

# Energy Levels of Light Nuclei $A = 7$

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**Abstract:** An evaluation of  $A = 5-7$  was published in *Nuclear Physics A708* (2002), p. 3. This version of  $A = 7$  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 are in the NNDC/TUNL format.

(References closed August 23, 2001)

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## A = 7

GENERAL: References to articles on general properties of  $A = 7$  nuclei published since the previous review (1988AJ01) are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for  $A = 7$  located on our website at ([www.tunl.duke.edu/NuclData/General\\_Tables/07.shtml](http://www.tunl.duke.edu/NuclData/General_Tables/07.shtml)).

### ${}^7\text{H}$

(Not illustrated)

${}^7\text{H}$  has not been observed. Attempts have been made to detect it in the spontaneous fission of  ${}^{252}\text{Cf}$  (1982AL33) and in the  ${}^7\text{Li}(\pi^-, \pi^+)$  reaction [see (1984AJ01)]. A study of  ${}^9\text{Be}(\pi^-, 2p)$  (1987GO25) found no evidence for  ${}^7\text{H}$ . See also the review of (1989OG1B) and the  ${}^7\text{Li}(\pi^-, \pi^+)$  investigation reported in (1989GR06). The ground state is calculated to have  $J^\pi = \frac{1}{2}^+$  and to be unstable with respect to  $1n$ ,  $2n$ ,  $3n$  and  $4n$  emission. Excited states are predicted at 4.84, 5.00 and 6.96 MeV, with  $J^\pi = \frac{3}{2}^+$ ,  $\frac{5}{2}^+$ , and  $\frac{5}{2}^-$  [ $(0+1)\hbar\omega$  model space] and at 3.88, 3.94 and 5.99 MeV with  $J^\pi = \frac{3}{2}^+$ ,  $\frac{5}{2}^+$  and  $\frac{1}{2}^+$  [ $(0+2)\hbar\omega$  model space] (1985PO10). See also references cited in (1988AJ01).

### ${}^7\text{He}$

(Figs. 8 and 11)

GENERAL: References to articles on general properties of  ${}^7\text{He}$  published since the previous review (1988AJ01) are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for  ${}^7\text{He}$  located on our website at ([www.tunl.duke.edu/NuclData/General\\_Tables/7he.shtml](http://www.tunl.duke.edu/NuclData/General_Tables/7he.shtml)).

*Mass of  ${}^7\text{He}$ :* The atomic mass excess of  ${}^7\text{He}$  is  $26.11 \pm 0.03$  MeV:  ${}^7\text{He}$  is then unbound with respect to decay into  ${}^6\text{He} + n$  by 0.44 MeV: see (1984AJ01). The ground state is calculated to have  $J^\pi = \frac{3}{2}^-$  and to be unstable with respect to decay into  ${}^6\text{He} + n$  by about 1 MeV (1985PO10). See (1988AJ01).

*${}^7\text{He}$  excited-state calculations:* In addition to the  $(0+1)\hbar\omega$  and  $(0+2)\hbar\omega$  model space calculation of (1985PO10) cited in (1988AJ01), a number of calculations have been reported since the previous evaluation. They include calculations: in a  $(0+2)\hbar\omega$  model space (1990WO10); in a two-frequency shell model (2001CO21); in a large-basis shell model (1998NA17); with Green's Function Monte-Carlo methods (1997PU03, 2000WI09, 2001PI07); and in a refined resonating group model (1997WU01).

1.  ${}^1\text{H}({}^8\text{He}, d){}^7\text{He}$

$$Q_m = -0.36$$

Table 7.1: Energy levels of  ${}^7\text{He}$

$E_x$ (MeV)	$J^\pi; T$	$\Gamma_{\text{cm}}$	Decay	Reactions
g.s.	$(\frac{3}{2})^-; \frac{3}{2}$	$150 \pm 20 \text{ keV}^{\text{a}}$	n	1, 2, 3, 4, 5, 6, 7
$2.92 \pm 0.09^{\text{a}}$	$(\frac{5}{2})^-; \frac{3}{2}^{\text{a}}$	$1990 \pm 170 \text{ keV}^{\text{a}}$	n	1, 5, 6
$(5.8 \pm 0.3)^{\text{a}}$		$4 \pm 1 \text{ MeV}^{\text{a}}$	n	5, 6

<sup>a</sup> Newly adopted in this evaluation or revised from the previous evaluation (1988AJ01).

This reaction was studied at  $E({}^8\text{He}) = 50 \text{ MeV}/A$  (1999KO14, 2000KO46). Deuterons, neutrons,  ${}^4\text{He}$  and  ${}^6\text{He}$  were detected. Spectra indicate a level in  ${}^7\text{He}$  at  $E_x = 2.9 \pm 0.3 \text{ MeV}$ ,  $\Gamma = 2.2 \pm 0.3 \text{ MeV}$  which decays mainly into  $3n + {}^4\text{He}$ ,  $\Gamma_{\alpha+3n}/\Gamma_{\text{tot}} = 0.7 \pm 0.2$ . Arguments are given for a tentative assignment  $J^\pi = (\frac{5}{2}^-)$ .

$$2. {}^7\text{Li}(\pi^-, \gamma){}^7\text{He} \quad Q_{\text{m}} = 128.37$$

Capture  $\gamma$ -rays from the transition to  ${}^7\text{He}_{\text{g.s.}}$  are reported by (1986PE05).

$$3. {}^7\text{Li}(n, p){}^7\text{He} \quad Q_{\text{m}} = -10.42$$

The proton group corresponding to  ${}^7\text{He}_{\text{g.s.}}$  has  $\Gamma < 0.2 \text{ MeV}$ : see (1979AJ01). At  $E_n = 60 \text{ MeV}$  broad bumps in the spectra are ascribed to states at  $E_x \approx 20 \pm 1 \text{ MeV}$  [ $\Gamma = 9 \pm 2 \text{ MeV}$ ] and, possibly, at  $\approx 6 \text{ MeV}$  (1983BR32, 1984BR03; see for discussion of the GDR). See also (1987HE24) and (1987BR32). Analyzing powers measured at  $E_n = 0.88 \text{ GeV}$  are reported in (1996BB23).

$$4. {}^7\text{Li}(t, {}^3\text{He}){}^7\text{He} \quad Q_{\text{m}} = -11.18$$

The  ${}^3\text{He}$  particles leading to the ground state of  ${}^7\text{He}$  have been observed at  $E_t = 22 \text{ MeV}$ . The width of the ground state given in (1988AJ01) is  $160 \pm 30 \text{ keV}$ ; for a radius of  $2.2 \text{ fm}$  and  $l_n = 1$ , this width is 0.22 of the Wigner limit. The angular distribution is peaked in the forward direction. No other states of  ${}^7\text{He}$  were observed for  $E_x < 2.4 \text{ MeV}$ : see (1979AJ01).

$$5. \text{(a)} {}^6\text{Li}({}^{14}\text{C}, {}^{13}\text{N}){}^7\text{He} \quad Q_{\text{m}} = -14.36$$

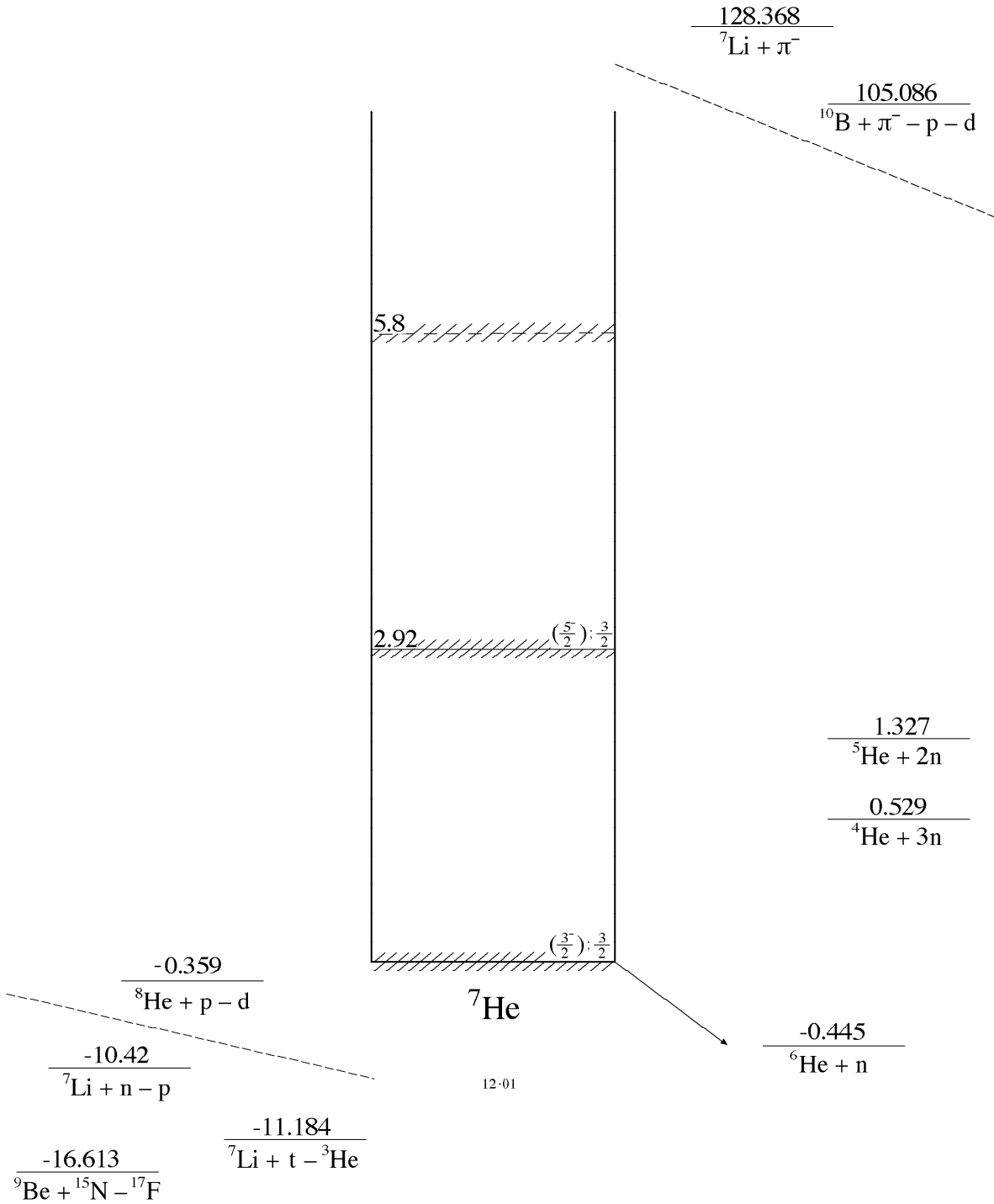


Figure 8: Energy levels of  ${}^7\text{He}$ . For notation see Fig. 5.

(b) ${}^7\text{Li}({}^7\text{Li}, {}^7\text{Be}){}^7\text{He}$	$Q_m = -12.06$
(c) ${}^7\text{Li}({}^{11}\text{B}, {}^{11}\text{C}){}^7\text{He}$	$Q_m = -13.19$
(d) ${}^9\text{Be}({}^6\text{Li}, {}^8\text{B}){}^7\text{He}$	$Q_m = -23.60$
(e) ${}^9\text{Be}({}^9\text{Be}, {}^{11}\text{C}){}^7\text{He}$	$Q_m = -14.07$
(f) ${}^9\text{Be}({}^{11}\text{B}, {}^{13}\text{N}){}^7\text{He}$	$Q_m = -11.44$
(g) ${}^9\text{Be}({}^{14}\text{C}, {}^{16}\text{O}){}^7\text{He}$	$Q_m = -7.01$
(h) ${}^9\text{Be}({}^{15}\text{N}, {}^{17}\text{F}){}^7\text{He}$	$Q_m = -16.61$

Reaction (a) was investigated at  $E({}^{14}\text{C}) = 24$  MeV/A (1995BO10, 1995VO05). The  ${}^7\text{He}$  ground state was populated strongly, but no excited states were observed. At  $E({}^6\text{Li}) = 72$  MeV and at  $E({}^7\text{Li}) = 70$  MeV (reactions (b) and (d)) there is no evidence for excited states with  $\Gamma \leq 2$  MeV for  $E_x < 10$  MeV (1985AL1G, 1985AL29, 1985ALZM). The ground state of  ${}^7\text{He}$  is strongly populated. Reactions (c), (e), (f) and (g) have been investigated at  $E({}^{11}\text{B}) = 88$ ,  $E({}^9\text{Be}) = 106.7$  and  $E({}^{14}\text{C}) = 152.6$  MeV. The ground state of  ${}^7\text{He}$  is populated. There is some evidence for a second state in reaction (g) at  $E_x = 2.9 \pm 0.5$ ,  $\Gamma = 1.5 \pm 0.5$  MeV (1988BE34). See also (1979AJ01) and (1988BEYJ). At  $E({}^{15}\text{N}) = 240$  MeV, reaction (h) shows evidence for a level at  $E_x = 3.2 \pm 0.2$  MeV,  $\Gamma = 1.5 \pm 0.2$  MeV (1998BO1M, 1998BO38, 1999BO26).

A more recent experiment with incident energies  $E_{\text{lab}} = 240$  MeV and 318.5 MeV is described in (2001BO35). The width of the  ${}^7\text{He}$  ground state resonance was measured to be  $0.14 \pm 0.02$  MeV. An excited state with  $E_x = 2.95 \pm 0.10$  MeV, corresponding to a resonance energy  $E_R = 3.39 \pm 0.10$  and width  $\Gamma_R = 1.9 \pm 0.2$  MeV, was observed. There was no indication of a state at  $E_x = 0.8$  MeV reported by (2001MA05) [See reaction 7]. Evidence for a broad excited state at  $E_x = 5.8 \pm 0.3$  MeV with  $\Gamma = 4 \pm 1$  MeV was also obtained.

## 6. ${}^{10}\text{B}(\pi^-, \text{pd}){}^7\text{He}$ $Q_m = 105.10$

Stopped negative pion absorption on  ${}^{10}\text{B}$  was studied with detection of protons and deuterons (1998GO30). The missing-mass spectra show evidence for a level in  ${}^7\text{He}$  with  $E_x = 2.8 \pm 0.2$  MeV,  $\Gamma \approx 2.0$  MeV.

## 7. ${}^{\text{nat}}\text{C}({}^8\text{He}, {}^6\text{He} + \text{n} + \text{n})$

The relative energy spectra of fragments from 227 MeV/A  ${}^8\text{He}$  on a carbon target were measured (2001MA05). The  ${}^6\text{He} + \text{n}$  spectra show a structure which is interpreted as being due to a  $J^\pi = \frac{3}{2}^-$  resonance (the  ${}^7\text{He}$  ground state) with  $E_R = 0.44$  MeV,  $\Gamma = 0.16$  MeV with about equal contribution from a  $J^\pi = \frac{1}{2}^-$  resonance with  $E_R = 1.2 \pm 0.2$  MeV,  $\Gamma = 1.0 \pm 0.2$  MeV ( $E_x = 0.8 \pm 0.2$  MeV).

**<sup>7</sup>Li**  
(Figs. 9 and 11)

GENERAL: References to articles on general properties of <sup>7</sup>Li published since the previous review (1988AJ01) are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for <sup>7</sup>Li located on our website at ([www.tunl.duke.edu/NuclData/General\\_Tables/7li.shtml](http://www.tunl.duke.edu/NuclData/General_Tables/7li.shtml)).

$$\mu = +3.256427(2) \text{ nm: see (1989RA17).}$$

$Q = -40.6 \pm 0.8 \text{ mb}$  (1988DI1B). See (1988DI1B) for a review of earlier determinations, particularly those of (1984SU09, 1984VE03, 1984VE08, 1985WE08). See also (1989RA17).

$B(E2): \frac{3}{2}^- \rightarrow \frac{1}{2}^- = 8.3 \pm 0.5 e^2 \text{ fm}^4$  (1985WE08). See also (1984VE08), (1988TA1D) and (1984AJ01).

*Isotopic abundance:*  $92.5 \pm 0.2\%$  (1984DE53). See also (1987LA1J, 1988LA1C).

The interaction nuclear radius of <sup>7</sup>Li is  $2.23 \pm 0.02 \text{ fm}$  (1985TA18). [See also for derived nuclear matter, charge and neutron matter r.m.s. radii].

1.  $^1\text{H}(^6\text{He}, \gamma)^7\text{Li}$   $Q_m = 9.9754$

Gamma spectra were measured for 40 MeV/A <sup>6</sup>He incident on a solid hydrogen target (2001SA37). The <sup>7</sup>Li ground state and the 0.48 MeV first excited states were not resolved. Measurements of momentum spectra of fragments as well as gamma-ray intensity distributions are described in (2001SA37). See also (2001SAZS).

2.  $^3\text{H}(\alpha, \gamma)^7\text{Li}$   $Q_m = 2.4670$

Excitation functions and angular distributions have been studied for  $E_\alpha = 0.5$  to 2.0 MeV. The cross section rises smoothly as expected for a direct capture process: see (1966LA04) and (1987BU18;  $\gamma_0, \gamma_1$ ). Measurements of the astrophysical  $S$ -factor,  $S(E)$ , and the branching ratio  $R$  for direct capture to the 478 keV state compared to direct capture to the ground state were reported by (1987SC18). They deduce  $S(0) = 0.14 \pm 0.02 \text{ keV b}$ ,  $R = 0.32 \pm 0.01$ . More recently, available data on <sup>3</sup>H +  $\alpha$  scattering were analyzed (1993MO11) in the optical model framework to predict  $S(0) = 0.10 \text{ keV b}$  and branching ratio  $R = 0.43$ . Measurements of the cross sections and angular distributions in the energy range  $50 \leq E \leq 1200 \text{ keV}$  were reported by (1994BR25). They determined  $R \approx 0.45$  at low energies in disagreement with (1987SC18). An extended two-cluster model study for  $E_{c.m.} < 5 \text{ MeV}$  is described in (2000CS06). Effects of inclusion of the <sup>6</sup>Li + n

Table 7.2: Energy levels of  ${}^7\text{Li}$ 

$E_x$ (MeV $\pm$ keV)	$J^\pi; T$	$\tau_m$ or $\Gamma_{\text{cm}}$ (keV)	Decay	Reactions
g.s.	$\frac{3}{2}^-; \frac{1}{2}$		stable	1, 2, 3, 5, 6, 7, 11, 12, 13, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 49, 50, 51, 52, 54, 55, 57
$0.477612 \pm 0.003$	$\frac{1}{2}^-; \frac{1}{2}$	$\tau_m = 105 \pm 3 \text{ fsec}^{\text{a}}$	$\gamma$	1, 5, 6, 7, 11, 12, 16, 17, 18, 19, 20, 21, 22, 23, 26, 27, 30, 33, 34, 37, 38, 39, 40, 41, 42, 44, 45, 46, 47, 49, 50, 52, 54, 55, 57
$4.652^{\text{b}}$	$\frac{7}{2}^-; \frac{1}{2}$	$\Gamma = 69 \text{ keV}^{\text{b}}$	t, $\alpha$	4, 5, 11, 12, 17, 18, 19, 20, 21, 22, 23, 27, 39, 40, 42, 47, 51
$6.604^{\text{b}}$	$\frac{5}{2}^-; \frac{1}{2}$	$918^{\text{b}}$	t, $\alpha$	4, 12, 17, 18, 19, 23, 40, 47, 55
$7.454^{\text{b}}$	$\frac{5}{2}^-; \frac{1}{2}$	$80^{\text{b}}$	n, t, $\alpha$	3, 4, 8, 9, 10, 12, 17, 18, 19, 20, 23, 37, 39, 40, 47
$8.75^{\text{b}}$	$\frac{3}{2}^-; \frac{1}{2}$	$4712^{\text{b}}$	n, $\alpha$	8, 37
$9.09^{\text{b}}$	$\frac{1}{2}^-; \frac{1}{2}^{\text{b}}$	$2752^{\text{b}}$	n, t, $\alpha$	4, 8, 10
$9.57^{\text{b}}$	$\frac{7}{2}^-; \frac{1}{2}$	$437^{\text{b}}$	n, t, $\alpha$	3, 4, 12, 18, 20, 23, 40
$11.24 \pm 30$	$\frac{3}{2}^-; \frac{3}{2}$	$260 \pm 35$	n, p	8, 9, 39
13.7		$\approx 500$	n	15
$14.7^{\text{c}}$		$\approx 700$	n	15

<sup>a</sup> See Table 7.2 in (1979AJ01), Table 7.5 here and reaction 40.

