35 ± 10 and 35 ± 15 keV, respectively. J for the latter is ≥ 4: see (79AJ01).

3. ^{7}Li(n, γ)^{8}Li $\qquad Q_m = 2.033$

The cross section for capture radiation has been measured for $E_n = 40$ to 1000 keV; it decreases from 50 μb to 5 μb over that interval. The cross section shows the resonance corresponding to ^{8}Li*(2.26): $E_{res} = 254 \pm 3$ keV, $\Gamma_n = 31 \pm 7$ keV, $\Gamma_\gamma = 0.07 \pm 0.03$ eV: see table 8.3 and (74AJ01). See also (85SM1B), (81MUZQ, 84SH1N, 86AB1E). The decay of ^{8}Li*(2.26)$\rightarrow$^{7}Li$_{g.s.}$ + n in the interaction of 35 MeV/A ^{14}N ions on Ag is reported by (87BL13).

4. ^{7}Li(n, n)^{7}Li $\qquad E_b = 2.033$

The thermal cross section is 0.97 ± 0.04 b [see (81MUZQ)], $\sigma_{free} = 1.07 \pm 0.03$ b (83KO17). The real coherent scattering length is -2.22 ± 0.01 fm. The complex scattering lengths are $b_+ = -4.15 \pm 0.06$ fm and $b_- = 1.00 \pm 0.08$ fm (83KO17); see also (79GL12). See (84AJ01) for earlier references.

Table 8.3
Resonance parameters for ^{8}Li*(2.26) [a])

$E_{\rm res}$ (keV)	254 ± 3
$E_{\rm x}$ (MeV) [b])	2.261
Γ (keV)	35 ± 5
$\Gamma_{\rm n}$ ($E_{\rm r}$) (keV)	31 ± 7
Γ_γ (eV) [b])	0.07 ± 0.03
$\gamma^2_{\rm n}$ (keV)	594
θ^2	0.091
radius (fm)	3.30
$\sigma_{\rm max}$	12.0
J^π	3^+
$l_{\rm n}$	1

[a]) Energies in lab system except for those labeled (b). For references see (74AJ01, 79AJ01).
[b]) Energies in c.m. system.

Total and elastic cross sections have been reported for $E_{\rm n} = 5$ eV to 49.6 MeV: see (74AJ01, 79AJ01, 84AJ01). Cross sections have also been reported for $\rm n_0$, $\rm n_{0+1}$ and $\rm n_2$ at $E_{\rm n} = 6.82$, 8.90 and 9.80 MeV. (87SC08; $\rm n_2$ at the two higher energies).

A pronounced resonance is observed at $E_{\rm n} = 254$ keV with $J^\pi = 3^+$, formed by p-waves: see table 8.3. A good account of the polarization is given by the assumption of levels at $E_{\rm n} = 0.25$ and 3.4 MeV, with $J^\pi = 3^+$ and 2^-, together with a broad $J^\pi = 3^-$ level at higher energy. Broad peaks are reported at $E_{\rm n} = 4.6$ and 5.8 MeV ($\pm$ 0.1 MeV) [^{8}Li*(6.1, 7.1)] with $\Gamma \sim 1.0$ and 0.4 MeV, respectively, and there is indication of a narrow peak at $E_{\rm n} = 5.1$ MeV [^{8}Li*(6.5)] with $\Gamma \ll 80$ keV and of a weak, broad peak at $E_{\rm n} = 3.7$ MeV: see (74AJ01, 84AJ01). A multi-level, multi-channel R-matrix calculation is reported by (87KN04). This analysis leads to predictions for the cross section for elastic scattering, for (n, n′) to ^{7}Li*(0.48, 4.68, 6.68) and for triton production. A number of additional (broad) states of ^{8}Li, unobserved directly in this and in other reactions, derive from this analysis (87KN04). See also (84FE1A, 84MO1J), (83DA22, 83GO1H, 84SH1N, 84SH1B, 86BO1J, 87LE1D, 88MA1H) and (83FA17, 86BA2F, 86FI1E, 87VE02; theor.).

5. (a) ^{7}Li(n, n′)^{7}Li $\qquad E_{\rm b} = 2.033$
(b) ^{7}Li(n, n′)^{3}H + ^{4}He $\qquad Q_{\rm m} = -2.4678$

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 ($\Gamma \simeq 1$ MeV) at $E_{\rm n} = 1.35$ MeV. A good fit is obtained with either $J^\pi = 1^-$ or 1^+ (2^+ not excluded),

$\Gamma_{lab} = 1.14$ MeV. A prominent peak is observed at $E_n = 3.8$ MeV ($\Gamma_{lab} = 0.75$ MeV) and there is some indication of a broad resonance ($\Gamma_{lab} = 1.30$ MeV) at $E_n = 5.0$ MeV. At higher energies there is some evidence for structuree at $E_n = 6.8$ and 8 MeV followed by a decrease in the cross section to 20 MeV: see (79AJ01, 84AJ01). The total cross section for ($n_0 + n_1$) and n_2 have been reported at $E_n = 8.9$ MeV (84FE1A; prelim.). For R-matrix analyses see (87KN04) in reaction 4 and (84AJ01).

The cross section for reaction (b) rises from threshold to ∼360 mb at $E_n \sim 6$ MeV and then decreases slowly to ∼250 mb at $E_n \sim 16$ MeV: see (85SW01, 87QA01). Cross sections for tritium production have been reported recently from threshold to $E_n = 16$ MeV (83LI1C; prelim.), 4.57 to 14.1 MeV (85SW01), 7.9 to 10.5 MeV (87QA01), 14.74 MeV (84SM1B; prelim.) and at 14.94 MeV (GO85U: 302±18 mb). At $E_n = 14.95$ MeV the total α production cross section [which includes to (n, 2n d) process] is 336 ± 16 mb (86KN06). Spectra at 14.6 MeV may indicate the involvement of states of ^{4}H (86MI11). The half-life of ^{3}H has recently been measured to be 12.38 ± 0.03 mean solar years (87OL04). See also (87TI07).

See also (86DE1L, 86DR1D), (84SH1N, 85BO1D, 86BO1J, 86LI1H) and (86CH1S, 86FA1B, 86GO1K, 86IG1A, 86KO32, 86MA1R, 86SE1D, 86SH1T, 86SH1U, 86TA1H, 86VE1A, 86YA1K, 86YO1D; applications).

6. ^{7}Li(n, 2n)^{6}Li $\quad Q_m = -7.2501 \quad E_b = 2.033$

See (85CH37, 86CH1R). See also (84SH1B, 86BO1J, 88MA1H).

7. ^{7}Li(p, π^+)^{8}Li $\quad Q_m = -138.318$

Angular distributions and analyzing powers for the transitions to ^{8}Li*(0, 0.98, 2.26) have been studied at $E_{\vec{p}} = 200.4$ MeV. [The (p, π^-) reaction to the analog states in ^{8}B is discussed there.] The (p, π^+) cross sections are an order of magnitude greater than the (p, π^-) cross sections and show a much stronger angular dependence (87CA06). Angular distributions and A_y have also been measured at $E_{\vec{p}} = 250$, 354 and 489 MeV to the first three states of ^{8}Li. Those to ^{8}Li*(0, 2.26) have differential cross sections which exhibit a maximum near the invariant mass of the Δ_{1232} and A_y which are similar to each other and to those of the $\bar{p}p \rightarrow d\pi^+$ reaction. ^{8}Li*(6.53) is clearly populated (87HU12).

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

Angular distributions of the p_0 and p_1 groups [$l_n = 1$] at $E_d = 12$ MeV have been analyzed by DWBA: $S_{exp} = 0.87$ and 0.48 respectively for ^{8}Li*(0, 0.98). Angular distributions have also been measured at several energies in the range of $E_d = 0.49 \rightarrow 3.44$ MeV (p_0) and 0.95 to 2.94 MeV (p_1). The lifetime of ^{8}Li*(0.98) is 10.1 ± 4.5 fsec: see (79AJ01). See also (85FI1D; astrophysics).

9. (a) ^{7}Li(^{6}Li, ^{5}Li)^{8}Li $\qquad Q_m = -3.63$
   (b) ^{7}Li(^{7}Li, ^{6}Li)^{8}Li $\qquad Q_m = -5.217$

See (84KO25).

10. ^{8}He(β^-)^{8}Li $\qquad Q_m = 10.652$

See ^{8}He.

11. (a) ^{9}Be(e, ep)^{8}Li $\qquad Q_m = -16.887$
    (b) ^{9}Be(p, 2p)^{8}Li $\qquad Q_m = -16.887$

For reaction (a) see (84AJ01) and (85KI1A). The summed proton spectrum (reaction (b)) at $E_p = 156$ MeV shows peaks corresponding to ^{8}Li(0) and ^{8}Li*(0.98 + 2.26) [unresolved]. In addition s-states [$J^\pi = 1^-, 2^-$] are suggested at $E_x = 9$ and 16 MeV, with $\Gamma_{c.m.} \simeq 6$ and 8 MeV; the latter may actually be due to continuum protons: see (74AJ01). At $E_p = 1$ GeV the separation energy between 5 and 8 MeV broad $1p_{3/2}$ and $1s_{1/2}$ groups is reported to be 10.7 ± 0.5 MeV (85BE1J, 85DO1B). See also (87GAZM).

12. ^{9}Be(d, ^{3}He)^{8}Li $\qquad Q_m = -11.393$

Angular distributions have been reported for the ^{3}He ions to ^{8}Li*(0, 0.98, 2.26, 6.53) at $E_d = 28$ MeV [C^2S (abs.) = 1.63, 0.61, 0.48, 0.092] and 52 MeV. The distributions to ^{8}Li*(6.53)[$\Gamma < 100$ keV] are featureless: see (79AJ01).

13. ^{9}Be(t, α)^{8}Li $\qquad Q_m = 2.927$

At $E_t = 12.98$ MeV, angular distributions of the α-particles to ^{8}Li*(0, 0.98, 2.26, 6.53 ± 0.02 [$\Gamma_{c.m.} < 40$ keV]) have been measured: see (74AJ01). At $E_t = 17$ MeV angular distributions to these four states have been analyzed by ZRDWBA and C^2S have been derived (88LI1B). At $E_t = 17$ MeV, $\sigma(\theta)$ and A_y measurements, analyzed by CCBA, lead to $J^\pi = 4^+$ for ^{8}Li*(6.53): see (84AJ01). For ^{8}Li*(0.98), $\tau_m = 14 \pm 5$ fsec, $E_x = 980.80 \pm 0.10$ keV: see (74AJ01).

14. ^{9}Be(^{7}Li, ^{8}Be)^{8}Li $Q_{\rm m} = 0.367$

See (84KO25).

15. ^{9}Be(^{11}B, ^{12}C)^{8}Li $Q_{\rm m} = -0.930$

See (86BE1Q).

16. ^{10}Be(p, ^{3}He)^{8}Li $Q_{\rm m} = -15.981$

At $E_{\rm p} = 45$ MeV, ^{3}He ions are observed to a state at $E_{\rm x} = 10.8222 \pm 0.0055$ MeV ($\Gamma_{\rm c.m.} < 12$ keV): the angular distributions for the transition to this state, and to its analog (^{8}Be*(27.49)), measured in the analog reaction [^{10}Be(p, t)^{8}Be] are very similar. They are both consistent with $L = 0$ using a DWBA (LZR) analysis: see (79AJ01).

