Energy Levels of Light Nuclei

$A = 6$

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Abstract: An evaluation of $A = 5–7$ was published in Nuclear Physics A708 (2002), p. 3. This version of $A = 6$ 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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F. Erratum to this Publication: PS or PDF
A = 6

GENERAL: References to articles on general properties of \(A = 6\) 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 \(A = 6\) located on our website at (www.tunl.duke.edu/NuclData/General_Tables/06.shtml).

\(^6\text{n}\)

(Not illustrated)

\(^6\text{n}\) has not been observed. See (1979AJ01, 1988AJ01) and references cited there. More recently (1990AL40) reports a search for \(^6\text{n}\) in a \(^{14}\text{C}(^{7}\text{Li}, ^{6}\text{n})\) activation experiment at \(E(^{7}\text{Li}) = 82\) MeV. No evidence for \(^6\text{n}\) was obtained.

The method of angular potential functions was used by (1989GO18) in a calculation of the properties of multi-neutron systems which indicated that these systems have no bound states. The ground state energy of a six-neutron drop has been computed with variational and Green’s function Monte Carlo methods (1997SM07).

\(^6\text{H}\)

(Fig. 7)

\(^6\text{H}\) was reported in the \(^7\text{Li}(^{7}\text{Li}, ^{8}\text{B})^6\text{H}\) reaction at \(E(^{7}\text{Li}) = 82\) MeV (1984AL08, 1985AL1G) \([\sigma(\theta) \approx 60\ \text{nb/sr at } \theta = 10^{\circ}]\) and in the \(^9\text{Be}(^{11}\text{B}, ^{14}\text{O})^6\text{H}\) reaction at \(E(^{11}\text{B}) = 88\) MeV (1986BE35) \([\sigma(\theta) \approx 16\ \text{nb/sr at } \theta \approx 8^{\circ}]\). \(^6\text{H}\) is unstable with respect to breakup into \(^3\text{H} + 3\text{n}\) by \(2.7 \pm 0.4\) MeV, \(\Gamma = 1.8 \pm 0.5\) MeV (1984AL08), \(2.6 \pm 0.5\) MeV, \(\Gamma = 1.3 \pm 0.5\) MeV (1986BE35). The value adopted in the previous review (1988AJ01) is \(2.7 \pm 0.3\) MeV, \(\Gamma = 1.6 \pm 0.4\) MeV. See also (1987BO40). The atomic mass excess of \(^6\text{H}\) using the (1995AU04) masses for \(^3\text{H}\) and \(\text{n}\), is then \(41.9 \pm 0.3\) MeV. There is no evidence for the formation of \(^6\text{H}\) in the \(^6\text{Li}(\pi^-, \pi^+)\) reaction at \(E_{\pi^-} = 220\) MeV as reported in (1990PA25). (1991SE06) shows that the continuum missing mass spectra can be explained in terms of the presence of dineutrons in the breakup products. An analysis of the proton spectra for the \(^7\text{Li}(\pi^-, p)\) reaction (1990AM04) showed no evidence for \(^6\text{H}\).

The ground state of \(^6\text{H}\) is calculated to have \(J^\pi = 2^-\). Excited states are predicted at 1.78, 2.80 and 4.79 MeV with \(J^\pi = 1^-, 0^-\) and \(1^+\) \([\{(0 + 1)\hbar\omega \text{ model space}\}]\) (1985PO10) [see also for \((0 + 2)\hbar\omega \text{ calculations}\)]. See also the additional references cited in (1988AJ01).
GENERAL: References to articles on general properties of \(^{6}\)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 \(^{6}\)He located on our website at (www.tunl.duke.edu/NuclData/General_Tables/6he.shtml).

Ground State Properties:

The interaction radius of \(^{6}\)He, obtained from measurements of the total interaction cross section, is 2.18 ± 0.02 fm (1985TA13, 1985TA18). These authors have also derived nuclear matter, charge and neutron r.m.s. radii.

