

# Energy Levels of Light Nuclei $A = 8$

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**Abstract:** An evaluation of  $A = 5-10$  was published in *Nuclear Physics A490* (1988), 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. The introduction and introductory tables have been omitted from this manuscript. [Reference](#) key numbers have been changed to the NNDC/TUNL format.

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## ${}^8\text{n}$

(Not illustrated)

${}^8\text{n}$  has not been observed in the interaction of 700 MeV or of 400 GeV protons with uranium: see (1979AJ01). See also (1987FL1A) and (1987SIZX; theor.).

## ${}^8\text{He}$

(Figs. 1 and 4)

GENERAL: See also (1984AJ01).

*Model calculations:* (1984VA06, 1985PO10, 1987BL18).

*Complex reactions involving  ${}^8\text{He}$ :* (1982AL33, 1983AN13, 1985MA13, 1985TA1D, 1986SA30, 1987AR1G, 1987BO40, 1987KO1Z, 1987PE1C, 1987TAZU, 1988GA10, 1988ST06, 1988TA1A).

*Hypernuclei:* (1982KA1D, 1983DO1B, 1984BO1H, 1985AH1A, 1985IK1A, 1986BA1W, 1986DA1B, 1987MI38, 1987PO1H).

*Other topics:* (1983GL1B, 1985AN28, 1987AJ1A, 1988AJ1B).

*Ground-state properties of  ${}^8\text{He}$ :* (1983AN1C, 1984FR13, 1985SA32, 1986HE26, 1987BL18, 1987HA30, 1987SA15, 1988JO1C).

*Mass of  ${}^8\text{He}$ :* The atomic mass excess of  ${}^8\text{He}$  adopted by us and by (1988WA18) is  $31598 \pm 7$  keV.  ${}^8\text{He}$  is then stable with respect to decay into  ${}^6\text{He} + 2\text{n}$  by 2.137 MeV. See (1979AJ01, 1984AJ01).

The interaction nuclear radius of  ${}^8\text{He}$  is  $2.48 \pm 0.03$  fm (1985TA18, 1985TA13) [see also for derived nuclear matter, charge and neutron matter r.m.s. radii].

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

The half-life of  ${}^8\text{He}$  is  $119.0 \pm 1.5$  msec. The decay takes place  $(84 \pm 1)\%$  to  ${}^8\text{Li}^*(0.98)$  [ $\log ft = 4.20$ ] and  $(16 \pm 1)\%$  via the neutron unstable states  ${}^8\text{Li}^*(3.21, 5.4)$ .  $(32 \pm 3)\%$  of the emitted neutrons then populate  ${}^7\text{Li}^*(0.48)$ . The decay to  ${}^8\text{Li}^*(3.21, 5.4)$  suggest  $\pi = +$  for  ${}^8\text{Li}^*(3.21)$  and  $0^+$  or  $1^+$  for  ${}^8\text{Li}^*(5.4)$  (1981BJ03). [(1986BO41) suggest  $\log ft = 5.0$  for the transition to  ${}^8\text{Li}^*(3.21)$ ]. (1986BO41) report  $\beta$ -delayed tritons with a branching ratio of  $(0.9 \pm 0.1)\%$ . This decay appears to require a  $1^+$  state in  ${}^8\text{Li}$  at 8.8 MeV with a width,  $\Gamma_{\text{c.m.}} \approx 1$  MeV;  $\log ft$  is then 4.3 (1986BO41). See also (1988JO1C).

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

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

$E_x$ (MeV)	$J^\pi; T$	$\tau_{1/2}$ (msec)	Decay	Reactions
g.s.	$0^+; 2$	$119 \pm 1.5$	$\beta^-$	1, 2, 3
$2.8 \pm 0.4$ <sup>a</sup>	$(2^+); 2$			2, 3

<sup>a</sup> 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  $0^+$  (1985PO10). See reaction 3 for possible evidence of other states in  ${}^8\text{He}$  (1987BEYI; prelim.).

At  $E({}^7\text{Li}) = 83$  MeV,  $\theta = 10^\circ$ , the population of  ${}^8\text{He}_{\text{g.s.}}$ , an excited state at  $2.8 \pm 0.4$  MeV (presumably  $J^\pi = 2^+$ ) and a structure near  $E_x \approx 7$  MeV are reported by (1985AL1G). See also (1985AL29, 1985ALZL, 1985ALZM).

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

At  $E({}^9\text{Be}) = 106.7$  MeV and at  $E({}^{11}\text{B}) = 87$  MeV the ground state of  ${}^8\text{He}$  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 ( $\pm 0.3$  MeV). The width of the latter is  $0.5 \pm 0.3$  MeV (1987BEYI). See also (1988BEYJ).

${}^8\text{Li}$   
(Figs. 1 and 4)

GENERAL: See also (1984AJ01).

*Nuclear models:* (1983KU17, 1983SH38, 1984MO1H, 1984REZZ, 1984VA06, 1988WO04).

*Special states:* (1982PO12, 1983KU17, 1984REZZ, 1984VA06, 1986XU02).

*Electromagnetic transitions:* (1983KU17).

*Astrophysics:* (1987MA2C).

*Complex reactions involving  ${}^8\text{Li}$ :* (1983FR1A, 1983GU1A, 1983OL1A, 1983WI1A, 1984GR08, 1984HI1A, 1984LA27, 1985JA18, 1985MA02, 1985MA13, 1985MO17, 1985MO24, 1986AV1B, 1986CS1A, 1986GO1G, 1986HA1B, 1986MA19, 1986NAZV, 1986SA30, 1986SIZS, 1986WE1C, 1986XU02, 1987BA38, 1987BE58, 1987BL13, 1987CH26, 1987DE37, 1987GR11, 1987JA06, 1987LY04, 1987TAZU, 1987WA09, 1988AU1A, 1988BL09, 1988CA06, 1988KI05, 1988LI1A, 1988RU01, 1988ST06, 1988TA1A).

*Polarization of  ${}^8\text{Li}$ :* (1984KO25, 1986HA1P, 1986NO1C, 1986NO1D, 1987NO04).

*Applications:* (1985HA40, 1986NO1C, 1987NO04).

*Reactions involving pions and other mesons:* (1983HA45, 1986CE04, 1986GO1G).

*Hypernuclei:* (1982KA1D, 1982MO1B, 1983MO1C, 1983SH1E, 1984AS1D, 1984CH1G, 1984MI1C, 1984MI1E, 1984SH1J, 1984ZH1B, 1985MO1F, 1986AN1R, 1986DA1B, 1986YA1F, 1987MI38, 1987PO1H, 1987YA1M, 1988TA29).

*Other topics:* (1985AN28).

*Ground state of  ${}^8\text{Li}$ :* (1983ANZQ, 1985AN28, 1985SA32, 1986GL1A, 1987AR22, 1987HA30, 1987VA26, 1988JO1C, 1988POZS, 1988VA03, 1988WO04).

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Fig. 1: Energy levels of  ${}^8\text{Li}$ . In these diagrams, energy values are plotted vertically in MeV, based on the ground state as zero. Uncertain levels or transitions are indicated by dashed lines; levels which are known to be particularly broad are cross-hatched. Values of total angular momentum  $J$ , parity, and isobaric spin  $T$  which appear to be reasonably well established are indicated on the levels; less certain assignments are enclosed in parentheses. For reactions in which  ${}^8\text{Li}$  is the compound nucleus, some typical thin-target excitation functions are shown schematically, with the yield plotted horizontally and the bombarding energy vertically. Bombarding energies are indicated in laboratory coordinates and plotted to scale in cm coordinates. Excited states of the residual nuclei involved in these reactions have generally not been shown; where transitions to such excited states are known to occur, a brace is sometimes used to suggest reference to another diagram. For reactions in which the present nucleus occurs as a residual product, excitation functions have not been shown; a vertical arrow with a number indicating some bombarding energy, usually the highest, at which the reaction has been studied, is used instead. Further information on the levels illustrated, including a listing of the reactions in which each has been observed, is contained in the master table, entitled "Energy levels of  ${}^8\text{Li}$ ".

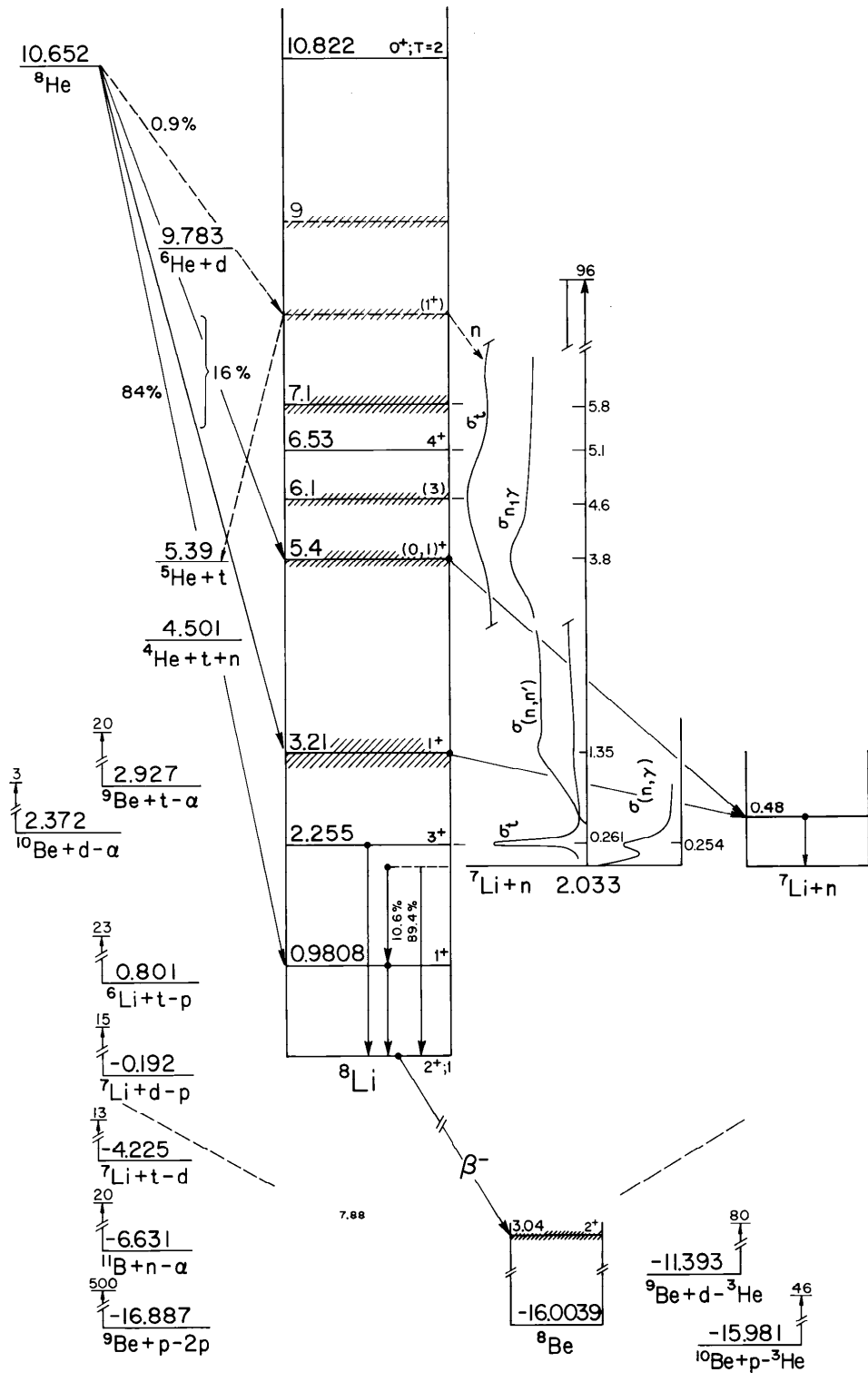


Table 8.2: Energy levels of  ${}^8\text{Li}$  <sup>a</sup>

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

<sup>a</sup> For additional states see reaction 4.

$$J = 2: \text{ see (1974AJ01)}$$

$$\mu = +1.65335 \pm 0.00035 \text{ nm: see (1978LEZA)}$$

$$Q = 24 \pm 2 \text{ mb: see (1979AJ01).}$$

The interaction nuclear radius of  ${}^8\text{Li}$  is  $2.36 \pm 0.02$  fm (1985TA18) [see also for derived nuclear matter, charge and neutron matter r.m.s. radii].

$$1. {}^8\text{Li}(\beta^-){}^8\text{Be} \quad Q_m = 16.0039$$

The  $\beta^-$  decay is to the broad  $2^+$  first-excited state of  ${}^8\text{Be}$ , which then breaks up into  $2\alpha$  [see reaction 24 in  ${}^8\text{Be}$ ]. The half-life is  $838 \pm 6$  msec [see (1984AJ01)];  $\log ft = 5.4$  (1986WA01).

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

Angular distributions have been obtained at  $E_t = 23$  MeV for the proton groups to  ${}^8\text{Li}^*(0, 0.98, 2.26, 6.54 \pm 0.03)$ ;  $\Gamma_{\text{c.m.}}$  for  ${}^8\text{Li}^*(2.26, 6.54)$  are  $35 \pm 10$  and  $35 \pm 15$  keV, respectively.  $J$  for the latter is  $\geq 4$ : see (1979AJ01).