17. ^{11}B(n, α)^{8}Li $Q_{\rm m} = -6.631$

Angular distributions of the α_0 and α_1 groups have been measured at $E_{\rm n} = 14.1$ and 14.4 MeV: see (74AJ01, 84AJ01).

18. ^{11}B(^{7}Li, ^{10}B)^{8}Li $Q_{\rm m} = -9.421$

At $E(^{7}{\rm Li}) = 34$ MeV angular distributions have been studied involving ^{8}Li(g.s., 0.98) and ^{10}B$_{\rm g.s.}$ (87CO16).

19. ^{13}C(d, ^{7}Be)^{8}Li $Q_{\rm m} = -20.454$

See (84NE1A).

^{8}Be
(Figs. 12 and 14)

GENERAL: See also (84AJ01).

Shell model: (84PA04, 84VA06, 84ZW1A, 85FI1E, 87BL18, 87KI1C, 88WO04).

Collective, rotational and deformed models: (84PA04, 85RO1G).

Cluster and α-particle models: (81PL1A, 83CA12, 83DR09, 83FU1D, 83HA41, 83JA09, 83SH38, 84DE24, 84DU17, 84LU1A, 84LU1B, 85FI1E, 86GU1F, 86KR12, 86SU06, 88KR01).

Special states: (81PL1A, 83AD1B, 83BI1C, 83FE07, 83FI1D, 83HA41, 84DE24, 84DU17, 84LU1A, 84LU1B, 84VA06, 84VA1C, 84ZW1A, 85FI1E, 85GO1A, 85PO19, 85PU03, 85RO1G, 86AN10, 87KA18, 87KI1C, 87SV1A, 87WA1J, 88BA75, 88KR01 88KW1A, 88KH03).

Electromagnetic transitions, giant resonances: (83FI1D, 84VA1B, 85FI1E, 85GO1A, 85GR1A, 86AN10, 86QU1B, 87KI1C).

Astrophysical questions: (85BO1E, 87FU04).

Complex reactions involving ^{8}Be: (82GU1B, 83DEZW, 83EL1A, 83SI1A, 83WA1F, 83XU1A, 84AB1C, 84PA13, 85BU16, 85HA1N, 85KA1E, 85KA1F, 85KA1G, 85KW03, 85PO11, 85PO19, 85WA22, 86BA2D, 86BL12, 86BR26, 86GA24, 86GU1F, 86IR01, 86MA1O, 86PO06, 86PO12, 86TA1M, 87AR19, 87BL16, 87CH26, 87CH33, 87CH32, 87DE1O, 87DU07, 87GE1B, 87GL1G, 87HA1M, 87PE1B, 87PO1I, 87RUZK, 88AR05, 88PO1A, 88RU01, 88SA09, 88VA1E).

Reactions involving pions and other mesons: (81MC09, 83SP06, 85BE1C, 87HU12).

Hypernuclei: (82KA1D, 83SH38, 83SH1E, 84ZH1B, 85AH1A, 85IK1A, 85MO1F, 86BA1W, 86DA1B, 87BA2K, 87MI1A, 87PO1H, 87YA1M, 88TA1B).

Other topics: (83AD1B, 83BI1C, 83FU1D, 83GR26, 83MI1E, 85AN28, 86BL1D, 86GL1E, 86MA1W, 87AB21, 87SV1A, 88AJ1B, 88BO04, 88KW1A, 88RU1B, 88RU1D, 88WA1E).

Ground-state properties of ^{8}Be: (83ANZQ, 83DR09, 84DU17, 84LU1A, 84LU1B, 85AN28, 85FI1E, 85GO1A, 85SH1A, 87BL18, 87BO42, 87KI1C, 87KO1U, 87SA15, 87SV1A, 88AR05, 88WO04).

1. $^{8}\mathrm{Be} \rightarrow 2\,^{4}\mathrm{He}$ $\qquad Q_{\mathrm{m}} = 0.09189$

$\Gamma_{\mathrm{c.m.}}$ for $^{8}\mathrm{Be}_{\mathrm{g.s.}} = 6.8 \pm 1.7$ eV: see (74AJ01). See also (87WE1C, 88BA1H; astrophysics) and (83DR09; theor.).

2. ^{4}He(α, γ)^{8}Be $\qquad Q_m = -0.09189$

The yield of γ_1 has been measured for $E_\alpha = 32$ to 36 MeV. The yield of γ_0 for $E_\alpha = 33$ to 38 MeV is twenty times lower than for γ_1, consistent with E2 decay. An angular correlation measurement at the resonances corresponding to ^{8}Be*(16.6 + 16.9)[2^+; $T = 0 + 1$] gives $\delta = 0.19 \pm 0.03$, Γ_γ(M1) $= 6.4 \pm 0.5$ eV [weighted mean of the two published measurements listed in (79AJ01)]. The E_x of ^{8}Be*(3.0) is determined in this reaction to be 3.18±0.05 MeV [see also table 8.4 in (74AJ01)].

The E2 bremsstrahlung cross section to ^{8}Be$_{\text{g.s.}}$ has been calculated as a function of E_x over the 3-MeV state: the total Γ_γ for this transition is 8.3 meV, corresponding to 75 W.u. (86LA05). A calculation of the Γ_γ from the decay of the 4^+ 11.4-MeV state to the 2^+ state yields 0.46 eV (19 W.u.). The maximum cross section for the intrastate γ-ray transition within the 2^+ resonance is calculated to be $\leq$2.5 nb at $E_x \sim 3.3$ MeV (86LA19). See also (85BA45; theor.).

3. (a) ^{4}He(α, n)^{7}Be $\qquad Q_m = -18.990 \qquad E_b = -0.09189$
(b) ^{4}He(α, p)^{7}Li $\qquad Q_m = -17.3462$
(c) ^{4}He(α, d)^{6}Li $\qquad Q_m = -22.3716$

The cross sections for formation of ^{7}Li*(0, 0.48) [$E_\alpha = 39$ to 49.5 MeV] and ^{7}Be*(0, 0.43) [39.4 to 47.4 MeV] both show structures at $E_\alpha \sim 40.0$ and ~ 44.5 MeV: they are due predominantly to the 2^+ states ^{8}Be*(20.1, 22.2): see (79AJ01). The excitation functions for p_0, p_2, d_0, d_1 for $E_\alpha = 54.96$ to 55.54 MeV have been measured in order to study the decay of the first $T = 2$ state in ^{8}Be: see table 8.5 in (84AJ01). Cross sections for p_{0+1} are also reported at $E_\alpha = 37.5$ to 140.0 MeV: see (79AJ01, 84AJ01). The cross sections for reaction (c) has been measured at three energies in the range $E_\alpha = 46.7$ to 49.5 MeV: see (79AJ01) and below.

The production of ^{6}Li, ^{7}Li and ^{7}Be [and ^{6}He] has been studied for $E_\alpha = 61.5$ to 158.2 MeV by (82GL01) and at 198.4 MeV by (85WO11). The production of ^{7}Li (via reactions (a) and (b)) and of ^{6}Li is discussed. At energies beyond $E_\alpha \sim 250$ MeV the $\alpha + \alpha$ reaction does not contribute to the natural abundance of lithium, reinforcing theories which produce ^{6}Li in cosmic-ray processes and the "missing" ^{7}Li in the Big Bang: thus the universe is open (85WO11, 82GL01).

The inclusive cross section for production of ^{3}He has been measured at $E_\alpha = 218$ MeV (84AL03). For a fragmentation study at 125 GeV see (85BE1E). See also (84AJ01, 84PA1E, 84RE1A).

4. ^{4}He(α, α)^{4}He $\qquad E_b = -0.09189$

The α-α scattering reveals the ground state as a resonance with $Q_0 = 92.12 \pm 0.05$ keV, $\Gamma_{\text{c.m.}} = 6.8 \pm 1.7$ eV [$\tau = (0.97 \pm 0.24) \times 10^{-16}$ sec]. For $E_\alpha = 30$ to 70 MeV the $l = 0$

Table 8.4
Energy levels of ^{8}Be [a])

E_x (MeV ± keV)	J^π; T	$\Gamma_{c.m.}$ (keV)	Decay	Reactions
g.s.	0^+; 0	6.8 ± 1.7 eV	α	1, 2, 4, 10, 11, 12, 13, 14, 19, 20, 21, 22, 23, 26, 27, 28, 29, 30, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52
3.04 ± 30	2^+; 0	1500 ± 20	α	2, 4, 10, 11, 12, 13, 14, 19, 20, 21, 22, 24, 25, 26, 27, 28, 29, 30, 32, 34, 35, 36, 37, 38, 41, 42, 44, 45
11.4 ± 300	4^+; 0	~ 3500 [b])	α	4, 12, 13, 19, 21, 27, 28, 29, 42, 44, 45
16.626 ± 3	2^+; $0+1$	108.1 ± 0.5	γ, α	2, 4, 10, 11, 13, 14, 19, 20, 21, 25, 28, 29, 34, 35, 38, 42, 44
16.922 ± 3	2^+; $0+1$	74.0 ± 0.4	γ, α	2, 4, 10, 11, 13, 14, 19, 20, 21, 27, 28, 29, 34, 35, 38, 42, 44
17.640 ± 1.0	1^+; 1	10.7 ± 0.5	γ, p	5, 11, 14, 16, 19, 20, 27, 28, 35, 44
18.150 ± 4	1^+; 0	138 ± 6	γ, p	11, 14, 16, 19, 20, 27, 28, 35, 38
18.91	2^-	122 [e])	γ, n, p	11, 14, 15, 16, 19, 23
19.07 ± 30	3^+; (1)	270 ± 20	γ, p	11, 14, 16, 19, 27, 28
19.24 ± 25	3^+; (0)	230 ± 30	n, p	15, 16, 19, 27, 28, 29, 35
19.4	1^-	~ 650	n, p	11, 15, 16
19.86 ± 50	4^+; 0	700 ± 100	p, α	4, 11, 18, 21, 22, 28, 29, 35
20.1	2^+; 0	~ 1100	n, p, α	4, 15, 16, 18, 22, 35
20.2	0^+; 0	< 1000	α	4, 35
20.9	4^-	1600 ± 200	p	16
21.5	$3^{(+)}$	1000	γ, n, p	14, 15
22.0 [c])	1^-; 1	~ 4000	γ, p	14
22.05 ± 100		270 ± 70		29

Table 8.4 (continued)
Energy levels of ^{8}Be [a])

E_x (MeV ± keV)	J^π; T	$\Gamma_{c.m.}$ (keV)	Decay	Reactions
22.2	2^+; 0	∼ 800	n, p, d, α	4, 9, 13, 15, 16, 18
22.63 ± 100		100 ± 50		29
22.98 ± 100		230 ± 50		29
24.0 [c])	(1, 2)$^-$; 1	∼ 7000	γ, p, α	14, 18
25.2	2^+; 0		p, d, α	4, 9, 18
25.5	4^+; 0	broad	d, α	9
27.4941 ± 1.8 [d])	0^+; 2	5.5 ± 2.0	γ, n, p, d, t, ^{3}He, α	5, 7, 9, 31
(28.6)		broad	γ, p	14

[a]) See also table 8.5 and reaction 4.
[b]) See, however, reaction 27.
[c]) Giant resonance: see reaction 14.
[d]) For the parameters of this state please see table 8.5 in (84AJ01).
[e]) See reaction 23.