<sup>b</sup> Newly adopted in this evaluation. These level parameters were obtained with the extended  $R$ -matrix prescription (see the Introduction) from an analysis of  ${}^6\text{Li}(n, n)$ ,  ${}^6\text{Li}(n, t)$ ,  ${}^4\text{He}(t, n)$ , and  ${}^4\text{He}(t, t)$  data, and are somewhat different from the corresponding parameters of (1988AJ01). The uncertainties in the widths and positions of the second through fourth excited states above the ground state are less than 5%. Uncertainties for the higher-lying states range from 10 – 30%.

<sup>c</sup> See also reactions 8, 10, 15, 22 and 38 for possible additional states.



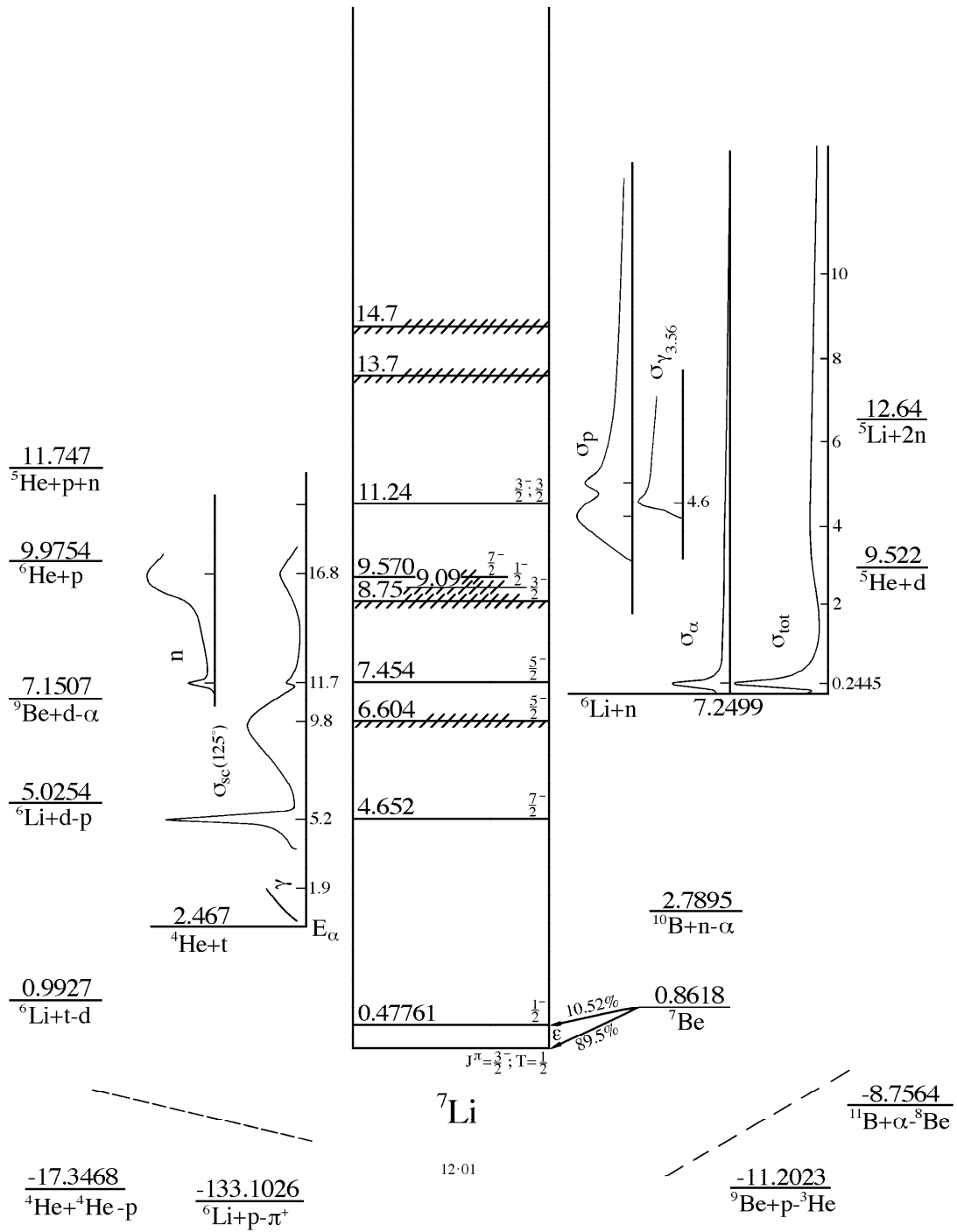


Figure 9: Energy levels of  ${}^7\text{Li}$ . For notation see Fig. 5.

Table 7.3:  ${}^7\text{Li}$  levels from  ${}^3\text{H} + {}^4\text{He}$  <sup>a</sup>

$E_x$ (MeV $\pm$ keV)	$J^\pi$	$l_\alpha$	$LS$ term	$R$ (fm)	$\theta_\alpha^2$ <sup>b</sup>	$\theta_{n_0}^2$ <sup>c</sup>
4.65 $\pm$ 20	$\frac{7}{2}^-$	3	${}^2\text{F}_{7/2}$	4.0	0.57 $\pm$ 0.04	0.000 $\pm$ 0.002
6.64 $\pm$ 100	$\frac{5}{2}^-$	3	${}^2\text{F}_{5/2}$	4.0	1.36 $\pm$ 0.13	
6.79 $\pm$ 90	$\frac{5}{2}^-$	3	${}^2\text{F}_{5/2}$	4.4	0.52	
7.47 $\pm$ 30	$\frac{5}{2}^-$	3	${}^4\text{P}_{5/2}$	4.0	0.011 $\pm$ 0.001	0.26 $\pm$ 0.02
9.67 $\pm$ 100	$\frac{7}{2}^-$	3	${}^4\text{D}_{7/2}$	4.0	0.53 $\pm$ 0.22	2.3 $\pm$ 0.7 <sup>d</sup>

<sup>a</sup> For references see Table 7.3 in (1979AJ01).

<sup>b</sup>  $\gamma_\lambda^2 2\mu R^2 / 3\hbar^2$ .

<sup>c</sup> See reaction 3:  ${}^3\text{H}(\alpha, n){}^6\text{Li}$ .

<sup>d</sup>  $\theta_{n_1}^2$  to  ${}^6\text{Li}^*(2.19)$ .

channel on the zero-energy cross section and astrophysical  $S$  factor as well as the quadrupole moment are explored. A recent analysis by (1999BU10) estimated the uncertainties in Big Bang nucleosynthesis  ${}^7\text{Li}$  yields. For astrophysical calculations related to  ${}^3\text{H}(\alpha, \gamma)$  see the General Table for  ${}^7\text{Li}$  located on our website at ([www.tunl.duke.edu/NuclData/GeneralTables/7li.shtml](http://www.tunl.duke.edu/NuclData/GeneralTables/7li.shtml)). See also references cited in (1988AJ01).

Thermonuclear reaction rates for this reaction calculated from evaluated data are presented in the compilation (1999AN35).

### 3. ${}^3\text{H}(\alpha, n){}^6\text{Li}$

$$Q_m = -4.7829$$

$$E_b = 2.4670$$

The cross section for this reaction has been measured for  $E_\alpha = 11$  to 18 MeV: the data show the effect of  ${}^7\text{Li}^*(7.46)$  and indicate a broad resonance near  $E_\alpha = 16.8$  MeV [ ${}^7\text{Li}^*(9.6)$ ]. The level parameters derived from this reaction and from reaction 4 are displayed in Table 7.3. The yield of  ${}^6\text{Li}$  ions at  $0^\circ$  (lab) has also been measured for  $E_\alpha = 11.310$  to 11.930 MeV with 2–3% accuracy: the data were then reduced to obtain the cm differential cross sections at  $0^\circ$  and  $180^\circ$  for the inverse reaction in the energy region corresponding to formation of  ${}^7\text{Li}^*(7.46)$ : see (1979AJ01). See also the compilation of (1985CA41). A resonating group calculation of  $\sigma(E)$  from threshold to 20 MeV is reported in (1991FU02).

### 4. ${}^3\text{H}(\alpha, \alpha){}^3\text{H}$

$$E_b = 2.4670$$

The excitation curves for the elastic scattering show the effects of  ${}^7\text{Li}^*(4.63, 6.68, 7.46, 9.67)$ . The derived level parameters are displayed in Table 7.3. Angular distributions have been studied for  $E_\alpha = 2.13$  to 2.98 MeV and  $E_t = 6.0$  to 17 MeV [see (1979AJ01, 1984AJ01)] and

at  $E_\alpha = 56.3$  to  $95.5$  MeV (1986YA1M; also  $A_y$ ]. More recently, cross sections and angular distributions were measured at  $E_\alpha = 27.2$  MeV and described in an RGM method and in the phenomenological optical model. A polarization extremum ( $A_y = -1$ ) occurs near  $E_t = 11.1$  MeV,  $\theta = 95^\circ$ : see (1984AJ01). For the breakup of  ${}^7\text{Li}$  into  $\alpha + t$  in various processes see (1984AJ01) and (1984SH17, 1987FO08, 1987PO03) as well as the General Table for  ${}^7\text{Li}$  located on our website at ([www.tunl.duke.edu/NuclData/General\\_Tables/7li.shtml](http://www.tunl.duke.edu/NuclData/General_Tables/7li.shtml)). For cross sections determined from shell-model and  $R$ -matrix calculations see (1987KN04). Other calculations that have been reported include: phase shifts for  $E_\alpha < 300$  MeV and  ${}^7\text{Li}$  charge form factor (1987RO24); scattering lengths (1988CH47, 1989CH34); phase-shift and transmission coefficients with RGM (1991FU02); phase-shift and astrophysical  $S$  factors in a two-cluster model (1995DU09, 1997DU15); RGM phase shifts (1995MA37); and phase shifts versus  $E$  in a three-body cluster model (1996SH02).

For muon catalysis see references cited in (1988AJ01).

$$5. {}^4\text{He}({}^3\text{He}, \pi^+){}^7\text{Li} \quad Q_m = -137.1217$$

${}^7\text{Li}^*(0 + 0.48, 4.63)$  have been populated at  $E({}^3\text{He}) = 266.5$  and  $280.5$  MeV: see (1984AJ01). See also (1984GE05, 1987KA09).

$$6. {}^4\text{He}(\alpha, p){}^7\text{Li} \quad Q_m = -17.3469$$

Angular distributions have been reported at  $E_\alpha = 39.9$  to  $140$  MeV [see (1979AJ01, 1984AJ01)] and at  $61.5$  to  $158.2$  MeV (1982GL01) and  $198.4$  MeV (1985WO11) for the transitions to  ${}^7\text{Li}^*(0, 0.48)$ . Cross sections for  $E_\alpha = 159.3, 279.6$  and  $619.8$  MeV were measured by (2001ME13) to enable calculation of the amount of  ${}^7\text{Li}$  produced in early-galaxy cosmic rays. See also (2001AU06). See (1982GL01, 1985WO11) for a discussion of  ${}^7\text{Li}$  production in the Big Bang. See also  ${}^8\text{Be}$  in (1988AJ01) and (1986KA26).

$$7. {}^6\text{Li}(n, \gamma){}^7\text{Li} \quad Q_m = 7.2499$$

$$Q_0 = 7251.02 \pm 0.09 \text{ keV (1985KO47)}$$

The thermal capture cross section is  $38.5 \pm 3.0$  mb (1981MUZQ). Gamma rays are observed corresponding to transitions to  ${}^7\text{Li}^*(0, 0.48)$  with branching ratios  $62 \pm 2\%$  and  $38 \pm 2\%$  (1985KO47).  ${}^7\text{Li}^*(4.63, 6.68)$  are not populated [ $\leq 5\%$ ] (1985KO47). See (1979AJ01) for the earlier work. The decay of  ${}^7\text{Li}^*(7.46) \rightarrow {}^6\text{Li}_{g.s.} + n$  in the interaction of  $35$  MeV/A  ${}^{14}\text{N}$  ions on Ag is reported by (1987BL13).

A recent study discussed in (1997NO04) analyzed reaction rates of  ${}^6\text{Li}(n, \gamma)$  and other reactions that bear on the possibility of observing primordial  ${}^6\text{Li}$ .

The real coherent scattering length is  $2.0 \pm 0.1$  fm; the complex scattering lengths are  $b_+ = (0.67 \pm 0.14) - i(0.08 \pm 0.01)$  fm,  $b_- = (4.67 \pm 0.17) - i(0.62 \pm 0.02)$  fm;  $\sigma_{\text{free}} = 0.70 \pm 0.01$  b (1983KO17). See also (1979GL12). (1983AL1E) report  $\sigma_s$  (below 10 keV) =  $0.72 \pm 0.02$  b. See also (1981MUZQ). The total cross section has been measured from  $E_n = 4$  eV to 49.6 MeV [see (1976GAYV, 1984AJ01)], at 0.6 to 80 keV (1982AL35) and at 0.08 to 3.0 MeV (1983KN1D).

A pronounced resonance occurs at  $E_n = 244.5 \pm 1.0$  keV [ $E_x = 7459.5 \pm 1.0$  keV] with a peak cross section of  $11.2 \pm 0.2$  b (1982SM02); see Table 7.4. No other clearly defined resonance is observed to  $E_n = 49.6$  MeV although the total cross section exhibits a broad maximum at  $E_n \approx 4.5$  MeV: see (1984AJ01). The analyzing power has been measured for  $E_n = 1.48$  to 5 MeV [see (1984AJ01)] and 5 to 17 MeV (1986PF1A). Multi-level, multi-channel  $R$ -matrix analyses (1987KN04, 1983KN06) for  $E_n \leq 8$  MeV [using also data from other channels] include 13 normal and 14 non-normal parity states with  $E_x \leq 17$  MeV. [Only ten states have been seen directly in reaction or compound nucleus cross-section work.] Two positive-parity states provide an explanation for the anisotropy of the  ${}^6\text{Li}(n, \alpha)$  work at low energies (1983KN06). For the results of an earlier  $R$ -matrix analysis see (1984AJ01).

The excitation function for 3.56 MeV  $\gamma$ -rays exhibits an anomaly, also seen in the (n, p) reaction (reaction 9). The data are well fitted assuming  $E_{\text{res}} = 3.50$  and 4.60 MeV [ $E_x = 10.25 \pm 0.10$  and  $11.19 \pm 0.05$  MeV],  $T = \frac{1}{2}$  and  $\frac{3}{2}$ ,  $\Gamma_{\text{cm}} = 1.40 \pm 0.10$  and  $0.27 \pm 0.05$  MeV, respectively; both  $J^\pi = \frac{3}{2}^-$ . However, (1979AJ01) notes that an  $R$ -matrix study of  ${}^4\text{He}(t, t)$ ,  ${}^6\text{Li}(n, n)$ , and  ${}^6\text{Li}(n, \alpha)$  data leads to the identification of a  $\frac{3}{2}^-$  state at  $E_x = 9.85$  MeV,  $\Gamma = 1.2$  MeV. See (1979AJ01) for a discussion of these and other unpublished data.

Differential cross sections for  $n_0$  and  $n_1$  were measured at  $E_n = 6.8$ – $9.8$  MeV and used with other data in an analysis to deduce  $\sigma(E)$  for  $E_n = 6$ – $14$  MeV (1987SC08). Elastic and inelastic scattering cross sections  $\sigma(\theta)$  were measured for  $E_n = 24$  MeV (1987HA25) and analyzed, along with existing proton scattering data to study neutron and proton transition densities. Elastic and inelastic scattering differential cross sections were measured at  $E_n = 11.5$ , 14.1 and 18.0 MeV (1998CH33) and used to determine a phenomenological optical model potential. A measurement of double-differential neutron emission cross sections for  $E_n = 11.5$  and 18.0 MeV was reported by (1998IB02). Theoretical work includes: a calculation of coherent and incoherent thermal cross sections (1990GO26); RGM calculations of  $\sigma(\theta)$  at  $E_n = 18$  MeV (1992KA06); calculation of phase shifts and cross sections for  $E_n < 18$  MeV using a potential description (1993DU09); a study of antisymmetry contribution to the nucleon-nucleon potentials (1995CO18); and a study of the applicability of optical-model potentials for nuclear data evaluations (1996CH33).

See also earlier references cited in (1988AJ01).

9. (a)  ${}^6\text{Li}(n, 2n){}^5\text{Li}$

$$Q_m = -5.39$$

$$E_b = 7.25$$

(b)  ${}^6\text{Li}(n, p){}^6\text{He}$

$$Q_m = -2.7254$$

(c)  ${}^6\text{Li}(n, d){}^5\text{He}$

$$Q_m = -2.272$$

Table 7.4: Resonance parameters for 7.5–7.2 MeV levels in  ${}^7\text{Li}$  and  ${}^7\text{Be}$  <sup>a</sup>

Reaction	${}^6\text{Li} + \text{n}$	${}^6\text{Li} + \text{p}$
$E_r$ (keV, lab)	262 <sup>b</sup>	1840 <sup>c</sup>
$\Gamma(E_r)$ (keV, cm)	154	836
$E_\lambda$ (keV above g.s.)	7700	7580
$\Gamma_{\text{n,p}}(E_r)$ (keV, cm)	118	798
radius (n, p) in fm	3.94	4.08
$\gamma_{\text{n,p}}^2$ (MeV · fm) <sup>d</sup>	4.85	5.02
$\theta_{\text{n,p}}^2$	0.26	0.28
$\Gamma_\alpha(E_r)$ (keV, cm)	36	38
radius ( $\alpha$ ) in fm	4.39	4.39
$\gamma_\alpha^2$ (MeV · fm) <sup>d</sup>	0.101	0.101
$\theta_\alpha^2$	0.012	0.012

<sup>a</sup> These states are believed to have a  ${}^4\text{P}_{5/2}$  character, consistent with their large  $\theta_n^2$  and  $\theta_p^2$ . See Table 7.4 in (1979AJ01). These parameters are from Table I of (1963MC09). See also (1959GA08).

<sup>b</sup>  $244.5 \pm 1.0$  keV (1982SM02).