Table 8.3: Resonance parameters for  ${}^8\text{Li}^*(2.26)$  <sup>a</sup>

$E_{\text{res}}$ (keV)	$254 \pm 3$
$E_x$ (MeV) <sup>b</sup>	2.261
$\Gamma$ (keV)	$35 \pm 5$
$\Gamma_n(E_r)$ (keV)	$31 \pm 7$
$\Gamma_\gamma$ (eV) <sup>b</sup>	$0.07 \pm 0.03$
$\gamma_n^2$ (keV)	594
$\theta^2$	0.091
radius (fm)	3.30
$\sigma_{\text{max}}$	12.0
$J^\pi$	$3^+$
$l_n$	1

<sup>a</sup> Energies in lab system except for those labeled <sup>b</sup>. For references see (1974AJ01, 1979AJ01).

<sup>b</sup> Energies in c.m. system.

### 3. ${}^7\text{Li}(n, \gamma){}^8\text{Li}$ $Q_m = 2.033$

The cross section for capture radiation has been measured for  $E_n = 40$  to 1000 keV; it decreases from  $50 \mu\text{b}$  to  $5 \mu\text{b}$  over that interval. The cross section shows the resonance corresponding to  ${}^8\text{Li}^*(2.26)$ :  $E_{\text{res}} = 254 \pm 3$  keV,  $\Gamma_n = 31 \pm 7$  keV,  $\Gamma_\gamma = 0.07 \pm 0.03$  eV: see Table 8.3 and (1974AJ01). See also (1985SM1B), (1981MUZQ, 1984SH1N, 1986AB1E). The decay of  ${}^8\text{Li}^*(2.26) \rightarrow {}^7\text{Li}_{\text{g.s.}} + n$  in the interaction of 35 MeV/A  ${}^{14}\text{N}$  ions on Ag is reported by (1987BL13).

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

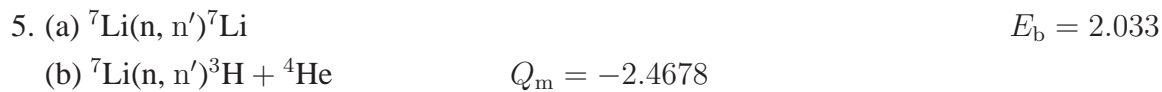
The thermal cross section is  $0.97 \pm 0.04$  b [see (1981MUZQ)],  $\sigma_{\text{free}} = 1.07 \pm 0.03$  b (1983KO17). The real coherent scattering length is  $-2.22 \pm 0.01$  fm. The complex scattering lengths are  $b_+ = -4.15 \pm 0.06$  fm and  $b_- = 1.00 \pm 0.08$  fm (1983KO17); see also (1979GL12). See (1984AJ01) for earlier references.

Total and elastic cross sections have been reported for  $E_n = 5$  eV to 49.6 MeV: see (1974AJ01, 1979AJ01, 1984AJ01). Cross sections have also been reported for  $n_0$ ,  $n_{0+1}$  and  $n_2$  at  $E_n = 6.82$ , 8.90 and 9.80 MeV. (1987SC08;  $n_2$  at the two higher energies).

A pronounced resonance is observed at  $E_n = 254$  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  $E_n = 0.25$  and



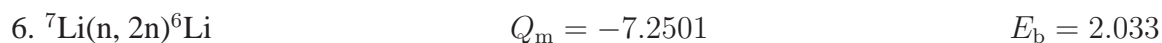
3.4 MeV, with  $J^\pi = 3^+$  and  $2^-$ , together with a broad  $J^\pi = 3^-$  level at higher energy. Broad peaks are reported at  $E_n = 4.6$  and  $5.8$  MeV ( $\pm 0.1$  MeV) [ $^8\text{Li}^*(6.1, 7.1)$ ] with  $\Gamma \approx 1.0$  and  $0.4$  MeV, respectively, and there is indication of a narrow peak at  $E_n = 5.1$  MeV [ $^8\text{Li}^*(6.5)$ ] with  $\Gamma \ll 80$  keV and of a weak, broad peak at  $E_n = 3.7$  MeV: see (1974AJ01, 1984AJ01). A multi-level, multi-channel  $R$ -matrix calculation is reported by (1987KN04). This analysis leads to predictions for the cross section for elastic scattering, for  $(n, n')$  to  $^7\text{Li}^*(0.48, 4.68, 6.68)$  and for triton production. A number of additional (broad) states of  $^8\text{Li}$ , unobserved directly in this and in other reactions, derive from this analysis (1987KN04). See also (1984FE1A, 1984MO1J), (1983DA22, 1983GO1H, 1984SH1N, 1984SH1B, 1986BOZG, 1987LE33, 1988MA1H) and (1983FA17, 1986BA09, 1986FIZX, 1987VE02; theor.).



The excitation function for  $0.48$  MeV  $\gamma$ -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. A good fit is obtained with either  $J^\pi = 1^-$  or  $1^+$  ( $2^+$  not excluded),  $\Gamma_{\text{lab}} = 1.14$  MeV. A prominent peak is observed at  $E_n = 3.8$  MeV ( $\Gamma_{\text{lab}} = 0.75$  MeV) and there is some indication of a broad resonance ( $\Gamma_{\text{lab}} = 1.30$  MeV) at  $E_n = 5.0$  MeV. At higher energies there is some evidence for structure at  $E_n = 6.8$  and  $8$  MeV followed by a decrease in the cross section to  $20$  MeV: see (1979AJ01, 1984AJ01). The total cross section for  $(n_0 + n_1)$  and  $n_2$  have been reported at  $E_n = 8.9$  MeV (1984FE1A; prelim.). For  $R$ -matrix analyses see (1987KN04) in reaction 4 and (1984AJ01).

The cross section for reaction (b) rises from threshold to  $\approx 360$  mb at  $E_n \approx 6$  MeV and then decreases slowly to  $\approx 250$  mb at  $E_n \approx 16$  MeV: see (1985SW01, 1987QA01). Cross sections for tritium production have been reported recently from threshold to  $E_n = 16$  MeV (1983LI1C; prelim.),  $4.57$  to  $14.1$  MeV (1985SW01),  $7.9$  to  $10.5$  MeV (1987QA01),  $14.74$  MeV (1984SMZX; prelim.) and at  $14.94$  MeV (1985GO18:  $302 \pm 18$  mb). At  $E_n = 14.95$  MeV the total  $\alpha$  production cross section [which includes to  $(n, 2n\text{d})$  process] is  $336 \pm 16$  mb (1986KN06). Spectra at  $14.6$  MeV may indicate the involvement of states of  $^4\text{H}$  (1986MI11). The half-life of  $^3\text{H}$  has recently been measured to be  $12.38 \pm 0.03$  mean solar years (1987OL04). See also (1987TI07).

See also (1986DE20, 1986DR10), (1984SH1N, 1985BO1D, 1986BOZG, 1986LI15) and (1986CH1S, 1986FA13, 1986GO1K, 1986IG1A, 1986KO32, 1986MA1R, 1986SE1D, 1986SH1T, 1986SH33, 1986TA1H, 1986VE1A, 1986YA1K, 1986YO1D; applications).



See (1985CH37, 1986CH24). See also (1984SH1B, 1986BOZG, 1988MA1H).

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

Angular distributions and analyzing powers for the transitions to  ${}^8\text{Li}^*(0, 0.98, 2.26)$  have been studied at  $E_{\bar{p}} = 200.4$  MeV. [The  $(p, \pi^-)$  reaction to the analog states in  ${}^8\text{B}$  is discussed there.] The  $(p, \pi^+)$  cross sections are an order of magnitude greater than the  $(p, \pi^-)$  cross sections and show a much stronger angular dependence (1987CA06). Angular distributions and  $A_y$  have also been measured at  $E_{\bar{p}} = 250, 354$  and  $489$  MeV to the first three states of  ${}^8\text{Li}$ . Those to  ${}^8\text{Li}^*(0, 2.26)$  have differential cross sections which exhibit a maximum near the invariant mass of the  $\Delta_{1232}$  and  $A_y$  which are similar to each other and to those of the  $\bar{p}p \rightarrow d\pi^+$  reaction.  ${}^8\text{Li}^*(6.53)$  is clearly populated (1987HU12).

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

Angular distributions of the  $p_0$  and  $p_1$  groups [ $l_n = 1$ ] at  $E_d = 12$  MeV have been analyzed by DWBA:  $S_{\text{exp}} = 0.87$  and  $0.48$  respectively for  ${}^8\text{Li}^*(0, 0.98)$ . 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  ${}^8\text{Li}^*(0.98)$  is  $10.1 \pm 4.5$  fsec: see (1979AJ01). See also (1985FI1D; astrophysics).

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

See (1984KO25).

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

See  ${}^8\text{He}$ .

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

For reaction (a) see (1984AJ01) and (1985KI1A). The summed proton spectrum (reaction (b)) at  $E_p = 156$  MeV shows peaks corresponding to  ${}^8\text{Li}(0)$  and  ${}^8\text{Li}^*(0.98 + 2.26)$  [unresolved]. In addition s-states [ $J^\pi = 1^-, 2^-$ ] are suggested at  $E_x = 9$  and  $16$  MeV, with  $\Gamma_{\text{c.m.}} \approx 6$  and  $8$  MeV; the latter may actually be due to continuum protons: see (1974AJ01). 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  $10.7 \pm 0.5$  MeV (1985BE30, 1985DO16). See also (1987GAZM).

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

Angular distributions have been reported for the  ${}^3\text{He}$  ions to  ${}^8\text{Li}^*(0, 0.98, 2.26, 6.53)$  at  $E_d = 28$  MeV [ $C^2S$  (abs.) = 1.63, 0.61, 0.48, 0.092] and 52 MeV. The distributions to  ${}^8\text{Li}^*(6.53)[\Gamma < 100$  keV] are featureless: see (1979AJ01).

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

At  $E_t = 12.98$  MeV, angular distributions of the  $\alpha$ -particles to  ${}^8\text{Li}^*(0, 0.98, 2.26, 6.53 \pm 0.02$  [ $\Gamma_{\text{c.m.}} < 40$  keV]) have been measured: see (1974AJ01). At  $E_t = 17$  MeV angular distributions to these four states have been analyzed by ZRDWBA and  $C^2S$  have been derived (1988LI27). At  $E_t = 17$  MeV,  $\sigma(\theta)$  and  $A_y$  measurements, analyzed by CCBA, lead to  $J^\pi = 4^+$  for  ${}^8\text{Li}^*(6.53)$ : see (1984AJ01). For  ${}^8\text{Li}^*(0.98)$ ,  $\tau_m = 14 \pm 5$  fsec,  $E_x = 980.80 \pm 0.10$  keV: see (1974AJ01).

14.  ${}^9\text{Be}({}^7\text{Li}, {}^8\text{Be}){}^8\text{Li}$   $Q_m = 0.367$

See (1984KO25).

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

See (1986BE1Q).

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

At  $E_p = 45$  MeV,  ${}^3\text{He}$  ions are observed to a state at  $E_x = 10.8222 \pm 0.0055$  MeV ( $\Gamma_{\text{c.m.}} < 12$  keV): the angular distributions for the transition to this state, and to its analog ( ${}^8\text{Be}^*(27.49)$ ), measured in the analog reaction [ ${}^{10}\text{Be}(p, t){}^8\text{Be}$ ] are very similar. They are both consistent with  $L = 0$  using a DWBA (LZR) analysis: see (1979AJ01).

17.  ${}^{11}\text{B}(n, \alpha){}^8\text{Li}$   $Q_m = -6.631$

Angular distributions of the  $\alpha_0$  and  $\alpha_1$  groups have been measured at  $E_n = 14.1$  and 14.4 MeV: see (1974AJ01, 1984AJ01).

18.  $^{11}\text{B}(^7\text{Li}, ^{10}\text{B})^8\text{Li}$   $Q_m = -9.421$

At  $E(^7\text{Li}) = 34$  MeV angular distributions have been studied involving  $^8\text{Li}(\text{g.s.}, 0.98)$  and  $^{10}\text{B}_{\text{g.s.}}$  (1987CO16).

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

See (1984NE1A).

${}^8\text{Be}$   
(Figs. 2 and 4)

GENERAL: See also (1984AJ01).

*Shell model:* (1984PA04, 1984VA06, 1984ZW1A, 1985FI1E, 1987BL18, 1987KI1C, 1988WO04).

*Collective, rotational and deformed models:* (1984PA04, 1985RO1G).

*Cluster and  $\alpha$ -particle models:* (1981PL1A, 1983CA12, 1983DR09, 1983FU1D, 1983HA41, 1983JA09, 1983SH38, 1984DE24, 1984DU17, 1984LU1A, 1984LU1B, 1985FI1E, 1986GU1F, 1986KR12, 1986SU06, 1988KR01).

*Special states:* (1981PL1A, 1983AD1B, 1983BI1C, 1983FE07, 1983FI11, 1983HA41, 1984DE24, 1984DU17, 1984LU1A, 1984LU1B, 1984VA06, 1984VAZS, 1984ZW1A, 1985FI1E, 1985GO1A, 1985PO19, 1985PU03, 1985RO1G, 1986AN10, 1987KA18, 1987KI1C, 1987SV1A, 1987WA36, 1988BA75, 1988KR01, 1988KW02, 1988KH03).

*Electromagnetic transitions, giant resonances:* (1983FI11, 1984VA1B, 1985FI1E, 1985GO1A, 1985GR1A, 1986AN10, 1986QUZZ, 1987KI1C).

*Astrophysical questions:* (1985BO1E, 1987FU04).