Table 8.5
Electromagnetic transitions in ^{8}Be [a])

Transition	Γ_γ (eV)	$\|M\|^2$ (W.u.)
17.6 → 0	16.7	0.15
17.6 → 3.0	8.15 ± 0.07 (M1) [b])	0.12
	0.15 ± 0.07 (E2)	
17.6 → 16.6	0.032 ± 0.003 [c])	1.48 ± 0.15 (M1)
17.6 → 16.9	0.0013 ± 0.0003	0.15 ± 0.04 (M1)
18.15 → 0	3.0	
18.15 → 3.0	3.8	
18.15 → 16.6	0.077 ± 0.019	1.04 ± 0.26 (M1)
18.15 → 16.9	0.062 ± 0.007	1.51 ± 0.17 (M1)
18.9 → 16.6	0.168	0.053 (E1)
18.9 → 16.9	0.099	0.045 (E1)
19.07 → 3.0	10.5	

[a]) See table 8.7 in (79AJ01) for the references. See also reaction 2 here.
[b]) δ(E2/M1) = 0.21 ± 0.04, averaged over the energy of the final state.
[c]) Nearly pure M1: δ(E2/M1) = −0.014 ± 0.013.

phase shift shows resonant behavior at $E_\alpha = 40.7$ MeV, corresponding to a 0^+ state at $E_x = 20.2$ MeV, $\Gamma < 1$ MeV, $\Gamma_\alpha/\Gamma < 0.5$. No evidence for other 0^+ states is seen above $E_\alpha = 43$ MeV.

The d-wave phase shift becomes appreciable for $E_\alpha > 2.5$ MeV and passes through resonance at $E_\alpha = 6$ MeV ($E_x = 3.18$ MeV, $\Gamma = 1.5$ MeV, $J^\pi = 2^+$): see table 8.4 in (74AJ01). Five 2^+ levels are observed from $l = 2$ phase shifts measured from $E_\alpha = 30$ to 70 MeV: ^{8}Be*(16.6, 16.9) with $\Gamma_\alpha = \Gamma$ [see table 8.6], and states with $E_x = 20.1$, 22.2 and 25.2 MeV. The latter has a small Γ_α. The l=2 α-α phase shifts have been analyzed by (86WA01) up to $E_\alpha = 34$ MeV: intruder states below $E_x = 26$ MeV need not be introduced.

The $l = 4$ phase shift rises from $E_\alpha \sim 11$ MeV and indicates a broad 4^+ level at $E_x = 11.5 \pm 0.3$ MeV [$\Gamma = 4.0 \pm 0.4$ MeV]. A rapid rise of δ_4 at $E_\alpha = 40$ MeV corresponds to a 4^+ state at 19.9 MeV with $\Gamma_\alpha/\Gamma \sim 0.96$; $\Gamma < 1$ MeV and therefore $\Gamma_\alpha < 1$ MeV, which is <5% of the Wigner limit. A broad 4^+ state is also observed near $E_\alpha = 51.3$ MeV ($E_x = 25.5$ MeV).

Over the range $E_\alpha = 30$ to 70 MeV a gradual increase in δ_6 is observed. Some indications of a 6^+ state at $E_x \sim 28$ MeV and of an 8^+ state at ∼57 MeV have been reported; $\Gamma_{\rm c.m.} \sim 20$ and ∼73 MeV, respectively. A resonance is not observed at the first $T = 2$ state, ^{8}Be*(27.49). See (79AJ01) for references.

The elastic scattering has also been studied at $E_\alpha = 56.3$ to 95.5 MeV (87NE1C; prelim.), 158.2 MeV, 650 and 850 MeV and at 4.32 and 5.07 GeV/c [see (79AJ01, 84AJ01)] as well as at 198.4 MeV (85WO11). For α-α correlations involving ^{8}Be*(0, 3.0) see (87CH33, 87PO03). See also (86FO04, 86GO1D, 86KR1B, 86UC1A, 87FO08) and p. 84. For inclusive cross sections see (84AJ01) and (84AL03; 218 MeV).

For studies at very high energies see reaction 3 and (82AB1B, 84SA1C, 84TA1D, 84TA1G, 85AB1A, 85AK1A, 85CA1C, BE86DD, 86BE1S, 86BE1T, 86TA1N, 86TA1P, 87BA13). See also (86CH1M), (82NA1B, 83FA1A, 84FA1B, 84FR1C, 85CA41, 85FA1A, 85FR1E, 85WI1B, 86AN1F, 86CH1J, 86ST1D, 87HE1B, 87OT1D), (85NO1B, 86LA16, 87FU04, 87MU1B; astrophysics) and (82WE15, 83AL1C, 83BU15, 83FI1D, 83GO25, 83KO41, 83MA73, 83OK06, 83PR1A, 83SA16, 84DE24, 84FI11, 84FI13, 84FR10, 84HE1D, 84KR10, 84LI1D, 84MA16, 84MA1H, 84MA68, 84NA11, 84OK03, 84TA1E, 84VA1C, 84ZA1B, 85BA45, 85FI1E, 85FR1F, 85HO1B, 85KI11, 85PR1A, 85PR1B, 85SP05, 85TH08, 85YA05, 85YI1B, 85YI1C, 86CR1B, 86FR12, 86HO33, 86LA12, 86MA03, 86OC1A, 86SA30, 86SU06, 86WI04, 86YU01, 87BA35, 87FR1D, 87KA1W, 87KR03, 87OC1B, 87PR01, 87SA37, 87SH1M, 87WA07, 88BA75, 88KR01, 88MO05; theor.).

5. ^{6}Li(d, γ)^{8}Be $\qquad Q_{\rm m} = 22.2798$

The yield of γ-rays to ^{8}Be*(17.64) [1^+; $T = 1$] has been measured for $E_d = 6.85$ to 7.10 MeV. A resonance is observed at $E_d = 6965$ keV [$E_x = 27495.8 \pm 2.4$ keV, $\Gamma_{\rm c.m.} = 5.5 \pm 2.0$ keV]; $\Gamma_\gamma = 23 \pm 4$ eV [1.14 ± 0.20 W.u.] for this M1 transition from the first 0^+; $T = 2$ state in ^{8}Be, in good agreement with the intermediate coupling model: see table 8.5 in (84AJ01). See also (79AJ01).

Table 8.6
Some ^{8}Be states with $16.6 < E_x < 23.0$ MeV [a]

E_x (MeV ± keV)	$\Gamma_{c.m.}$ (keV)	Reaction
16.627 ± 5	113 ± 3	^{7}Li(^{3}He, d)
	90 ± 5	^{10}B(d, α)
16.623 ± 3	107.7 ± 0.5	^{4}He(α, α) [b]
16.630 ± 3	108.5 ± 0.5	^{4}He(α, α) [c]
16.626 ± 3	108.1 ± 0.5	"best" value
16.901 ± 5	77 ± 3	^{7}Li(^{3}He, d)
	70 ± 5	^{10}B(d, α)
16.925 ± 3	74.4 ± 0.4	^{4}He(α, α) [b]
16.918 ± 3	73.6 ± 0.4	^{4}He(α, α) [c]
16.922 ± 3	74.0 ± 0.4	"best" value
17.640 ± 1.0	10.7 ± 0.5	^{7}Li(p, γ)
18.155 ± 5	147	^{7}Li(p, γ)
18.150 ± 5	138 ± 6	^{10}B(d, α)
18.144 ± 5		^{9}Be(d, t)
18.150 ± 4	138 ± 6	"best" value
19.06 ± 20	270 ± 20	^{7}Li(p, γ)
19.071 ± 10	270 ± 30	^{9}Be(d, t)
19.07 ± 30	270 ± 20	"best" value
19.21	208 ± 30	^{9}Be(p, d)
19.22 ± 30	265 ± 30	^{9}Be(^{3}He, α)
19.26 ± 30	220 ± 30	^{9}Be(d, t)
19.24 ± 25	230 ± 30	"best" value
19.86 ± 50	700 ± 100	^{9}Be(d, t)
22.05 ± 100	270 ± 70	^{9}Be(^{3}He, α)
22.63 ± 100	100 ± 50	^{9}Be(^{3}He, α)
22.98 ± 100	230 ± 50	^{9}Be(^{3}He, α)

[a]) See table 8.5 in (79AJ01) for references. See also tables 8.7 and 8.8 here.
[b]) R-matrix theory.
[c]) Complex eigenvalue theory.

6. ^{6}Li(d, n)^{7}Be $Q_m = 3.381$ $E_b = 22.2798$

Yield curves and cross sections have been measured for E_d = 48 keV to 17 MeV: see (79AJ01, 84AJ01). See also (83SZ1A). Polarization measurements are reported at E_d = 0.27 to 3.7 MeV. Comparisons of the populations of ^{7}Be*(0, 0.43) and of ^{7}Li*(0, 0.48) have been made at many energies, to E_d = 7.2 MeV. The n/p ratios are closely equal for analog states, as expected for charge symmetry: see (79AJ01). However, the n_1/p_1 yield ratio decreases from 1.05 at E_d = 160 keV to 0.94 at 60 keV: it is suggested that this is due to polarization of the deuteron (85CE12). See also ^{7}Be, (85WA1C) and (84KU15; theor.).

7. ^{6}Li(d, p)^{7}Li $Q_m = 5.0255$ $E_b = 22.2798$

Excitation functions have been measured for E_d = 30 keV to 5.4 MeV: see (79AJ01, 84AJ01). The thick target yield of 0.48-MeV γ-rays is reported from ∼50 to ∼170 keV (85CE12). See also (83SZ1A). An anomaly is observed in the p_1/p_0 intensity ratio at E_d = 6.945 MeV, corresponding to the first 0^+; $T = 2$ state, $\Gamma = 10 \pm 3$ keV, $\Gamma_{p_0} \ll \Gamma_{p_1}$, $\Gamma_{p_0} < \Gamma_d$. Polarization measurements have been reported at E_d = 0.6 to 10.9 MeV: see (79AJ01). See also ^{7}Li and (84KU15; theor.).

8. (a) ^{6}Li(d, d)^{6}Li $E_b = 22.2798$
(b) ^{6}Li(d, t)^{5}Li $Q_m = 0.59$

The yield of elastically scattered deuterons has been measured for E_d = 2 to 7.14 MeV. No resonances are observed: see (74AJ01). See also (83HA1D, 85LI1C; theor.). The cross section for tritium production rises rapidly to 190 mb at 1 MeV, then more slowly to 290 mb near 4 MeV: see (74AJ01). For VAP and TAP measurements at $E_{\vec{d}}$ = 191 and 395 MeV see (86GA18).