<sup>c</sup> See also the measurements and analysis of (1995SK01).

<sup>d</sup> The authors of (1959GA08, 1963MC09) use a definition of  $\gamma_{\text{n,p}}^2$  and  $\gamma_\alpha^2$  for which the units are MeV · fm.

For reaction (a) see (1985CH37, 1986CH24). The excitation function for reaction (b), measured from threshold to  $E_n = 8.9$  MeV, exhibits an anomaly at  $E_n = 4.6$  MeV. The excitation function, at forward angles, of  $p_0$  is approximately constant for  $E_n = 4.4$  to 7.25 MeV: see (1979AJ01). Measurements of particle spectra have been made at  $E_n = 198$  MeV (1987HE22),  $E_n = 118$  MeV (1987PO18, 1988HA12, 1998HA24). Studies of this reaction as a probe of Gamow-Teller strength are reported in (1988JA01, 1988WA24, 1992SO02). Measurements at  $E_n = 280$  MeV were used in a test of isospin symmetry (1990MI10). Measurements at  $E_n = 0.88$  GeV with polarized targets are reported in (1996BB27). Theoretical studies of this reaction include: a dynamical cluster model calculation for  $E_n = 280$  MeV (1991DA08); a calculation of phase shifts for  $E_n = 6.77$  MeV (1993DU09); a calculation with hyperspherical harmonics (1996DA31); and with a three-body cluster model for  $E_n = 50$  MeV (1997DA01). See also (1997ER05, 1997VA06). The excitation function, at forward angles, of deuterons (reaction (c)) increases monotonically for  $E_n = 5.4$  to 6.8 MeV: see (1979AJ01, 1988AJ01). A multiconfiguration resonating-group method calculation

of  $\sigma(\theta)$  for  $E_n = 12$  MeV is described in (1995FU16).

10.  ${}^6\text{Li}(n, \alpha){}^3\text{H}$

$$Q_m = 4.7829$$

$$E_b = 7.2499$$

The thermal cross section is  $940 \pm 4$  b: see (1981MUZQ). See also (1985SW01). A resonance occurs at  $E_n = 241 \pm 3$  keV with  $\sigma_{\max} = 3.3$  b: see (1984AJ01, 1986CA28). The resonance is formed by p-waves,  $J^\pi = \frac{5}{2}^-$ , and has a large neutron width and a small  $\alpha$ -width: see Table 7.4. Above the resonance the cross section decreases monotonically to  $E_n = 18.2$  MeV, except for a small bump near  $E_n \approx 1.8$  MeV and an inflection near  $E_n = 3.5$  MeV. For a description of  $R$ -matrix analyses which suggest the location of higher states of  ${}^7\text{Li}$ , see reaction 8 and (1984AJ01), as well as (1987KN04).

Angular distributions have been measured at many energies in the range  $E_n = 0.1$  to 14.1 MeV [see (1979AJ01, 1984AJ01)] as well as from 35 eV to 325 keV (1983KN03) and 2.16 to 4.20, 7.1 and 13.7 MeV (1986BA32, 1986BA68). Polarization measurements have been reported for  $E_n = 0.2$  to 2.4 MeV: the data suggest interference between s-waves and the p-wave resonance at 0.25 MeV. Interference between this  $\frac{5}{2}^-$  state and a broad  $\frac{3}{2}^-$  state 2 MeV higher also appears to contribute. At the higher energies  $A_y$  is close to +0.9 near  $90^\circ$  and varies slowly with  $E_n$ : see (1979AJ01). See also (1983VE10, 1984VEZW).

Measurements with polarized thermal neutrons for studying parity violation effects have been reported in (1990VE16, 1994GL07, 1996VE02). Reaction rates for  $E < 2$  MeV were analyzed (1997NO04) in connection with the possibility of observing primordial  ${}^6\text{Li}$ . Calculations of tritium production in applications of this reaction are described in (1993FA01).

For a study of coincidences in the  ${}^6\text{Li}(n, \alpha d)n$  reaction see (1986MI11). The triton production cross section at  $E_n = 14.92$  MeV is  $32 \pm 3$  mb (1985GO18). The total  $\alpha$ -production cross section [which includes the (n, nd) process] at  $E_n = 14.95$  MeV is  $512 \pm 26$  mb (1986KN06).

See also the references cited in (1988AJ01).

11.  ${}^6\text{Li}(p, \pi^+){}^7\text{Li}$

$$Q_m = -133.1026$$

At  $E_p = 600$  MeV, the reaction preferentially excites  ${}^7\text{Li}^*(4.63)$ . Angular distributions have been obtained for the pions to  ${}^7\text{Li}^*(0, 0.48, 4.63)$  at  $E_p = 600$  and 800 MeV.  ${}^7\text{Li}^*(11.24)$  [ $T = \frac{3}{2}$ ] is not observed: see (1984AJ01). Recently  $\sigma(\theta)$  and  $A_y$  measurements were reported at  $E_p = 800$  MeV (1987SO1C). See also (1985LE19). An analysis for  $E_p = 201$ –800 MeV utilizing a semi-phenomenological model is discussed in (1993AL05).

12.  ${}^6\text{Li}(d, p){}^7\text{Li}$

$$Q_m = 5.0254$$

Angular distributions of proton groups have been studied for  $E_d = 0.12$  to 15 MeV and at 698 MeV: see (1966LA04, 1974AJ01, 1979AJ01, 1984AJ01).  $J^\pi$  of  ${}^7\text{Li}^*(0.48)$  is  $\frac{1}{2}^-$ . The two higher states have  $E_x = 4630 \pm 9$  and  $7464 \pm 10$  keV,  $\Gamma_{\text{cm}} = 93 \pm 8$  and  $91 \pm 8$  keV. The breakup reactions involve  ${}^7\text{Li}^*(4.63, 7.46)$  and possibly  ${}^7\text{Li}^*(9.6)$  [ $\Gamma = 0.5 \pm 0.1$  MeV]: see (1979AJ01). See also  ${}^8\text{Be}$  in (1988AJ01) and (1988KO1C).

The (d, p)/(d, n) yield ratio for low deuteron energies ( $E_d < 1$  MeV) has been studied. Calculations in (1990KO26) concluded that Coulomb-induced predissociation of the deuteron should influence the ratio by  $< 10\%$ . Measurements in (1993CE02) found no evidence of an enhanced ratio for  $E_{\text{cm}} = 20\text{--}135$  keV. The yield ratio was studied in experiments of (1993CZ01, 1997CZ04). This work explained the charge-symmetry violation in terms of a subthreshold  $2^+$  state in  ${}^8\text{Be}$ . See also the instrumentation-related measurements of (1994YE09) and the thick-target gamma yield measurements of (2000EL08). Calculations involving conservation of channel spin are described in (1996MA36). This reaction was also discussed by (1997NO04) in connection with deduction of the primordial  ${}^6\text{Li}$  component. Calculations for energy balance in controlled fusion are described in (2000HA50). See also the compilation of charged-particle-induced thermonuclear reaction rates in (1999AN35).

$$13. {}^6\text{Li}({}^6\text{Li}, {}^5\text{Li}){}^7\text{Li} \quad Q_m = 1.86$$

See (1987MI34) and  ${}^5\text{Li}$ .

$$14. {}^6\text{Li}({}^7\text{Li}, {}^7\text{Be}){}^6\text{He} \quad Q_m = -4.3696$$

The reaction was studied by (1999NA36) for  $E({}^7\text{Li}) = 65$  MeV/A to compare the Gamow-Teller transition strengths to those deduced from  $\beta$  decay.

$$15. (a) {}^7\text{Li}(\gamma, n){}^6\text{Li} \quad Q_m = -7.2499$$

$$(b) {}^7\text{Li}(\gamma, 2n){}^5\text{Li} \quad Q_m = -12.64$$

$$(c) {}^7\text{Li}(\gamma, p){}^6\text{He} \quad Q_m = -9.9753$$

$$(d) {}^7\text{Li}(\gamma, pn){}^5\text{He} \quad Q_m = -11.747$$

$$(e) {}^7\text{Li}(\gamma, d){}^5\text{He} \quad Q_m = -9.522$$

$$(f) {}^7\text{Li}(\gamma, t){}^4\text{He} \quad Q_m = -2.4670$$

The total photoneutron cross section rises sharply from 10 MeV to reach a broad plateau at about 15 mb from 14 to 20 MeV, decreases more slowly to about 0.5 mb at 25 MeV and then decreases further to about 0.3 mb at  $E_\gamma = 30$  MeV (monoenergetic photons): there are indications

of weak structure through the entire region: see (1979AJ01), (1988DI02) and (1988AJ01). A study by (1986SI18) reported evidence for the excitation of  ${}^7\text{Li}^*(7.46)$ , as well as of states at  $E_x = 13.75 \pm 0.03$  and  $14.65 \pm 0.03$  MeV with  $\Gamma \approx 500$  and  $700$  keV [and integrated cross sections of  $\approx 0.14$  and  $0.17$  MeV  $\cdot$  mb], in addition to a major broad structure at 17 MeV. The integrated cross section to 23 MeV is  $39 \pm 4$  MeV  $\cdot$  mb for the  $n_0$  transition and  $17 \pm 4$  MeV  $\cdot$  mb for the  $n_1$  transition: together these account for 0.4 of the exchange augmented dipole sum of  ${}^7\text{Li}$ : see (1979AJ01). The integrated cross section for formation of  ${}^6\text{Li}^*(3.56)$  is  $4 \pm 1$  MeV  $\cdot$  mb to 30 MeV and  $11 \pm 3$  MeV  $\cdot$  mb to 55 MeV: see (1984AJ01).

The total absorption cross section for  ${}^{\text{nat}}\text{Li}$  in the range 10 to 340 MeV shows a broad peak at  $\approx 30$  MeV ( $\sigma_{\text{max}} \approx 3$  mb), a minimum centered at  $\approx 150$  MeV at  $\approx 0.3$  mb and a fairly smooth increase in cross section to  $\approx 3$  mb at  $\approx 320$  MeV: see (1984AJ01).

The cross section for the  $(\gamma, p)$  reaction (reaction (c)) shows a maximum at  $\approx 15.6$  MeV with a width of  $\approx 4$  MeV. It then decreases fairly smoothly to 27 MeV. The integrated cross section for  $11 \rightarrow 28$  MeV is  $13.2 \pm 2.0$  MeV  $\cdot$  mb: see (1974AJ01, 1979AJ01, 1984AJ01). Differential cross sections for the  $(\gamma, n_0 + n_2)$  and  $(\gamma, p_0)$  processes are reported by (1983SE07, 1985SE17;  $E_\gamma = 48$  to 141 MeV). Photodisintegration cross sections in the giant resonant range were analyzed by (1987VA05). Analyses of photodisintegration data for reactions (a, b, c, d) at  $E_\gamma < 50$  MeV (1990VA16) were used to deduce the role of cluster configuration. Reaction (e) has been studied in the giant resonance region with bremsstrahlung photons,  $E_{\text{brem}} \leq 30$  MeV. Deuteron groups to  ${}^5\text{He}_{\text{g.s.}}$  and possibly to the first excited state are reported. States of  ${}^7\text{Li}$  with  $E_x = 25\text{--}30$  MeV may be involved when  $E_{\text{brem}} = 37$  to 50 MeV is used: see (1979AJ01). At  $E_\gamma = 0.9$  GeV, (1985RE1A) have studied  $\pi^-$  emission with the population of  ${}^6\text{Li}^*(2.19)$ .

The cross section for reaction (f) at  $90^\circ$  displays a broad resonance at  $E \approx 7.7$  MeV ( $\Gamma = 7.2$  MeV) with an integrated cross section of 6.2 MeV mb, a plateau for  $12 \rightarrow 22$  MeV (at  $\approx 0.6$  the cross section at 7.7 MeV) and a gradual decrease to 48 MeV. The  $(\gamma, t)$  cross section integrated from threshold to 50 MeV is 8.1 MeV mb: see (1984AJ01), and (1986VO20). More recently, measurements of differential cross sections with linearly polarized photons ( $E_\gamma < 90$  MeV) were reported (1995BU08). Angular distributions at  $E_\gamma = 6.4, 6.7, 8.5, 9.0$  MeV have been measured by (1999LI02). Theoretical studies on this reaction include: a microscopic analysis for  $E < 70$  MeV (1987BU04); an analysis in the giant resonance range (1987VA05); a cluster structure study ( $E < 50$  MeV) (1990ZH19); and a calculation of photodisintegration observables for  $E < 90$  MeV (1998KO17). For earlier work, see references cited in (1988AJ01).

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

See Table 7.4 in (1966LA04) [summary of early measurements] for  $\tau_m$  of  ${}^7\text{Li}^*(0.48) = 107 \pm 5$  fsec. See also (1984AJ01), (1987BE1K) and (1986DU03).

## 17. (a) ${}^7\text{Li}(e, e){}^7\text{Li}$

(b)  ${}^7\text{Li}(e, e'\pi^+)X$



(c) ${}^7\text{Li}(e, ep){}^6\text{He}$	$Q_m = -9.9754$
(d) ${}^7\text{Li}(e, en){}^6\text{Li}$	$Q_m = -7.2499$

The electric form factor measurements for  $E_e = 100$  to  $600$  MeV are well accounted for by a simple harmonic-oscillator shell model with a quadrupole contribution described by an undeformed p-shell:  $r_{\text{r.m.s.}} = 2.39 \pm 0.03$  fm,  $|Q| = 42 \pm 2.5$  mb. From results obtained for  $E_e = 24.14$  to  $97.19$  MeV,  $r_{\text{r.m.s.}} = 2.35 \pm 0.10$  fm (model independent),  $2.29 \pm 0.04$  fm (shell model). A study of the ratio of the electric charge scattering from  ${}^6\text{Li}$  and from  ${}^7\text{Li}$  as a function of (momentum transfer)<sup>2</sup> yields  $\langle r^2 \rangle_6^{1/2} / \langle r^2 \rangle_7^{1/2} = 1.001 \pm 0.008$ . The r.m.s. radius of the ground state magnetization density distribution,  $\langle r^2 \rangle_M^{1/2} = 2.98 \pm 0.05$  fm. See (1979AJ01) for references. More recent theoretical studies include: a study by (1991BE40) which obtained vertex constants from an analysis of form factors; a shell-model calculation of large-basis space and mesonic effects (1992BO30); a calculation of form factors including meson exchange contributions (1992WA37); and a study of shell-model structures of low lying states (1997KA24).

Inelastic scattering studies show peaks corresponding to  ${}^7\text{Li}^*(0.48, 4.63, 6.68, 7.46)$ : see (1974AJ01) and Table 7.5. Form factors for  ${}^7\text{Li}^*(0, 0.48)$  have recently been studied at  $E_e = 80$  to  $680$  MeV (1989LI09, 1990LI21). Theoretical work includes: a calculation by (1989TA31) of cross section and reduced transition matrix elements for oriented nuclei; a calculation for polarized electron and polarized targets (1990LE14); a shell model calculation in a  $(0 + 2)\hbar\omega$  space (1990WO10); a study of spin modes (1991AR22); a microscopic cluster calculation (1991UN01); calculation of form factors including meson exchange contribution (1992BO30, 1992WA37); and a shell-model study of low lying states (1997KA24). For reaction (b) energy and angular distributions were measured at  $E_e = 203$  MeV (1999SH25) to study spin-isospin flip giant resonances.

For reactions (c) and (d) a measurement of the momentum distribution and study of clustering effects was reported in (1989LA22). Calculations discussed in (2000LA17) were used to study correlations in the  ${}^7\text{Li}$  ground-state wave function. See also the PWIA calculation for polarized electrons and targets of (1993CA11). See also (1988BO05). For earlier work see the references cited in (1988AJ01).

## 18. ${}^7\text{Li}(\pi, \pi){}^7\text{Li}$

${}^7\text{Li}^*(0, 0.48, 4.63, 6.68, 7.46, 9.67)$  have been populated in this reaction. Angular distributions have been measured at  $E_{\pi^+} = 49.7$  MeV and  $E_{\pi^\pm} = 143$  and  $164.4$  MeV: see (1984AJ01). Total and partial cross sections have been obtained for  $E_{\pi^\pm}$  in the range  $85 \rightarrow 315$  MeV [see (1984AJ01)] and at  $E_{\pi^+} = 50$  MeV (1983NA18). A measurement of inclusive analyzing power at  $E_\pi = 134, 164, 194$  MeV was reported by (1994ME01). A cluster-model calculation of quadrupole effects is described in (1994NO06). Calculations of pion scattering for  $E_\pi = 100$ – $240$  MeV are described in (2001LE01). Nuclear transition densities predicted by Quantum Monte-Carlo calculations were used. The  ${}^7\text{Li}(\pi^-, \pi^-p)$  reaction was studied at  $0.7$  GeV/c by (2000AB25). For  ${}^7\text{Li}(\pi^+, \pi^-p)$ , see (1998PA31). For the  $(\pi^+, 2p)$  reaction see  ${}^5\text{He}$  (1986RI01). For studies of

Table 7.5: Levels of  ${}^7\text{Li}$  from  ${}^7\text{Li}(e, e')$  <sup>a</sup>

$E_x$ (MeV)	$J^\pi; T$	$\Gamma_{\gamma_0}$ (eV)	Type
0.48	$\frac{1}{2}^-; \frac{1}{2}$	$(2.8 \pm 1.6) \times 10^{-7}$	C2
		$(6.30 \pm 0.31) \times 10^{-3}$	M1
$4.63 \pm 0.05$ <sup>b</sup>	$\frac{7}{2}^-; \frac{1}{2}$		C2 <sup>c</sup>
$6.6 \pm 0.1$ <sup>d</sup>	$\frac{5}{2}^-; \frac{1}{2}$		C2
$7.5 \pm 0.08$	$\frac{5}{2}^-; \frac{1}{2}$	$0.6 \pm 0.3$	C2
		$0.9 \pm 0.4$ <sup>e</sup>	

<sup>a</sup> For a summary of  $B(E2\uparrow)$  measurements, see Table 7.6 in (1966LA04) and the General Tables for  ${}^7\text{Li}$  located on our website at ([www.tunl.duke.edu/NuclData/General\\_Tables/7he.shtml](http://www.tunl.duke.edu/NuclData/General_Tables/7he.shtml)). For references see (1979AJ01, 1984AJ01).

<sup>b</sup>  $B(E2\uparrow) [\frac{3}{2}^- \rightarrow \frac{7}{2}^-] = 17.5 e^2 \cdot \text{fm}^4$ .

<sup>c</sup> Purely longitudinal.

<sup>d</sup>  $\Gamma_{\text{cm}} = 875_{-100}^{+200}$  keV.

<sup>e</sup> From  ${}^7\text{Li}(\gamma, n)$ . See also fit by (1980BA34).

( $\pi^+$ , pd) and ( $\pi^\pm$ , pn) see (1986WH01) and (1986YO06), respectively. For  $\pi^+$  induced fission of  ${}^7\text{Li}$  see (1983BA26). See also references in the General Table for  ${}^7\text{Li}$  located on our website at ([www.tunl.duke.edu/NuclData/General\\_Tables/7li.shtml](http://www.tunl.duke.edu/NuclData/General_Tables/7li.shtml)).