\(^{6}\)He is considered to be a neutron-halo nucleus because its interaction radius, which is deduced from the total interaction cross section in (1985TA13, 1985TA18), is appreciably larger than that of \(^{6}\)Li. A Glauber calculation using proton and neutron densities from an alpha-core valence-neutron model leads to the conclusion that the matter radius is much larger than the charge radius, as predicted by theoretical models of the \(^{6}\)He ground-state wave function. These theoretical models include three-body models (1993ZH1J, 1995HI15), cluster-orbital shell models (1991SU03, 1994FU04), no-core microscopic shell models (1996NA24), and microscopic cluster models for various effective nucleon-nucleon interactions (1993CS04, 1997WU01). See also (1992TA18). The point proton and point neutron radii are often compared in order to enhance the effect, and are found to differ by 0.4–0.8 fm. For other typical properties of halo nuclei see (1995HA56).

1. \(^{6}\)He(\(\beta^{-}\))\(^{6}\)Li

\(Q_{m} = 3.508\)

The half-life is 806.7 ± 1.5 ms (1984AJ01). The decay to the ground state of \(^{6}\)Li (\(J^{π} = 1^{+}\)) is via a super-allowed Gamow-Teller transition; \(\log ft = 2.910 ± 0.002\) (1984AJ01, 1988AJ01). A second beta-decay branch leading to an unbound final state consisting of a deuteron and an \(\alpha\) particle was reported (1990RI01) based on the observation of beta-delayed deuterons. The branching ratio for \(E_{d} > 350\) keV was measured (1993BO24, 1993RIZY) to be \((7.6 ± 0.6) \times 10^{-6}\). Calculations are presented which consider alternative decay routes. (One considers a decay to an unbound state of \(^{6}\)Li which then decays into \(\alpha + d\). In the other route \(^{6}\)He breaks up into an alpha particle plus a di-neutron which \(\beta\) decays to a deuteron). The calculation of (1994BA11) successfully reproduces the deuteron spectrum shape and branching ratios. References to theoretical work on the \(^{6}\)He(\(\beta^{-}\))\(^{6}\)Li decay are presented in Table 6.2.

2. \(^{1}\)H(\(^{6}\)He, \(^{6}\)He\(^{1}\)H

\(E_{b} = 9.975\)

Angular distributions for elastic scattering and for \(1n\) and \(2n\) transfer were measured at 25 MeV/A, and spectroscopic amplitudes were extracted by (1999WO13). An analysis of elastic
Figure 4: Energy levels of $^6$He. For notation see Fig. 5.
Table 6.1: Energy levels of $^6\text{He}$

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$J^\pi; T$</th>
<th>$\tau_{1/2}$ or $\Gamma_{\text{cm}}$</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>$0^+; 1$</td>
<td>$\tau_{1/2} = 806.7 \pm 1.5 \text{ ms}$</td>
<td>$\beta^-$</td>
<td>1, 5, 9, 10, 11, 12, 13, 14, 15, 16, 19, 20, 21, 22, 23, 24, 25, 30, 31</td>
</tr>
<tr>
<td>$1.797 \pm 25$</td>
<td>$2^+; 1^a$</td>
<td>$\Gamma = 113 \pm 20 \text{ keV}$</td>
<td>$n, \alpha$</td>
<td>5, 9, 10, 11, 12, 13, 15, 16, 19, 20, 21, 22, 23, 24, 26, 31</td>
</tr>
<tr>
<td>$5.6 \pm 300^a$</td>
<td>$(2^+, 1^-, 0^+); 1^a$</td>
<td>$12.1 \pm 1.1 \text{ MeV}^a$</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>$14.6 \pm 0.7^a$</td>
<td>$(1^-, 2^-); 1^a$</td>
<td>$7.4 \pm 1.0 \text{ MeV}^a$</td>
<td>9, 15, 19, 22, 24</td>
<td></td>
</tr>
<tr>
<td>$(15.5 \pm 500)$</td>
<td></td>
<td>$4 \pm 2 \text{ MeV}$</td>
<td>10, 11, 16, 19, 23, 24</td>
<td></td>
</tr>
<tr>
<td>$23.3 \pm 1.0^a$</td>
<td></td>
<td>$14.8 \pm 2.3 \text{ MeV}^a$</td>
<td>11, 15, 19</td>
<td></td>
</tr>
<tr>
<td>(32)</td>
<td></td>
<td>$\leq 2 \text{ MeV}$</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>(36)</td>
<td></td>
<td>$\leq 2 \text{ MeV}$</td>
<td>23</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Newly adopted in this evaluation or revised from the previous evaluation (1988AJ01).