9. (a) ^{6}Li(d, α)^{4}He $Q_m = 22.3716$ $E_b = 22.2798$
(b) ^{6}Li(d, αp)^{3}H $Q_m = 2.5576$

Cross sections and angular distributions (reaction (a)) have been measured at E_d = 30 keV to 31 MeV: see (79AJ01, 84AJ01). See also (83SZ1A). A critical analysis of the low-energy data has led to a calculation of the reaction rate parameters for thermonuclear reactions for plasma temperatures of 2 keV to 1 MeV: see (84AJ01). Polarization measurements are reported in the range 0.4 to 11 MeV: see (79AJ01, 84AJ01) and see below.

Pronounced variations are observed in the cross sections and in the analyzing powers. Maxima are seen at E_d = 0.8 MeV, $\Gamma_{lab} \sim 0.8$ MeV and E_d = 3.75 MeV, $\Gamma_{lab} \sim 1.4$ MeV.

The 4 MeV peak is also observed in the tensor component coefficients with $L = 0$, 4 and 8 and in the vector component coefficients: two overlapping resonances are suggested. At higher energies all coefficients show a fairly smooth behavior which suggests that only broad resonances can exist. The results are in agreement with those from reaction 4, that is with two 2^+ states at $E_x = 22.2$ and 25.2 MeV and a 4^+ state at 25.5 MeV. A strong resonance is seen in the α^* channel [to ^{4}He(20.1), $J^\pi = 0^+$] presumably due to ^{8}Be*(25.2, 25.5). In addition the ratio of the α^*/α differential cross sections at 30° shows a broad peak centered at $E_x \sim 26.5$ MeV (which may be due to interference effects) and suggests a resonance-like anomaly at $E_x \sim 28$ MeV. $A_{yy} = 1$ points are reported at $E_d = 5.55 \pm 0.12$ ($\theta_{c.m.} = 29.7 \pm 1.0°$) and 8.80 ± 0.25 MeV ($\theta_{c.m.} = 90.0 \pm 1.0°$) [corresponds to $E_x = 26.44$ and 28.87 MeV]. For references see (74AJ01, 79AJ01).

At $E_d = 6.945$ MeV, the α_0 yield shows an anomaly corresponding to ^{8}Be*(27.49), the 0^+; $T = 2$ analog of ^{8}He$_{g.s.}$. This $T = 2$ state has recently been studied using both polarized deuterons and ^{6}Li ions. The ratio of the partial widths for decay into ^{6}Li + d states with channel spin 2 and 0, $\Gamma_2/\Gamma_1 = 0.322 \pm 0.091$ (86SO07).

A kinematically complete study of reaction (b) has been reported at $E_d = 1.2$ to 8.0 MeV: the transition matrix element squared plotted as a function of $E_{\alpha\alpha^*}$ (the relative energy in the channel ^{4}He$_{g.s.}$ + ^{4}He*(20.1) [0^+]) shows a broad maximum at $E_x \sim 25$ MeV. Analysis of these results, and of a study of ^{7}Li(p, α)α^* [see reaction 18] which shows a peak of different shape at $E_x \sim 24$ MeV, indicate the formation and decay of overlapping states of high spatial symmetry, if the observed structures are interpreted in terms of ^{8}Be resonances: see (84AJ01). For other work see (84AJ01). See also ^{6}Li, (86ST1E), (84VO1A, 88KU1E; applications) and (83HA1D, 84KR1B, 84KU15; theor.).

10. ^{6}Li(t, n)^{8}Be $\qquad Q_m = 16.0225$

At $E_t = 2$ to 4.5 MeV ^{8}Be*(0, 3.0, 16.6, 16.9) are populated (84LIZY; prelim.). See also (66LA04, 74AJ01).

11. (a) ^{6}Li(^{3}He, p)^{8}Be $\qquad Q_m = 16.7863$

(b) ^{6}Li(^{3}He, p)2 ^{4}He $\qquad Q_m = 16.8782$

Angular distributions have been studied in the range $E(^3\text{He}) = 0.46$ to 17 MeV and at $E(^6\vec{\text{Li}}) = 21$ MeV. ^{8}Be*(0, 3.0, 16.63, 16.92, 17.64, 18.15, 19.0, 19.4, 19.9) are populated in this reaction: see (74AJ01, 79AJ01, 84AJ01). For reaction (b) see (74AJ01) and (87ZA07). See also ^{9}B.

12. (a) ^{6}Li(α, d)^{8}Be $\qquad Q_m = -1.5669$

(b) ^{6}Li(α, 2α)^{2}H $\qquad Q_m = -1.4750$

Deuteron groups have been observed to ^{8}Be*(0, 3.0, 11.3 $\pm$ 0.4). Angular distributions have been measured at E_α = 15.8 to 48 MeV: see (74AJ01, 79AJ01). A study of reaction (b) shows that the peak due to ^{8}Be*(3.0) is best fitted by using Γ = 1.2 $\pm$ 0.3 MeV. At E_α = 42 MeV the α-α FSI is dominated by ^{8}Be*(0, 3.0). See also table 8.4 in (74AJ01) and (83BE1H; theor.).

13. (a) ^{6}Li(^{6}Li, α)^{8}Be $\qquad Q_m = 20.805$

(b) ^{6}Li(^{6}Li, α)2 ^{4}He $\qquad Q_m = 20.897$

(c) ^{6}Li(^{6}Li, 2d)2 ^{4}He $\qquad Q_m = -2.950$

At E_{max}(^{6}Li) = 13 MeV reaction (a) proceeds via ^{8}Be* (0, 3.0, 16.6, 16.9, 22.5). The involvement of a state at E_x = 19.9 MeV (Γ = 1.3 MeV) is suggested. Good agreement with the shapes of the peaks corresponding to ^{8}Be*(16.6, 16.9) is obtained by using a simple two-level formula with interference, corrected for the effect of final-state Coulomb interaction, assuming Γ(16.6) = 90 keV and Γ(16.9) = 70 keV: see also table 8.6. The ratio of the intensities of the groups corresponding to ^{8}Be*(16.6, 16.9) remains constant for E(^{6}Li) = 4.3 to 5.5 MeV: $I(16.6)/I(16.9) = 1.22 \pm 0.08$. Partial angular distributions for the α_0 group have been measured at fourteen energies for E(^{6}Li) = 4 to 24 MeV. See (79AJ01) for the references.

At E(^{6}Li) = 36 to 46 MeV sequential decay (reaction (b)) via ^{8}Be states at E_x = 3.0, 11.4, 16.9 and 19.65 MeV is reported: see (84AJ01). (87LA25) report the possible involvement of the 2^+ state ^{8}Be*(22.2).

For reaction (c) see (83WA09) and ^{12}C in (85AJ01). See also (83MI10) and (82LA19, 85NO1A; theor.).

14. ^{7}Li(p, γ)^{8}Be $\qquad Q_m = 17.2543$

Cross sections and angular distributions have been reported from E_p = 30 keV to 18 MeV. Gamma rays are observed to the ground (γ_0) and to the broad, 2^+, excited state at 3.0 MeV (γ_1) and to ^{8}Be*(16.6, 16.9) (γ_3, γ_4). Resonances for both γ_0 and γ_1 occur at E_p = 0.44 and 1.03 MeV, and for γ_1 alone at 2, 4.9, 6.0, 7.3, and possibly at 3.1 and 11.1 MeV. In addition broad resonances are reported at $E_p \sim 5$ MeV (γ_0), $\Gamma \sim$ 4–5 MeV, and at $E_p \sim 7.3$ MeV (γ_1), $\Gamma \sim 8$ MeV: see table 8.7. The $E_p \sim 5$ MeV resonance ($E_x \sim 22$ MeV) represents the giant dipole resonance based on ^{8}Be(0) while the γ_1 resonance, $\sim$ 2.2 MeV higher, is based on ^{8}Be*(3.0). The γ_0 and γ_1 giant resonance peaks each contain about 10% of the dipole sum strength. The main trend between E_p = 8 and 17.5 MeV is a decreasing cross section.

Table 8.7
^{8}Be levels from ^{7}Li(p, γ)^{8}Be [a]

E_{res} (keV)	Γ_{lab} (keV)	^{8}Be* (MeV)	l_p	J^π	Res. [d]
441.4 ± 0.5 [b]	12.2 ± 0.5	17.640	1	1^+	γ_0, γ_1, γ_3, γ_4
1030 ± 5	168	18.155	1	1^+	γ_0, γ_1, γ_3, γ_4
1890	150 ± 50	18.91		(2^-)	γ_3, γ_4
2060 ± 20	310 ± 20	19.06		$J = 1, 2, 3,$ $\pi = (-)$ [c]	γ_1
(3100)		(20.0)			γ_1
4900		21.5			γ_1
5000	~ 4500	21.6	0	$1^-; T = 1$	γ_0
6000		22.5			γ_1
7500	~ 8000	23.8	(0)	$(1^-, 2^-); T = 1$	γ_1
(11100)		(27.0)			γ_1
13000	broad	28.6			

[a]) See tables 8.6 in (74AJ01, 79AJ01) for the references.
[b]) See (59AJ76). See also (83FI13, 84JE1B).
[c]) See, however, reaction 16.
[d]) γ_0, γ_1, γ_3, γ_4 represent transitions to ^{8}Be*(0, 3.0, 16.6, 16.9), respectively.

At the $E_p = 0.44$ MeV resonance ($E_x = 17.64$ MeV) the radiation is nearly isotropic consistent with p-wave formation, $J^\pi = 1^+$, with channel spin ration $\sigma(J_c = 2)/\sigma(J_c = 1) = 3.2 \pm 0.5$. Radiative widths for the γ_0 and γ_1 decay are displayed in table 8.5. A careful study of the α-breakup of ^{8}Be*(16.63, 16.92) [both $J^\pi = 2^+$] for $E_p = 0.44$ to 2.45 MeV shows that the non-resonant part of the cross section for production of ^{8}Be*(16.63) is accounted for by an extranuclear direct-capture process. Resonances for production of ^{8}Be*(16.63, 16.92) are observed at $E_p = 0.44$, 1.03 and 1.89 MeV [^{8}Be*(17.64, 18.15, 18.9)]. The results are consistent with the hypothesis of nearly maximal isospin mixing for ^{8}Be*(16.63, 16.92): decay to these states is not observed from the 3^+ states at $E_x =$ 19 MeV, but rather from the 2^- state at $E_x = 18.9$ MeV. Squared $T = 1$ components calculated for ^{8}Be*(16.6, 16.9) are 40 and 60%, and 95 and 5% for ^{8}Be*(17.6, 18.2). The cross section for $(\gamma_3 + \gamma_4)$ has also been measured for $E_p = 11.5$ to 30 MeV ($\theta = 90°$) by detecting the γ-rays and for $E_p = 4$ to 13 MeV (at five energies) by detecting the two α-particles from the decay of ^{8}Be*(16.6, 16.9): a broad bump is observed at $E_p = 8 \pm 2$ MeV (81MA33). The angle and energy integrated yield only exhausts 8.6% of the classical dipole sum for $E_p = 4$ to 30 MeV, suggesting that this structure does not represent the GDR built on ^{8}Be*(16.6, 16.9). A weak, very broad [$\Gamma \geq 20$ MeV] peak may also be present at $E_x = 20$–30 MeV. A direct capture calculation adequately describes the observed cross section (81MA33). A study of the γ-decay of ^{8}Be*(17.64, 18.15) shows no evidence for a pseudoscalar particle postulated to account for narrow peaks in e^+ spectra in heavy-ion reactions (88SA2A). For the earlier references see (79AJ01). See also (83CH1C), (86WE1D), (84DA1H; astrophysics), (88KI1C; applied) and (83GO1B, 84SE16, 85GO1B, 87KI1C; theor.).