19. (a)  ${}^7\text{Li}(n, n){}^7\text{Li}$

(b)  ${}^7\text{Li}(n, nt){}^4\text{He}$   $Q_m = -2.4673$

Angular distributions have been measured at  $E_n = 0.5\text{--}3$  MeV (1991AL04),  $E_n = 1.5$  to 18 MeV [see (1979AJ01, 1984AJ01)],  $E_n = 5.4, 6.0, 14.2$  MeV (1985CH37;  $n_{0+1}, n_2$ ),  $E_n = 6.82\text{--}9.80$  MeV (1987SC08;  $n_{0+1}$ ), 7 to 14 MeV (1983DA22;  $n_0$ ),  $E_n = 11, 13$  MeV (1988CH09), 8.0 and 24.0 MeV (1988HA25;  $n_0$  and  $n_2$  at 24 MeV),  $E_n = 9, 9.5, 10$  MeV (1995HU17;  $n_1$ ) and at 14.7 MeV (1984SH01;  $n_{0+1}$ ). Double differential cross sections were measured at  $E_n = 11.5$  and 18.0 MeV (1998IB02). Theoretical work includes: calculations of coherent and incoherent scattering for  $E_n = 0.0728$  eV (1987VE02, 1990GO26); DWBA calculations of  $\sigma(\theta)$  for inelastic excitation of  ${}^7\text{Li}^*(0, 478)$  MeV (1992HU05); multi-configuration RGM calculations,  $E_n = 9.58\text{--}12.2$  MeV (1995FU16); and studies of optical model potentials for nuclear data evaluation,  $E_n < 200$  MeV (1996CH33). Reaction (b) at  $E_n = 14.4$  MeV proceeds primarily via  ${}^7\text{Li}^*(4.63)$  although some involvement of  ${}^7\text{Li}^*(6.68)$  may also occur: see (1979AJ01). Cross sections have been measured by activation methods at  $E_n = 14.7$  MeV (1987ME18) and 7.9–10.5

MeV (1987QA01). See also the evaluation of tritium production cross section for  $E < 17$  MeV (1990YU02). See also  $^8\text{Li}$  and references cited in (1988AJ01) and (1985CO18; applications).

20. (a) $^7\text{Li}(p, p)^7\text{Li}$	
(b) $^7\text{Li}(p, 2p)^6\text{He}$	$Q_m = -9.9754$
(c) $^7\text{Li}(p, pd)^5\text{He}$	$Q_m = -9.522$
(d) $^7\text{Li}(p, pn)^6\text{Li}$	$Q_m = -7.2499$
(e) $^7\text{Li}(p, pt)^4\text{He}$	$Q_m = -2.4670$
(f) $^7\text{Li}(p, p\alpha)^3\text{H}$	$Q_m = -2.4670$
(g) $^7\text{Li}(p, \alpha)^4\text{He}$	$Q_m = 17.3468$

Angular distributions of protons have been measured for  $E_p = 1.0$  to 185 MeV [see (1974AJ01, 1984AJ01)] and at  $E_p = 1.89$  to 2.59 MeV (1986SA1P;  $p_0$ ). Inelastic proton groups have been observed to  $^7\text{Li}^*(0.48, 4.63, 6.68, 7.46, 9.6)$ : see (1952AJ38, 1974AJ01). Double differential cross sections for the continuum are reported at  $E_p = 65$  MeV and 85 MeV (1987TO06, 1989TO04). Measurements of differential cross sections and analyzing powers for  $p_0$ ,  $p_1$  and  $p_2$  for  $E_p = 200$  MeV were used to deduce radial transition density differences (1991GL01). Cross sections for inelastic scattering to the  $^7\text{Li}$   $E_x = 0.478$  MeV level have been measured in application-related experiments for  $E_p = 2.2$ –3.8 MeV (1988BO37), 3.2–3.6 MeV (1990BO15), 2.5–3.5 MeV (1994MI21), 1.03 MeV (1994WI15), 0.7–3.2 MeV (1995RI14). See also (1999SA16).

For reaction (b) see (1984PA1B, 1985PA1B; 50–100 MeV) and (1985BE30, 1985DO16; 1 GeV). See also  $^6\text{He}$  and (1984AJ01). Cross section measurements at  $E_p = 70$  MeV were used to distinguish contributions of 1p and 1s shell nucleons by (1988PA26, 1998SH33). Proton spectra and polarization measurements at  $E_p = 1$  GeV are reported by (2000MI17). For reaction (c) see (1986WA11). For reaction (d) see (1985BE30) and  $^6\text{Li}$ . Reaction (d) has been studied at  $E_p = 200$  MeV (1986WA11): the deuteron spectroscopic factor is close to unity and the results indicate that the deuteron cluster momentum distribution is characterized, at small momentum, by a FWHM of 140 MeV/ $c$ . For measurements at  $E_p = 70$  MeV, see (1998SH33). Cross sections for the (p, pt) reaction (reaction (e)) are very small but are consistent with a spectroscopic factor of unity for  $t + ^4\text{He}$  in  $^7\text{Li}$  (1986WA11). For reaction (f) recent measurements of cross sections and analyzing powers measured for  $E_p = 296$  MeV were used to deduce alpha spectroscopic factor for  $^7\text{Li}$  (1998YO09). See also (1983GO06, 1985PA1C, 1985PA04). See also  $^5\text{He}$  and (1984AJ01).

See also  $^8\text{Be}$  in (1988AJ01), and references to earlier work cited in (1988AJ01). For early theoretical work on these reactions see references cited in (1988AJ01). More recent calculations include: threshold effects in elastic scattering for  $E_p = 1.35$ –3 MeV (1990GU22); differential cross section calculated at high energies with a geometric model (1990HU09); a potential description of  $^7\text{Li}(p, p)$  with  $E_p < 7$  MeV (1992DU07); calculation with a microscopic effective interaction (1993KO44); a folding model description for  $E_p = 25$ –50 MeV (1993PE13); a microscopic three-cluster model calculation for  $E_{cm} = 0.5$ –25 MeV,  $\sigma(E)$ ,  $S$  factors (1994DE09); a

fully microscopic analysis for  $E_p = 200$  MeV (1997DO01); an analysis of  $E_p = 200$  MeV data studying shell model structures of low lying  ${}^7\text{Li}$  levels (1997KA24); a microscopic analysis of elastic scattering at  $E_p = 25, 30$  and  $40$  MeV (2000DE61),  $E_p = 65$  MeV (1998DO16), and at  $60$ – $70$  MeV (1998FUZP); a resonance optical-model calculation for  $E_p = 1$ – $10$  MeV (2000LA40); and a Glauber-Sitenko diffraction theory calculation for  $E_p = 0.16$ – $1.04$  GeV (2000ZH50). See also (2000ZH53). Reaction rate uncertainties for reaction (g) were analyzed by (1998FI02).

## 21. ${}^7\text{Li}(d, d){}^7\text{Li}$

Angular distributions have been reported for  $E_d = 1.0$  to  $28$  MeV [see (1974AJ01, 1979AJ01)] and at  $50$  MeV (1988KO1C). See also  ${}^9\text{Be}$  in (1988AJ01) and (1987GOZF) for a breakup study.

## 22. (a) ${}^7\text{Li}({}^3\text{He}, {}^3\text{He}){}^7\text{Li}$

(b)  ${}^7\text{Li}({}^3\text{He}, \text{pd}){}^7\text{Li}$   $Q_m = -5.4935$

Angular distributions have been reported at  $E({}^3\text{He}) = 11$  MeV to  $44.0$  MeV and at  $E({}^3\text{He}) = 33.3$  MeV: see (1974AJ01, 1984AJ01). See also the compilation and analysis of differential cross sections for  $E({}^3\text{He}) = 24$  MeV (1995MI16). The missing mass spectrum in reaction (b) at  $E({}^3\text{He}) = 120$  MeV indicates, in addition to the unresolved group to  ${}^7\text{Li}^*(0, 0.48)$ , a small peak at  $E_x = 17.8 \pm 0.5$  MeV, possibly some structure between  $30$  and  $40$  MeV, a peak at  $40.5 \pm 0.5$  MeV ( $\Gamma \approx 2$ – $3$  MeV) and possibly some structure at higher energies (1985FR01). Measurements of cross sections for yields of protons, deuterons,  ${}^4\text{He}$ ,  ${}^3\text{H}$  and  ${}^3\text{He}$  from  $93$  MeV  ${}^3\text{He}$  on  ${}^7\text{Li}$  are reported by (1994DO32). For pion production see (1984BR22).

## 23. (a) ${}^7\text{Li}(\alpha, \alpha){}^7\text{Li}$

(b)  ${}^7\text{Li}(\alpha, 2\alpha){}^3\text{H}$   $Q_m = -2.4673$

Angular distributions (reaction (a)) have been reported for  $E_\alpha = 3.6$  to  $29.4$  MeV [see (1974AJ01, 1984AJ01)] and at  $E_\alpha = 35.3$  MeV (1985DI08;  $\alpha$  to  ${}^7\text{Li}^*(0, 0.48, 4.63, 6.68, 7.46, 9.67)$ ; collective coupled channel analysis). See also (1987BU27). More recently, differential cross sections were measured at  $E_\alpha = 50.5$  MeV for inelastic scattering to  ${}^7\text{Li}^*(0, 0.478, 4.63$  MeV) by (1996BU06). The  $\alpha, t$  cluster spectroscopic factor extracted for the  ${}^7\text{Li}$  ground state is  $S_{\alpha t} = 1.03 \pm 0.1$ . Measurements of target polarization in  ${}^7\text{Li}(\alpha, \alpha')$  to  $E_x = 4.63$  MeV for  $E_\alpha = 27.2$  MeV were reported by (1991KO41). See also coupled-channels calculations for these data (1997DM02). Gamma emission yields for  $E_\alpha = 0.7$ – $3.2$  MeV were measured for nuclear microprobe applications by (1995RI14).

Reaction (b) has been studied at  $E_\alpha = 18$  to  $64.3$  MeV [see (1974AJ01, 1984AJ01)] and at  $27.2$  MeV (1985KO29).  ${}^7\text{Li}^*(4.63)$  is strongly involved in the sequential decay, as are possibly

${}^7\text{Li}^*(6.68, 7.46)$ . Cross sections measured for  $E_\alpha = 77\text{--}119$  MeV were used to deduce triton momentum distributions for  $\alpha+t$  states in  ${}^7\text{Li}$  by (1992WA09). An analysis is reported in (1996JA01). See also references cited in (1988AJ01).

24. (a)  ${}^7\text{Li}({}^6\text{Li}, {}^6\text{Li}){}^7\text{Li}$   
 (b)  ${}^7\text{Li}({}^7\text{Li}, {}^7\text{Li}){}^7\text{Li}$   
 (c)  ${}^7\text{Li}({}^{11}\text{Li}, {}^{11}\text{Li}){}^7\text{Li}$

Elastic and inelastic ( ${}^7\text{Li}$ ,  $E_x = 0.476$  MeV) differential cross sections for reaction (a) have been reported for  $E_\alpha = 9\text{--}40$  MeV (1998PO03). See also  ${}^6\text{Li}$ . The elastic angular distribution (reaction (b)) has been studied for  $E({}^7\text{Li}) = 4.0$  to  $6.5$  MeV [see (1974AJ01)] and  $2.0$  to  $5.5$  MeV (1983NO08). Elastic and inelastic ( ${}^7\text{Li}$ ,  $E_x = 0.476$  MeV) cross sections for  $E_\alpha = 8\text{--}17$  MeV were measured and analyzed with an optical model (1993BA43, 1997PO03). For reaction (c) cross sections for  $E({}^{11}\text{Li}) = 300$  MeV were calculated in connection with a study of nuclear matter compressibility (1998GR21).

25.  ${}^7\text{Li}({}^9\text{Be}, {}^9\text{Be}){}^7\text{Li}$

Elastic angular distributions have been measured at  $E({}^7\text{Li}) = 34$  MeV [see (1979AJ01)] and at  $78$  MeV (1986GLZV, 1986GLZU; also to  ${}^7\text{Li}^*(4.63)$ ). For the interaction cross section at  $790$  MeV/A see (1985TA18).

26. (a)  ${}^7\text{Li}({}^{10}\text{B}, {}^{10}\text{B}){}^7\text{Li}$   
 (b)  ${}^7\text{Li}({}^{11}\text{B}, {}^{11}\text{B}){}^7\text{Li}$

For reaction (a) see  ${}^{10}\text{B}$  in (1988AJ01). Angular distributions have been studied for reaction (b) to  ${}^7\text{Li}^*(0, 0.48)$  at  $E({}^7\text{Li}) = 34$  MeV (1987CO07, 1987CO02). See also (1987HNZZ).

27. (a)  ${}^7\text{Li}({}^{12}\text{C}, {}^{12}\text{C}){}^7\text{Li}$   
 (b)  ${}^7\text{Li}({}^{13}\text{C}, {}^{13}\text{C}){}^7\text{Li}$

Angular distributions (reaction (a)) involving  ${}^7\text{Li}^*(0, 0.48)$  have been studied at  $E({}^7\text{Li}) = 4.5$  to  $89$  MeV [see (1975AJ02, 1979AJ01, 1984AJ01)] and at  $E({}^7\text{Li}) = 53.8$  MeV and  $E({}^{12}\text{C}) = 92.3$  MeV (1984VI02, 1986CO02; also to  ${}^7\text{Li}^*(4.63)$ ) and at  $E({}^7\text{Li}) = 131.8$  MeV (1988KA09;  ${}^7\text{Li}^*(0 + 0.48)$ ); and various states in  ${}^{12}\text{C}$  as well as at  $E({}^7\text{Li}) = 21.1$  MeV (1984MO06; elastic).

See also (1986GLZU) and  $^{12}\text{C}$  in (1985AJ01, 1990AJ01). Breakup studies involving  $^7\text{Li}^*(4.63)$  are reported at  $E(^7\text{Li}) = 70$  MeV (1986DAZP, 1986YOZU) and 132 MeV (1986SHZP). See also the measurement at  $E(^{12}\text{C}) = 58.4$  MeV reported by (1987PA12). The interaction cross section on carbon at 790 MeV/A has been measured by (1985TA18).

The elastic scattering in reaction (b) has been studied for  $E(^7\text{Li}) = 4.5$  to 34 MeV [see  $^{13}\text{C}$  in (1985AJ01)] and by (1987CO02, 1987CO16; 34 MeV; also to  $^7\text{Li}^*(0.48)$ ). For earlier work, see references cited in (1988AJ01).

28. (a)  $^7\text{Li}(^{14}\text{N}, ^{14}\text{N})^7\text{Li}$   
 (b)  $^7\text{Li}(^{15}\text{N}, ^{15}\text{N})^7\text{Li}$

Elastic angular distributions (reaction (a)) are reported at  $E(^7\text{Li}) = 36$  MeV [see (1981AJ01)] and  $E(^{14}\text{N}) = 150$  MeV (1986GO1H) while those for reaction (b) have been studied at  $E(^7\text{Li}) = 28.8$  MeV [see  $^{15}\text{N}$  in (1986AJ01)].

29.  $^7\text{Li}(^{16}\text{O}, ^{16}\text{O})^7\text{Li}$

The elastic scattering has been studied from  $E(^7\text{Li}) = 9.0$  to 20 and at 68 MeV [see  $^{16}\text{O}$  in (1986AJ04)] as well as at  $E(^7\text{Li}) = 50$  MeV (1984CO20). For fusion cross sections and breakup studies see (1984MA28, 1986MA19, 1986SC28, 1988MA07). See also (1982GU21, 1988PR02).

30.  $^7\text{Li}(^{20}\text{Ne}, ^{20}\text{Ne})^7\text{Li}$

Angular distributions have been studied at  $E(^7\text{Li}) = 36, 68$  and 89 MeV: see  $^{20}\text{Ne}$  in (1983AJ01).

31. (a)  $^7\text{Li}(^{24}\text{Mg}, ^{24}\text{Mg})^7\text{Li}$   
 (b)  $^7\text{Li}(^{25}\text{Mg}, ^{25}\text{Mg})^7\text{Li}$   
 (c)  $^7\text{Li}(^{26}\text{Mg}, ^{26}\text{Mg})^7\text{Li}$   
 (d)  $^7\text{Li}(^{27}\text{Al}, ^{27}\text{Al})^7\text{Li}$

The elastic scattering has been studied at  $E(^7\text{Li}) = 89$  MeV and at 27 MeV (reaction (b)): see (1984AJ01). A study of the breakup on  $^{27}\text{Al}$  is reported by (1986NAZV) and the interaction cross section at 790 MeV/A has been measured by (1985TA18). See also (1988OT01, 1988SA10).

32. (a)  ${}^7\text{Li}({}^{28}\text{Si}, {}^{28}\text{Si}){}^7\text{Li}$   
 (b)  ${}^7\text{Li}({}^{40}\text{Ca}, {}^{40}\text{Ca}){}^7\text{Li}$   
 (c)  ${}^7\text{Li}({}^{48}\text{Ca}, {}^{48}\text{Ca}){}^7\text{Li}$

Angular distributions involving  ${}^7\text{Li}^*(0, 0.48)$  and various states of  ${}^{28}\text{Si}$  and  ${}^{40}\text{Ca}$  have been studied at  $E({}^7\text{Li}) = 45$  MeV. The elastic scattering on  ${}^{40}\text{Ca}$  and  ${}^{48}\text{Ca}$  has been studied at  $E({}^7\text{Li}) = 28, 34$  and  $89$  MeV [the latter also to  ${}^7\text{Li}^*(0.48)$ ]: see (1984AJ01). Angular distributions (reaction (b)) involving  ${}^7\text{Li}^*(0, 0.48)$  have also been reported at  $E({}^7\text{Li}) = 34$  MeV (1985SA25). See also (1985GO11, 1986SA1D, 1987SA1C).

33.  ${}^7\text{Be}(\epsilon){}^7\text{Li}$   $Q_m = 0.8618$

The decay proceeds to the ground and 0.48 MeV states. The branching ratio to  ${}^7\text{Li}^*(0.48)$  is  $10.44 \pm 0.04\%$ , and the adopted half-life is  $53.22 \pm 0.06$  d. Both transitions are superallowed:  $\log ft = 3.32$  and  $3.55$  for the decays to  ${}^7\text{Li}^*(0, 0.48)$ . See also (1979AJ01). The first excited state has  $E_x$  [from  $E_\gamma$ ] =  $477.612 \pm 0.002$  keV: see (1984AJ01). A recent investigation of the decay utilized a high efficiency BeO calorimeter developed for use in a  ${}^7\text{Li}$  solar neutrino experiment (1998GA08). The decay rate of BeOH<sub>2</sub> was studied under pressures up to 441 kbar (2000LI21) and showed systematic dependences at the 1% level. A large change in the decay rate for  ${}^7\text{Be}$  implanted in Au and Al<sub>2</sub>O<sub>3</sub> was observed by (1999RA12) indicating that the chemical environment affects the  ${}^7\text{Be}$  lifetime. A further decay study using  ${}^7\text{Be}$  in BeO, BeOH<sub>2</sub> and Be<sup>2+</sup>(OH<sub>2</sub>)<sub>4</sub> molecular forms (1999HU20) found considerable variation ( $\approx 1.5\%$ ) in the lifetime. Less significant effects of the chemical environment on the measured half-life have been measured by (1949SE20, 1953KR16, 1956BO36, 1970JO21, 1973HE27). The authors of (2000HU20) deduced a half-life value of  $53.42 \pm 0.01$  d for  ${}^7\text{Be}$  in BeOH<sub>2</sub>. A systematic discussion of  ${}^7\text{Be}$  half-lives is included in the evaluation of R. Helmer (see Table 7.6). Helmer's evaluation produced a general-use value of the half-life,  $53.22 \pm 0.06$  d, which is intended to be valid for Be and BeO samples and adequate for various chemical forms. In spite of more precise measurements of the  ${}^7\text{Be}$  lifetime that show these environmental effects, we presently adopt this value.