*Complex reactions involving  ${}^8\text{Be}$ :* (1982GU21, 1983DEZW, 1983EL1A, 1983SI1A, 1983WA1F, 1983XU1A, 1984AB1C, 1984PA13, 1985BU16, 1985HA1N, 1985KA1E, 1985KA1G, 1985KAZQ, 1985KW03, 1985PO11, 1985PO19, 1985WA22, 1986BA2D, 1986BL12, 1986BR26, 1986GA24, 1986GU1F, 1986IR01, 1986MA1O, 1986PO06, 1986PO12, 1986TA1M, 1987AR19, 1987BL16, 1987CH26, 1987CH33, 1987CH32, 1987DE1O, 1987DU07, 1987GE1B, 1987GL05, 1987HA45, 1987PE1B, 1987PO23, 1987RUZX, 1988AR05, 1988POZZ, 1988RU01, 1988SA09, 1988VA1E).

*Reactions involving pions and other mesons:* (1981MC09, 1983SP06, 1985BE1C, 1987HU12).

*Hypernuclei:* (1982KA1D, 1983SH38, 1983SH1E, 1984ZH1B, 1985AH1A, 1985IK1A, 1985MO1F, 1986BA1W, 1986DA1B, 1987BA2K, 1987MI38, 1987PO1H, 1987YA1M, 1988TA29).

*Other topics:* (1983AD1B, 1983BI1C, 1983FU1D, 1983GR26, 1983MI1E, 1985AN28, 1986BL1D, 1986GL1E, 1986MA1W, 1987AB21, 1987SV1A, 1988AJ1B, 1988BO04, 1988KW02, 1988RU1B, 1988RU1D, 1988WA1E).

*Ground-state properties of  ${}^8\text{Be}$ :* (1983ANZQ, 1983DR09, 1984DU17, 1984LU1A, 1984LU1B, 1985AN28, 1985FI1E, 1985GO1A, 1985SH1A, 1987BL18, 1987BO42, 1987KI1C, 1987KO1U, 1987SA15, 1987SV1A, 1988AR05, 1988WO04).

1.  ${}^8\text{Be} \rightarrow 2 {}^4\text{He}$   $Q_m = 0.09189$

$\Gamma_{\text{c.m.}}$  for  ${}^8\text{Be}_{\text{g.s.}} = 6.8 \pm 1.7$  eV: see (1974AJ01). See also (1987WE1C, 1988BA86; astrophysics) and (1983DR09; theor.).

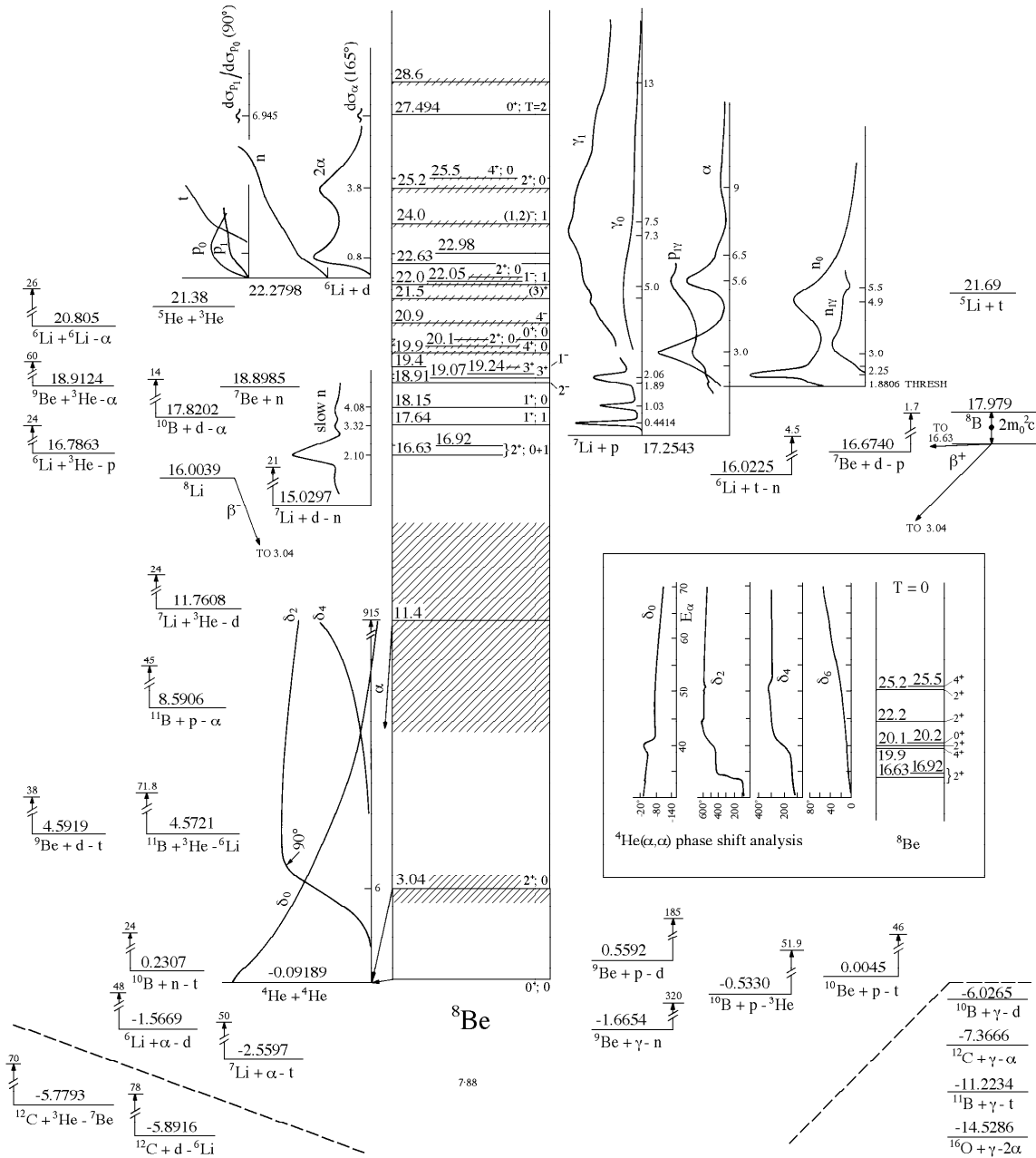


Fig. 2: Energy levels of  ${}^8\text{Be}$ . For notation see Fig. 1.

Table 8.4: Energy levels of  ${}^8\text{Be}$  <sup>a</sup>

$E_x$ (MeV $\pm$ keV)	$J^\pi; T$	$\Gamma_{\text{c.m.}}$ (keV)	Decay	Reactions
g.s.	$0^+; 0$	$6.8 \pm 1.7$ eV	$\alpha$	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
$3.04 \pm 30$	$2^+; 0$	$1500 \pm 20$	$\alpha$	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
$11.4 \pm 300$	$4^+; 0$	$\approx 3500$ <sup>b</sup>	$\alpha$	4, 12, 13, 19, 21, 27, 28, 29, 42, 44, 45
$16.626 \pm 3$	$2^+; 0 + 1$	$108.1 \pm 0.5$	$\gamma, \alpha$	2, 4, 10, 11, 13, 14, 19, 20, 21, 25, 28, 29, 34, 35, 38, 42, 44
$16.922 \pm 3$	$2^+; 0 + 1$	$74.0 \pm 0.4$	$\gamma, \alpha$	2, 4, 10, 11, 13, 14, 19, 20, 21, 27, 28, 29, 34, 35, 38, 42, 44
$17.640 \pm 1.0$	$1^+; 1$	$10.7 \pm 0.5$	$\gamma, \text{p}$	5, 11, 14, 16, 19, 20, 27, 28, 35, 44
$18.150 \pm 4$	$1^+; 0$	$138 \pm 6$	$\gamma, \text{p}$	11, 14, 16, 19, 20, 27, 28, 35, 38
18.91	$2^-$	122 <sup>e</sup>	$\gamma, \text{n}, \text{p}$	11, 14, 15, 16, 19, 23
$19.07 \pm 30$	$3^+; (1)$	$270 \pm 20$	$\gamma, \text{p}$	11, 14, 16, 19, 27, 28
$19.24 \pm 25$	$3^+; (0)$	$230 \pm 30$	$\text{n}, \text{p}$	15, 16, 19, 27, 28, 29, 35
19.4	$1^-$	$\approx 650$	$\text{n}, \text{p}$	11, 15, 16
$19.86 \pm 50$	$4^+; 0$	$700 \pm 100$	$\text{p}, \alpha$	4, 11, 18, 21, 22, 28, 29, 35
20.1	$2^+; 0$	$\approx 1100$	$\text{n}, \text{p}, \alpha$	4, 15, 16, 18, 22, 35
20.2	$0^+; 0$	$< 1000$	$\alpha$	4, 35
20.9	$4^-$	$1600 \pm 200$	$\text{p}$	16
21.5	$3^{(+)}$	1000	$\gamma, \text{n}, \text{p}$	14, 15

Table 8.4: Energy Levels of  ${}^8\text{Be}$  <sup>a</sup> (continued)

$E_x$ (MeV $\pm$ keV)	$J^\pi; T$	$\Gamma_{\text{c.m.}}$ (keV)	Decay	Reactions
22.0 <sup>c</sup>	$1^-; 1$	$\approx 4000$	$\gamma, p$	14
$22.05 \pm 100$		$270 \pm 70$		29
22.2	$2^+; 0$	$\approx 800$	$n, p, d, \alpha$	4, 9, 13, 15, 16, 18
$22.63 \pm 100$		$100 \pm 50$		29
$22.98 \pm 100$		$230 \pm 50$		29
24.0 <sup>c</sup>	$(1, 2)^-; 1$	$\approx 7000$	$\gamma, p, \alpha$	14, 18
25.2	$2^+; 0$		$p, d, \alpha$	4, 9, 18
25.5	$4^+; 0$	broad	$d, \alpha$	9
$27.4941 \pm 1.8$ <sup>d</sup>	$0^+; 2$	$5.5 \pm 2.0$	$\gamma, n, p, d, t, {}^3\text{He}, \alpha$	5, 7, 9, 31
(28.6)		broad	$\gamma, p$	14

<sup>a</sup> See also Table 8.5 and reaction 4.

<sup>b</sup> See, however, reaction 27.

<sup>c</sup> Giant resonance: see reaction 14.

<sup>d</sup> For the parameters of this state please see Table 8.5 in (1984AJ01).

<sup>e</sup> See reaction 23.

## 2. ${}^4\text{He}(\alpha, \gamma){}^8\text{Be}$ $Q_m = -0.09189$

The yield of  $\gamma_1$  has been measured for  $E_\alpha = 32$  to  $36$  MeV. The yield of  $\gamma_0$  for  $E_\alpha = 33$  to  $38$  MeV is twenty times lower than for  $\gamma_1$ , consistent with E2 decay. An angular correlation measurement at the resonances corresponding to  ${}^8\text{Be}^*(16.6 + 16.9)[2^+; T = 0 + 1]$  gives  $\delta = 0.19 \pm 0.03$ ,  $\Gamma_\gamma(\text{M1}) = 6.4 \pm 0.5$  eV [weighted mean of the two published measurements listed in (1979AJ01)]. The  $E_x$  of  ${}^8\text{Be}^*(3.0)$  is determined in this reaction to be  $3.18 \pm 0.05$  MeV [see also Table 8.4 in (1974AJ01)].

The E2 bremsstrahlung cross section to  ${}^8\text{Be}_{\text{g.s.}}$  has been calculated as a function of  $E_x$  over the 3-MeV state: the total  $\Gamma_\gamma$  for this transition is 8.3 meV, corresponding to 75 W.u. (1986LA05). A calculation of the  $\Gamma_\gamma$  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  $\gamma$ -ray transition within the  $2^+$  resonance is calculated to be  $\leq 2.5$  nb at  $E_x \approx 3.3$  MeV (1986LA19). See also (1985BA45; theor.).

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



Table 8.5: Electromagnetic transitions in  ${}^8\text{Be}$  <sup>a</sup>

Transition	$\Gamma_\gamma$ (eV)	$ M ^2$ (W.u.)
17.6 $\rightarrow$ 0	16.7	0.15
17.6 $\rightarrow$ 3.0	$8.15 \pm 0.07$ (M1) <sup>b</sup>	0.12
	$0.15 \pm 0.07$ (E2)	
17.6 $\rightarrow$ 16.6	$0.032 \pm 0.003$ <sup>c</sup>	$1.48 \pm 0.15$ (M1)
17.6 $\rightarrow$ 16.9	$0.0013 \pm 0.0003$	$0.15 \pm 0.04$ (M1)
18.15 $\rightarrow$ 0	3.0	
18.15 $\rightarrow$ 3.0	3.8	
18.15 $\rightarrow$ 16.6	$0.077 \pm 0.019$	$1.04 \pm 0.26$ (M1)
18.15 $\rightarrow$ 16.9	$0.062 \pm 0.007$	$1.51 \pm 0.17$ (M1)
18.9 $\rightarrow$ 16.6	0.168	0.053 (E1)
18.9 $\rightarrow$ 16.9	0.099	0.045 (E1)
19.07 $\rightarrow$ 3.0	10.5	

<sup>a</sup> See Table 8.7 in (1979AJ01) for the references. See also reaction 2 here.

<sup>b</sup>  $\delta(\text{E2/M1}) = 0.21 \pm 0.04$ , averaged over the energy of the final state.

<sup>c</sup> Nearly pure M1:  $\delta(\text{E2/M1}) = -0.014 \pm 0.013$ .