15. ^{7}Li(p, n)^{7}Be $\qquad Q_m = -1.644 \qquad E_b = 17.2543$

Measurements of cross sections have been reported for E_p = 1.9 to 199.1 MeV [see (74AJ01, 79AJ01, 84AJ01)] and in the range 60.1 to 480.0 MeV (84DA22; activation σ). Polarization measurements have been reported at E_p = 2.05 to 5.5 MeV, 30 and 50 MeV [see (74AJ01)] and at $E_{\vec{p}}$ = 52.8 MeV (88HE08) [$K_z^{z'} = 0.07 \pm 0.02$]. See also below.

The yield of ground state neutrons (n_0) rises steeply from threshold and shows pronounced resonances at E_p = 2.25 and 4.9 MeV. The yield of n_1 also rises steeply from threshold and exhibits a broad maximum near E_p = 3.2 MeV and a broad dip at $E_p \sim$ 5.5 MeV, also observed in the p_1 yield. Multi-channel scattering length approximation analysis of the 2^- partial wave near the n_0 threshold indicates that the 2^- state at E_x = 18.9 MeV is virtual relative to the threshold and that its width $\Gamma = 50 \pm 20$ keV. The ratio of the cross section for ^{7}Li(p, γ)^{8}Be*(18.9)→^{8}Be*(16.6+16.9)+γ to the thermal neutron capture cross section ^{7}Be(n, γ)^{8}Be*(18.9)→^{8}Be*(16.6+16.9)+γ, provides a rough estimate of the isospin impurity of ^{8}Be*(18.9): $\sigma_{p,\gamma}/\sigma_{n,\gamma} \sim 1.5 \times 10^{-5}$. The $T = 1$ isospin impurity is $\leq 10\%$ in intensity. See also reaction 23. See (79AJ01, 84AJ01).

The structure at E_p = 2.25 MeV is ascribed to a 3^+, $T = (1)$, $l = 1$ resonance with $\Gamma_n \sim \Gamma_p$ and γ_n^2/γ_p^2 = 3 to 10: see (66LA04). At higher energies the broad peak in the n_0 yield at E_p = 4.9 MeV can be fitted by $J^\pi = 3^{(+)}$ with Γ = 1.1 MeV, $\gamma_n^2 \sim \gamma_p^2$. The behavior of the n_1 cross section can be fitted by assuming a 1^- state at E_x = 19.5 MeV and a J = 0, 1, 2, positive-parity state at 19.9 MeV [presumably the 20.1–20.2 MeV states reported in reaction 4]. In addition the broad dip at $E_p \sim$ 5.5 MeV may be accounted for by the interference of two 2^+ states. See table 8.8 in (79AJ01). The 0° differential cross section increases rapidly to ∼35 mb/sr at 30 MeV and then remains constant to 100 MeV: see (85BO1C). The total reaction cross section [^{7}Be*(0, 0.43)] decreases inversely with E_p in the range 60.1 to 480.0 MeV (84DA22) [note: the values of σ_t supersede those reported earlier]. The transverse polarization transfer, $D_{NN}(0°)$, for the g.s. transition has been measured at $E_{\vec{p}}$ = 160 MeV (84TA07). See also (86MC09; $E_{\vec{p}}$ = 800 MeV), (87WA1K), (84BA1U), (85CA41; astrophysics), (83LO12; applications), (86RA1F, 87TA22) and (88GU1F; theor.).

16. (a) ^{7}Li(p, p)^{7}Li $\qquad E_b = 17.2543$

(b) ^{7}Li(p, p′)^{7}Li*

Absolute differential cross sections for elastic scattering have been reported for E_p = 0.4 to 12 MeV and at 14.5, 20.0 and 31.5 MeV. The yields of inelastically scattered protons (to ^{7}Li*(0.48)) and of 0.48 MeV γ-rays have been measured for E_p = 0.8 to 12 MeV: see (74AJ01). Polarization measurements have been reported at a number of energies in the range E_p = 0.67 MeV to 2.1 GeV/c [see (74AJ01, 79AJ01, 84AJ01)], at $E_{\vec{p}}$ = 1.89 to

Table 8.8
^{8}Be levels from ^{7}Li(p, p$_0$)^{7}Li and ^{7}Li(p, p$_1$)^{7}Li* [a]

E_p (MeV)	Γ_{lab} (keV)	^{8}Be* (MeV)	J^π	$\Gamma_{p'}$ (keV)
0.441	12.2 [c]	17.640 [h]	1^+	
1.030 ± 0.005	168	18.155	1^+	~ 6
1.88 [b]	55 ± 20	18.90	2^-	
2.05	$\simeq 400$	19.05	3^+	small
2.25		19.22	3^+	small
2.5 [d]	$\simeq 750$	19.4	1^-	res
[e]				
4.2 ± 0.2 [f]	1800 ± 200	20.9	4^-	(res)
5.6	broad	22.2	[g]	res

[a] See references in table 8.9 (79AJ01).
[b] (p, n) threshold: see reaction 15.
[c] $\theta^2_p = 0.064$.
[d] See also table 8.8, γ^2_{n1} and $\gamma^2_{p1} \simeq 1\%$ of Wigner limit.
[e] A 2^+ state at $E_x \sim 20$ MeV appears to be necessary to account for the cross sections: see table 8.3 and reaction 4.
[f] Reduced width is 70% of the Wigner limit.
[g] May be due to two 2^+ states. See also reaction 15.
[h] See also (81BA36; theor.).

2.59 MeV (86SA1P; p$_0$; prelim.) and at 65 MeV (87TO06; continuum; prelim.). See also (83GL1A).

Anomalies in the elastic scattering appear at $E_p = 0.44$, 1.03, 1.88, 2.1, 2.5, 4.2 and 5.6 MeV. Resonances at $E_p = 1.03$, 3 and 5.5 MeV and an anomaly at $E_p = 1.88$ MeV appear in the inelastic channel. A phase-shift analysis and a review of the cross-section data show that the 0.44 and 1.03 MeV resonances are due to 1^+ states which are a mixture of ^{5}P$_1$ and ^{3}P$_1$ with a mixing parameter of +25°; that the 2^- state at the neutron threshold (E_p = 1.88 MeV) has a width of about 50 keV [see also reaction 14]; and that the $E_p = 2.05$ MeV resonance corresponds to a 3^+ state. The anomalous behavior of the ^{5}P$_3$ phase around $E_p = 2.2$ MeV appears to result from the coupling of the two 3^+ states [resonances at $E_p = 2.05$ and 2.25 MeV]. The ^{3}S$_1$ phase begins to turn positive after 2.2 MeV suggesting a 1^- state at $E_p = 2.5$ MeV: see table 8.8. The polarization data show structures at $E_p = 1.9$ and 2.3 MeV. A phase-shift analysis of the (p, p) data finds no indication of a possible 1^- state with $17.4 < E_x < 18.5$ MeV [see, however, reaction 15 in (79AJ01)].

An attempt has been made to observe the $T = 2$ state [^{8}Be*(27.47)] in the p$_0$, p$_1$ and p$_2$ yields. None of these shows the effect of the $T = 2$ state. Table 8.5 in (84AJ01) displays the upper limit for Γ_{p_0}/Γ.

The proton total reaction has been reported for $E_p = 25.1$ to 48.1 MeV by (85CA36). (87CH33, 87PO03) have studied p-^{7}Li correlations involving ^{8}Be*(17.64, 18.15, 18.9 + 19.1 + 19.2). See also ^{7}Li (84BA1U), (86BA1N), (86RA1D; applications) and (86HA1K, 88GU1F; theor.) and p. 84.

17. ^{7}Li(p, d)^{6}Li $\qquad Q_m = -5.025 \qquad E_b = 17.2543$

The excitation function for d_0 measured for $E_p = 11.64$ to 11.76 MeV does not show any effect from the $T = 2$ state [^{8}Be*(27.47)]: see (79AJ01). See also (84BA1T).

18. ^{7}Li(p, α)^{4}He $\qquad Q_m = 17.3462 \qquad E_b = 17.2543$

The cross section increases from $(4.3 \pm 0.9) \times 10^{-5}$ mb at $E_p = 28.1$ keV to 6.33 mb at 998 keV. Astrophysical S-factors have been calculated over that range: $S(0) = 52 \pm 8$ keV · b (86RO13). For the earlier work see (84AJ01).

Excitation functions and angular distributions have been measured at many energies in the range $E_p = 23$ keV to 62.5 MeV: see (79AJ01, 84AJ01). Polarization measurements have been carried out for $E_p = 0.8$ to 10.6 MeV [see (AJ74)]: in the range $E_p = 3$ to 10 MeV the asymmetry has one broad peak in the angular distribution at all energies except near 5 MeV; the peak value is 0.98 ± 0.04 at 6 MeV and is essentially 1.0 for $E_p = 8.5$ to 10 MeV.

Broad resonances are reported to occur at $E_p = 3.0$ MeV [$\Gamma \simeq 1$ MeV] and at ~ 5.7 MeV [$\Gamma \sim 1$ MeV]. Structures are also reported at $E_p = 6.8$ MeV and at $E_p = 9.0$ MeV: see (79AJ01). The 9.0 MeV resonance is also reflected in the behavior of the A_2 coefficient. The experimental data on yields and on polarization appear to require including two 0^+ states [at $E_x \sim 19.7$ and 21.8 MeV] with very small α-particle widths, and four 2^+ states [at $E_x \sim 15.9$, 20.1, 22.2 and 25 MeV]. See, however, reaction 4. A 4^+ state near 20 MeV was also introduced in the calculation but its contribution was negligible. The observed discrepancies are said to be probably due to the assumption of pure $T = 0$ for these states. At $E_p = 11.64$ to 11.76 MeV the excitation function does not show any effect due to the $T = 2$ state at $E_x = 27.47$ MeV. See (79AJ01) for references.

A study of the ^{7}Li(p, α)^{4}He* reaction to ^{4}He*(20.1) [0^+] at $E_p = 4.5$ to 12.0 MeV shows a broad maximum at $E_x \sim 24$ MeV: see reaction 9 and (84AJ01). See also (86ZA09), (84HA1M, 84YA1A, 85BO1K, 85CA41, 85DE1K, 86BO1H, 87AS05, 87KA1R, 87RO1D, 88BA1H, 88FO1A; astrophysics), (86RA1D, 86ST1E, 86TU1B; applications) and (84BL21, 84KR1B; theor.).