In related threshold investigations, the polarization of the internal bremsstrahlung has been calculated (1988ME06) as well as the effect of daughter atom ionization (1994RE18) and the fractional electron probabilities (1998SC28). For earlier work, see references cited in (1988AJ01).

34.  ${}^7\text{Be}(n, p){}^7\text{Li}$   $Q_m = 1.6441$

Total cross sections have been measured at  $E_n = 0.025$ – $13.5$  keV (1988KO03). The cross sections obtained for the  ${}^7\text{Li}$  ground and first excited states ( $E_x = 0.477$  MeV) were  $38400 \pm 800$  b and  $420 \pm 120$  b, respectively. The astrophysical reaction rate  $N_A \langle \sigma v \rangle$  was calculated. Uncertainties in elemental abundances from primordial nucleosynthesis were deduced in (1998FI02).

Table 7.6:  ${}^7\text{Be}(\epsilon){}^7\text{Li}$  decay <sup>a</sup>

Branching ratio to ${}^7\text{Li}^*(0.48)$		${}^7\text{Be}$ Half-life	
Branching ratio (%)	References	Half-life (days)	References
$10_{-7}^{+20}$	(1938RU01)	$53 \pm 2$	(1940HI01)
$10.7 \pm 2.0$	(1949WI13)	$52.93 \pm 0.22$	(1949SE20)
$11.8 \pm 1.2$	(1949TU06)	$53.61 \pm 0.17$	(1953KR16)
$12.3 \pm 0.6$	(1951DI12)	$53.0 \pm 0.4$	(1956BO36)
$10.35 \pm 0.08$	(1969TAZX)	$53.5 \pm 0.2$	(1957WR37)
$10.47 \pm 0.20$	(1970MUZU)	$53.1 \pm 0.3$	(1965EN01)
$10.42 \pm 0.18$	(1973PO10)	$53.52 \pm 0.10$	(1970JO21)
$10.35 \pm 0.08$	(1974GO26)	$53.0 \pm 0.3$	(1974CR05)
$10.10 \pm 0.45$	(1983BA15)	$53.17 \pm 0.02$	(1975LA16)
$10.61 \pm 0.23$	(1983DA14)	$53.16 \pm 0.01$	(1982CHZF)
$10.6 \pm 0.5$	(1983DO07)	$53.284 \pm 0.004$	(1982RUZV)
$10.9 \pm 1.1$	(1983KN10)	$53.12 \pm 0.07$	(1996JA10)
$10.7 \pm 0.2$	(1983MA34)		
$9.8 \pm 0.5$	(1983NO03)		
$11.4 \pm 0.7$	(1984EV01)		
$10.61 \pm 0.17$	(1984FI10)		
$10.49 \pm 0.07$	(1984SK01)		
$10.44 \pm 0.04$	weighted average	$53.22 \pm 0.06$ <sup>b</sup>	adopted

<sup>a</sup> Evaluated by R. Helmer in conjunction with the Decay Evaluation Project (1999BEZQ, 1999BEZS). We are grateful to Dr. Helmer for providing this information to us.

<sup>b</sup> Adopted by the evaluator from Limitation of Relative Statistical Weight (LRSW) (1985ZIZY, 1992RA09) analysis.



35.  ${}^8\text{Li}(\alpha, \alpha n){}^7\text{Li}$   $Q_m = -2.0328$

Cross sections  $\sigma(E)$  for  $E_\alpha = 2\text{--}7$  MeV were measured by (1998MIZY). See (1999ZHZN) for a compilation and evaluation of cross section data.

36.  ${}^9\text{Be}(\gamma, d){}^7\text{Li}$   $Q_m = -16.6958$

Differential cross sections for  $E_\alpha = 21\text{--}39$  MeV were measured by (1999SH05). See (1999ZHZN) for a compilation and evaluation of cross section data.

37.  ${}^9\text{Be}(\pi^-, 2n){}^7\text{Li}$   $Q_m = 119.8674$

The capture of stopped pions has been studied in a kinematically complete experiment:  ${}^7\text{Li}^*(0, 0.48)$  are weakly populated. Two large peaks are attributed to the excitation of  ${}^7\text{Li}^*(7.46, 10.25)$ . The recoil momentum distributions corresponding to these peaks are rather similar and both indicate a strong  $L = 0$  component: see (1979AJ01).

38.  ${}^9\text{Be}(n, t){}^7\text{Li}$   $Q_m = -10.4387$

An angular distribution is reported at  $E_n = 14.6$  MeV (1987ZA01;  $t_{0+1}$ ). See also (1979AJ01) and  ${}^{10}\text{Be}$  in (1988AJ01). Cross section measurements have also been reported for  $E_n = 12.9\text{--}19.6$  MeV (1988LI05) and for  $E_n = 16\text{--}19.6$  MeV with Hauser-Feshbach calculations (1990WO07).

39. (a)  ${}^9\text{Be}(p, {}^3\text{He}){}^7\text{Li}$   $Q_m = -11.2021$

(b)  ${}^9\text{Be}(p, pd){}^7\text{Li}$   $Q_m = -16.6961$

At  $E_p = 43.7$  MeV, angular distributions have been obtained for the  ${}^3\text{He}$  particles corresponding to  ${}^7\text{Li}^*(0, 0.48, 4.63, 7.46)$ . The 7.46-MeV state is strongly excited while the analog state in  ${}^7\text{Be}$  is not appreciably populated in the  ${}^9\text{Be}(p, t){}^7\text{Be}$  reaction (see reaction 21 in  ${}^7\text{Be}$ ). The angular distribution indicates that the transition to  ${}^7\text{Li}^*(7.46)$  involves both  $L = 0$  and 2, with a somewhat dominant  $L = 0$  character. The  $J^\pi = \frac{3}{2}^-$ ,  $T = \frac{3}{2}$  state is located at  $E_x = 11.28 \pm 0.04$  MeV,  $\Gamma = 260 \pm 50$  keV: see (1979AJ01). Reaction (b) at  $E_p = 58$  MeV involved  ${}^7\text{Li}^*(0, 0.48, 7.47)$  (1985DE17). See also (1987KA25).

40. (a)  ${}^9\text{Be}(d, \alpha){}^7\text{Li}$   $Q_m = 7.1509$   
 (b)  ${}^9\text{Be}(d, t){}^4\text{He}{}^4\text{He}$   $Q_m = 4.6836$

Angular distributions have been measured for  $E_d = 0.4$  to  $27.5$  MeV [see (1966LA04, 1974AJ01, 1979AJ01)] and at  $E_d = 2.0$  to  $2.8$  MeV (1984AN16;  $\alpha_0, \alpha_1$ ). A study at  $11$  MeV finds  $\Gamma_{\text{cm}} = 93 \pm 25$  and  $80 \pm 20$  keV, respectively for  ${}^7\text{Li}^*(4.63, 7.46)$ . No evidence is found for the  $T = \frac{3}{2}$  state  ${}^7\text{Li}^*(11.25)$ . Differential cross sections measured at  $E_d = 67$ – $75$  MeV for excitation of  ${}^7\text{Li}^*(0, 0.48, 4.63, 7.46)$  were used to deduce spectroscopic amplitudes (1989SZ02). Measurements of vector analyzing powers for  ${}^7\text{Li}^*(0, 0.48)$  were reported by (1994LY02) for  $E_d = 1.3$ – $3.1$  MeV. Measurements at  $E_{\text{cm}} = 57$ – $139$  keV (1997YA02) and  $E_{\text{cm}} = 30$ – $130$  keV (1997YA08) were used to deduce astrophysical  $S$ -factors. Differential cross sections for  $E_d = 90$ – $290$  keV are reported in (2001OCZZ). Astrophysical  $S$  factors were deduced. See also (1999OCZZ). The previous review (1988AJ01) notes that in a kinematically complete study of reaction (b) at  $E_d = 26.3$  MeV,  ${}^7\text{Li}^*(4.6, 6.5 + 7.5, 9.4)$  are strongly excited. No sharp  $\alpha$ -decaying states of  ${}^7\text{Li}$  are observed with  $10 < E_x < 25$  MeV. Parameters for  ${}^7\text{Li}^*(9.7)$  are  $E_x = 9.36 \pm 0.05$  MeV,  $\Gamma = 0.8 \pm 0.2$  MeV: see (1979AJ01). [ $E_x = 6.75 \pm 0.20$  MeV,  $\Gamma = 0.87 \pm 0.20$  MeV (1986PAZN)]. A study of inclusive  $\alpha$ -spectra at  $E_d = 50$  MeV has been reported by (1987KA17) who suggest the involvement of a  ${}^7\text{Li}$  state at  $E_x = 18 \pm 1$  MeV,  $\Gamma = 5 \pm 1$  MeV. For reaction (b) see also (1987VA29). See also  ${}^{11}\text{B}$  in (1990AJ01) and (1988NE1A). In more recent studies of reaction (b), differential cross sections have been measured at  $E_d = 18$  MeV (1988GO02, 1988GU20) and  $E_d = 7$  MeV (1988SZ02). See also the measurements of  $\sigma(E)$  for  $E_d = 0.9$ – $11.2$  MeV (1994AB25),  $A_y(\theta)$  for  $E_d = 1.3$ – $3.1$  MeV (1994LY02),  $\sigma(\theta)$  at  $E_d = 3$ – $11$  MeV (1995AB41) and  $E_d = 8$ – $50$  MeV (1995GU22). Astrophysical  $S$  factors were determined in measurements at  $E_{\text{cm}} = 57$ – $139$  keV (1997YA02, 1997YA08).

41. (a)  ${}^9\text{Be}({}^6\text{Li}, {}^8\text{Be}){}^7\text{Li}$   $Q_m = 5.5845$   
 (b)  ${}^9\text{Be}({}^9\text{Be}, {}^{11}\text{B}){}^7\text{Li}$   $Q_m = -0.8805$

Angular distributions involving  ${}^7\text{Li}^*(0, 0.48)$  have been reported at  $E({}^6\text{Li}) = 32$  MeV (1985CO09) and  $E({}^9\text{Be}) = 14$  MeV (1985JA09). Reaction cross sections have been calculated by (2001BH02) for  $E({}^6\text{Li}) = 790$  MeV/A.

42.  ${}^{10}\text{B}(n, \alpha){}^7\text{Li}$   $Q_m = 2.7891$

Angular distributions of  $\alpha_0, \alpha_1$  and of  $\alpha_2$  at the higher energies have been measured from  $E_n = 2$  keV to  $14.4$  MeV: see (1979AJ01, 1984AJ01).  $\tau_m(0.48) = 102 \pm 5$  fsec (1985KO47). More recently measurements of the ground to excited-state transition ratio  $\sigma(n, \alpha_0)/\sigma(n, \alpha\gamma)$  for  $E_n = 0.2$ – $1.0$  MeV were reported by (1991WE11). A relative measurement of the  ${}^{10}\text{B}(n,$

$\alpha\gamma$ ) $^7\text{Li}$  cross section has been made (1993SC20) for  $E_n = 0.2\text{--}4.0$  MeV. A study of P-odd effects (in the mixing of opposite-parity levels) in this reaction determined forward-backward asymmetries for the  $\alpha_0$  and  $\alpha_1$  groups  $(3.4 \pm 6.7) \times 10^{-7}$  and  $(-2.5 \pm 1.6) \times 10^{-7}$  respectively (1996VE02). Earlier work was reported in (1986ER05, 1994GL07). Measurement and analysis of the Doppler-broadened gamma line shapes produced in the  $(n, \alpha, \gamma)$  reaction for the purpose of boron concentration determination are described in (1994SA72, 1998MA61). See also (1997SA70). For early polarization studies (involving both n and  $^{10}\text{B}$ ) see (1986KO19) and  $^{11}\text{B}$  in (1990AJ01). See also (1986CO1M; applications). See also the more recent measurements and calculations of (1999VE03) and the measurement at thermal energies of (2000GO03). A calculation of  $\alpha - \gamma$  correlation parameters and study of time-reversal invariance related features are described in (2000GA43).

$$43. \text{}^{10}\text{B}(d, \text{}^5\text{Li})\text{}^7\text{Li} \quad Q_m = -1.12$$

See  $^5\text{Li}$ .

$$44. \text{}^{10}\text{B}(\alpha, \text{}^7\text{Be})\text{}^7\text{Li} \quad Q_m = -16.2015$$

Angular distributions involving  $^7\text{Li}_{g.s.}$  and  $^7\text{Be}_{g.s.}$  and  $^7\text{Li}^*(0.48) + ^7\text{Be}^*(0.43)$  have been studied at  $E_\alpha = 91.8$  MeV (1985JA12, 1986JA03). See also (1988SH1E; theor.).

$$45. \text{}^{11}\text{Be}(\beta^-)\text{}^{11}\text{B}^* \rightarrow \text{}^7\text{Li} + \alpha \quad Q_m = 1.211$$

Delayed  $\alpha$ -particles have been observed in the  $\beta^-$  decay of  $^{11}\text{Be}$ : they are due to the decay of  $^{11}\text{B}^*(9.88)$  [ $J^\pi = \frac{3}{2}^+$ ]. This state decays by  $\alpha$ -emission  $87.4 \pm 1.2\%$  to the ground state of  $^7\text{Li}$  and  $12.6 \pm 1.2\%$  to  $^7\text{Li}^*(0.48)$  (1981AL03). See also  $^{11}\text{Be}$  and  $^{11}\text{B}$  in (1985AJ01).

$$46. \text{}^{11}\text{B}(\text{}^3\text{He}, \text{}^7\text{Be})\text{}^7\text{Li} \quad Q_m = -7.0780$$

Angular distributions involving  $^7\text{Li}_{g.s.}$  and  $^7\text{Be}_{g.s.}$  and  $^7\text{Li}^*(0.48) + ^7\text{Be}^*(0.43)$  have been studied at  $E(^3\text{He}) = 71.8$  MeV (1986JA02, 1986JA03). See also (1987KW01, 1987KW03).

$$47. \text{}^{11}\text{B}(\alpha, \text{}^8\text{Be})\text{}^7\text{Li} \quad Q_m = -8.7567$$

Angular distributions have been measured at  $E_\alpha = 27.2$  to  $29.0$  MeV and at  $65$  MeV. At  $E_\alpha = 65$  and  $72.5$  MeV,  ${}^7\text{Li}^*(0, 4.63)$  are very strongly populated while  ${}^7\text{Li}^*(0.48, 6.68, 7.46)$  are weakly excited: see (1979AJ01, 1984AJ01).

$$48. {}^{12}\text{C}(\gamma, p\alpha){}^7\text{Li} \quad Q_m = -24.6216$$

Cross sections were measured at  $E_\gamma = 27$ – $47$  MeV with bremsstrahlung photons by (1998KO77).

$$49. {}^{12}\text{C}(d, {}^7\text{Be}){}^7\text{Li} \quad Q_m = -17.5415$$

Angular distributions involving  ${}^7\text{Li}_{g.s.}$  and  ${}^7\text{Be}_{g.s.}$  and  ${}^7\text{Li}^*(0.48) + {}^7\text{Be}^*(0.43)$  have been studied at  $E_d = 39.8$  MeV [see (1979AJ01)] and at  $78.0$  MeV (1986JA03, 1986JA15). See also (1984NE1A) and (1987KW01, 1987KW03).

More recently differential cross sections at  $E_d = 78$  MeV were measured in a study of five-nucleon transfer (1996JA12).

$$50. {}^{12}\text{C}(t, {}^8\text{Be}){}^7\text{Li} \quad Q_m = -4.8997$$

Angular distributions have been studied at  $E_t = 38$  MeV to  ${}^8\text{Be}_{g.s.}$  and  ${}^7\text{Li}^*(0, 0.48)$  (1986SIZS).

$$51. {}^{12}\text{C}(\alpha, {}^9\text{B}){}^7\text{Li} \quad Q_m = -24.8985$$

Angular distributions are reported at  $E_\alpha = 49.0$  and  $80.1$  MeV (1984GO03). See also (1984AJ01). Differential cross sections were measured at  $E_\alpha = 90$  MeV by (1991GL03).

$$52. {}^{12}\text{C}({}^6\text{Li}, {}^{11}\text{C}){}^7\text{Li} \quad Q_m = -11.4719$$

Angular distributions have been obtained at  $E({}^6\text{Li}) = 36$  MeV for the transitions to  ${}^7\text{Li}^*(0, 0.48)$ : see (1979AJ01). See also (1986GL1E). More recently differential cross sections and polarization observables were measured at  $E({}^6\text{Li}) = 50$  MeV in a study of mirror states in  ${}^7\text{Li}$ ,  ${}^7\text{Be}$  (1997KE04).

$$53. {}^{12}\text{C}({}^7\text{Li}, {}^7\text{Be}){}^{12}\text{B} \quad Q_m = -14.2307$$

The reaction was studied (1999NA36) at  $E(^7\text{Li}) = 65 \text{ MeV}/A$ , and Gamow-Teller transition strengths were compared to those deduced from  $\beta$  decay.

$$54. \text{}^{13}\text{C}(\text{d}, \text{}^8\text{Be})^7\text{Li} \quad Q_{\text{m}} = -3.5887$$

At  $E_{\text{d}} = 14.6 \text{ MeV}$  angular distributions are reported for the transitions to  $^7\text{Li}^*(0, 0.48)$  and  $^8\text{Be}_{\text{g.s.}}$ : see (1979AJ01). See also (1984NE1A, 1984SH1D).

$$55. \text{}^{14}\text{N}(\text{n}, 2\alpha)^7\text{Li} \quad Q_{\text{m}} = -8.8228$$

At  $E_{\text{n}} = 14.1 \text{ MeV}$ ,  $^7\text{Li}^*(0, 0.48)$  are approximately equally populated: see (1979AJ01). Differential cross sections have been measured at  $E_{\text{n}} = 14.4$  and  $18.2 \text{ MeV}$  involving  $^8\text{Be}_{\text{g.s.}}$  and  $^7\text{Li}^*(0 + 0.48, 4.63)$  (1986TU02).

$$56. \text{}^{14}\text{O}(\text{n}, \gamma)^7\text{Li}X$$

Gamma ray intensities and photo production cross sections were measured for  $E_{\text{n}} = 4\text{--}200 \text{ MeV}$  by (2001NE09).

$$57. \text{(a) } ^{17}\text{O}(\text{d}, ^{12}\text{C})^7\text{Li} \quad Q_{\text{m}} = -2.5807$$

$$\text{(b) } ^{18}\text{O}(\text{d}, ^{13}\text{C})^7\text{Li} \quad Q_{\text{m}} = -5.6791$$

$$\text{(c) } ^{19}\text{F}(\text{d}, ^{14}\text{N})^7\text{Li} \quad Q_{\text{m}} = -6.1228$$

At  $E_{\text{d}} = 14.6$  to  $15.0 \text{ MeV}$ , angular distributions have been measured for the transitions to  $^{12}\text{C}_{\text{g.s.}} + ^7\text{Li}^*(0, 0.48)$  [reaction (a)],  $^{13}\text{C}_{\text{g.s.}} + ^7\text{Li}^*(0, 0.48)$  [reaction (b)] and  $^{14}\text{N}_{\text{g.s.}} + ^7\text{Li}^*(0, 0.48)$  [reaction (c)]: see (1979AJ01). See also (1984AJ01).

$$58. \text{}^{27}\text{Al}(^7\text{Li}, \text{t}\alpha)X$$

A Coulomb breakup experiment reported by (2001TO07) used a  $42 \text{ MeV } ^7\text{Li}$  beam incident on target of  $^{27}\text{Al}$ ,  $^{58}\text{Ni}$ ,  $^{64}\text{Zn}$ ,  $^{90}\text{Zr}$ ,  $^{120}\text{Sn}$ ,  $^{144}\text{Sm}$ ,  $^{169}\text{Tm}$ ,  $^{197}\text{Au}$  and  $^{208}\text{Pb}$ . The spectra of breakup particles were studied and the astrophysical  $S$  factors,  $S(E)$  for  $^3\text{H}(\alpha, \gamma)^7\text{Li}$ , were deduced.