scattering data at 700 MeV/A is described in (1998AL05). See also the analysis (2000DE43) of data at $E = 25, 40 \text{ MeV}$ and that of (2000GU19) at $E = 25–70 \text{ MeV}$. The reaction cross section was measured for 36 MeV/A $^6\text{He}$ on hydrogen, and a value of $\sigma_R = 409 \pm 22 \text{ mb}$ was obtained (2001DE19). Analysis within a microscopic model allowed the $^6\text{He}$ density distribution to be explored.

The use of elastic and inelastic scattering with secondary beams to probe ground-state transition densities of halo nuclei has been explored in a theoretical study (1995BE26). Cross sections for $E = 151 \text{ MeV}$ were calculated by (2000AV02), and density-distribution features were deduced. See also the discussion of (1999EG02).

3. (a) $^3\text{H}(t, n)^5\text{He}$
   \[ Q_m = 10.534 \]
   \[ E_b = 12.305 \]
(b) $^3\text{H}(t, 2n)^4\text{He}$
   \[ Q_m = 11.332 \]
(c) $^3\text{H}(t, t)^3\text{H}$

The cross section for reaction (b) was measured for $E_t = 30$ to 115 keV by (1986BR20, 1985JA16) who also calculated the astrophysical $S$-factors [the extrapolated $S(0) \approx 180 \text{ keV} \cdot \text{b}$] and discussed the earlier measurements. See also (1974AJ01, 1979AJ01) and (1986JA1E). Calculations have also been made within the framework of the two-channel resonating group method.
Table 6.2: $^6\text{He}(\beta^-)^6\text{Li} – \text{Theoretical work}$

<table>
<thead>
<tr>
<th>Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1989DO1B</td>
<td>Meson exchange corrections to the $^6\text{He} \rightarrow ^6\text{Li}$, beta decay</td>
</tr>
<tr>
<td>1989SA20</td>
<td>Polarization effects of second-class currents in the direct and inverse decay of nuclei</td>
</tr>
<tr>
<td>1989TE04</td>
<td>Neutral current effect in nuclear $\beta$-decays</td>
</tr>
<tr>
<td>1990DA1H</td>
<td>Two body phase space in alpha-deuteron breakup at 40 MeV</td>
</tr>
<tr>
<td>1990DAZR</td>
<td>Beta-decay of the ground state of $^6\text{He}$ in three-particle $\alpha + 2n$ model</td>
</tr>
<tr>
<td>1990DO04</td>
<td>Particle-hole symmetry and meson exchange corrections to the $^6\text{He}$ beta decay amplitude</td>
</tr>
<tr>
<td>1990HA29</td>
<td>A review of recent results on nuclear structure at the drip lines</td>
</tr>
<tr>
<td>1991DA24</td>
<td>Decay of the ground state of the $^6\text{He}$ nucleus in the three-particle $\alpha + 2n$ model</td>
</tr>
<tr>
<td>1992DAZV</td>
<td>Static electromagnetic characteristics and beta-decay of $^6\text{He}$</td>
</tr>
<tr>
<td>1992DE12</td>
<td>Beta-delayed deuteron emission of $^6\text{He}$ in a potential model</td>
</tr>
<tr>
<td>1993CH06</td>
<td>Gamow-Teller beta-decay rates for $A \leq 18$ nuclei, a comprehensive analysis</td>
</tr>
<tr>
<td>1993ZH09</td>
<td>$^6\text{He}$ beta decay to the $\alpha + d$ channel in a three-body model</td>
</tr>
<tr>
<td>1994BA11</td>
<td>Deuteron emission following $^6\text{He}$ beta decay</td>
</tr>
<tr>
<td>1994BB03</td>
<td>Evidence for halo in quenching of $^6\text{He}$ beta-decay into alpha and deuteron</td>
</tr>
<tr>
<td>1994CS01</td>
<td>Microscopic description of the beta delayed deuteron emission from $^6\text{He}$</td>
</tr>
<tr>
<td>1994SK01</td>
<td>Improved limits on time-reversal-violating, tensor weak couplings in $^6\text{He}$</td>
</tr>
<tr>
<td>1994SU02</td>
<td>Glauber theory microscopic analysis of fragmentation and beta-delayed particle emission</td>
</tr>
<tr>
<td>1995SU13</td>
<td>Study of halo structure in light nuclei with a multicluster model</td>
</tr>
<tr>
<td>1998GL01</td>
<td>Order-(\alpha) radiative correction to $^6\text{He}$ beta-decay recoil spectrum</td>
</tr>
<tr>
<td>1999ER02</td>
<td>Antisymmetrization in multicluster model &amp; nucleon exchange effects</td>
</tr>
</tbody>
</table>