The cross sections for formation of  ${}^7\text{Li}^*(0, 0.48)$  [ $E_\alpha = 39$  to 49.5 MeV] and  ${}^7\text{Be}^*(0, 0.43)$  [39.4 to 47.4 MeV] both show structures at  $E_\alpha \approx 40.0$  and  $\approx 44.5$  MeV: they are due predominantly to the  $2^+$  states  ${}^8\text{Be}^*(20.1, 22.2)$ : see (1979AJ01). 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  ${}^8\text{Be}$ : see Table 8.5 in (1984AJ01). Cross sections for  $p_{0+1}$  are also reported at  $E_\alpha = 37.5$  to 140.0 MeV: see (1979AJ01, 1984AJ01). The cross sections for reaction (c) has been measured at three energies in the range  $E_\alpha = 46.7$  to 49.5 MeV: see (1979AJ01) and below.

The production of  ${}^6\text{Li}, {}^7\text{Li}$  and  ${}^7\text{Be}$  [and  ${}^6\text{He}$ ] has been studied for  $E_\alpha = 61.5$  to 158.2 MeV by (1982GL01) and at 198.4 MeV by (1985WO11). The production of  ${}^7\text{Li}$  (via reactions (a) and (b)) and of  ${}^6\text{Li}$  is discussed. At energies beyond  $E_\alpha \approx 250$  MeV the  $\alpha + \alpha$  reaction does not contribute to the natural abundance of lithium, reinforcing theories which produce  ${}^6\text{Li}$  in cosmic-ray processes and the “missing”  ${}^7\text{Li}$  in the Big Bang: thus the universe is open (1985WO11, 1982GL01).

The inclusive cross section for production of  ${}^3\text{He}$  has been measured at  $E_\alpha = 218$  MeV (1984AL03). For a fragmentation study at 125 GeV see (1985BE1E). See also (1984AJ01, 1984PA1E, 1984RE14).

4.  ${}^4\text{He}(\alpha, \alpha){}^4\text{He}$

$E_b = -0.09189$

The  $\alpha$ - $\alpha$  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  $l = 0$  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 (1974AJ01). Five  $2^+$  levels are observed from  $l = 2$  phase shifts measured from  $E_\alpha = 30$  to 70 MeV:  ${}^8\text{Be}^*(16.6, 16.9)$  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  $\Gamma_\alpha$ . The  $l = 2$   $\alpha - \alpha$  phase shifts have been analyzed by (1986WA01) up to  $E_\alpha = 34$  MeV: intruder states below  $E_x = 26$  MeV need not be introduced.

The  $l = 4$  phase shift rises from  $E_\alpha \approx 11$  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  $\delta_4$  at  $E_\alpha = 40$  MeV corresponds to a  $4^+$  state at 19.9 MeV with  $\Gamma_\alpha/\Gamma \approx 0.96$ ;  $\Gamma < 1$  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  $\delta_6$  is observed. Some indications of a  $6^+$  state at  $E_x \approx 28$  MeV and of an  $8^+$  state at  $\approx 57$  MeV have been reported;  $\Gamma_{\text{c.m.}} \approx 20$  and  $\approx 73$  MeV, respectively. A resonance is not observed at the first  $T = 2$  state,  ${}^8\text{Be}^*(27.49)$ . See (1979AJ01) for references.

The elastic scattering has also been studied at  $E_\alpha = 56.3$  to 95.5 MeV (1987NE1C; pre-lim.), 158.2 MeV, 650 and 850 MeV and at 4.32 and 5.07 GeV/ $c$  [see (1979AJ01, 1984AJ01)] as well as at 198.4 MeV (1985WO11). For  $\alpha$ - $\alpha$  correlations involving  ${}^8\text{Be}^*(0, 3.0)$  see (1987CH33, 1987PO03). See also (1985KR21, 1986FO04, 1986GOZY, 1986UC1A, 1987FO08) and the ‘‘General’’ section here. For inclusive cross sections see (1984AJ01) and (1984AL03; 218 MeV).

For studies at very high energies see reaction 3 and (1982AB1B, 1984SA39, 1984TA1D, 1984TA1G, 1985AB1A, 1985AK1A, 1985CA1C, 1986BE2N, 1986BE1S, 1986BE1T, 1986TA1N, 1986TA1P, 1987BA13). See also (1986CH1M), (1982NA1B, 1983FA1A, 1984FA1B, 1984FR1C, 1985CA41, 1985FA1A, 1985FR1E, 1985WI1B, 1986AN1F, 1986CH1J, 1986ST1D, 1987HE1B, 1987OT1D), (1985NO1B, 1986LA16, 1987FU04, 1987MU1B; astrophysics) and (1982WE15, 1983AL1C, 1983BU15, 1983FI11, 1983GO25, 1983KO41, 1983MA73, 1983OK06, 1983PR09, 1983SA16, 1984DE24, 1984FI11, 1984FI13, 1984FR10, 1984HE1D, 1984KR10, 1984LI28, 1984MA16, 1984MA1H, 1984MA68, 1984NA11, 1984OK03, 1984TA1E, 1984VAZS, 1984ZA1B, 1985BA45, 1985FI1E, 1985FR1F, 1985HO1B, 1985KI11, 1985PR1A, 1985PR1B, 1985SP05, 1985TH08, 1985YA05, 1985YI1B, 1985YI1C, 1986CR1B, 1986FR12, 1986HO33, 1986LA12, 1986MA03, 1986OC1A, 1986SA30, 1986SU06, 1986WI04, 1986YU1A, 1987BA35, 1987FR1D, 1987KA1W, 1987KR03, 1987OC1B, 1987PR01, 1987SA37, 1987SH1M, 1987WA07, 1988BA75, 1988KR01, 1988MO05; theor.).

## 5. ${}^6\text{Li}(d, \gamma){}^8\text{Be}$

$$Q_m = 22.2798$$

The yield of  $\gamma$ -rays to  ${}^8\text{Be}^*(17.64)$  [ $1^+$ ;  $T = 1$ ] 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,  $\Gamma_{\text{c.m.}} = 5.5 \pm 2.0$  keV];

Table 8.6: Some  ${}^8\text{Be}$  states with  $16.6 < E_x < 23.0$  MeV <sup>a</sup>

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

<sup>a</sup> See Table 8.5 in (1979AJ01) for references. See also Tables 8.7 and 8.8 here.

<sup>b</sup>  $R$ -matrix theory.

<sup>c</sup> Complex eigenvalue theory.

$\Gamma_\gamma = 23 \pm 4$  eV [ $1.14 \pm 0.20$  W.u.] for this M1 transition from the first  $0^+$ ;  $T = 2$  state in  ${}^8\text{Be}$ , in good agreement with the intermediate coupling model: see Table 8.5 in (1984AJ01). See also (1979AJ01).

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

Yield curves and cross sections have been measured for  $E_d = 48$  keV to 17 MeV: see (1979AJ01, 1984AJ01). See also (1983SZZY). Polarization measurements are reported at  $E_d = 0.27$  to 3.7 MeV. Comparisons of the populations of  ${}^7\text{Be}^*(0, 0.43)$  and of  ${}^7\text{Li}^*(0, 0.48)$  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 (1979AJ01). 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 (1985CE12). See also  ${}^7\text{Be}$ , (1985WA1C) and (1984KU15; theor.).

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

Excitation functions have been measured for  $E_d = 30$  keV to 5.4 MeV: see (1979AJ01, 1984AJ01). The thick target yield of 0.48-MeV  $\gamma$ -rays is reported from  $\approx 50$  to  $\approx 170$  keV (1985CE12). See also (1983SZZY). 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 (1979AJ01). See also  ${}^7\text{Li}$  and (1984KU15; theor.).

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

The yield of elastically scattered deuterons has been measured for  $E_d = 2$  to 7.14 MeV. No resonances are observed: see (1974AJ01). See also (1983HA1D, 1985LI1C; 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 (1974AJ01). For VAP and TAP measurements at  $E_d^- = 191$  and 395 MeV see (1986GA18).

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

Table 8.7:  ${}^8\text{Be}$  levels from  ${}^7\text{Li}(p, \gamma){}^8\text{Be}$  <sup>a</sup>

$E_{\text{res}}$ (keV)	$\Gamma_{\text{lab}}$ (keV)	${}^8\text{Be}^*$ (MeV)	$l_p$	$J^\pi$	Res. <sup>d</sup>
$441.4 \pm 0.5$ <sup>b</sup>	$12.2 \pm 0.5$	17.640	1	$1^+$	$\gamma_0, \gamma_1, \gamma_3, \gamma_4$
$1030 \pm 5$	168	18.155	1	$1^+$	$\gamma_0, \gamma_1, \gamma_3, \gamma_4$
1890	$150 \pm 50$	18.91		$(2^-)$	$\gamma_3, \gamma_4$
$2060 \pm 20$	$310 \pm 20$	19.06		$J = 1, 2, 3,$ $\pi = (-)$ <sup>c</sup>	$\gamma_1$
(3100)		(20.0)			$\gamma_1$
4900		21.5			$\gamma_1$
5000	$\approx 4500$	21.6	0	$1^-; T = 1$	$\gamma_0$
6000		22.5			$\gamma_1$
7500	$\approx 8000$	23.8	(0)	$(1^-, 2^-); T = 1$	$\gamma_1$
(11100)		(27.0)			$\gamma_1$
13000	broad	28.6			

<sup>a</sup> See Tables 8.6 in (1974AJ01, 1979AJ01) for the references.

<sup>b</sup> See (1959AJ76). See also (1983FI13, 1984JE1B).

<sup>c</sup> See, however, reaction 16.

<sup>d</sup>  $\gamma_0, \gamma_1, \gamma_3, \gamma_4$  represent transitions to  ${}^8\text{Be}^*(0, 3.0, 16.6, 16.9)$ , respectively.

Cross sections and angular distributions (reaction (a)) have been measured at  $E_d = 30$  keV to 31 MeV: see (1979AJ01, 1984AJ01). See also (1983SZZY). 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 (1984AJ01). Polarization measurements are reported in the range 0.4 to 11 MeV: see (1979AJ01, 1984AJ01) 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,  $\Gamma_{\text{lab}} \approx 0.8$  MeV and  $E_d = 3.75$  MeV,  $\Gamma_{\text{lab}} \approx 1.4$  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  $\alpha^*$  channel [to  ${}^4\text{He}(20.1)$ ,  $J^\pi = 0^+$ ] presumably due to  ${}^8\text{Be}^*(25.2, 25.5)$ . In addition the ratio of the  $\alpha^*/\alpha$  differential cross sections at  $30^\circ$  shows a broad peak centered at  $E_x \approx 26.5$  MeV (which may be due to interference effects) and suggests a resonance-like anomaly at  $E_x \approx 28$  MeV.  $A_{yy} = 1$  points are reported at  $E_d = 5.55 \pm 0.12$  ( $\theta_{\text{c.m.}} = 29.7 \pm 1.0^\circ$ ) and  $8.80 \pm 0.25$  MeV ( $\theta_{\text{c.m.}} = 90.0 \pm 1.0^\circ$ ) [corresponds to  $E_x = 26.44$  and 28.87 MeV]. For references see (1974AJ01, 1979AJ01).

At  $E_d = 6.945$  MeV, the  $\alpha_0$  yield shows an anomaly corresponding to  ${}^8\text{Be}^*(27.49)$ , the  $0^+$ ;  $T = 2$  analog of  ${}^8\text{He}_{\text{g.s.}}$ . This  $T = 2$  state has recently been studied using both polarized deuterons and  ${}^6\text{Li}$  ions. The ratio of the partial widths for decay into  ${}^6\text{Li} + d$  states with channel spin 2 and 0,  $\Gamma_2/\Gamma_1 = 0.322 \pm 0.091$  (1986SO07).

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  ${}^4\text{He}_{\text{g.s.}} + {}^4\text{He}^*(20.1) [0^+]$ ) shows a broad maximum at  $E_x \approx 25$  MeV. Analysis of these results, and of a study of  ${}^7\text{Li}(p, \alpha)\alpha^*$  [see reaction 18] which shows a peak of different shape at  $E_x \approx 24$  MeV, indicate the formation and decay of overlapping states of high spatial symmetry, if the observed structures are interpreted in terms of  ${}^8\text{Be}$  resonances: see (1984AJ01). For other work see (1984AJ01). See also  ${}^6\text{Li}$ , (1986ST1E), (1984VO1A, 1988KU1E; applications) and (1983HA1D, 1984KR1B, 1984KU15; theor.).

Table 8.8:  ${}^8\text{Be}$  levels from  ${}^7\text{Li}(p, p_0){}^7\text{Li}$  and  ${}^7\text{Li}(p, p_1){}^7\text{Li}^*$  <sup>a</sup>

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

<sup>a</sup> See references in Table 8.9 (1979AJ01).

<sup>b</sup> (p, n) threshold: see reaction 15.

<sup>c</sup>  $\theta_p^2 = 0.064$ .

<sup>d</sup> See also Table 8.7,  $\gamma_{n1}^2$  and  $\gamma_{p1}^2 \approx 1\%$  of Wigner limit.

<sup>e</sup> A  $2^+$  state at  $E_x \approx 20$  MeV appears to be necessary to account for the cross sections: see Table 8.3 and reaction 4.

<sup>f</sup> Reduced width is 70% of the Wigner limit.

<sup>g</sup> May be due to two  $2^+$  states. See also reaction 15.

<sup>h</sup> See also (1981BA36; theor.).