59.  $^{nat}\text{Ag}(^7\text{Li}, \text{X})$

Measurements of charged particle multipolarity, angular distributions and rapidity distributions were reported in (2001AB25).  $^7\text{Li}$  cluster structure was deduced.

60.  $^{208}\text{Pb}(^7\text{Li}, ^7\text{Li})^{208}\text{Pb}$

Elastic and inelastic cross sections and analyzing powers were measured at  $E(^7\text{Li}) = 27 \text{ MeV}$  to study the effect of electric dipole polarizability of  $^7\text{Li}$  (1998MA65).

**<sup>7</sup>Be**  
(Figs. 10 and 11)

GENERAL: References to articles on general properties of <sup>7</sup>Be published since the previous review (1988AJ01) are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for <sup>7</sup>Be located on our website at ([www.tunl.duke.edu/NuclData/General\\_Tables/7be.shtml](http://www.tunl.duke.edu/NuclData/General_Tables/7be.shtml)).

The interaction nuclear radius of <sup>7</sup>Be is  $2.22 \pm 0.02$  fm (1985TA18). [See also for derived nuclear matter, charge and neutron matter r.m.s. radii]. A measurement of the magnetic moment by (1998KAZN) gave a preliminary result  $\mu_1 = -1.398 \pm 0.015 \mu_N$ .

1. <sup>7</sup>Be( $\epsilon$ )<sup>7</sup>Li  $Q_m = 0.8618$

The  $\epsilon$ -capture decay is complex: see reaction 33 in <sup>7</sup>Li.

2. <sup>4</sup>He(<sup>3</sup>He,  $\gamma$ )<sup>7</sup>Be  $Q_m = 1.5866$

The capture cross sections have been measured for  $E_\alpha = 0.250$  to  $5.80$  MeV and at  $E(^3\text{He}) = 19$  to  $26$  MeV [see (1974AJ01, 1984AJ01)], at  $E_{\text{cm}} = 195$  to  $686$  keV (1988HI06), and at  $E_\alpha = 385$  to  $2728$  keV (1984OS03) and  $1225$  keV (1984AL24). One of the main reasons for doing these measurements is to determine the astrophysical  $S(0)$  factor. The values of  $S(0)$  appear, on the average, to be higher if the experiment involves measurement of the  $0.48$  MeV  $\gamma$  following  $\epsilon$ -capture rather than if it involves a direct measurement of the capture  $\gamma$ -rays. It is not entirely clear why this should be so. Contaminant production of <sup>7</sup>Be may be involved: see (1988HI06) and e.g. (1984AL24, 1985FI1D, 1986LA22). Earlier measurements, sometimes recalculated, are discussed by (1986LA22, 1987KA1R, 1988HI06). The latter adopt best values of  $S(0) = 0.51 \pm 0.02$  keV b [prompt  $\gamma$ -rays] and  $0.58 \pm 0.02$  keV b [<sup>7</sup>Be activity] (1988HI06). See also (1984AL24, 1985FI1D, 1987KA1R, 1988BA86). More recently, (1993MO11) measured differential cross sections for <sup>3</sup>He- $\alpha$  scattering for  $E_{\text{lab}}(^3\text{He}) < 3$  MeV and obtained optical potentials which were used to calculate  $S(0)$  for the capture reaction. They obtained  $S(0) = 0.516$  keV · b in agreement with (1988HI06). They also calculated the branching ratio for transition to the first excited state and ground state to be  $R = 0.43$ . Theoretical calculations are in general agreement with the experimental values. See (1988AJ01) for examples from some of the early work. Calculations of astrophysical  $S$  factors for the capture reaction are included in (1988BU17, 1988KA07, 1989CH37, 1989CH48, 1989KA18, 1995DU09, 1995LI07, 1997DU15, 2001NO04). Phase shifts and cross sections ( $E_{\text{cm}} < 5$  MeV) were calculated in an extended two-cluster model by (2000CS06). Astrophysical  $S$  factors were deduced. See also the  $S$ -factor calculation of

Table 7.7: Energy levels of  ${}^7\text{Be}$ 

$E_x$ (MeV $\pm$ keV)	$J^\pi; T$	$\tau$ or $\Gamma_{\text{c.m.}}$	Decay	Reactions
g.s.	$\frac{3}{2}^-; \frac{1}{2}$	$\tau_{1/2} = 53.22 \pm 0.06 \text{ d}^{\text{a}}$	$\epsilon$ -capture	1, 2, 4, 5, 9, 10, 11, 13, 14, 15, 16, 17, 21, 22, 24, 25, 26, 27, 28, 29, 33, 34
$0.42908 \pm 0.10$	$\frac{1}{2}^-; \frac{1}{2}$	$\tau_{\text{m}} = 192 \pm 25 \text{ fsec}$	$\gamma$	2, 4, 5, 9, 10, 14, 16, 17, 21, 22, 23, 24, 25, 26, 27, 28, 29, 33, 34
$4.57 \pm 50$	$\frac{7}{2}^-; \frac{1}{2}$	$\Gamma = 175 \pm 7 \text{ keV}$	${}^3\text{He}, \alpha$	3, 5, 10, 14, 16, 17, 21, 22
$6.73 \pm 100$	$\frac{5}{2}^-; \frac{1}{2}$	1.2 MeV	${}^3\text{He}, \alpha$	3, 8, 9, 14, 21
$7.21 \pm 60$	$\frac{5}{2}^-; \frac{1}{2}$	$0.40 \pm 0.05^{\text{a}}$	p, ${}^3\text{He}, \alpha$	3, 6, 8, 9, 14, 17
$9.27 \pm 100$	$\frac{7}{2}^-; \frac{1}{2}$		p, ${}^3\text{He}, \alpha$	3
9.9	$\frac{3}{2}^-; \frac{1}{2}$	$\approx 1.8 \text{ MeV}$	p, ${}^3\text{He}, \alpha$	3, 6
$11.01 \pm 30$	$\frac{3}{2}^-; \frac{3}{2}$	$320 \pm 30 \text{ keV}$	p, ${}^3\text{He}, \alpha$	3, 6, 14, 21
17 <sup>b</sup>	$\frac{1}{2}^-; \frac{1}{2}$	$\approx 6.5 \text{ MeV}$	${}^3\text{He}$	3

<sup>a</sup> Newly adopted in this evaluation or revised from the previous evaluation (1988AJ01).

<sup>b</sup> For possible states at higher  $E_x$  see reactions 3 and 6.

(2001CS03). The reaction rate at  $T = 300 \text{ K}$  was calculated in (1989SC25). See also the related work of (1990SC16, 1990SC26). The reaction rate and the effects of electron screening on the solar neutrino flux has been calculated by (2000LI13). The reaction rate and a correction to the Gamow penetration factor were calculated by (1994KA02). See also the calculations described in (1998FI02, 1999BU10, 1999SH13, 2000BA09). As noted in (1988AJ01), the solar model calculations of (1982BA80) used  $S_{34}[S(0)] = 0.52 \pm 0.02 \text{ keV} \cdot \text{b}$ . It appears clear that the uncertainty in  $S_{34}$  is not of severe consequence to the solar neutrino problem [see, e.g. (1985FI1D)]. For other early astrophysical-related work see (1984AJ01, 1988AJ01). See also (1986LI04).

3. (a)  ${}^4\text{He}({}^3\text{He}, {}^3\text{He}){}^4\text{He}$

$$E_{\text{b}} = 1.5866$$

(b)  ${}^4\text{He}({}^3\text{He}, \text{p}){}^6\text{Li}$

$$Q_{\text{m}} = -4.0193$$

Elastic-scattering studies have been reported for  $E = 0.25$  to  $198.4 \text{ MeV}$  [see (1974AJ01, 1979AJ01, 1984AJ01)] and at  $E_{\alpha} = 56.3$  to  $95.5 \text{ MeV}$  (1985NE08, 1986YA14). Analyzing power



Table 7.8:  ${}^7\text{Be}$  level parameters <sup>a</sup> from  ${}^3\text{He} + {}^4\text{He}$ 

$E_x$ (MeV $\pm$ keV)	$J^\pi$	$l_\alpha$	$LS$ term	$\theta_\alpha^2$ <sup>b</sup>	$\theta_p^2$
$4.57 \pm 50$	$\frac{7}{2}^-$	3	${}^2\text{F}_{7/2}$	$0.70 \pm 0.04$	
$6.73 \pm 100$	$\frac{5}{2}^-$	3	${}^2\text{F}_{5/2}$	$1.36 \pm 0.13$	$0.000 \pm 0.002$
$7.21 \pm 60$	$\frac{5}{2}^-$	3	${}^4\text{P}_{5/2}$	$0.010 \pm 0.001$	$0.26 \pm 0.02$
$9.27 \pm 100$	$\frac{7}{2}^-$	3	${}^4\text{D}_{7/2}$	$0.70 \pm 0.26$	$0.29^{+0.09}_{-0.18}$ <sup>c</sup>
$10.0$ <sup>d</sup>	$\frac{3}{2}^-$	1	$({}^4\text{P}_{3/2})$		
$\approx 10.0$ <sup>e</sup>	$\frac{1}{2}^-$		$({}^4\text{P}_{1/2})$		
$11.00 \pm 50$ <sup>f</sup>	$\frac{3}{2}^-$	1	$({}^2\text{P}_{3/2}, {}^2\text{D}_{3/2})$		$0.13 \pm 0.02$ <sup>g</sup>

<sup>a</sup> See also Table 7.10 (1966LA04). For references see Table 7.7 in (1979AJ01).

<sup>b</sup>  $\gamma_\lambda^2 2\mu R^2 / 3\hbar^2$ .  $R = 4.0$  fm.

<sup>c</sup>  $\theta_{p1}^2 = 1.8 \pm 0.5$ .

<sup>d</sup>  $\Gamma = 1.8$  MeV.

<sup>e</sup> Broad.

<sup>f</sup>  $\Gamma = 0.4 \pm 0.05$  MeV;  $T = \frac{3}{2}$ .

<sup>g</sup>  $\theta_{p2}^2$ .

measurements have been carried out at  $E = 4.3$  to 98 MeV [see (1979AJ01)] and at  $E({}^3\text{He}) = 55$  to 95 MeV (1986YA14).

For  $l \leq 4$ , only f-wave phase shifts show resonance structure for  $E({}^3\text{He}) < 18$  MeV, corresponding to  ${}^7\text{Be}^*(4.57, 6.73, 9.27)$ : see Table 7.8. No structure corresponding to  ${}^7\text{Be}^*(7.21)$  ( $J^\pi = \frac{5}{2}^-$ ) is seen in the elastic data. The s-wave phase shift is somewhat greater than hard-sphere. The decay of  ${}^7\text{Be}^*(9.27)$  ( $J^\pi = \frac{7}{2}^-$ ) to  ${}^6\text{Li}_{\text{g.s.}}$  requires f-shell configuration admixture. An estimate of the yield of ground-state protons relative to those corresponding to  ${}^6\text{Li}^*(2.19)$  yields  $\gamma^2(p_0)/\gamma^2(p_1) = (16^{+5}_{-10})\%$  (1967SP10). A phase-shift analysis (single-level  $R$ -matrix) has been carried out for  $E({}^3\text{He}) = 18$  to 32 MeV: the p-wave phase shifts indicate a  $\frac{1}{2}^-$  state at  $E_x \approx 16.7$  MeV ( $E_r = 26.4$  MeV), with  $\Gamma = 6.5$  MeV (1978LU05). An  $R$ -matrix and  $S$ -matrix analysis (1992ZU03) of elastic scattering at  $E_\alpha(\text{cm}) = 11 - 41$  MeV on a polarized  ${}^3\text{He}$  target gave evidence of broad  $\frac{9}{2}^+$  and  $\frac{11}{2}^-$  resonances. The  $R$ -matrix center-of-mass resonance energies and widths for the  $\frac{9}{2}^+$  and  $\frac{11}{2}^-$  resonances are  $E_{\text{res}} = 29.5 \pm 1.0$  MeV,  $\Gamma = 8.5 \pm 2.5$  MeV and  $E_{\text{res}} = 32.5 \pm 1.5$  MeV,  $\Gamma = 10.5 \pm 3.0$  MeV, respectively (see Table 7.9). See also the earlier analysis reported in (1989OS06). Differential cross sections were measured for  $E({}^3\text{He}) = 1 - 3$  MeV by (1993MO11). The data together with other available data were analyzed, and the optical potentials obtained were used to calculate astrophysical  $S$  factors for the radiative capture reaction (see reaction 1).

The differential cross section for reaction (b) has been determined for  $E({}^3\text{He}) = 8$  to 28 MeV [see (1979AJ01)] and at  $E_\alpha = 22.2$  to 26.5 MeV. Resonances are observed corresponding to

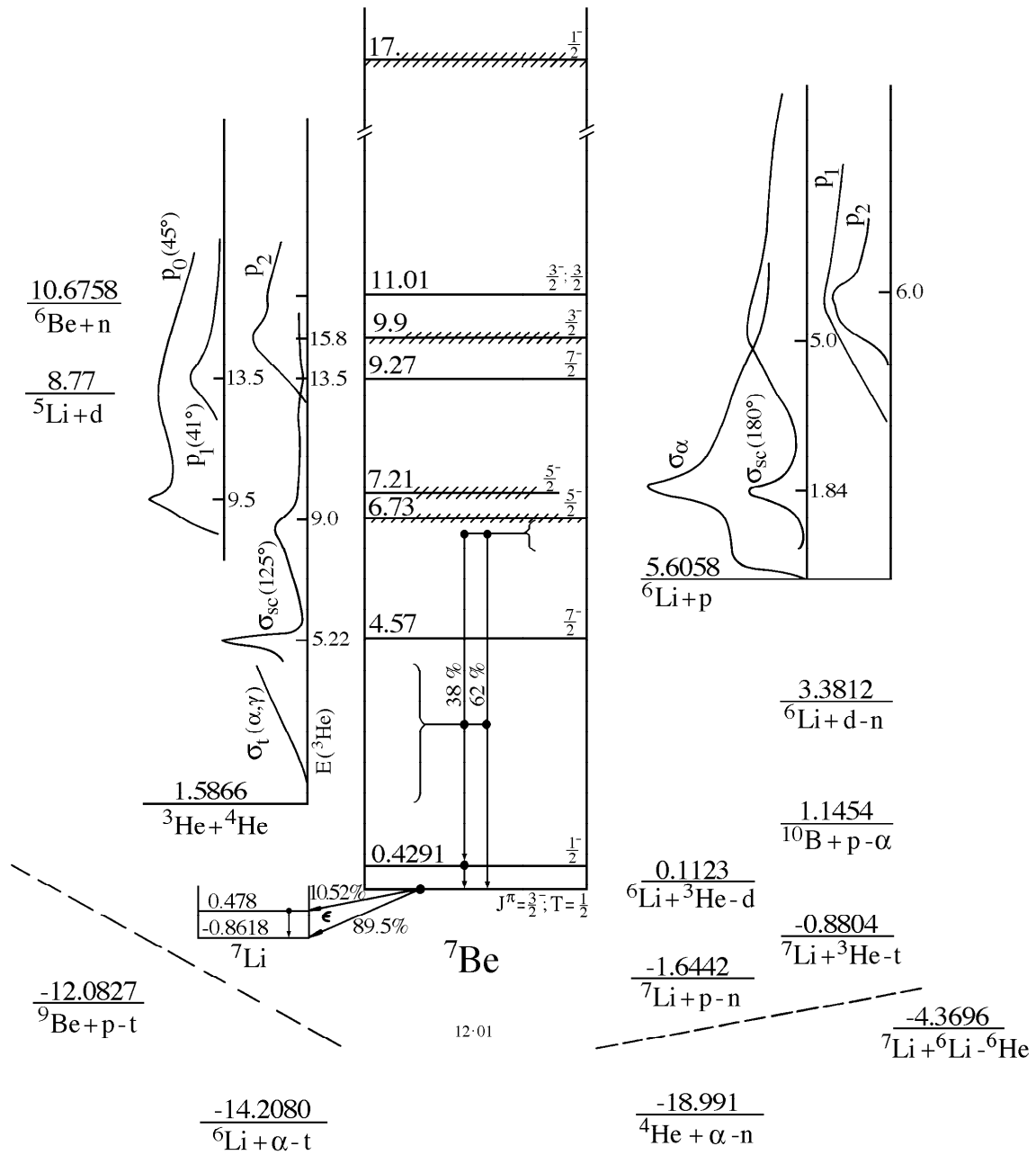


Figure 10: Energy levels of  ${}^7\text{Be}$ . For notation see Fig. 5.

Table 7.9:  ${}^7\text{Be}$  levels from  ${}^3\text{He}(\alpha, \alpha)$  <sup>a</sup> for  $l \geq 4$

$E_{\text{res}}$ (MeV) <sup>b</sup>	$\Gamma$ (MeV)	$E_x$	$J^\pi$
$29.5 \pm 1.0$	$8.5 \pm 2.5$	$31.1 \pm 1.0$	$\frac{9}{2}^+$
$32.5 \pm 1.5$	$10.5 \pm 3.0$	$34.1 \pm 1.5$	$\frac{11}{2}^-$

<sup>a</sup> From  $R$ -matrix analysis (1992ZU03). See also the analysis of (1989OS06).

<sup>b</sup> Center of mass energies.

${}^7\text{Be}^*(7.21, 9.27)$  in the  $p_0$  yield, to  ${}^7\text{Be}^*(9.27)$  in the  $p_1$  yield and to states at  $E_x \approx 10$  MeV ( $T = \frac{1}{2}$ ) and 11.0 MeV ( $T = \frac{3}{2}$ ) in the yield of 3.56 MeV  $\gamma$ -rays. The evidence for the latter derives mainly from interference arguments. There is also some evidence for an extremely broad  $J^\pi = \frac{1}{2}^-$  structure at  $E_x \geq 10$  MeV [see also  ${}^6\text{Li}(p, p)$ : reaction 6]: see Table 7.8 and (1974AJ01, 1984AJ01). For  $\alpha + {}^3\text{He}$  correlations see (1987PO03). See also the General Table for  ${}^7\text{Be}$  located on our website at ([www.tunl.duke.edu/NuclData/General\\_Tables/7be.shtml](http://www.tunl.duke.edu/NuclData/General_Tables/7be.shtml)). For elastic and inelastic inclusive scattering cross sections at  $p_\alpha = 7.0$  GeV/ $c$  see (1984SA39, 1987BA13). See also (1984IW01; astrophys.).