4. $^4\text{He}(2n, \gamma)^6\text{He}$

\[ Q_m = 0.973 \]

A mechanism for this reaction in astrophysical processes is suggested, and a reaction rate is calculated (1996EF02).

5. $^4\text{He}(t, p)^6\text{He}$

\[ Q_m = -7.508 \]

Angular distributions of the protons to $^6\text{He}^*(0, 1.80)$ have been measured at $E_t = 22$ and 23 MeV. [No $L$-values were assigned.] No other states are observed with $E_x \leq 4.2$ MeV; see (1979AJ01). Cross sections and angular distributions for the reaction products of the $^3\text{H}(\alpha, p)^6\text{He}$
reaction were measured at $E_\alpha = 27.2$ MeV (1992GO21). A potential description of $^3\text{H} + ^4\text{He}$ elastic scattering is discussed in (1993DU09).

6. $^4\text{He}(\alpha, 2p)^6\text{He}$

$$Q_m = -27.322$$

Total cross sections for the production of $^6\text{He}$ have been measured (2001AU06) at $E_\alpha = 159, 280$ and $620$ MeV in a study of cosmic ray nucleosynthesis. The resulting cross sections decrease rapidly with energy.

7. $^4\text{He}(^6\text{He}, ^6\text{He})^4\text{He}$

$$E_b = 7.412$$

Differential cross sections were measured at $E(^6\text{He}) = 151$ MeV. DWBA analysis suggests a spectroscopic factor of $\approx 1$ for the di-neutron cluster. (1998TE1D, 1998TE03). Measurements at $E_{\text{cm}} = 11.6$ and 15.9 MeV (1999RA15) also show evidence for the 2n transfer process in the elastic scattering. However, a couple-discretized-continuum channel analysis discussed in (2000RU03) suggests a smaller 2n transfer process than commonly assumed (2001TE03). See also the analyses and calculations of (1998GO1J, 1999OG06, 1999OG09). A microscopic multicluster model description of the elastic scattering process is discussed in (1999FU03).

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

$$E_b = 9.975$$

See reaction 2 for experimental information on the $^6\text{He} + ^1\text{H}$ system.

Calculations of the elastic scattering of protons from $^6\text{He}$ at $E_p \geq 100$ MeV are described in (1992GA27). A folding model with target densities which reproduce the r.m.s. radii and a range of electroweak data was used.

A calculation of the expansion of the Glauber amplitude described in (1999AB37) found that a $^6\text{He}$ matter radius constant with the analysis is 2.51 fm. Finite-range coupled channel calculations have been performed below the $^6\text{He}$ three-body breakup threshold (2000TI02). A theoretical study (2000WE03) with four differential nuclear structure models concluded that elastic scattering at $< 100$ MeV/A does not provide good constraints on the structure of the $^6\text{He}$ ground state. First order optical potentials were studied for 20–40 MeV scattering by (2000DE43). A microscopic multicluster calculation of $\sigma(\theta)$ and $\sigma(E)$ for $E_{\text{cm}} = 0–5$ MeV is reported in (2001AR05).