10.  ${}^6\text{Li}(t, n){}^8\text{Be}$

$Q_m = 16.0225$

At  $E_t = 2$  to  $4.5$  MeV  ${}^8\text{Be}^*(0, 3.0, 16.6, 16.9)$  are populated (1984LIZY; prelim.). See also (1966LA04, 1974AJ01).

11. (a)  ${}^6\text{Li}({}^3\text{He}, p){}^8\text{Be}$   $Q_m = 16.7863$   
 (b)  ${}^6\text{Li}({}^3\text{He}, p)2\ {}^4\text{He}$   $Q_m = 16.8782$

Angular distributions have been studied in the range  $E({}^3\text{He}) = 0.46$  to  $17$  MeV and at  $E({}^6\text{Li}) = 21$  MeV.  ${}^8\text{Be}^*(0, 3.0, 16.63, 16.92, 17.64, 18.15, 19.0, 19.4, 19.9)$  are populated in this reaction: see (1974AJ01, 1979AJ01, 1984AJ01). For reaction (b) see (1974AJ01) and (1987ZA07). See also  ${}^9\text{B}$ .

12. (a)  ${}^6\text{Li}(\alpha, d){}^8\text{Be}$   $Q_m = -1.5669$   
 (b)  ${}^6\text{Li}(\alpha, 2\alpha){}^2\text{H}$   $Q_m = -1.4750$

Deuteron groups have been observed to  ${}^8\text{Be}^*(0, 3.0, 11.3 \pm 0.4)$ . Angular distributions have been measured at  $E_\alpha = 15.8$  to  $48$  MeV: see (1974AJ01, 1979AJ01). A study of reaction (b) shows that the peak due to  ${}^8\text{Be}^*(3.0)$  is best fitted by using  $\Gamma = 1.2 \pm 0.3$  MeV. At  $E_\alpha = 42$  MeV the  $\alpha$ - $\alpha$  FSI is dominated by  ${}^8\text{Be}^*(0, 3.0)$ . See also Table 8.4 in (1974AJ01) and (1983BE51; theor.).

13. (a)  ${}^6\text{Li}({}^6\text{Li}, \alpha){}^8\text{Be}$   $Q_m = 20.805$   
 (b)  ${}^6\text{Li}({}^6\text{Li}, \alpha)2\ {}^4\text{He}$   $Q_m = 20.897$   
 (c)  ${}^6\text{Li}({}^6\text{Li}, 2d)2\ {}^4\text{He}$   $Q_m = -2.950$

At  $E_{\text{max}}({}^6\text{Li}) = 13$  MeV reaction (a) proceeds via  ${}^8\text{Be}^*(0, 3.0, 16.6, 16.9, 22.5)$ . The involvement of a state at  $E_x = 19.9$  MeV ( $\Gamma = 1.3$  MeV) is suggested. Good agreement with the shapes of the peaks corresponding to  ${}^8\text{Be}^*(16.6, 16.9)$  is obtained by using a simple two-level formula with interference, corrected for the effect of final-state Coulomb interaction, assuming  $\Gamma(16.6) = 90$  keV and  $\Gamma(16.9) = 70$  keV: see also Table 8.6. The ratio of the intensities of the groups corresponding to  ${}^8\text{Be}^*(16.6, 16.9)$  remains constant for  $E({}^6\text{Li}) = 4.3$  to  $5.5$  MeV:  $I(16.6)/I(16.9) = 1.22 \pm 0.08$ . Partial angular distributions for the  $\alpha_0$  group have been measured at fourteen energies for  $E({}^6\text{Li}) = 4$  to  $24$  MeV. See (1979AJ01) for the references.

At  $E({}^6\text{Li}) = 36$  to  $46$  MeV sequential decay (reaction (b)) via  ${}^8\text{Be}$  states at  $E_x = 3.0, 11.4, 16.9$  and  $19.65$  MeV is reported: see (1984AJ01). (1987LA25) report the possible involvement of the  $2^+$  state  ${}^8\text{Be}^*(22.2)$ .

For reaction (c) see (1983WA09) and  ${}^{12}\text{C}$  in (1985AJ01). See also (1983MI10) and (1982LA19, 1985NO1A; theor.).

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

$$Q_m = 17.2543$$

Cross sections and angular distributions have been reported from  $E_p = 30$  keV to 18 MeV. Gamma rays are observed to the ground ( $\gamma_0$ ) and to the broad,  $2^+$ , excited state at 3.0 MeV ( $\gamma_1$ ) and to  ${}^8\text{Be}^*(16.6, 16.9)$  ( $\gamma_3, \gamma_4$ ). Resonances for both  $\gamma_0$  and  $\gamma_1$  occur at  $E_p = 0.44$  and 1.03 MeV, and for  $\gamma_1$  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  $E_p \approx 5$  MeV ( $\gamma_0$ ),  $\Gamma \approx 4 - 5$  MeV, and at  $E_p \approx 7.3$  MeV ( $\gamma_1$ ),  $\Gamma \approx 8$  MeV: see Table 8.7. The  $E_p \approx 5$  MeV resonance ( $E_x \approx 22$  MeV) represents the giant dipole resonance based on  ${}^8\text{Be}(0)$  while the  $\gamma_1$  resonance,  $\approx 2.2$  MeV higher, is based on  ${}^8\text{Be}^*(3.0)$ . The  $\gamma_0$  and  $\gamma_1$  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.

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 ratio  $\sigma(J_c = 2)/\sigma(J_c = 1) = 3.2 \pm 0.5$ . Radiative widths for the  $\gamma_0$  and  $\gamma_1$  decay are displayed in Table 8.5. A careful study of the  $\alpha$ -breakup of  ${}^8\text{Be}^*(16.63, 16.92)$  [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  ${}^8\text{Be}^*(16.63)$  is accounted for by an extranuclear direct-capture process. Resonances for production of  ${}^8\text{Be}^*(16.63, 16.92)$  are observed at  $E_p = 0.44, 1.03$  and 1.89 MeV [ ${}^8\text{Be}^*(17.64, 18.15, 18.9)$ ]. The results are consistent with the hypothesis of nearly maximal isospin mixing for  ${}^8\text{Be}^*(16.63, 16.92)$ : 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  ${}^8\text{Be}^*(16.6, 16.9)$  are 40 and 60%, and 95 and 5% for  ${}^8\text{Be}^*(17.6, 18.2)$ . The cross section for  $(\gamma_3 + \gamma_4)$  has also been measured for  $E_p = 11.5$  to 30 MeV ( $\theta = 90^\circ$ ) by detecting the  $\gamma$ -rays and for  $E_p = 4$  to 13 MeV (at five energies) by detecting the two  $\alpha$ -particles from the decay of  ${}^8\text{Be}^*(16.6, 16.9)$ : a broad bump is observed at  $E_p = 8 \pm 2$  MeV (1981MA33). 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  ${}^8\text{Be}^*(16.6, 16.9)$ . 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 (1981MA33). A study of the  $\gamma$ -decay of  ${}^8\text{Be}^*(17.64, 18.15)$  shows no evidence for a pseudoscalar particle postulated to account for narrow peaks in  $e^+$  spectra in heavy-ion reactions (1988SA2A). For the earlier references see (1979AJ01). See also (1983CH1C), (1986WE1D), (1984DA1H; astrophysics), (1988KI1C; applied) and (1983GO1B, 1984SE16, 1985GO1B, 1987KI1C; theor.).

15.  ${}^7\text{Li}(p, n){}^7\text{Be}$ 

$$Q_m = -1.644$$

$$E_b = 17.2543$$

Measurements of cross sections have been reported for  $E_p = 1.9$  to 199.1 MeV [see (1974AJ01, 1979AJ01, 1984AJ01)] and in the range 60.1 to 480.0 MeV (1984DA22; activation  $\sigma$ ). Polarization measurements have been reported at  $E_p = 2.05$  to 5.5 MeV, 30 and 50 MeV [see (1974AJ01)] and at  $E_p = 52.8$  MeV (1988HE08) [ $K_z^{z'} = 0.07 \pm 0.02$ ]. 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  $E_p \approx 5.5$  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  ${}^7\text{Li}(p, \gamma){}^8\text{Be}^*(18.9) \rightarrow {}^8\text{Be}^*(16.6 + 16.9) + \gamma$  to the thermal neutron capture cross section  ${}^7\text{Be}(n, \gamma){}^8\text{Be}^*(18.9) \rightarrow {}^8\text{Be}^*(16.6 + 16.9) + \gamma$ , provides a rough estimate of the isospin impurity of  ${}^8\text{Be}^*(18.9)$ :  $\sigma_{p,\gamma}/\sigma_{n,\gamma} \approx 1.5 \times 10^{-5}$ . The  $T = 1$  isospin impurity is  $\leq 10\%$  in intensity. See also reaction 23. See (1979AJ01, 1984AJ01).

The structure at  $E_p = 2.25$  MeV is ascribed to a  $3^+$ ,  $T = (1)$ ,  $l = 1$  resonance with  $\Gamma_n \approx \Gamma_p$  and  $\gamma_n^2/\gamma_p^2 = 3$  to 10: see (1966LA04). 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  $\Gamma = 1.1$  MeV,  $\gamma_n^2 \approx \gamma_p^2$ . 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  $E_p \approx 5.5$  MeV may be accounted for by the interference of two  $2^+$  states. See Table 8.8 in (1979AJ01). The  $0^\circ$  differential cross section increases rapidly to  $\approx 35$  mb/sr at 30 MeV and then remains constant to 100 MeV: see (1985BO1C). The total reaction cross section [ ${}^7\text{Be}^*(0, 0.43)$ ] decreases inversely with  $E_p$  in the range 60.1 to 480.0 MeV (1984DA22) [note: the values of  $\sigma_t$  supersede those reported earlier]. The transverse polarization transfer,  $D_{NN}(0^\circ)$ , for the g.s. transition has been measured at  $E_p = 160$  MeV (1984TA07). See also (1986MC09;  $E_p = 800$  MeV), (1987WAZT), (1984BA1U), (1985CA41; astrophysics), (1983LO12; applications), (1986RA21, 1987TA22) and (1988GU1F; theor.).

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

$E_b = 17.2543$

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

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  ${}^7\text{Li}^*(0.48)$ ) and of 0.48 MeV  $\gamma$ -rays have been measured for  $E_p = 0.8$  to 12 MeV: see (1974AJ01). Polarization measurements have been reported at a number of energies in the range  $E_p = 0.67$  MeV to 2.1 GeV/ $c$  [see (1974AJ01, 1979AJ01, 1984AJ01)], at  $E_p = 1.89$  to 2.59 MeV (1986SA1P;  $p_0$ ; prelim.) and at 65 MeV (1987TO06; continuum; prelim.). See also (1983GLZZ).

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  ${}^5P_1$  and  ${}^3P_1$  with a mixing parameter of  $+25^\circ$ ; 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  ${}^5P_3$  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  ${}^3S_1$  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 (1979AJ01)].

An attempt has been made to observe the  $T = 2$  state [ $^8\text{Be}^*(27.47)$ ] 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 (1984AJ01) displays the upper limit for  $\Gamma_{p_0}/\Gamma$ .

The proton total reaction has been reported for  $E_p = 25.1$  to  $48.1$  MeV by (1985CA36). (1987CH33, 1987PO03) have studied  $p$ - $^7\text{Li}$  correlations involving  $^8\text{Be}^*(17.64, 18.15, 18.9 + 19.1 + 19.2)$ . See also  $^7\text{Li}$  (1984BA1U), (1986BA88), (1986RA1D; applications) and (1986HA1K, 1988GUIF; theor.) and the “General” section here.

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

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 [ $^8\text{Be}^*(27.47)$ ]: see (1979AJ01). See also (1984BA1T).

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

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  $\cdot$  b (1986RO13). For the earlier work see (1984AJ01).

Excitation functions and angular distributions have been measured at many energies in the range  $E_p = 23$  keV to  $62.5$  MeV: see (1979AJ01, 1984AJ01). Polarization measurements have been carried out for  $E_p = 0.8$  to  $10.6$  MeV [see (1974AJ01)]: 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  $0.98 \pm 0.04$  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 [ $\Gamma \approx 1$  MeV] and at  $\approx 5.7$  MeV [ $\Gamma \approx 1$  MeV]. Structures are also reported at  $E_p = 6.8$  MeV and at  $E_p = 9.0$  MeV: see (1979AJ01). 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  $E_x \approx 19.7$  and  $21.8$  MeV] with very small  $\alpha$ -particle widths, and four  $2^+$  states [at  $E_x \approx 15.9, 20.1, 22.2$  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 (1979AJ01) for references.

A study of the  $^7\text{Li}(p, \alpha)^4\text{He}^*$  reaction to  $^4\text{He}^*(20.1)$  [ $0^+$ ] at  $E_p = 4.5$  to  $12.0$  MeV shows a broad maximum at  $E_x \approx 24$  MeV: see reaction 9 and (1984AJ01). See also (1986ZA09), (1984HA1M, 1984YA1A, 1985BO1K, 1985CA41, 1985DE1K, 1986BO1H, 1987AS05, 1987KA1R, 1987RO25, 1988BA86, 1988FO1A; astrophysics), (1986RA1D, 1986ST1E, 1986TU1B; applications) and (1984BL21, 1984KR1B; theor.).