References to early theoretical work on  ${}^3\text{He} + {}^4\text{He}$  reactions are given in (1988AJ01). More recent theoretical studies include: an RGM study of the  $d + {}^5\text{He}$  cluster configuration (1991FU02); a potential description of cluster channels (1993DU02); inversion of phase shifts and  ${}^7\text{Be}$  bound-state energies to obtain potentials (1994CO08); a calculation of  ${}^7\text{Be}$  charge form factors (1987RO24); microscopic cluster theory (1987TA06); Glauber amplitude expansion calculation of  $\sigma(\theta)$  (1988CH16, 1990LI11); a calculation of scattering lengths and astrophysical  $S$  factors (1988CH47, 1989CH34); a study of potentials deduced from phase shifts (1995MA37); and a multiconfiguration RGM calculation of reaction cross sections (1995FU16).

$$4. {}^4\text{He}(\alpha, n){}^7\text{Be} \quad Q_m = -18.9910$$

Angular distributions have been reported at  $E_\alpha = 61.5$  to 158.2 MeV (1982GL01) and 198.4 MeV (1985WO11) for the transitions to  ${}^7\text{Be}^*(0 + 0.43)$ . Cross section measurements at  $E_\alpha = 160, 280, 620$  MeV are reported in (2001ME13). See also (2001AU06). Thermonuclear reaction rates for this reaction calculated from evaluated data are presented in the compilation (1999AN35).

$$5. {}^6\text{Li}(p, \gamma){}^7\text{Be} \quad Q_m = 5.6058$$

At low energies ( $E_p = 0.2$  to 1.2 MeV) gamma transitions to the ground ( $\gamma_0$ ) and to the 0.43 MeV ( $\gamma_1$ ) states have been observed. The yield shows no resonance and the branching ratio

remains approximately constant at  $61 \pm 5\%$  to the ground state and  $39 \pm 2\%$  to  ${}^7\text{Be}^*(0.43)$ : see (1974AJ01, 1984AJ01). Angular distributions of  $\gamma_0$  and  $\gamma_1$  have been studied at  $E_p = 0.50, 0.80$  and  $1.00$  MeV (1987TI05). At  $E_p = 44.4$  MeV,  ${}^7\text{Li}^*(4.57)$  is strongly populated (1985HA05). See also (1983OS04), (1983HA1B, 1984BO1C, 1985CA41; astrophys.) and (1985BL1B).

In other work,  $\gamma$  angular distributions and  $\gamma$ -to-charged-particle ratios were measured for  $E_p = 40\text{--}180$  keV and used to deduce astrophysical  $S$  factors (1992CE02). See also the measurements at  $E_p = 30\text{--}180$  keV of (1993BRZQ). Measurements of thick-target yields and analyzing power versus  $\theta$  were made with  $80$  keV polarized beams and used to deduce relative s-p wave contributions and astrophysical  $S$  factors (1996LA10). The slope of the astrophysical  $S$  factor was deduced from measurements at  $E_p = 80, 95$  and  $110$  keV (1999KEZY). See also the cross section measurements at  $E_p = 0.8$  MeV of (2000SK02). A compilation and review of Coulomb dissociation experiments of astrophysical significance is presented in (1996RE16). Reaction rates for  $E_p < 2$  MeV were analyzed by (1997NO04). The primordial  ${}^6\text{Li}$  component was deduced. A compilation of charged-particle induced thermonuclear reaction rates is presented in (1999AN35). Cross section measurements at  $E_p = 0.8$  MeV are reported by (2000SK02).

6. (a) ${}^6\text{Li}(p, p){}^6\text{Li}$	$E_b = 5.6058$
(b) ${}^6\text{Li}(p, 2p){}^5\text{He}$	$Q_m = -4.497$
(c) ${}^6\text{Li}(p, p\alpha){}^2\text{H}$	$Q_m = -1.4747$

The previous review (1988AJ01) notes that measurements of elastic angular distributions have been reported for  $E_p = 0.5$  to  $600$  MeV: see (1966LA04, 1974AJ01) and  ${}^6\text{Li}$ . Two resonances are reported at  $E_p = 1.84$  and  $5$  MeV in the elastic yield [ ${}^7\text{Be}^*(7.21, 9.9)$ ]. The parameters of the lower resonance are shown in Table 7.4. The  $5$ -MeV resonance has  $\Gamma \approx 1.8$  MeV and appears to also be formed by p-waves:  $\gamma_p^2$  is then  $3 \pm 2$  MeV fm. A weak rise near  $E_p = 8$  to  $9$  MeV may indicate a further level,  ${}^7\text{Be}^* \approx 13$  MeV. A broad resonance at  $E_p = 14$  MeV has also been suggested. Polarization measurements have been carried out for  $E_p = 1.2$  to  $800$  MeV [see (1974AJ01, 1979AJ01, 1984AJ01)] and at  $E_p = 4$  to  $10$  MeV (1986BE1H;  $p_0$ ) and  $25$  and  $35$  MeV (1982ROZT, 1983PO1B, 1983POZX;  $p_0, p_1$ ). A phase-shift analysis for  $E_p = 0.5$  to  $5.6$  MeV shows that only  ${}^2\text{S}$ ,  ${}^4\text{S}$  and  ${}^4\text{P}$  are involved. The  ${}^4\text{P}_{5/2}$  amplitude resonates at  $E_p = 1.8$  MeV, and the broad resonance at  $5$  MeV can be reproduced equally well by either  ${}^4\text{P}_{3/2}$  or  ${}^4\text{P}_{1/2}$ : tensor polarization measurements are necessary to distinguish between the two: see (1974AJ01).

In more recent work, cross sections and analyzing powers were measured at  $E_p = 1.6\text{--}10$  MeV (1989HA17), at  $E_p = 200$  MeV (1990GL04) and at  $E_p = 0.4\text{--}2.2$  MeV (1995SK01). Parameters for the  $E_p(\text{lab}) = 1.8$  MeV resonance were measured by (1995SK01) (see Table 7.10). The depolarization parameter was measured at  $E_p = 72$  MeV (1994HE11).

The reaction cross section for formation of  ${}^6\text{Li}^*(2.19)$  has been measured for  $E_p = 3.6$  to  $9.40$  MeV: a broad resonance indicates the presence of a state with  $E_x \approx 10$  MeV,  $\Gamma = 1.8$  MeV,  $J^\pi = (\frac{3}{2}, \frac{5}{2})^-$ ,  $T = \frac{1}{2}$ . The cross-section and angular distributions of  $p_2$  ( ${}^6\text{Li}^*(3.56)$ ) for  $E_p = 4.26$  to  $9.40$  MeV are analyzed in terms of two  $J^\pi = \frac{3}{2}^-$  states at  $E_x \approx 10$  and

Table 7.10:  ${}^7\text{Be}$  level parameters from  ${}^6\text{Li} + \text{p}$  phase shift analysis <sup>a, b</sup>

Phase Shift	$E_{\text{res}}^c$ (MeV)	$E_x$ (MeV)	$\Gamma_p$ (MeV)	$\Gamma$ (MeV)
${}^4\text{P}_{5/2}^a$	$1.56 \pm 0.1$	$7.2 \pm 0.1$	$0.19 \pm 0.05$	$0.40 \pm 0.05$
${}^2\text{P}_{1/2}^b$	$3.68 \pm 0.31$	$9.29 \pm 0.31$	$0.47 \pm 0.33$	$1.93 \pm 0.96$
${}^4\text{P}_{1/2}^b$	$4.20 \pm 0.12$	$9.81 \pm 0.12$	$1.65 \pm 0.25$	$2.21 \pm 0.29$
${}^4\text{P}_{5/2}^b$	$4.39 \pm 0.17$	$10.00 \pm 0.17$	$0.42 \pm 0.14$	$1.68 \pm 0.58$
${}^4\text{P}_{3/2}^b$	$6.76 \pm 1.27$	$12.37 \pm 1.27$	$1.81 \pm 1.03$	$4.95 \pm 3.23$

<sup>a</sup> From Table 1 of (1995SK01).

<sup>b</sup> From Table 2 of (1989HA18).

<sup>c</sup> Center of mass energies.

11 MeV: see reaction 3. The total cross section for formation of  ${}^6\text{Li}^*(3.56)$  decreases slowly with energy for  $E_p = 24.3$  to 46.4 MeV. The total reaction cross section has been measured for  $E_p = 25.0$  to 48 MeV (1985CA36).  $K_y^y$  spectra at  $E_p = 50, 65$  and 80 MeV,  $\theta = 3^\circ\text{--}20^\circ$ , are reported by (1987SA46). For the inclusive cross section at  $E_p = 200$  MeV [back angles] see (1984AV07). See also the measurement of cross sections and analyzing powers for excitation of  ${}^6\text{Li}^*(2.18, 3.56)$  at  $E_p = 200$  MeV (1990GL04). Theoretical work on this reaction published since the previous review (1988AJ01) includes: a folding-model calculation to deduce halo effects (1992GA27); self-consistent calculation with matter-cluster dynamic model (1992KA06); a potential description study with a supermultiplet symmetry approximation (1993DU09); a description with a microscopic effective interaction (1993KO44); a consistent folding-model description (1993PE13); a calculation for (p, p) and (p, p') with Glauber-Sitenko diffraction theory (1994ZH28, 1994ZH34); an analysis with phenomenological microscopic optical potentials (1995GA24); a consistent analysis of the analyzing power puzzle (1995KA03); a continuum-continuum coupling analysis (1995KA07); a fully-microscopic analysis at  $E_p = 200$  MeV (1997DO01); an RGM study of a  $\frac{5}{2}^-$  resonance (1997IG04); a study of shell-model structures observed in proton and electron scattering (1997KA24); and a microscopic-model analysis for  $E_p = 65$  MeV (1998DO16).

For reaction (b) see  ${}^5\text{He}$  and  ${}^6\text{Li}$ . For reaction (c) see  ${}^6\text{Li}$ , and references cited in (1988AJ01).

7.  ${}^6\text{Li}(\text{p}, \text{n}){}^6\text{Be}$

$$Q_m = -5.0700$$

$$E_b = 5.6058$$

The yield of neutrons increases approximately monotonically from threshold to  $E_p = 14.3$  MeV: see (1974AJ01). The transverse polarization transfer,  $D_{\text{NN}}(0^\circ)$ , for the g.s. transition has been measured for  $E_p = 30$  to 160 MeV: see (1984TA07, 1986TA1E) and  ${}^6\text{Be}$ . Analyzing-power measurements are reported at  $E_p = 50$  and 80 MeV (1987SA46) and at 52.8 MeV (1988HE08) [ $K_y^{y'}$  ( $0^\circ$ ) =  $-0.33 \pm 0.04$ ; also  $K_z^{z'}$ ]. See also (1986MC09;  $E_p = 800$  MeV) and (1984BA1U, 1986RA21, 1986SA1Q). For more recent work see the discussion on this reaction under  ${}^6\text{Be}$ .

8.  ${}^6\text{Li}(p, \alpha){}^3\text{He}$ 

$$Q_m = 4.0193$$

$$E_b = 5.6058$$

Thermonuclear reaction rates and the astrophysical  $S$ -factor have been derived from the low-energy ( $E_p < 0.7$  MeV) cross section measurements:  $S(0) \approx 3.1$  MeV b: see (1974AJ01, 1979AJ01, 1984AJ01). At higher energies the cross section exhibits a broad, low maximum near  $E_p = 1$  MeV and a pronounced resonance at  $E_p = 1.85$  MeV ( $\Gamma < 0.5$  MeV). No other structure is reported up to  $E_p = 5.6$  MeV. Measurements between  $E_p = 0.4$  and 3.4 MeV show that the polarizations are generally large and positive: see (1974AJ01).

Angular distributions have been reported for  $E_p = 0.15$  to 45 MeV [see (1974AJ01, 1979AJ01, 1984AJ01)] and at 47.8, 53.5, 58.5 and 62.5 MeV (1984NE05). For other early work see references cited in (1988AJ01). More recently, measurements of analyzing power versus  $E_p$  for  $E_p = 180$ –280 keV were reported by (1991BU14). Tests of isotopic dependence of electron-screening effects on the astrophysical  $S$  factor were reported for  $E_{\text{cm}} = 10$ –1004 keV (1992EN01, 1992EN04). See also: an analysis of  $S$ -factor data for  $E_{\text{cm}} = 10$ –1000 keV (1992SO25); a study of atomic screening and other small effects in reaction rates (1997BA95); a study of screening effects for solid targets (1997BO12); an optical-model formulation and  $S$  factor calculation for  $E = 10$ –100 keV (1997KI02); a study of reaction rates and the primordial  ${}^6\text{Li}$  component (1997NO04); and a study of  $R$ -matrix parameterization for  $E_{\text{cm}} < 1$  MeV (1998AN18). Thermonuclear reaction rates for this reaction calculated from evaluated data are presented in the compilation (1999AN35).

9.  ${}^6\text{Li}(d, n){}^7\text{Be}$ 

$$Q_m = 3.3812$$

Angular distributions of the  $n_0$  and  $n_1$  groups have been measured at  $E_d = 0.20$  to 15.25 MeV: see (1974AJ01, 1979AJ01). The  $n_1$ - $\gamma$  correlations are isotropic, indicating  $J^\pi = \frac{1}{2}^-$  for  ${}^7\text{Be}^*(0.43)$ . Broad maxima are observed in the ratio of low-energy to high-energy neutrons at  $E_d = 4.2$  and 5.1 MeV [ ${}^7\text{Be}^*(6.5, 7.2)$ ,  $\Gamma_{\text{cm}} = 1.2$  and 0.5 MeV, respectively]: see (1966LA04). See also  ${}^8\text{Be}$  in (1988AJ01) and (1988KO1C).

Measurements at  $E < 1$  MeV and determination of the astrophysical  $S$ -factor as well as studies of the (d, n)/(d, p) ratio are described in (1993CZ01, 1997CZ04). Cross section measurements and  $S$ -factor determinations at  $E_d = 24$ –111 keV are reported in (2001HO23). A calculation of the (d, n)/(d, p) branching ratio and discussions of the rate of Coulomb-induced predissociation is presented in (1990KO26). Cross sections for  $E < 1$  MeV were calculated and reaction rates were deduced by (2001VO02). Calculations of radiated power vs. plasma temperature in controlled fusion are described in (1999HA50). See also (1996BO27, 1997NO04).

10.  ${}^6\text{Li}({}^3\text{He}, d){}^7\text{Be}$ 

$$Q_m = 0.1123$$

Angular distributions of the  $d_0$  and  $d_1$  groups to  ${}^7\text{Be}^*(0, 0.43)$  have been measured at  $E({}^3\text{He}) = 8, 10, 14$  and 18 MeV and at  $E({}^3\text{He}) = 33.3$  MeV [ ${}^7\text{Be}^*(4.57)$  is also populated]: see (1974AJ01, 1984AJ01).

11.  ${}^6\text{Li}({}^6\text{Li}, {}^5\text{He}){}^7\text{Be}$   $Q_m = 1.1091$

See (1987MI34) and  ${}^5\text{He}$ .

12.  ${}^6\text{Li}({}^7\text{Li}, {}^7\text{Be}){}^6\text{He}$   $Q_m = -4.3696$

The reaction was used by (1998NA14) to separate  $\Delta S = 0$  and  $\Delta S = 1$  transitions through coincidence measurements of  $\gamma$ -rays from the  ${}^7\text{Be}$  0.43 MeV state.

13.  ${}^7\text{Li}(\pi^+, \pi^0){}^7\text{Be}$   $Q_m = 3.7318$

Forward-angle differential cross sections have been measured at  $E_{\pi^+} = 20$  MeV (1987IR01; also at  $155^\circ$  and  $166^\circ$ ), at 33.5, 41.1, 48.7 and 58.8 MeV (1985IR01, 1985IR02), 70 to 180 MeV [see (1984AJ01)] and from 300 to 550 MeV (1988RO03).

A Glauber-model analysis of  $\sigma(\theta)$  for  $E = 250$ – $650$  MeV is described in (1990OS01). Model calculations of cross sections and polarization observables are presented in (1999NO02).

14.  ${}^7\text{Li}(p, n){}^7\text{Be}$   $Q_m = -1.6442$   
 $E_{\text{thresh.}} = 1880.443 \pm 0.020$  keV (1985WH1A)

The excitation energy of  ${}^7\text{Be}^*(0.43)$  is  $429.20 \pm 0.10$  keV,  $\tau_m = 192 \pm 25$  fsec: see (1979AJ01). Angular distributions of  $n_0$  and  $n_1$  have been reported at  $E_p = 1.9$  to 119.8 MeV [see (1974AJ01, 1979AJ01, 1984AJ01)] and at 200, 300 and 400 MeV (1987WAZT;  $n_{0+1}$ ).  ${}^7\text{Be}^*(4.55, 6.51, 7.19, 10.79)$  have also been populated: see (1974AJ01, 1979AJ01). The ratios of  $\sigma_1/\sigma_0$  ( ${}^7\text{Be}^*(0.43)/{}^7\text{Be}_{g.s.}$ ) have been measured at 24.8, 35 and 45 MeV and yield the ratio of spin-flip to non spin-flip strength  $|V_{0\tau}/V_\tau|^2$  (1980AU02).