9. $^6\text{Li}(e, \pi^+)^6\text{He}$

$$Q_m = -143.078$$
(1986SH14) report breaks in (e, π+) spectra at $E_e = 202$ MeV corresponding to $E_x = 7, 9, 12, 13.6, 17.7$ and $24.0$ MeV. Using the shape of the virtual photon spectrum results in groups with angular distributions that suggest that the states at $13.6, 17.7$ and $24.0$ MeV are spin-dipole isovector states [$J^\pi = 1^-, 2^-$]. See also (1990SH11). For the earlier work see (1984AJ01). [Note: The states reported here at 7, 9 and 12 MeV are inconsistent with the work reported in reactions 12, 13, 22 and 23, and with the work on the analog region in $^6$Be].

10. (a) $^6$Li($\pi^-, \gamma$)$^6$He $\quad Q_m = 136.062$
(b) $^6$Li($\pi^-, \pi^0$)$^6$He $\quad Q_m = 1.086$

The excitation of $^6$He*(0, 1.8) and possibly of (broad) states at $E_x = 15.6 \pm 0.5, 23.2 \pm 0.7$ and $29.7 \pm 1.3$ MeV has been reported: see (1979AJ01). A study of capture branching ratios to $^6$He*(0, 1.8) was reported in (1986PE05). For reaction (b) see (1984AJ01).

11. $^6$Li(n, p)$^6$He $\quad Q_m = -2.725$

Angular distributions of the ground state proton group, $p_0$ have been reported at $E_n = 4.7$ to 6.8 MeV, at 14 MeV and at 59.6 MeV [see (1979AJ01, 1984AJ01)] and at 118 MeV (1987PO18, 1988HA2C, 1988WA24). At $E_n = 59.6$ MeV broad structures in the spectra are ascribed to states at $E_x = 15.5 \pm 0.5$ and $25 \pm 1$ MeV with $\Gamma = 4 \pm 1.5$ and $8 \pm 2$ MeV (1983BR32, 1984BR03) [see for discussions of the GDR strength]. The ground state reaction has also been studied at $E_n = 198$ MeV (1988JA01). Proton spectra were measured at $E_n = 118$ MeV by (1998HA24).

An angular distribution of the proton group corresponding to population of the $E_x = 1.8$ MeV $J^\pi = 2^+$ state in $^6$He was also reported (1988WA24). See also (1989WA1F). Angular distributions were measured for $p_0$ at $E_n = 280$ MeV in tests of isospin symmetry in (n, p), (p, p') and (p, n) reactions populating the $T = 1$ isospin triads in $A = 6$ nuclei (1990MI10). Cross sections for $\theta_{lab} = 1^0$–$10^0$ for $E_n = 60$–$260$ MeV were measured to obtain the energy dependence of the Gamow-Teller strength (1991SOZZ, 1992SO02).

Several theoretical studies have been reported since the previous review. A dynamical multi-cluster model was used to generate transition densities for $^6$He and $^6$Li (1991DA08). A microscopic calculation in the framework of the $\alpha + 2$N model (1993SH1G) reproduced energy spectra and cross sections reliably. Predictions for the structure of a second $2^{(+)}$ resonance in the $^6$He continuum were made with a $\alpha + N + N$ cluster model (1997DA01). Halo excitation of $^6$He in $^6$Li(n, p)$^6$He was studied using four-body distorted wave theory (1997ER05); see also (1997VA06). The status of experimental and theoretical research on nuclei featuring a two-particle halo is reviewed in (1996DA31).

12. $^6$Li(d, 2p)$^6$He $\quad Q_m = -4.950$
The previous review ([1988AJ01]) notes that at $E_d = 55$ MeV, $^6$He*(0, 1.8) [the latter weak] are populated: no other states are observed with $E_x \leq 25$ MeV [see ([1984AJ01])]. More recently cross sections at $0^\circ$ were measured at $E_d = 260$ MeV ([1993OH01]) and at $E_d = 125.2$ MeV ([1995XU02]). In both studies the cross section for (d, $^2$He) showed a linear relationship with Gamow-Teller strength from $\beta$ decay or (p, n) reactions.