19. (a)  ${}^7\text{Li}(d, n){}^8\text{Be}$   $Q_m = 15.0297$   
 (b)  ${}^7\text{Li}(d, n)2\text{ }{}^4\text{He}$   $Q_m = 15.1216$

The population of  ${}^8\text{Be}^*(0, 3.0, 16.6, 16.9, 17.6, 18.2, 18.9, 19.1, 19.2)$  has been reported in reaction (a). For the parameters of  ${}^8\text{Be}^*(3.0)$  see Table 8.4 in (1974AJ01). 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 (1974AJ01, 1979AJ01)] and at  $0.19$  MeV (1983DA32, 1987DA25) and  $0.40$  and  $0.46$  MeV (1984GA07;  $n_0$  only). The angular distributions of the neutrons to  ${}^8\text{Be}^*(16.6, 17.6, 18.2)$  are fit by  $l_p = 1$ : see (1974AJ01).

Reaction (b) at  $E_d = 2.85$  to  $14.97$  MeV proceeds almost entirely through the excitation and sequential decay of  ${}^8\text{Be}^*(16.6, 16.9)$  (1987WA21).  ${}^8\text{Be}^*(11.4)$  may also be involved [ $E_x = 11.4 \pm 0.05$  MeV,  $\Gamma_{\text{c.m.}} = 2.8 \pm 0.2$  MeV] as may state(s) at  $E_x \approx 20$  MeV: see (1979AJ01). See also  ${}^9\text{Be}$ , (1983BL17, 1986BA40), (1986LE1E; applications) and (1983MU13, 1984BL21; theor.).

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

Deuteron groups are observed to  ${}^8\text{Be}^*(0, 3.0, 16.6, 16.9, 17.6, 18.2)$ . For the parameters of  ${}^8\text{Be}^*(3.0)$  see Table 8.4 in (1974AJ01). 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 (1974AJ01, 1979AJ01, 1984AJ01). Reaction (b) has been studied at  $E({}^3\text{He}) = 5.0$  MeV (1985DA29) and at  $9, 11$  and  $12$  MeV (1986ZA09).  ${}^8\text{Be}^*(0, 3.0)$  are reported to be involved (1985DA29). See also  ${}^{10}\text{B}$  and (1983KU17; theor.).

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

Angular distributions have been measured to  $E_\alpha = 50$  MeV: see (1966LA04, 1974AJ01, 1979AJ01). The ground state of  ${}^8\text{Be}$  decays isotropically in the c.m. system:  $J^\pi = 0^+$ . Sequential decay (reaction (b)) is reported at  $E_\alpha = 50$  MeV via  ${}^8\text{Be}^*(0, 3.0, 11.4, 16.6, 16.9, 19.9)$ : see (1974AJ01). See also (1983BE51, 1985PU03; theor.).

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

${}^8\text{Be}^*(0, 3.0)$  have been populated in this reaction (1987BO1M;  $E({}^7\text{Li}) = 22$  MeV). See also (1988AL1G).

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

The total (n, p) cross section has been measured from  $25 \times 10^{-3}$  eV to 13.5 keV. For thermal neutrons the cross sections to  ${}^7\text{Li}^*(0, 0.48)$  are  $38\,400 \pm 800$  and  $420 \pm 120$  b, respectively. A departure from a  $1/v$  shape in  $\sigma_t$  is observed for  $E_n > 100$  eV. The astrophysical reaction rate is  $\approx \frac{1}{3}$  lower than that previously used: this could lead to an increase in the calculated rate of production of  ${}^7\text{Li}$  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  ${}^8\text{Be}^*(18.9)$ , and a  $T = 1$  impurity of  $\approx 24\%$  (1988KO03). At thermal energies the (n,  $\alpha$ ) cross section is  $\leq 0.1$  mb and the (n,  $\gamma\alpha$ ) cross section is 155 mb: see (1974AJ01). See also (1987GLZZ, 1987GL1D), (1979AJ01, 1988BO15) and (1984YA1A, 1985BO1K, 1985DE1K; astrophysics).

24. ${}^8\text{Li}(\beta^-){}^8\text{Be}$	$Q_m = 16.0039$
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${}^8\text{Li}$  decays to the broad 3.0 MeV,  $2^+$  level of  ${}^8\text{Be}$ , which decays into two  $\alpha$ -particles. Both the  $\beta$ -spectrum and the resulting  $\alpha$ -spectrum have been extensively studied: see (1955AJ61, 1966LA04). See also  ${}^8\text{B}(\beta^+)$ . Studies of the distribution of recoil momenta and neutrino recoil correlations indicate that the decay is overwhelmingly GT, axial vector [see reaction 1 in  ${}^8\text{Li}$ ] and that the ground state of  ${}^8\text{Li}$  has  $J^\pi = 2^+$ : see (1980MC07).

(1986WA01) has performed a many-level one-channel approximation  $R$ -matrix analysis of the  $\beta$ -delayed  $\alpha$ -particle spectra in the decay of both  ${}^8\text{Li}$  and  ${}^8\text{B}$ , obtained by (1971WI05) [as well as of the  $L = 2$   $\alpha$ - $\alpha$  phase shifts]. Warburton finds that there is no need to introduce “intruder” states below  $E_x \approx 26$  MeV [see, e.g., (1974AJ01)]. He extracts the GT matrix elements for the decay to  ${}^8\text{Be}^*(3.0)$  and the doublet near 16 MeV; and he points out the difficulties in extracting meaningful  $E_x$  and  $\Gamma$  values from the  $\beta^\pm$  decay for  ${}^8\text{Be}^*(3.0)$ , as well as the  $\log ft$  values for the transitions to that state (1986WA01).

Beta- $\alpha$  angular correlations have been measured for the decays of  ${}^8\text{Li}$  and  ${}^8\text{B}$  for the entire final-state distribution: see Table 8.10 in (1979AJ01). (1980MC07) have measured the  $\beta$ - $\nu$ - $\alpha$  correlations as a function of  $E_x$  in the decay of  ${}^8\text{Li}$  and  ${}^8\text{B}$ , detecting both  $\alpha$ -particles involved in the  ${}^8\text{Be}$  decay. They find that the decay is GT for  $2 < E_x < 8$  MeV. The absence of Fermi decay strength is expected because the isovector contributions from the tails of  ${}^8\text{Be}^*(16.6, 16.9)$  interfere destructively in this energy region: see (1980MC07). The measurement of the  $\beta$ -decay asymmetry as a function of  $E_\beta$  is reported by (1986BI1D, 1985BIZZ; prelim.). (1986NAZZ; prelim.) have measured the  $\beta$ -spectrum and compared it with the spectrum predicted from the  $\alpha$ -breakup data. See also (1984KO25, 1985GR1A), (1986HA1P, 1988WA1E), (1986MA1T, 1986NAZZ; astrophysics) and (1983KU17, 1984BA25, 1986QUZZ, 1987LY05, 1988BA75; theor.).

25.  ${}^8\text{B}(\beta^+){}^8\text{Be}$

$$Q_m = 17.979$$

The decay [see reaction 1 in  ${}^8\text{B}$ ] proceeds mainly to  ${}^8\text{Be}^*(3.0)$  [see Table 8.4 in (1974AJ01) for its parameters]. Detailed study of the high-energy portion of the  $\alpha$ -spectrum reveals a maximum near  $E_\alpha = 8.3$  MeV, corresponding to transitions to  ${}^8\text{Be}^*(16.63)$ , for which parameters  $E_x = 16.67$  MeV,  $\Gamma = 150$  to 190 keV or  $E_x = 16.62$  MeV,  $\Gamma = 95$  keV are derived: see (1974AJ01). Log  $ft$  for the transition to  ${}^8\text{Be}^*(16.6)$  is 3.3. An analysis by (1986WA01) of the  $\beta^+$  delayed  $\alpha$ -spectrum is described in reaction 24. See also (1988WA1E) and (1988BA75; theor.). The  $\beta^+$  spectrum has been measured by (1987NA08) for momenta greater than 9 MeV/c. Then using the  $\alpha$  spectra from (1986WA01) the  ${}^8\text{B}$  neutrino spectrum is calculated. The average cross section for the “solar neutrino”  ${}^{37}\text{Cl}(\nu_e, e^-){}^{37}\text{Ar}$  reaction is then  $(1.07 \pm 0.02) \times 10^{-42}$  cm<sup>2</sup> [certain corrections may increase this value by as much as 4%] (1987NA08). See also (1982BA1J, 1983CO1D, 1983FO1A, 1983HA1B, 1983VO1C, 1984DA1H, 1984HA1M, 1985BA1N, 1985BA1M, 1985CH1B, 1986BA21, 1986BE1K, 1986DE1H, 1986GR04, 1986HA1I, 1986MA1T, 1986RO1N, 1986WO1B, 1987BA1X, 1987BA89, 1987CH1G, 1987FR1C, 1987FU1G, 1987KR10, 1987RI1E, 1987WE1C, 1988BA86, 1988EW1A, 1988HA1M; astrophysics).

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

Neutron groups to  ${}^8\text{Be}^*(0, 3.0)$  have been studied for  $E_\gamma = 18$  to 26 MeV: see (1974AJ01, 1979AJ01) and  ${}^9\text{Be}$ . Reaction (b) appears to proceed largely via excited states of  ${}^9\text{Be}$  with subsequent decay mainly to  ${}^8\text{Be}^*(3.0)$ : see (1966LA04, 1974AJ01),  ${}^9\text{Be}$  and  ${}^{10}\text{Be}$ . Reaction (c) has been studied at  $E_p = 45$  and 47 MeV: the reaction primarily populates  ${}^8\text{Be}^*(0, 3.0)$ : see (1979AJ01),  ${}^9\text{Be}$  and  ${}^9\text{B}$ . For work at  $E_p = 1$  GeV see (1985BE30, 1985DO16). For reactions (d) and (e) see (1974AJ01) and  ${}^9\text{Be}$ . For reaction (e) see (1979AJ01).

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

Angular distributions of deuteron groups have been reported at  $E_p = 0.11$  to 185 MeV [see (1974AJ01, 1979AJ01, 1984AJ01)] and at 18.6 MeV (1986GO23, 1987GO27;  $d_0$  and  $d_1$ ) and 50 and 72 MeV (1984ZA07; to  ${}^8\text{Be}^*(0, 3.0, 16.9, 19.2)$ ). For spectroscopic factors see (1979AJ01,

1984ZA07). The angular distributions to  ${}^8\text{Be}^*(0, 3.0, 16.9, 17.6, 18.2, 19.1)$  are consistent with  $l_n = 1$ : see (1974AJ01).

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  $\theta$ )  $E_x = 0.6 \pm 0.1$  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  $J^\pi = 0^+$   ${}^8\text{Be}_{g.s.}$ : it contains  $< 10\%$  of the g.s. transfer strength. An analysis of reported  $\Gamma_{c.m.}$  for  ${}^8\text{Be}^*(3.0)$  in this reaction shows that there is no  $E_p$  dependence. The average  $\Gamma_{c.m.}$  at  $E_p = 14.3$  and  $26.2$  MeV is  $1.47 \pm 0.04$  MeV.  $\Gamma_{c.m.} = 5.5 \pm 1.3$  eV for  ${}^8\text{Be}_{g.s.}$  and  $5.2 \pm 0.1$  MeV for  ${}^8\text{Be}^*(11.4)$ . Spectroscopic factors for  ${}^8\text{Be}_{g.s.}$  (including the “ghost” anomaly) and  ${}^8\text{Be}^*(3.0)$  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  ${}^8\text{Be}^*(3.0)$  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  $\Gamma_{c.m.} = 1.50 \pm 0.02$  MeV for  ${}^8\text{Be}^*(3.0)$ : the corresponding observed and formal reaction widths and channel radii are  $\gamma_R^2 = 580 \pm 50$  keV,  $\gamma_\lambda^2 = 680 \pm 100$  keV and  $s = 4.8$  fm. See (1979AJ01) for the earlier work. A study of the continuum part of the inclusive deuteron spectra is reported at  $E_p = 60$  MeV (1987KA25). For reaction (b) see (1988BO47). For reaction (c) [FSI through  ${}^8\text{Be}^*(0, 3.0)$ ] see (1974AJ01, 1984AJ01). See also (1985PU03; theor.) and  ${}^{10}\text{B}$ .

$$\begin{aligned} 28. \text{ (a) } {}^9\text{Be}(d, t){}^8\text{Be} & \quad Q_m = 4.5919 \\ \text{ (b) } {}^9\text{Be}(d, t)2\text{ }^4\text{He} & \quad Q_m = 4.6838 \end{aligned}$$

Angular distributions have been measured for  $E_d = 0.3$  to  $28$  MeV [see (1979AJ01)], at  $E_d = 18$  MeV (1988GO02;  $t_0, t_1$ ) and at  $E_d = 2.0$  to  $2.8$  MeV (1984AN16;  $t_0$ ). At  $E_d = 28$  MeV angular distributions of triton groups to  ${}^8\text{Be}^*(16.6, 16.9, 17.6, 18.2, 19.1, 19.2, 19.8)$  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  $0.21 \pm 0.03$  is found for  ${}^8\text{Be}^*(17.6, 18.2)$ : see (1979AJ01).

A kinematically complete study of reaction (b) at  $E_d = 26.3$  MeV indicates the involvement of  ${}^8\text{Be}^*(0, 3.0, 11.4, 16.9, 19.9 + 20.1)$ : see (1974AJ01). (1986PAZN; prelim.) report  $E_x = 3.10 \pm 0.15$  MeV,  $\Gamma \approx 0.9 - 1.3$  MeV. See also (1988NE1A; theor.).

$$\begin{aligned} 29. \text{ (a) } {}^9\text{Be}({}^3\text{He}, \alpha){}^8\text{Be} & \quad Q_m = 18.9124 \\ \text{ (b) } {}^9\text{Be}({}^3\text{He}, \alpha)2\text{ }^4\text{He} & \quad Q_m = 19.0043 \end{aligned}$$

Angular distributions have been measured in the range  $E({}^3\text{He}) = 3.0$  to  $26.7$  MeV and at  $E({}^3\text{He}) = 33.3$  MeV (to  ${}^8\text{Be}^*(16.9, 17.6, 19.2)$ ) [ $S = 1.74, 0.72, 1.17$ , assuming mixed isospin for  ${}^8\text{Be}^*(16.9)$ ]. The possibility of a broad state at  $E_x \approx 25$  MeV is also suggested: see (1979AJ01). See also (1987VA1I).