19. (a) ^{7}Li(d, n)^{8}Be $\qquad Q_m = 15.0297$

(b) ^{7}Li(d, n)2 ^{4}He $\qquad Q_m = 15.1216$

The population of ^{8}Be*(0, 3.0, 16.6, 16.9, 17.6, 18.2, 18.9, 19.1, 19.2) has been reported in reaction (a). For the parameters of ^{8}Be*(3.0) see table 8.4 in (74AJ01). Angular distributions of n_0 and n_1 have been reported at $E_d = 0.7$ to 3.0 MeV and at $E_d = 15.25$ MeV [see (74AJ01, 79AJ01)] and at 0.19 MeV (83DA32, 87DA25) and 0.40 and 0.46 MeV (84GA07; n_0 only). The angular distributions of the neutrons to ^{8}Be*(16.6, 17.6, 18.2) are fit by $l_p = 1$: see (74AJ01).

Reaction (b) at $E_d = 2.85$ to 14.97 MeV proceeds almost entirely through the excitation and sequential decay of ^{8}Be*(16.6, 16.9) (87WA21). ^{8}Be*(11.4) may also be involved [$E_x = 11.4 \pm 0.05$ MeV, $\Gamma_{c.m.} = 2.8 \pm 0.2$ MeV] as may state(s) at $E_x \sim 20$ MeV: see (79AJ01). See also ^{9}Be, (83BL17, 86BA40), (86LE1E; applications) and (83MU13, 84BL21; theor.).

20. (a) ^{7}Li(^{3}He, d)^{8}Be　　$Q_m = 11.7608$
    (b) ^{7}Li(^{3}He, αd)^{4}He　　$Q_m = 11.8527$

Deuteron groups are observed to ^{8}Be*(0, 3.0, 16.6, 16.9, 17.6, 18.2). For the parameters of ^{8}Be*(3.0) see table 8.4 in (74AJ01). For the $J^\pi = 2^+$ mixed isospin states see table 8.6. Angular distributions have been measured for $E(^3\text{He}) = 0.9$ to 24.3 MeV and at $E(^3\vec{\text{He}}) = 33.3$ MeV: see (74AJ01, 79AJ01, 84AJ01). Reaction (b) has been studied at $E(^3\text{He}) = 5.0$ MeV (85DA29) and at 9, 11 and 12 MeV (86ZA09). ^{8}Be*(0, 3.0) are reported to be involved (85DA29). See also ^{10}B and (83KU17; theor.).

21. (a) ^{7}Li(α, t)^{8}Be　　$Q_m = -2.5597$
    (b) ^{7}Li(α, αt)^{4}He　　$Q_m = -2.4678$

Angular distributions have been measured to $E_\alpha = 50$ MeV: see (66LA04, 74AJ01, 79AJ01). The ground state of ^{8}Be decays isotropically in the c.m. system: $J^\pi = 0^+$. Sequential decay (reaction (b)) is reported at $E_\alpha = 50$ MeV via ^{8}Be*(0, 3.0, 11.4, 16.6, 16.9, 19.9): see (74AJ01). See also (83BE1H, 85PU03; theor.).

22. ^{7}Li(^{7}Li, ^{6}He)^{8}Be　　$Q_m = 7.280$

^{8}Be*(0, 3.0) have been populated in this reaction (87BO1M; $E(^7\text{Li}) = 22$ MeV). See also (88AL1G).

23. (a) ^{7}Be(n, p)^{7}Li　　$Q_m = 1.644$　　$E_b = 18.8985$
    (b) ^{7}Be(n, α)^{4}He　　$Q_m = 18.9905$
    (c) ^{7}Be(n, $\gamma\alpha$)^{4}He　　$Q_m = 18.9905$

The total (n, p) cross section has been measured from 25×10^{-3} eV to 13.5 keV. For thermal neutrons the cross sections to ^{7}Li*(0, 0.48) are 38400 ± 800 and 420 ± 120 b, respectively. A departure from a $1/v$ shape in σ_t is observed for $E_n > 100$ eV. The astrophysical reaction rate is $\sim\frac{1}{3}$ lower than that previously used: this could lead to an increase in the calculated rate of production of ^{7}Li in the Big Bang by as much as 20%. A multi-level R-matrix analysis of the data indicates $\Gamma = 122$ keV for the 2^- state ^{8}Be*(18.9), and a $T = 1$ impurity of ∼24% (88KO03). At thermal energies the (n, α) cross section is ≤ 0.1 mb and the (n, $\gamma\alpha$) cross section is 155 mb: see (74AJ01). See also (87GLZZ, 87GL1D), (79AJ01, 88BO15) and (84YA1A, 85BO1K, 85DE1K; astrophysics).

24. ^{8}Li(β^-)^{8}Be $\qquad Q_{\rm m} = 16.0039$

^{8}Li decays to the broad 3.0 MeV, 2^+ level of ^{8}Be, which decays into two α-particles. Both the β-spectrum and the resulting α-spectrum have been extensively studied: see (55AJ61, 66LA04). See also ^{8}B(β^+). Studies of the distribution of recoil momenta and neutrino recoil correlations indicate that the decay is overwhelmingly GT, axial vector [see reaction 1 in ^{8}Li] and that the ground state of ^{8}Li has $J^\pi = 2^+$: see (80MC07).

(86WA01) has performed a many-level one-channel approximation R-matrix analysis of the β-delayed α-particle spectra in the decay of both ^{8}Li and ^{8}B, obtained by (71WI05) [as well as of the $L = 2$ α-α phase shifts]. Warburton finds that there is no need to introduce "intruder" states below $E_{\rm x} \sim 26$ MeV [see, e.g., (74AJ01)]. He extracts the GT matrix elements for the decay to ^{8}Be*(3.0) and the doublet near 16 MeV; and he points out the difficulties in extracting meaningful $E_{\rm x}$ and Γ values from the $\beta^\pm$ decay for ^{8}Be*(3.0), as well as the log ft values for the transitions to that state (86WA01).

Beta-α angular correlations have been measured for the decays of ^{8}Li and ^{8}B for the entire final-state distribution: see table 8.10 in (79AJ01). (80MC07) have measured the β-ν-α correlations as a function of $E_{\rm x}$ in the decay of ^{8}Li and ^{8}B, detecting both α-particles involved in the ^{8}Be decay. They find that the decay is GT for $2 < E_{\rm x} < 8$ MeV. The absence of Fermi decay strength is expected because the isovector contributions from the tails of ^{8}Be*(16.6, 16.9) interfere destructively in this energy region: see (80MC07). The measurement of the β-decay asymmetry as a function of E_β is reported by (86BI1D, 85BI1B; prelim.). (86NA1C; prelim.) have measured the β-spectrum and compared it with the spectrum predicted from the α-breakup data. See also (84KO25, 85GR1A), (86HA1P, 88WA1E), (86MA1T, 86NA1C; astrophysics) and (83KU17, 84BA1J, 86QU1B, 87LY05, 88BA75; theor.).

25. ^{8}B(β^+)^{8}Be $\qquad Q_{\rm m} = 17.979$

The decay [see reaction 1 in ^{8}B] proceeds mainly to ^{8}Be*(3.0) [see table 8.4 in (74AJ01) for its parameters]. Detailed study of the high-energy portion of the α-spectrum reveals a maximum near $E_\alpha = 8.3$ MeV, corresponding to transitions to ^{8}Be*(16.63), for which parameters $E_{\rm x} = 16.67$ MeV, $\Gamma = 150$ to 190 keV or $E_{\rm x} = 16.62$ MeV, $\Gamma = 95$ keV are derived: see (74AJ01). Log ft for the transition to ^{8}Be*(16.6) is 3.3. An analysis by (86WA01) of the β^+ delayed α-spectrum is described in reaction 24. See also (88WA1E) and (88BA75; theor.). The β^+ spectrum has been measured by (87NA08) for momenta greater than 9 MeV/c. Then using the α spectra from (86WA01) the ^{8}B neutrino spectrum is calculated. The average cross section for the "solar neutrino" ^{37}Cl($\nu_{\rm e}$, e$^-$)^{37}Ar reaction is then $(1.07 \pm 0.02) \times 10^{-42}$ cm^2 [certain corrections may increase this value by as much as 4%] (87NA08). See also (82BA1J, 83CO1D, 83FO1A, 83HA1B, 83VO1C, 84DA1H, 84HA1M, 85BA1N, 85BA1M, 85CH1B, 86BA21, 86BE1K, 86DE1H, 86GR04, 86HA1I, 86MA1T, 86RO1N, 86WO1B, 87BA1X, 87BA1U, 87CH1G, 87FR1C, 87FU1G, 87KR10, 87RI1E, 87WE1C, 88BA1H, 88EW1A, 88HA1M; astrophysics).

26. (a) ^{9}Be(γ, n)^{8}Be $\quad Q_m = -1.6654$
(b) ^{9}Be(n, 2n)^{8}Be $\quad Q_m = -1.6654$
(c) ^{9}Be(p, pn)^{8}Be $\quad Q_m = -1.6654$
(d) ^{9}Be(t, tn)^{8}Be $\quad Q_m = -1.6654$
(e) ^{9}Be(α, αn)^{8}Be $\quad Q_m = -1.6654$

Neutron groups to ^{8}Be*(0, 3.0) have been studied for $E_\gamma = 18$ to 26 MeV: see (74AJ01, 79AJ01) and ^{9}Be. Reaction (b) appears to proceed largely via excited states of ^{9}Be with subsequent decay mainly to ^{8}Be*(3.0): see (66LA04, 74AJ01), ^{9}Be and ^{10}Be. Reaction (c) has been studied at $E_p = 45$ and 47 MeV: the reaction primarily populates ^{8}Be*(0, 3.0): see (79AJ01), ^{9}Be and ^{9}B. For work at $E_p = 1$ GeV see (85BE1J, 85DO1B). For reactions (d) and (e) see (74AJ01) and ^{9}Be. For reaction (e) see (79AJ01).

27. (a) ^{9}Be(p, d)^{8}Be $\quad Q_m = 0.5592$
(b) ^{9}Be(p, pn)^{8}Be $\quad Q_m = -1.6654$
(c) ^{9}Be(p, d)2 ^{4}He $\quad Q_m = 0.6511$

Angular distributions of deuteron groups have been reported at $E_p = 0.11$ to 185 MeV [see (74AJ01, 79AJ01, 84AJ01)] and at 18.6 MeV (86GO1N, 87GO27; d_0 and d_1) and 50 and 72 MeV (84ZA07; to ^{8}Be*(0, 3.0, 16.9, 19.2)). For spectroscopic factors see (79AJ01, 84ZA07). The angular distributions to ^{8}Be*(0, 3.0, 16.9, 17.6, 18.2, 19.1) are consistent with $l_n = 1$: see (74AJ01).