13. $^6$Li(t, $^3$He)$^6$He  

$Q_m = -3.489$

The ground-state angular distribution has been studied at $E_t = 17$ MeV. At $E_t = 22$ MeV only $^6$He*(0, 1.8) are populated for $E_x \leq 8.5$ MeV: see ([1979AJ01]). Differential cross sections for the transition to $^6$He*(1.8) are reported at $E(^6$Li) = 65 MeV ([1987AL23]). In a more recent experiment at $E_t = 336$ MeV reported in ([2000NA35]), the $^6$He ground and 1.8 MeV states were populated. In addition, a broad asymmetric structure around $E_x \approx 5$ MeV was observed with an angular distribution which exhibited $\Delta L = 1$ dominance. Another structure at $E_x \approx 14.6$ MeV was observed with the angular distribution indicating $\Delta L = 1$.

14. $^6$Li($^6$Li, $^6$Be)$^6$He  

$Q_m = -7.796$

Angular distributions have been studied for $E(^6$Li) = 32 and 36 MeV for the transitions to $^6$He$_{g.s}$, $^6$Be$_{g.s}$ and, in inelastic scattering of $^6$Li [see $^6$Li], to the analog state $^6$Li*(3.56): for a discussion of these see the references quoted in ([1979AJ01]).

15. $^6$Li($^7$Li, $^7$Be)$^6$He  

$Q_m = -4.370$

Measurements of differential cross sections at $E(^7$Li) = 82 MeV are reported in ([1992GLZX, 1993GLZZ, 1994SAZZ]) and at $E(^7$Li) = 78 MeV in ([1993SA35, 1994RUZZ]). The $^6$He levels at $E_x = 0$ $J^\pi = 0^+$ and $E_x = 1.80$ $J^\pi = 2^+$ were identified. A maximum at $E_x \approx 6$ MeV is interpreted as consistent with a soft-dipole response expected in neutron-halo nuclei. A study ([1996JA11, 1999AN13]) at $E(^7$Li) = 350 MeV utilized magnetic analysis to observe transitions to the $J^\pi = 0^+$ ground state, and the $J^\pi = 2^+$ state at $E_x = 1.8$ MeV, as well as pronounced resonances at $\approx 5.6$ MeV, $\approx 14.6$ MeV and $\approx 23.3$ MeV ([1996JA11]). See Table 6.3. In experiments at $E = 65$ MeV/A with this reaction, isovector spin-flip and spin non-flip resonances were deduced ([1998NAZP, 1998NAZR]). See also the more recent measurements described in ([2000NA22] and [2001NA18]).

A theoretical study of $^6$He structure with an extended microscopic three-cluster model is described in ([1999AR08]).
Table 6.3: Levels in $^6\text{He}$ from $^6\text{Li}(^7\text{Li}, ^7\text{Be})^6\text{He}$

<table>
<thead>
<tr>
<th>$E_x$</th>
<th>$J^\pi$</th>
<th>$\Gamma$</th>
<th>$d\sigma/d\Omega$</th>
<th>$G$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(MeV)</td>
<td>(mb/sr)</td>
<td></td>
</tr>
<tr>
<td>g.s.</td>
<td>$0^+$</td>
<td></td>
<td>0.72 ± 0.08</td>
<td>0.46 ± 0.05</td>
</tr>
<tr>
<td>1.92 ± 0.17</td>
<td>$2^+$</td>
<td></td>
<td>0.25 ± 0.04</td>
<td>0.40 ± 0.10</td>
</tr>
<tr>
<td>5.6 ± 0.3</td>
<td>$(2^+, 1^-, 0^+)$</td>
<td>12.1 ± 1.1</td>
<td>4.56 ± 0.48</td>
<td>0.39 ± 0.04</td>
</tr>
<tr>
<td>14.6 ± 0.7</td>
<td>$(1, 2)^-$</td>
<td>7.4 ± 1.0</td>
<td>2.11 ± 0.23</td>
<td>0.43 ± 0.06</td>
</tr>
<tr>
<td>23.3 ± 1.0</td>
<td></td>
<td>14.8 ± 2.3</td>
<td>1.75 ± 0.19</td>
<td>0.47 ± 0.07</td>
</tr>
</tbody>
</table>

$^a$ (1996JA11). $E(7\text{Li}) = 350$ MeV.