Reaction (b) has been studied at  $E(^3\text{He}) = 1.0$  to  $10$  MeV [see (1979AJ01, 1984AJ01)], at  $E(^3\text{He}) = 3$  to  $12$  MeV (1986LA26) and at  $11.9$  to  $24.0$  MeV (1987WA25). The reaction is reported to proceed via  $^8\text{Be}^*(0, 3.0, 11.4, 16.6, 16.9, 19.9, 22.5)$ : see (1979AJ01) and (1986LA26, 1987WA25). For a discussion of the width of  $^8\text{Be}^*(11.4)$  see (1987WA25). See also  $^9\text{Be}$ , and  $^{12}\text{C}$  in (1980AJ01), (1985MC1C, applications) and (1985PU03; theor.).

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

Angular distributions have been studied at  $E(^6\text{Li}) = 32$  MeV involving  $^8\text{Be}^*(0, 3.0)$  and  $^7\text{Li}^*(0, 0.48)$  (1985CO09). For reaction (b) see (1984KO25). For reaction (c) see  $^{10}\text{Be}$  (1985JA09). For the earlier work see (1979AJ01).

31.  $^{10}\text{Be}(p, t)^8\text{Be}$   $Q_m = 0.0045$

Angular distributions for the transition to the first  $T = 2$  state  $^8\text{Be}^*(27.49)$ , and to  $^8\text{Li}^*(10.82)$  reached in the  $(p, ^3\text{He})$  reaction, are very similar. They are both consistent with  $L = 0$  using a DWBA (LZR) analysis: see (1979AJ01, 1984AJ01) and Table 8.5 in (1984AJ01).

32.  $^{10}\text{B}(\pi^+, 2p)^8\text{Be}$   $Q_m = 132.100$

See (1988RIZZ; prelim).

33.  $^{10}\text{B}(n, t)^8\text{Be}$   $Q_m = 0.2307$

The breakup of  $^{10}\text{B}$  by  $14.4$  MeV neutrons involves, among others,  $^8\text{Be}_{g.s.}$  (1984TU02). See also (1979AJ01) and  $^{11}\text{B}$  in (1990AJ01).

34.  $^{10}\text{B}(p, ^3\text{He})^8\text{Be}$   $Q_m = -0.5332$

Angular distributions of the  $^3\text{He}$  ions to  $^8\text{Be}^*(0, 3.0, 16.6, 16.9)$  have been studied at  $E_p = 39.4$  MeV [see (1974AJ01)] and at  $E_p = 51.9$  MeV (1983YA05; see for a discussion of isospin mixing of the  $16.8$  MeV states).

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

Angular distributions have been reported at  $E_{\text{d}} = 0.5$  to  $7.5$  MeV: see (1974AJ01, 1979AJ01). At  $E_{\text{d}} = 7.5$  MeV the population of  $^8\text{Be}^*(16.63, 16.92)$  is closely the same consistent with their mixed isospin character while  $^8\text{Be}^*(17.64)$  is relatively weak consistent with its nearly pure  $T = 1$  character.  $^8\text{Be}^*(16.63, 16.92, 17.64, 18.15)$  have been studied for  $E_{\text{d}} = 4.0$  to  $12.0$  MeV. Interference between the  $2^+$  states [ $^8\text{Be}^*(16.63, 16.92)$ ] varies as a function of energy. The cross-section ratios for formation of  $^8\text{Be}^*(17.64, 18.15)$  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  $E_{\text{x}}$  only the  $3^+$  state at  $E_{\text{x}} = 19.2$  MeV is observed, the neighboring  $3^+$  state at  $E_{\text{x}} = 19.07$  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 (1979AJ01).

Reaction (b) [ $E_{\text{d}} < 5$  MeV] takes place mainly by a sequential process involving  $^8\text{Be}^*(0, 2.9, 11.4, 16.6, 16.9)$ : see (1979AJ01). See also (1983DA11). [The work quoted in (1984AJ01) has not been published.] At  $E_{\text{d}} = 13.6$  MeV in addition to  $^8\text{Be}^*(16.6, 16.9)$ , states with  $E_{\text{x}} \approx 19.9$ – $20.2$  MeV with  $\Gamma \approx 0.7$ – $1.1$  MeV are involved (1988KA1K; prelim.). See also (1984SH1D, 1984SHZJ) and (1985PU03, 1988BA75, 1988KA1M; theor.).

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

See  $^6\text{Li}$  here and reaction 40 in (1984AJ01). See also (1984SH1D, 1988SH1E).

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

Angular distributions have been measured at  $E_{\text{p}} = 0.78$  to  $45$  MeV [see (1974AJ01, 1979AJ01, 1984AJ01)], at  $E = 0.12$  to  $1.10$  MeV (1987BE17;  $^{11}\text{B}$  and  $\text{p}$ ;  $\alpha_0, \alpha_1$ ) and at  $E_{\text{p}} = 4.5$  to  $7.5$  MeV (1983BO19;  $\alpha_0$ ). Reaction (b) has been studied for  $E_{\text{p}} = 0.15$  to  $20$  MeV: see (1974AJ01, 1984AJ01). The reaction proceeds predominantly by sequential two-body decay via  $^8\text{Be}^*(0, 3.0)$ . See also  $^{12}\text{C}$  in (1990AJ01) and (1983CO1A, 1985MAZG, 1985PU03; theor.).

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

At  $E(^3\text{He}) = 71.8$  MeV angular distributions of the  $^6\text{Li}$  ions to  $^8\text{Be}^*(0, 3.0, 16.6, 16.9, 17.6, 18.2)$  are reported (1986JA14). For the earlier work at  $25.6$  MeV see (1979AJ01). See also (1986JA02).



39.  $^{11}\text{B}(\alpha, ^7\text{Li})^8\text{Be}$   $Q_m = -8.7556$

The work reported in (1984AJ01) has not been published. See also  $^7\text{Li}$  here and (1984SH1D, 1988SH1E).

40.  $^{11}\text{B}(^9\text{Be}, ^{12}\text{B})^8\text{Be}$   $Q_m = 1.705$

See (1984DA17) and  $^{12}\text{B}$  in (1990AJ01).

41. (a)  $^{12}\text{C}(\text{n}, \text{n}\alpha)^8\text{Be}$   $Q_m = -7.3666$   
 (b)  $^{12}\text{C}(\text{p}, \text{p}\alpha)^8\text{Be}$   $Q_m = -7.3666$   
 (c)  $^{12}\text{C}(\text{p}, \text{d}^3\text{He})^8\text{Be}$   $Q_m = -25.7198$

The first two of these reactions involve  $^8\text{Be}^*(0, 3.0)$ : see (1974AJ01, 1979AJ01, 1984AJ01, 1985AJ01). See also (1986AN22) [reaction (a)] and (1982ZH06, 1985GA1B, 1986VD01; theor.). For reaction (c) see (1983LI18; theor.).

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

Angular distributions have been studied at  $E_d = 12.7$  to  $54.3$  MeV [see (1974AJ01, 1979AJ01, 1984AJ01)] and at  $E_d = 18$  and  $22$  MeV (1986YA12; to  $^8\text{Be}_{\text{g.s.}}$ ; also VAP, TAP) and  $51.7$  MeV (1986YA12; to  $^8\text{Be}^*(0, 3.0, 11.4)$ ; also VAP) as well as at  $E_d = 50$  MeV (1987GO1S),  $54.2$  MeV (1984UM04; FRDWBA) [ $S_\alpha = 0.48, 0.51$  and  $0.82$  for  $^8\text{Be}^*(0, 3.0, 11.4)$ ] and  $78.0$  MeV (1986JA14; to  $^8\text{Be}^*(0, 3.0, 16.6, 16.9)$ ). See also (1985GO1G;  $E_d = 50$  MeV). For reaction (b) see (1984AJ01). See also (1984NE1A) and (1983GA14, 1983SH39, 1985GA1B, 1987KA1L; theor.).

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

See  $^7\text{Li}$ .

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

Angular distributions have been obtained at  $E(^3\text{He}) = 25.5$  to  $70$  MeV [see (1979AJ01, 1984AJ01)] and at  $E(^3\vec{\text{He}}) = 33.4$  MeV (1986CL1B;  $^8\text{Be}_{\text{g.s.}}$ ; also  $A_y$ ; prelim.).  $^8\text{Be}^*(0, 3.0, 11.4, 16.6, 16.9, 17.6)$  have been populated. See also (1986RA15; theor.).

$$45. \text{ (a) } ^{12}\text{C}(\alpha, 2\alpha)^8\text{Be} \quad Q_{\text{m}} = -7.3666$$

$$\text{ (b) } ^{12}\text{C}(\alpha, ^8\text{Be})^8\text{Be} \quad Q_{\text{m}} = -7.4585$$

These reactions have been studied at  $E_{\alpha}$  to  $104$  MeV [see (1979AJ01, 1984AJ01, and  $^{12}\text{C}$  in 1985AJ01)] and at  $31.2$  MeV (1986XI1A; reaction (a)):  $^8\text{Be}^*(0, 3.0, 11.4)$  are populated. See also (1984ZE1A, 1985GA1B, 1987KO1E; theor.).

$$46. \text{ (a) } ^{12}\text{C}(^9\text{Be}, ^{13}\text{C})^8\text{Be} \quad Q_{\text{m}} = 3.2810$$

$$\text{ (b) } ^{12}\text{C}(^{11}\text{B}, ^{15}\text{N})^8\text{Be} \quad Q_{\text{m}} = 3.6250$$

Angular distributions involving  $^8\text{Be}_{\text{g.s.}} + ^{13}\text{C}_{\text{g.s.}}$  (reaction (a)) have been reported at  $E(^9\text{Be}) = 20$  to  $22.9$  MeV and  $E(^{12}\text{C}) = 10.5$  to  $13.5$  MeV: see (1984AJ01). For both reactions see also (1983DEZW).

$$47. \text{ (a) } ^{12}\text{C}(^{12}\text{C}, ^{16}\text{O})^8\text{Be} \quad Q_{\text{m}} = -0.2047$$

$$\text{ (b) } ^{12}\text{C}(^{16}\text{O}, ^{20}\text{Ne})^8\text{Be} \quad Q_{\text{m}} = -2.631$$

$$\text{ (c) } ^{12}\text{C}(^{20}\text{Ne}, \alpha^{20}\text{Ne})^8\text{Be} \quad Q_{\text{m}} = -7.3666$$

For reaction (a) see  $^{16}\text{O}$  in (1986AJ04), (1983DEZW, 1984HU1E, 1984SP1C, 1986ALZN, 1986SH10) and (1984DA1B; theor.). For reaction (b) see reaction 18 in  $^{20}\text{Ne}$  (1987AJ02), (1985MU14) and (1988AL07; location of a  $10^+$  state in  $^{20}\text{Ne}$  at  $E_x \approx 27.5$  MeV). For reaction (c) see (1987SI06).

$$48. ^{13}\text{C}(\text{d}, ^7\text{Li})^8\text{Be} \quad Q_{\text{m}} = -3.5879$$

See  $^7\text{Li}$ .

$$49. ^{13}\text{C}(\alpha, ^9\text{Be})^8\text{Be} \quad Q_{\text{m}} = -10.7395$$

See (1984SH1D, 1988SH1F; prelim.;  $E_{\alpha} = 27.2$  MeV) and  $^9\text{Be}$  in (1979AJ01).

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

See  $^{14}\text{C}$  in (1986AJ01).

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

See  $^7\text{Li}$ .

52.  $^{16}\text{O}(\text{p}, \text{p}2\alpha)^8\text{Be}$   $Q_m = -14.5286$

See (1986VD04;  $E_p = 50$  MeV).

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

See (1987CZ02).

**${}^8\text{B}$**   
(Figs. 3 and 4)

GENERAL: See also (1984AJ01).

*Model calculations:* (1983SH38).

*Special states:* (1982PO12, 1988KH03).

*Complex reactions involving  ${}^8\text{B}$ :* (1982AL08, 1983OL1A, 1984GR08, 1986HA1B, 1987TAZU, 1988AR05, 1988KI05).

*Astrophysical questions:* (1984HA1B, 1985BO1E, 1985GI1C, 1985KL1A, 1985LA1C, 1988BA86).

*Reactions involving pions:* (1983SP06).

*Hypernuclei:* (1983SH38).

*Other topics:* (1985AN28).

*Ground state of  ${}^8\text{B}$ :* (1983ANZQ, 1985AN28, 1986GL1A, 1987VA26, 1988AR05, 1988VA03)

$$\mu = 1.0355 \pm 0.0003 \text{ nm: see (1978LEZA).}$$

1.  ${}^8\text{B}(\beta^+){}^8\text{Be}$   $Q_m = 17.979$

The  $\beta^+$  decay leads mainly to  ${}^8\text{Be}^*(3.0)$ . The mean of half-lives listed in (1974AJ01) is  $770 \pm 3$  msec;  $\log ft = 5.6$ . There is also a branch to  ${}^8\text{Be}^*(16.63)$ : see (1986WA01) and reactions 24 and 25 in  ${}^8\text{Be}$ .  $\log ft = 3.3$ . See also (1985GR1A) and (1986QUZZ; theor.).