An anomalous group is reported in the deuteron spectra between the d_0 and the d_1 groups. At $E_p = 26.2$ MeV, its (constant with θ) $E_x = 0.6 \pm 0.1$ MeV. Analyses of the spectral shape and transfer cross sections are consistent with this "ghost" feature being part of the Breit-Wigner tail of the $J^\pi = 0^+$ ^{8}Be$_{\text{g.s.}}$: it contains $< 10\%$ of the g.s. transfer strength. An analysis of reported $\Gamma_{\text{c.m.}}$ for ^{8}Be*(3.0) in this reaction shows that there is no E_p dependence. The average $\Gamma_{\text{c.m.}}$ at $E_p = 14.3$ and 26.2 MeV is 1.47 ± 0.04 MeV. $\Gamma_{\text{c.m.}} = 5.5 \pm 1.3$ eV for ^{8}Be$_{\text{g.s.}}$ and 5.2 ± 0.1 MeV for ^{8}Be*(11.4). Spectroscopic factors for ^{8}Be$_{\text{g.s.}}$ (including the "ghost" anomaly) and ^{8}Be*(3.0) are 1.23 and 0.22 respectively at $E_p = 14.3$ MeV, and 1.53 and 1.02 respectively at $E_p = 26.2$ MeV. The width of ^{8}Be*(3.0) is not appreciably ($< 10\%$) reaction dependent but the nearness of the decay threshold indicates that care must be taken in comparing decay widths from reaction and from scattering data: $E_R = 3130 \pm 25$ keV (resonance energy in the $\alpha + \alpha$ c.m. system) [$E_x = 3038 \pm 25$ keV] and $\Gamma_{\text{c.m.}} = 1.50 \pm 0.02$ MeV for ^{8}Be*(3.0): the corresponding observed and formal reaction widths and channel radii are $\gamma^2_{\rm R} = 580 \pm 50$ keV, $\gamma^2_\lambda = 680 \pm 100$ keV and s = 4.8 fm. See (79AJ01) for the earlier work. A study of the continuum part of the inclusive deuteron spectra is reported at $E_{\bar{\rm p}} = 60$ MeV (87KA25). For reaction (b) see (88BO1H). For reaction (c) [FSI through ^{8}Be*(0, 3.0)] see (74AJ01, 84AJ01). See also (85PU03; theor.) and ^{10}B.

28. (a) ^{9}Be(d, t)^{8}Be $\qquad Q_{\rm m} = 4.5919$
(b) ^{9}Be(d, t)2 ^{4}He $\qquad Q_{\rm m} = 4.6838$

Angular distributions have been measured for $E_{\rm d} = 0.3$ to 28 MeV [see (79AJ01)], at $E_{\rm d} = 18$ MeV (88GO02; t_0, t_1) and at $E_{\vec{\rm d}} = 2.0$ to 2.8 MeV (84AN1D; t_0). At $E_{\rm d} = 28$ MeV angular distributions of triton groups to ^{8}Be*(16.6, 16.9, 17.6, 18.2, 19.1, 19.2, 19.8) have been analyzed using DWUCK: absolute C^2S are 0.074, 1.56, 0.22, 0.17, 0.41, 0.48, 0.40 respectively. See also table 8.6. An isospin amplitude impurity of 0.21 ± 0.03 is found for ^{8}Be*(17.6, 18.2): see (79AJ01).

A kinematically complete study of reaction (b) at $E_{\rm d} = 26.3$ MeV indicates the involvement of ^{8}Be*(0, 3.0, 11.4, 16.9, 19.9 + 20.1): see (74AJ01). (86PA1E; prelim.) report $E_{\rm x} = 3.10 \pm 0.15$ MeV, $\Gamma \sim 0.9$–1.3 MeV. See also (88NE1A; theor.).

29. (a) ^{9}Be(^{3}He, α)^{8}Be $\qquad Q_{\rm m} = 18.9124$
(b) ^{9}Be(^{3}He, α)2 ^{4}He $\qquad Q_{\rm m} = 19.0043$

Angular distributions have been measured in the range $E(^3{\rm He}) = 3.0$ to 26.7 MeV and at $E(^3\vec{\rm He}) = 33.3$ MeV (to ^{8}Be*(16.9, 17.6, 19.2)) [$S = 1.74$, 0.72, 1.17, assuming mixed isospin for ^{8}Be*(16.9)]. The possibility of a broad state at $E_{\rm x} \sim 25$ MeV is also suggested: see (79AJ01). See also (87VA1I).

Reaction (b) has been studied at $E(^3{\rm He}) = 1.0$ to 10 MeV [see (79AJ01, 84AJ01)], at $E(^3{\rm He}) = 3$ to 12 MeV (86LA26) and at 11.9 to 24.0 MeV (87WA25). The reaction is reported to proceed via ^{8}Be*(0, 3.0, 11.4, 16.6, 16.9, 19.9, 22.5): see (79AJ01) and (86LA26, 87WA25). For a discussion of the width of ^{8}Be*(11.4) see (87WA25). See also ^{9}Be, and ^{12}C in (80AJ01), (85MC1C, applications) and (85PU03; theor.).

30. (a) ^{9}Be(^{6}Li, ^{7}Li)^{8}Be $\qquad Q_{\rm m} = 5.585$
(b) ^{9}Be(^{7}Li, ^{8}Li)^{8}Be $\qquad Q_{\rm m} = 0.367$
(c) ^{9}Be(^{9}Be, ^{10}Be)^{8}Be $\qquad Q_{\rm m} = 5.1466$

Angular distributions have been studied at $E(^6{\rm Li}) = 32$ MeV involving ^{8}Be*(0, 3.0) and ^{7}Li*(0, 0.48) (85CO09). For reaction (b) see (84KO25). For reaction (c) see ^{10}Be (85JA09). For the earlier work see (79AJ01).

31. ^{10}Be(p, t)^{8}Be $\qquad Q_{\rm m} = 0.0045$

Angular distributions for the transition to the first $T = 2$ state ^{8}Be*(27.49), and to ^{8}Li*(10.82) reached in the (p, ^{3}He) reaction, are very similar. They are both consistent with $L = 0$ using a DWBA (LZR) analysis: see (79AJ01, 84AJ01) and table 8.5 in (84AJ01).

32. ^{10}B(π^{+}, 2p)^{8}Be $\qquad Q_{\rm m} = 132.100$

See (88R1ZZ; prelim).

33. ^{10}B(n, t)^{8}Be $\qquad Q_{\rm m} = 0.2307$

The breakup of ^{10}B by 14.4 MeV neutrons involves, among others, ^{8}Be$_{\rm g.s.}$ (84TU02). See also (79AJ01) and ^{11}B in (90AJ01).

34. ^{10}B(p, ^{3}He)^{8}Be $\qquad Q_{\rm m} = -0.5332$

Angular distributions of the ^{3}He ions to ^{8}Be*(0, 3.0, 16.6, 16.9) have been studied at $E_{\rm p} = 39.4$ MeV [see (74AJ01)] and at $E_{\rm p} = 51.9$ MeV (83YA05; see for a discussion of isospin mixing of the 16.8 MeV states).

35. (a) ^{10}B(d, α)^{8}Be $\qquad Q_{\rm m} = 17.8202$
(b) ^{10}B(d, α)2 ^{4}He $\qquad Q_{\rm m} = 17.9121$

Angular distributions have been reported at $E_{\rm d} = 0.5$ to 7.5 MeV: see (74AJ01, 79AJ01). At $E_{\rm d} = 7.5$ MeV the population of ^{8}Be*(16.63, 16.92) is closely the same consistent with their mixed isospin character while ^{8}Be*(17.64) is relatively weak consistent with its nearly pure $T = 1$ character. ^{8}Be*(16.63, 16.92, 17.64, 18.15) have been studied for $E_{\rm d} = 4.0$ to 12.0 MeV. Interference between the 2^{+} states [^{8}Be*(16.63, 16.92)] varies as a function of energy. The cross-section ratios for formation of ^{8}Be*(17.64, 18.15) vary in a way consistent with a change in the population of the $T = 1$ part of the wave function over the energy range: at the higher energies, there is very little isospin violation. At higher $E_{\rm x}$ only the 3^{+} state at $E_{\rm x} = 19.2$ MeV is observed, the neighboring 3^{+} state at $E_{\rm x} = 19.07$ MeV is not seen. $\Gamma_{16.6} = 90 \pm 5$ keV, $\Gamma_{16.9} = 70 \pm 5$ keV, $\Delta Q = 290 \pm 7$ kev: see table 8.6 and (79AJ01).

Reaction (b) [$E_{\rm d} < 5$ MeV] takes place mainly by a sequential process involving ^{8}Be*(0, 2.9, 11.4, 16.6, 16.9): see (79AJ01). See also (83DA11). [The work quoted in (84AJ01) has not been published.] At $E_{\rm d} = 13.6$ MeV in addition to ^{8}Be*(16.6, 16.9), states with $E_{\rm x} \sim 19.9$–20.2 MeV with $\Gamma \sim 0.7$–1.1 MeV are involved (88KA1K; prelim.). See also (84SH1D, 84SH1E) and (85PU03, 88BA75, 88KA1M; theor.).

36. ^{10}B(α, ^{6}Li)^{8}Be $\qquad Q_{\rm m} = -4.552$

See ^{6}Li here and reaction 40 in (84AJ01). See also (SH84D,SH88D).

37. (a) ^{11}B(p α)^{8}Be $\qquad Q_{\rm m} = 8.5906$
(b) ^{11}B(p, α)2 ^{4}He $\qquad Q_{\rm m} = 8.6825$

Angular distributions have been measured at $E_{\rm p} = 0.78$ to 45 MeV [see (74AJ01, 79AJ01, 84AJ01)], at $E = 0.12$ to 1.10 MeV (87BE17; ^{11}B and p; α_0, α_1) and at $E_{\rm p} = 4.5$ to 7.5 MeV (83BO19; α_0). Reaction (b) has been studied for $E_{\rm p} = 0.15$ to 20 MeV: see (74AJ01, 84AJ01). The reaction proceeds predominantly by sequential two-body decay via ^{8}Be*(0, 3.0). See also ^{12}C in (90AJ01) and (83CO1A, 85MA1F, 85PU03; theor.).

38. ^{11}B(^{3}He, ^{6}Li)^{8}Be $\qquad Q_{\rm m} = 4.5721$

At $E(^{3}{\rm He}) = 71.8$ MeV angular distributions of the ^{6}Li ions to ^{8}Be*(0, 3.0, 16.6, 16.9, 17.6, 18.2) are reported (86JA14). For the earlier work at 25.6 MeV see (79AJ01). See also (86JA02).

39. ^{11}B(α, ^{7}Li)^{8}Be $\qquad Q_{\rm m} = -8.7556$

The work reported in (84AJ01) has not been published. See also ^{7}Li here and (84SH1D, 88SH1E).

40. ^{11}B(^{9}Be, ^{12}B)^{8}Be $\qquad Q_{\rm m} = 1.705$

See (84DA17) and ^{12}B in (90AJ01).

41. (a) ^{12}C(n, nα)^{8}Be $\qquad Q_{\rm m} = -7.3666$
(b) ^{12}C(p, pα)^{8}Be $\qquad Q_{\rm m} = -7.3666$
(c) ^{12}C(p, d^{3}He) ^{8}Be $\qquad Q_{\rm m} = -25.7198$

The first two of these reactions involve ^{8}Be*(0, 3.0): see (74AJ01, 79AJ01, 84AJ01, 85AJ01). See also (86AN1M) [reaction (a)] and (82ZH06, 85GA1B, 86VD01; theor.). For reaction (c) see (83LI18; theor.).