Cross section measurements related to neutron production targets and detector efficiency calibration include (1987TE04, 1988HE08, 1989AM03, 1989BY02, 1989GU13, 1990BR24, 1990DR10, 1990TA11, 1992AM03, 1992DA20, 1997TA03, 1998KA20, 1998MA49, 1999BA73, 1999NA02, 1999NA15). Measurements or analyses of Gamow-Teller transition strength are reported in (1987TA13, 1989RA09, 1990RA08, 1994SA43). See also (1987HE22, 1987OR02). An analysis of neutron spectra for  $E_p = 120, 160$  MeV and deduction of Gamow-Teller matrix elements are described in (2001GO25). A compilation of analyzing-power data is presented in (1987TA22). For studies of quadrupole excitation see (1994RA23, 1994WA22) and (1995YA12). Application-related measurements are described in (1987RA23, 1988BO33, 1989CR05, 1995RI14, 1996BB13, 1996SH29, 1996TA23, 1997DE54, 1997UW01, 1997ZH35, 1999LE16, 1999NA02, 1999SA16, 1999SH16). See also the astrophysical-related analysis in (1989BU10). See also the analysis

(1998IO03) of 647 and 800 MeV data, and the study of the isovector part of optical potentials for 35 MeV (p, n) data (1998JOZW, 2000JO17). For earlier work see (1988AJ01).

$$\begin{aligned} 15. \text{ (a) } {}^7\text{Li}(\text{d}, 2\text{n}){}^7\text{Be} & \quad Q_{\text{m}} = -3.8687 \\ \text{ (b) } {}^7\text{Li}(\text{t}, 3\text{n}){}^7\text{Be} & \quad Q_{\text{m}} = -10.1260 \end{aligned}$$

See (1987AL10;  $E({}^7\text{Li}) = 65$  MeV).

$$16. {}^7\text{Li}({}^3\text{He}, \text{t}){}^7\text{Be} \quad Q_{\text{m}} = -0.8804$$

Angular distributions of  $t_0$  and  $t_1$  have been measured at  $E({}^3\text{He}) = 3.0$  to  $4.0$  MeV and at  $E({}^3\text{He}) = 33.3$  MeV: see (1974AJ01, 1984AJ01). The width of  ${}^7\text{Be}^*(4.57)$ ,  $\Gamma_{\text{cm}} = 175 \pm 7$  keV: see (1974AJ01). See also  ${}^{10}\text{B}$  in (1988AJ01).

$$17. {}^7\text{Li}({}^6\text{Li}, {}^6\text{He}){}^7\text{Be} \quad Q_{\text{m}} = -4.3696$$

This reaction has been studied at  $E({}^6\text{Li}) = 14, 25$  and  $35$  MeV/A.  ${}^7\text{Be}^*(0, 0.43)$  are strongly populated and  ${}^7\text{Be}^*(4.57, 7.21)$  are also evident. At the highest energy the reaction mechanism is predominantly one-step (1986AN29, 1987WI09). See also  ${}^6\text{He}$  and references cited in (1988AJ01). See also reaction 12.

$$18. {}^7\text{Li}({}^7\text{Li}, {}^7\text{Be}){}^7\text{He} \quad Q_{\text{m}} = -12.0641$$

See (1998NA14).

$$19. {}^8\text{Be}(\gamma, \text{n}){}^7\text{Be} \quad Q_{\text{m}} = -18.8991$$

Neutron yields have been measured with backscattered laser photons (1999TOZZ).

$$20. {}^9\text{Be}(\text{n}, 3\text{n}){}^7\text{Be} \quad Q_{\text{m}} = -20.5645$$

Cross sections were measured at  $E_{\text{n}} = 28$ – $68$  MeV (1998DU06).



21.  ${}^9\text{Be}(p, t){}^7\text{Be}$   $Q_m = -12.0827$

Angular distributions of tritons have been measured at  $E_p = 43.7$  and  $46$  MeV [see (1979AJ01)] and at  $50$  and  $72$  MeV (1984ZA07;  $t_{0+1}, t_2$ ). The  $11$ -MeV state has  $E_x = 11.01 \pm 0.04$  MeV,  $\Gamma = 298 \pm 25$  keV,  $J^\pi = \frac{3}{2}^-$ ;  $T = \frac{3}{2}$  [the  $J^\pi$ ;  $T$  assignments are based on the similarity of the angular distribution to that in the  $(p, {}^3\text{He})$  reaction to  ${}^7\text{Li}^*(11.13)$ ]: see (1979AJ01).

22.  ${}^{10}\text{B}(p, \alpha){}^7\text{Be}$   $Q_m = 1.1454$

Angular distributions have been studied for  $E_p = 2.8$  to  $7.0$  MeV [see (1974AJ01)] and for  $18$  to  $45$  MeV (1986HA27;  $\alpha_0, \alpha_1, \alpha_2$ ; see for spectroscopic factors).  $E_x$  of  ${}^7\text{Be}^*(0.43) = 428.89 \pm 0.13$  keV (1979RI12). See also  ${}^{11}\text{C}$  in (1985AJ01), (1983DO07) and (1988KOZL; applied).

More recently several studies at astrophysical energies have been reported. They include measurements of  $\sigma(\theta)$  and  $\sigma(E)$  at  $E_p = 120$ – $480$  keV (1991YO04) and at  $E_p = 37$ – $120$  keV (1993KNZZ); measurements of electron screening corrections at  $E_{\text{cm}} = 17$ – $134$  keV and determination of  $S(E)$  (1993AN06); direct-model calculations of astrophysical reaction rates (1996RA14); and a calculation of small-effect corrections in fusion reactions (1997BA95). A calculation of  ${}^7\text{Be}$  level population intensities at  $E_p = 45$  MeV is described in (1992KW01). For application-related measurements see (1990BO15, 1995RI14, 1995SJ01, 1999SA16).

23.  ${}^{10}\text{B}(d, {}^5\text{He}){}^7\text{Be}$   $Q_m = -1.8770$

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

24.  ${}^{10}\text{B}(\alpha, {}^7\text{Li}){}^7\text{Be}$   $Q_m = -16.2015$

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

25.  ${}^{11}\text{B}({}^3\text{He}, {}^7\text{Li}){}^7\text{Be}$   $Q_m = -7.0780$

Spectroscopic amplitudes calculated with an intermediate-coupling model are reported in (1987KW03). See also the discussion under  ${}^7\text{Li}$ .

26.  ${}^{12}\text{C}(p, {}^6\text{Li}){}^7\text{Be}$   $Q_m = -22.5668$

Yields of fragments, observed in protons at  $E_p = 1$  GeV incident on  $^{12}\text{C}$ , were measured by (2000ANZX). A calculation of spectroscopic amplitudes in an intermediate coupling model analysis is reported in (1987KW03). See also the discussion under  $^6\text{Li}$ .

$$27. \ ^{12}\text{C}(\text{d}, \ ^7\text{Li})^7\text{Be} \quad Q_m = -17.5415$$

Differential cross sections were measured at  $E_d = 78$  MeV in a study of 5-nucleon simultaneous transfer (1996JA12). Spectroscopic amplitudes were calculated in an intermediate coupling model by (1987KW03). See (1995CH69) for a measurement of  $^{12}\text{C}(\text{d}, \ ^7\text{Be})^7\text{Li}$ , and see  $^7\text{Li}$  in this review.

$$28. \ ^{12}\text{C}(^3\text{He}, \ ^8\text{Be})^7\text{Be} \quad Q_m = -5.7780$$

Angular distributions involving  $^7\text{Be}^*(0, 0.43)$  have been reported at  $E(^3\text{He}) = 25.5$  to  $70$  MeV [see (1979AJ01, 1984AJ01)] and at  $E(^3\text{He}) = 33.4$  MeV (1986CL1B; also  $A_y$ ). See also (1986RA15) and see discussions of  $^{12}\text{C}(^3\text{He}, \ ^7\text{Be})^8\text{Be}$  [reaction 44] under  $^8\text{Be}$  in (1988AJ01).

$$29. \ ^{12}\text{C}(\alpha, \ ^9\text{Be})^7\text{Be} \quad Q_m = -24.6922$$

At  $E_\alpha = 42$  MeV, angular distributions have been measured involving  $^7\text{Be}^*(0, 0.43)$  and  $^9\text{Be}_{g.s.}$ : see (1974AJ01). Angular distributions have also been measured at  $E_\alpha = 49.0$  and  $80.1$  MeV (1984GO03). An angular distribution and DWBA analysis for  $^{12}\text{C}(\alpha, \ ^7\text{Be})^9\text{Be}$  is reported in (1991GL03).

$$30. \ ^{12}\text{C}(^7\text{Li}, \ ^{12}\text{B})^7\text{Be} \quad Q_m = -14.2307$$

See (1984BA53, 1998NA14, 1998NA16).

$$31. \ ^{14}\text{N}(\text{p}, \ ^7\text{Be})\text{X}$$

Cross sections for  $^7\text{Be}$  produced by protons and neutrons at  $E = 10$ – $10,000$  MeV were analyzed (2000NA34) and atmospheric production rates were deduced.

$$32. \ ^{16}\text{O}(\gamma, \ ^7\text{Be})\text{X}$$

${}^7\text{Be}$  yields were measured with 250–1050 MeV bremsstrahlung photons on O, Al, Cr, Cl, CO targets (1998SH18).

33.  ${}^{16}\text{O}({}^3\text{He}, {}^{12}\text{C}){}^7\text{Be}$   $Q_m = -5.5753$

Angular distributions have been reported at  $E({}^3\text{He}) = 25.5$  to 70 MeV to  ${}^7\text{Be}^*(0, 0.43)$  and to various states of  ${}^{12}\text{C}$ : see  ${}^{12}\text{C}$  in (1985AJ01). See also (1986BA89). A measurement of  $\sigma(\theta)$  for  ${}^{16}\text{O}({}^3\text{He}, {}^7\text{Be}){}^{12}\text{C}$  at  $E({}^3\text{He}) = 41$  MeV is reported in (1987RA37). See also the calculation for  $E({}^3\text{He}) = 60$  MeV in (1995MA57).

34.  ${}^{16}\text{O}({}^7\text{Li}, {}^{16}\text{N}){}^7\text{Be}$   $Q_m = -11.2822$

Angular distributions have been studied at  $E({}^7\text{Li}) = 50$  MeV involving  ${}^7\text{Be}^*(0, 0.43)$  and various states of  ${}^{16}\text{N}$  (1984CO20, 1986CL03). See also  ${}^{16}\text{N}$  in (1986AJ04) and (1984BA53). A compilation and analysis of data for  $E({}^7\text{Li}) = 78$  MeV is presented in (1989GA26).

35.  ${}^{27}\text{Al}(\gamma, {}^7\text{Be})\text{X}$

Target dependence of  ${}^7\text{Be}$  production by bremsstrahlung photons ( $E_\gamma < 1200$  MeV) incident on  ${}^{27}\text{Al}$  and several other targets were studied by (2000MA75). See also (1998SH18).

36.  ${}^{24}\text{Mg}({}^3\text{He}, {}^{20}\text{Ne}){}^7\text{Be}$   $Q_m = -7.7297$

See the calculations reported in (1986RA15). Measurements of  $\sigma(\theta)$  for  ${}^{24}\text{Mg}({}^3\text{He}, {}^7\text{Be})$  at  $E({}^3\text{He}) = 41$  MeV are reported in (1987RA37). Spectroscopic factors were deduced (1988RA20).

37.  ${}^{58}\text{Ni}({}^8\text{B}, \text{p}){}^7\text{Be}\text{X}$

Cross sections have been calculated for  $E({}^8\text{B}) = 25.8, 415$  MeV (1999SH20).

38.  ${}^{124}\text{Sn}(\text{p}, {}^7\text{Be})\text{X}$

Production cross sections for  ${}^7\text{Be}$  for protons with  $E_p = 0.66, 1.0$  and  $8.1$  GeV incident on separated tin isotopes  ${}^{112}\text{Sn}$ ,  ${}^{118}\text{Sn}$ ,  ${}^{120}\text{Sn}$  and  ${}^{124}\text{Sn}$  were measured by an activation technique (1998DAZI).

39.  ${}^{\text{nat}}\text{Pb}(p, {}^7\text{Be})X$

Production cross sections were measured for  $E_p = 65\text{--}2600$  MeV (2001GL05).

40.  ${}^{208}\text{Pb}({}^8\text{B}, p{}^7\text{Be})X$

Dissociation of  ${}^8\text{B}$  in the Coulomb field of  ${}^{208}\text{Pb}$  was measured at  $E({}^8\text{B}) = 51.9$  MeV/A. Cross sections for  ${}^7\text{Be}(p, \gamma){}^8\text{B}$  were extracted (1998KI19).

41.  ${}^{232}\text{Th}(\gamma, {}^7\text{Be})X$

Yields of  ${}^7\text{Be}$  from photon-induced  ${}^{232}\text{Th}$  fission were measured by (1998KAZL).

### ${}^7\text{B}$

(Fig. 11)

The mass excess of  ${}^7\text{B}$  adopted by (1997AU04) is  $27.870 \pm 0.070$  MeV. It was obtained by averaging the values of  $27.94 \pm 0.10$  MeV from the  ${}^{10}\text{B}({}^3\text{He}, {}^6\text{He}){}^7\text{B}$  reaction (1967MC14, 1988AJ01) and the value  $27.800 \pm 0.10$  MeV obtained in the  ${}^7\text{Li}(\pi^+, \pi^-){}^7\text{B}$  reaction (1981SEZR). The width of the ground state is  $\Gamma = 1.4 \pm 0.2$  MeV: see (1967MC14, 1988AJ01).  ${}^7\text{B}$  is unbound with respect to  ${}^6\text{Be} + p$ ,  ${}^5\text{Li} + 2p$  and  ${}^4\text{He} + 3p$  by 2.21, 1.61 and 3.38 MeV, respectively.

The predicted mass excess for  ${}^7\text{B}$  based on the isobaric multiplet mass equation using the  $T = \frac{3}{2}$  level energies in  ${}^7\text{He}$ ,  ${}^7\text{Li}$  and  ${}^7\text{Be}$  is  $27.76 \pm 0.17$  MeV (1967MC14). See also the early references cited in (1988AJ01, 1984AJ01, 1979AJ01, 1974AJ01). Recent cross section measurements for  ${}^7\text{Li}(\pi^+, \pi^-){}^7\text{B}$  (1998PA40) were used to deduce information on  ${}^7\text{B}$  proton halo features. Measurements at  $E_\pi = 30\text{--}90$  MeV reported by (2000DR19) were used to deduce energy-dependent features. Theoretical studies relevant to  ${}^7\text{B}$  include work on the spherical properties of nuclei (1995JA06, 1997AB27); Skyrme Hartree-Fock model calculations (1997BA54); Coulomb-energy studies (1997PO12); and large-basis shell-model calculations of level energies and other properties (1998NA17).

Table 7.11: Mirror states in  $A = 7$  nuclei <sup>a</sup>

<sup>7</sup> Li		<sup>7</sup> Be		$\Delta E_x$ (MeV) <sup>b</sup>
$E_x$ (MeV)	$J^\pi$	$E_x$ (MeV)	$J^\pi$	
0	$\frac{3}{2}^-$	0	$\frac{3}{2}^-$	—
0.478	$\frac{1}{2}^-$	0.429	$\frac{1}{2}^-$	-0.049
4.65	$\frac{7}{2}^-$	4.57	$\frac{7}{2}^-$	-0.08
6.60	$\frac{5}{2}^-$	6.73	$\frac{5}{2}^-$	+0.13
7.45	$\frac{5}{2}^-$	7.21	$\frac{5}{2}^-$	-0.24
8.75	$\frac{3}{2}^-$	9.9	$\frac{3}{2}^-$	+1.15 <sup>c</sup>
9.09	$\frac{1}{2}^-$			
9.57	$\frac{7}{2}^-$	9.27	$\frac{7}{2}^-$	-0.3

<sup>a</sup> As taken from Tables 7.2 and 7.7.

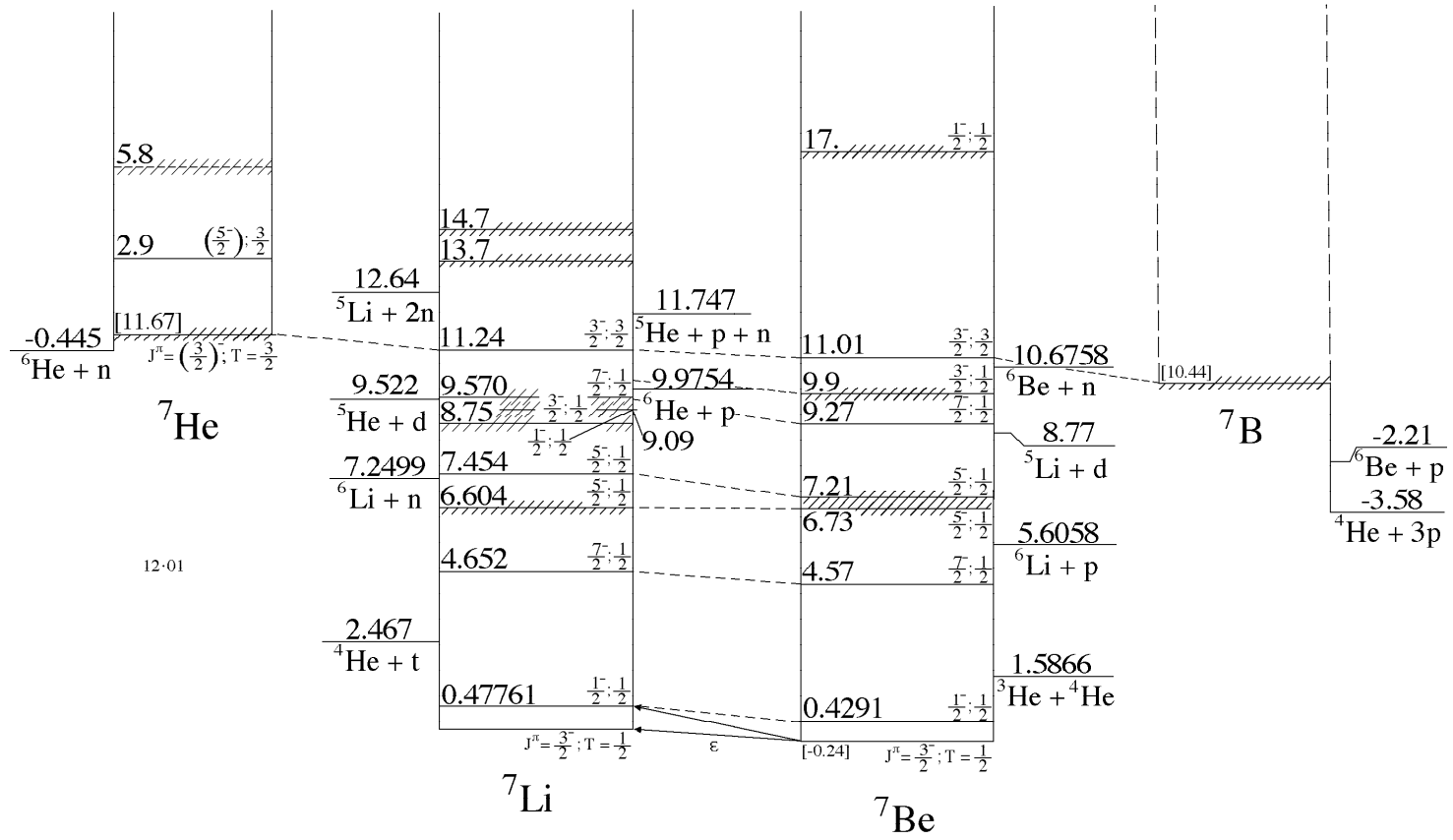
<sup>b</sup> Defined as  $E_x(^7\text{Be}) - E_x(^7\text{Li})$ .

<sup>c</sup> This difference may be unphysical since the <sup>7</sup>Li level parameters were obtained from the “extended  $R$ -matrix prescription” (see the Introduction in this publication). The equivalent information for <sup>7</sup>Be levels is not available.

Table 7.12: Isospin quadruplet components ( $T = \frac{3}{2}$ ) in  $A = 7$  <sup>a</sup>

<sup>7</sup> He		<sup>7</sup> Li		<sup>7</sup> Be		<sup>7</sup> B
$E_x$ (MeV)	$J^\pi$	$E_x$ (MeV)	$J^\pi; T$	$E_x$ (MeV)	$J^\pi; T$	$E_x$ (MeV)
0	$(\frac{3}{2}^-)$	11.24	$\frac{3}{2}^-; \frac{3}{2}$	11.01	$\frac{3}{2}^-; \frac{3}{2}$	
2.9	$(\frac{5}{2}^-)$					

<sup>a</sup> As taken from Tables 7.1, 7.2 and 7.7.

Figure 11: Isobar diagram,  $A = 7$ . For notation see Fig. 3.

## References

(Closed 23 August 2001)

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

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