2.  ${}^6\text{Li}(d, \pi^-){}^8\text{B}$   $Q_m = -135.267$

At  $E_d = 300$  and  $600$  MeV  ${}^8\text{B}^*(0, 0.77, 2.32)$  are populated: see (1984AJ01).

3.  ${}^6\text{Li}({}^3\text{He}, n){}^8\text{B}$   $Q_m = -1.975$

Angular distributions for the  $n_0$  group have been reported at  $E({}^3\text{He}) = 4.8$  to  $5.7$  MeV:  $L = 0$ . Two measurements for the  $E_x$  of  ${}^8\text{B}^*(0.77)$  are  $767 \pm 12$  and  $783 \pm 10$  keV [ $\Gamma = 40 \pm 10$  keV]: see (1974AJ01) and  ${}^9\text{B}$ .

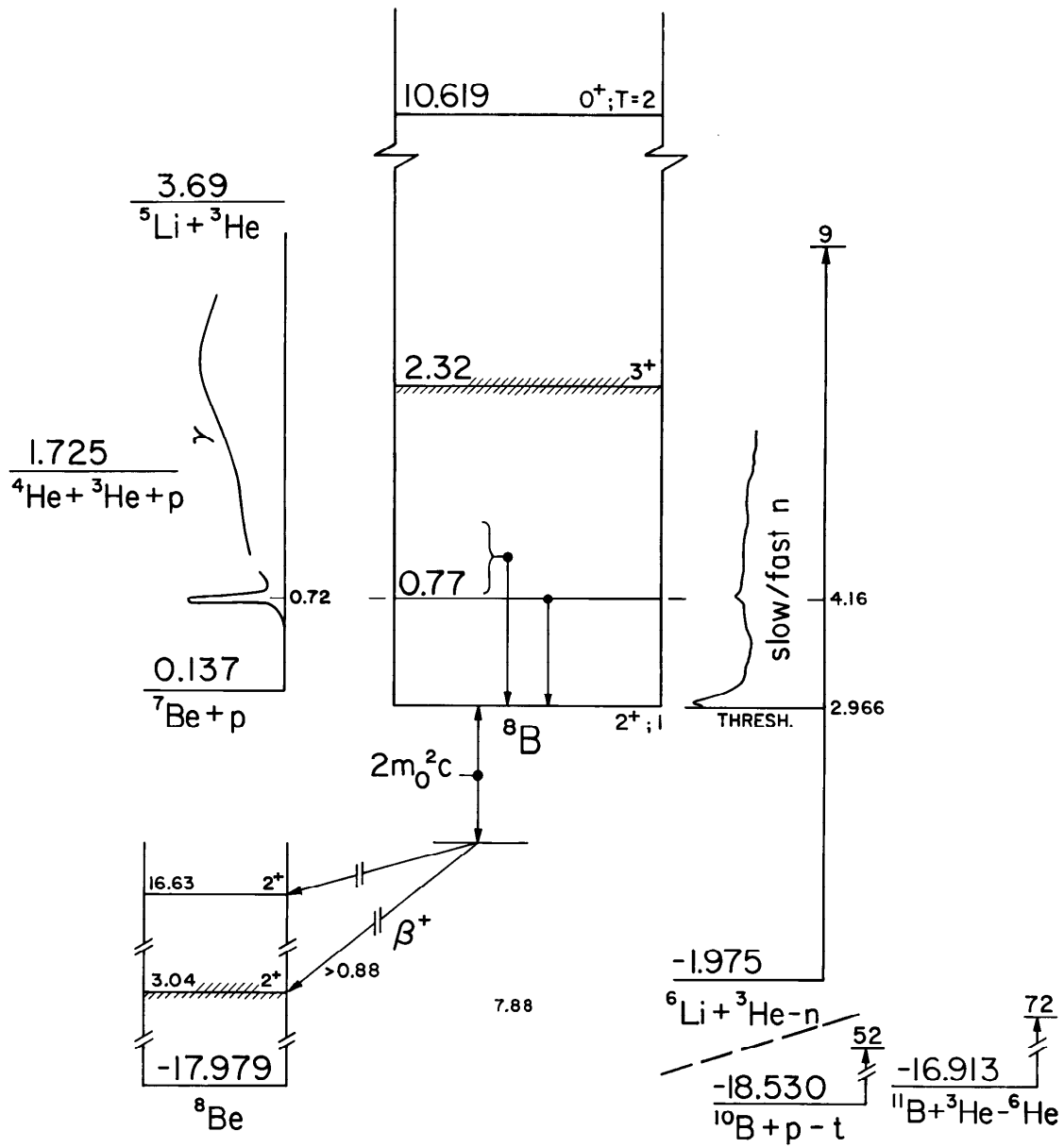


Fig. 3: Energy levels of  ${}^8\text{B}$ . For notation see Fig. 1.

Table 8.9: Energy levels of  ${}^8\text{B}$

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



Angular distributions and analyzing powers have been measured for the transitions to  ${}^8\text{B}^*(0, 0.77, 2.32)$  at  $E_p = 199.2$  MeV: the  $A_y$  to  ${}^8\text{B}^*(2.32)$  is characteristic of that to a stretched high-spin, two-particle one-hole final state [ $J^\pi$  of  ${}^8\text{B}^*(2.32)$  is  $3^+$ ] (1987CA06). See also (1987CA05).



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



Absolute cross sections have been measured for  $E_p = 134$  keV to 10.0 MeV. A resonance is observed at  $E_p = 723$  keV [ $E_R(\text{c.m.}) = 632 \pm 10$  keV;  $E_x = 770 \pm 10$  keV],  $\Gamma_{\text{c.m.}} = 37 \pm 5$  keV [assuming  $\Gamma_p \gg \Gamma_\gamma$ ] and  $\sigma_{\text{peak}} = 1.18 \pm 0.12$   $\mu\text{b}$ .  $\Gamma_\gamma$  is then  $25 \pm 4$  meV. The zero-energy cross-section factor  $S_{17}(0) = 0.0238 \pm 0.0023$  keV  $\cdot$  b (1983FI13). See (1979AJ01) for the earlier work, and the discussion in (1986BA38). See also (1984AJ01), (1984HA1F, 1987SA1L) and (1982BA1J, 1982KA1E, 1983BA45, 1983FO1A, 1983HA1B, 1984DA1H, 1984HA1M, 1984YA1A, 1985BA1Q, 1985CA41, 1985FI1D, 1986FI15, 1987KI01, 1987RO25, 1988BA86, 1988BA29, 1988FO1A; astrophysics).



See (1983HA17, 1985HA40).



At  $E_p = 49.5$  MeV [see (1974AJ01)] and 51.9 MeV (1983YA05) angular distributions have been measured for the tritons to  ${}^8\text{B}^*(0, 2.32)$ :  $L = 2$  and  $L = 0 + 2$  leading to  $J^\pi = 2^+$  and  $3^+$ , respectively. Measurements of  $E_x$  for  ${}^8\text{B}^*(2.32)$  yield  $2.29 \pm 0.05$  MeV,  $2.34 \pm 0.04$  MeV [ $\Gamma_{\text{lab}} = 0.39 \pm 0.04$  MeV].  ${}^8\text{B}^*(0.77)$  is also observed: see (1974AJ01).

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

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  $\theta_{\text{lab}} = 9^\circ$ . No other states are observed within 2.4 MeV of this state.  ${}^8\text{B}^*(0, 0.77, 2.32)$  have also been populated: see (1979AJ01).

${}^8\text{C}$   
(Fig. 4)

*Mass of  ${}^8\text{C}$ :* The atomic mass excess of  ${}^8\text{C}$  is  $35095 \pm 24$  keV (1985WA02);  $\Gamma_{\text{c.m.}} = 230 \pm 50$  keV: see (1979AJ01).  ${}^8\text{C}$  is stable with respect to  ${}^7\text{B} + \text{p}$  ( $Q = -0.13$  MeV) and unstable with respect to  ${}^6\text{Be} + 2\text{p}$  ( $Q = 21.4$ ),  ${}^5\text{Li} + 3\text{p}$  ( $Q = 1.55$ ),  ${}^4\text{He} + 4\text{p}$  ( $Q = 3.51$ ). At  $E({}^3\text{He}) = 76$  MeV the differential cross section for formation of  ${}^8\text{C}_{\text{g.s.}}$  in the  ${}^{14}\text{N}({}^3\text{He}, {}^9\text{Li})$  reaction is  $\approx 5$  nb/sr at  $\theta_{\text{lab}} = 10^\circ$ . The  ${}^{12}\text{C}(\alpha, {}^8\text{He}){}^8\text{C}$  reaction has been studied at  $E_\alpha = 156$  MeV:  $d\sigma/d\Omega \approx 20$  nb/sr at  $\theta_{\text{lab}} = 20^\circ$ : see (1979AJ01). See also (1985AN28) and (1983ANZQ, 1986HE26, 1987BL18, 1987SA15; theor.).

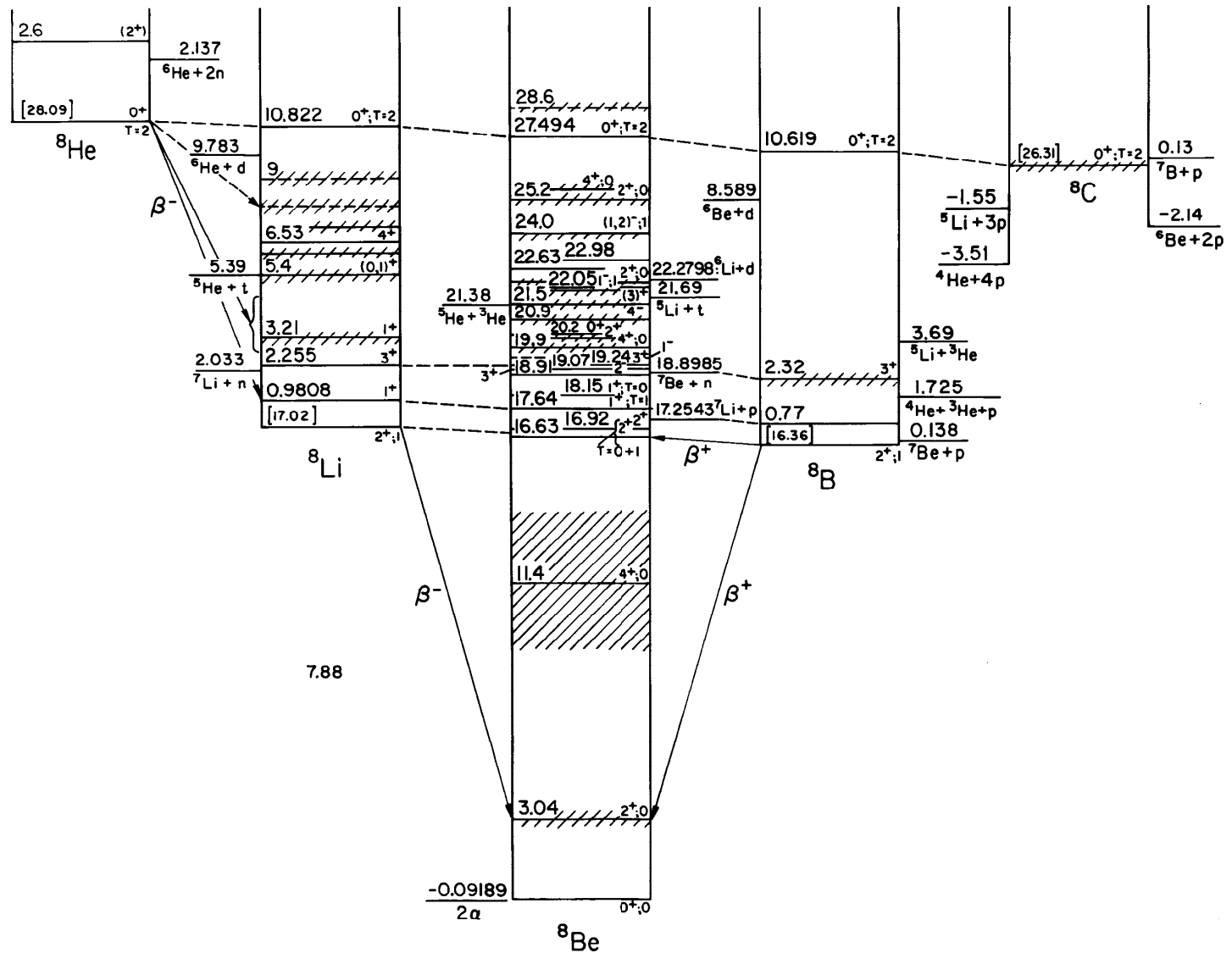


Fig. 4: Isobar diagram,  $A = 8$ . The diagrams for individual isobars have been shifted vertically to eliminate the neutron-proton mass difference and the Coulomb energy, taken as  $E_C = 0.60Z(Z - 1)/A^{1/3}$ . Energies in square brackets represent the (approximate) nuclear energy,  $E_N = M(Z, A) - ZM(H) - NM(n) - E_C$ , minus the corresponding quantity for  ${}^8\text{Be}$ : here  $M$  represents the atomic mass excess in MeV. Levels which are presumed to be isospin multiplets are connected by dashed lines.



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