42. (a) ^{12}C(d, ^{6}Li)^{8}Be $\qquad Q_m = -5.8916$
(b) ^{12}C(d, dα)^{8}Be $\qquad Q_m = -7.3666$

Angular distributions have been studied at E_d = 12.7 to 54.3 MeV [see (74AJ01, 79AJ01, 84AJ01)] and at $E_{\vec{d}}$ = 18 and 22 MeV (86YA12; to ^{8}Be$_{g.s.}$; also VAP, TAP) and 51.7 MeV (86YA12; to ^{8}Be*(0, 3.0, 11.4; also VAP) as well as at E_d = 50 MeV (87GO1S), 54.2 MeV (84UM04; FRDWBA) [S_α = 0.48, 0.51 and 0.82 for ^{8}Be*(0, 3.0, 11.4)] and 78.0 MeV (86JA14; to ^{8}Be*(0, 3.0, 16.6, 16.9)). See also (85GO1G; E_d = 50 MeV). For reaction (b) see (84AJ01). See also (84NE1A) and (83GA14, 83SH39, 85GA1B, 87KA1L; theor.).

43. ^{12}C(t, ^{7}Li)^{8}Be $\qquad Q_m = -4.8988$

See ^{7}Li.

44. ^{12}C(^{3}He, ^{7}Be)^{8}Be $\qquad Q_m = -5.7793$

Angular distributions have been obtained at E(^{3}He) = 25.5 to 70 MeV [see (79AJ01, 84AJ01)] and at E($^3\vec{\rm He}$) = 33.4 MeV (86CL1B; ^{8}Be$_{g.s.}$; also A_y; prelim.). ^{8}Be*(0, 3.0, 11.4, 16.6, 16.9, 17.6) have been populated. See also (86RA15; theor.).

45. (a) ^{12}C(α, 2α)^{8}Be $\qquad Q_m = -7.3666$
(b) ^{12}C(α, ^{8}Be)^{8}Be $\qquad Q_m = -7.4585$

These reactions have been studied at E_α to 104 MeV [see (79AJ01, 84AJ01, and ^{12}C in 85AJ01)] and at 31.2 MeV (86XI1A; reaction (a)): ^{8}Be*(0, 3.0, 11.4) are populated. See also (84ZE1A, 85GA1B, 87KO1E; theor.).

46. (a) ^{12}C(^{9}Be, ^{13}C)^{8}Be $\qquad Q_m = 3.2810$
(b) ^{12}C(^{11}B, ^{15}N)^{8}Be $\qquad Q_m = 3.6250$

Angular distributions involving ^{8}Be$_{g.s.}$ + ^{13}C$_{g.s.}$ (reaction (a)) have been reported at E(^{9}Be) = 20 to 22.9 MeV and E(^{12}C) = 10.5 to 13.5 MeV: see (84AJ01). For both reactions see also (83DEZW).

47. (a) ^{12}C(^{12}C, ^{16}O)^{8}Be $\qquad Q_m = -0.2047$
(b) ^{12}C(^{16}O, ^{20}Ne)^{8}Be $\qquad Q_m = -2.631$
(c) ^{12}C(^{20}Ne, α^{20}Ne)^{8}Be $\qquad Q_m = -7.3666$

For reaction (a) see ^{16}O in (86AJ04), (83DEZW, 84HU1E, 84SP1C, 86ALZN, 86SH10) and (84DA1B; theor.). For reaction (b) see reaction 18 in ^{20}Ne (87AJ02), (85MU14) and (88AL07; location of a 10^+ state in ^{20}Ne at $E_x \simeq 27.5$ MeV). For reaction (c) see (87SI06).

48. ^{13}C(d, ^{7}Li)^{8}Be $\qquad Q_m = -3.5879$

See ^{7}Li.

49. ^{13}C(α, ^{9}Be)^{8}Be $\qquad Q_m = -10.7395$

See (84SH1D, 88SH1F; prelim.; $E_\alpha = 27.2$ MeV) and ^{9}Be in (79AJ01).

50. ^{13}C(^{9}Be, ^{14}C)^{8}Be $\qquad Q_m = 6.511$

See ^{14}C in (86AJ01).

51. ^{14}N(n, ^{7}Li)^{8}Be $\qquad Q_m = -8.9139$

See ^{7}Li.

52. ^{16}O(p, p2α)^{8}Be $\qquad Q_m = -14.5286$

See (86VD04; $E_p = 50$ MeV).

53. ^{16}O(^{16}O, ^{24}Mg)^{8}Be $\qquad Q_m = -0.483$

See (87CZ02).

^{8}B

(Figs. 13 and 14)

GENERAL: See also (84AJ01).

Model calculations: (83SH38).

Special states: (82PO12, 88KH03).

Complex reactions involving ^{8}B: (82AL1A, 83OL1A, 84GR08, 86HA1B, 87TA1F, 88AR05, 88KI05).

Astrophysical questions: (84HA1B, 85BO1E, 85GI1C, 85KL1A, 85LA1C, 88BA1H).

Reactions involving pions: (83SP06).

Hypernuclei: (83SH38).

Other topics: (85AN28).

Ground state of ^{8}B: (83ANZQ, 85AN28, 86GL1A, 87VA26, 88AR05, 88VA03)

$$\mu = 1.0355 \pm 0.0003 \text{ n.m.: see (78LEZA).}$$

1. ^{8}B(β^{+})^{8}Be $\qquad Q_{\mathrm{m}} = 17.979$

The β^{+} decay leads mainly to ^{9}Be*(3.0). The mean of half-lives listed in (74AJ01) is 770 ± 3 msec; $\log ft = 5.6$. There is also a branch to ^{8}Be*(16.63): see (86WA01) and reactions 24 and 25 in ^{8}Be. Log $ft = 3.3$. See also (85GR1A) and (86QU1B; theor.).

2. ^{6}Li(d, π^{-})^{8}B $\qquad Q_{\mathrm{m}} = -135.267$

At $E_{\mathrm{d}} = 300$ and 600 MeV, ^{8}B*(0, 0.77, 2.32) are populated: see (84AJ01).

3. ^{6}Li(^{3}He, n)^{8}B $\qquad Q_{\mathrm{m}} = -1.975$

Angular distributions for the n_0 group have been reported at $E(^{3}\mathrm{He}) = 4.8$ to 5.7 MeV: $L = 0$. Two measurements for the E_{x} of ^{8}B*(0.77) are 767 ± 12 and 783 ± 10 keV [$\Gamma = 40 \pm 10$ keV]: see (74AJ01) and ^{9}B.

Table 8.9
Energy levels of ^{8}B

E_x (MeV ± keV)	J^π; T	$\tau_{1/2}$ or $\Gamma_{c.m.}$ (keV)	Decay	Reactions
g.s.	2^+; 1	$\tau_{1/2} = 770 \pm 3$ msec	β^+	1, 2, 3, 4, 5, 6, 7, 8, 9
0.774 ± 6		$\Gamma = 37 \pm 5$	γ, p	2, 3, 4, 6, 8, 9
2.32 ± 30	3^+; 1	350 ± 40		4, 8, 9
10.619 ± 9	0^+; 2	< 60		9

4. ^{7}Li(p, π^-)^{8}B $\qquad Q_m = -140.293$

Angular distributions and analyzing powers have been measured for the transitions to ^{8}B*(0, 0.77, 2.32) at $E_{\vec{p}} = 199.2$ MeV: the A_y to ^{8}B*(2.32) is characteristic of that to a stretched high-spin, two-particle one-hole final state [J^π of ^{8}B*(2.32) is 3^+] (87CA06). See also (87CA05).

5. ^{7}Li(^{7}Li, ^{6}H)^{8}B $\qquad Q_m = -35.01$

See ^{6}H.

6. ^{7}Be(p, γ)^{8}B $\qquad Q_m = 0.138$

Absolute cross sections have been measured for $E_p = 134$ keV to 10.0 MeV. A resonance is observed at $E_p = 723$ keV [E_R(c.m.) $= 632 \pm 10$ keV; $E_x = 770 \pm 10$ keV], $\Gamma_{c.m.} = 37 \pm 5$ keV [assuming $\Gamma_p \gg \Gamma_\gamma$] and $\sigma_{peak} = 1.18 \pm 0.12$ μb. Γ_γ is then 25 ± 4 meV. The zero-energy cross-section factor $S_{17}(0) = 0.0238 \pm 0.0023$ keV · b (83FI13). See (79AJ01) for the earlier work, and the discussion in (86BA38). See also (84AJ01), (84HA1F, 87SA1L) and (82BA1J, 82KA1E, 83BA45, 83FO1A, 83HA1B, 84DA1H, 84HA1M, 84YA1A, 85BA1Q, 85CA41, 85FI1D, 86FI1B, 87KI01, 87RO1D, 88BA1H, 88BA29, 88FO1A; astrophysics).

7. ^{7}Be(d, n)^{8}B $\qquad Q_m = -2.087$

See (83HA17, 85HA40).

8. ^{10}B(p, t)^{8}B $\qquad$ $Q_m = -18.530$

At $E_p = 49.5$ MeV [see (74AJ01)] and 51.9 MeV (83YA05) angular distributions have been measured for the tritons to ^{8}B*(0, 2.32): $L = 2$ and $L = 0+2$ leading to $J^\pi = 2^+$ and 3^+, respectively. Measurements of E_x for ^{8}B*(2.32) yield 2.29 ± 0.05 MeV, 2.34 ± 0.04 MeV [$\Gamma_{lab} = 0.39 \pm 0.04$ MeV]. ^{8}B*(0.77) is also observed: see (74AJ01).

9. ^{11}B(^{3}He, ^{6}He)^{8}B $\qquad$ $Q_m = -16.913$

At $E(^{3}\text{He}) = 72$ MeV the first $T = 2$ state is observed at $E_x = 10.619 \pm 0.009$ MeV, $\Gamma < 60$ keV: $d\sigma/d\Omega$ (lab) = 190 nb/sr at $\theta_{lab} = 9°$. No other states are observed within 2.4 MeV of this state. ^{8}B*(0, 0.77, 2.32) have also been populated: see (79AJ01).

^{8}C

(Fig. 14)

Mass of ^{8}C: The atomic mass excess of ^{8}C is 35095 ± 24 keV (85WA02); $\Gamma_{c.m.} = 230 \pm 50$ keV: see (79AJ01). ^{8}C is stable with respect to ^{7}B + p ($Q = -0.13$ MeV) and unstable with respect to ^{6}Be + 2p ($Q = 21.4$), ^{5}Li + 3p ($Q = 1.55$), ^{4}He + 4p ($Q = 3.51$). At $E(^{3}\text{He}) = 76$ MeV the differential cross section for formation of $^{8}\text{C}_{g.s.}$ in the ^{14}N(^{3}He, ^{9}Li) reaction is $\sim$5 nb/sr at $\theta_{lab} = 10°$. The ^{12}C(α, ^{8}He)^{8}C reaction has been studied at $E_\alpha = 156$ MeV: $d\sigma/d\Omega \sim 20$ nb/sr at $\theta_{lab} = 20°$: see (79AJ01). See also (85AN28) and (83ANZQ, 86HE26, 87BL18, 87SA15; theor.).

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(Closed 1 June 1988)

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