$^b$ $\theta_{\text{cm}} = 4.5^\circ$.

$^c$ Averaged spin-flip signatures $G = Y_{\text{coinc}}/Y_{\text{singles}}$.

$^d$ (1999AN13) and J. Jänecke, private communication.

16. (a) $^7\text{Li}(\gamma, p)^6\text{He}$

(b) $^7\text{Li}(e, ep)^6\text{He}$

$Q_m = -9.975$

At $E_{\gamma} = 60$ MeV, the proton spectrum shows two prominent peaks attributed to $^6\text{He}^*(0 + 1.8, 18 \pm 3)$: see (1979AJ01). Reactions (a) and (b) have been studied by (1985SE17). See also $^7\text{Li}$, (1984AJ01) and (1986BA2G). An analysis of the available experimental data on $^7\text{Li}$ photodisintegration at energies up to $E_{\gamma} = 50$ MeV is presented in (1990VAZM, 1990VA16). See also the discussion of reactions involving scattering of polarized electrons from polarized targets (1993CA11). In more recent work a broad excited state was observed (2001BO38) in $^6\text{He}$ with energy $E_x = 5 \pm 1$ MeV and width $\Gamma = 3 \pm 1$ MeV. In experiments with reaction (b) momentum distributions from transitions to the $^6\text{He}$ ground and first excited states were measured by (1999LA13, 2000LA17). The deduced spectroscopic factor for both reactions is $0.58 \pm 0.05$ in agreement with variational Monte Carlo calculations.

17. $^7\text{Li}(\pi^-, ^6\text{He})n$

$Q_m = 128.812$

The results of measurements of inclusive spectra made with $\pi^-$ mesons with momentum 90 MeV/c are presented in (1993AM09). The yield of one-neutron emission was found to be $Y = (1.1 \pm 0.2) \times 10^{-3}$ per stopped $\pi^-$. 

18. $^7\text{Li}(\pi^-, \pi^-p)^6\text{He}$

$Q_m = -9.975$
Pion and proton spectra were measured at 0.7, 0.9, 1.25 GeV/c by (2000AB25). Fermi-momentum distributions were deduced.

19. $^7\text{Li}(n, d)^6\text{He}$ \quad $Q_m = -7.751$ 

At $E_n = 60$ MeV, the deuteron spectrum shows two prominent peaks attributed to states centered at $E_x = 13.6$, 15.4 and 17.7 MeV (±0.5 MeV) and a possible state or states (populated with an $l_p$ transfer $\geq 2$) at $E_x = 23.7$ MeV. DWBA analyses of the $d_0$ and $d_1$ groups are consistent with $l_p = 1$ and $S(1p_{3/2}) = 0.62$ for $^6\text{He}_{g.s.}$ and to $S(1p_{3/2}) = 0.37$, $S(1p_{1/2}) = 0.32$ for $^6\text{He}^*(1.8)$ (1977BR17): see (1979AJ01). Measurements of the cross section as a function of energy for $E_x = 10$–30 MeV were reported in (1989CO22). See also the measurements at $E_n = 14.1$ MeV (1989SHZS).

20. $^7\text{Li}(p, 2p)^6\text{He}$ \quad $Q_m = -9.975$ 

From measurements at $E_p = 1$ GeV (1985BE30, 1985DO16), the separation energy between 6–7 MeV broad $1p_{3/2}$ and $1s_{1/2}$ peaks is reported to be 14.1 ± 0.7 MeV. See also (1983GO06) and (1979AJ01). Differential cross section measurements at $E_p = 70$ MeV are reported in (1988PA26, 1998SH33, 2001SH03). Contributions from 1p and 1s nucleons in $^7\text{Li}$ were distinguished. Proton spectra measurements for $E_p = 1$ GeV were reported by (2000MI17, 2001MI07). Effective proton polarizations were deduced. See also the review of experimental and theoretical nucleon and cluster knockout reactions in light nuclei presented in (1987VD1A).

21. $^7\text{Li}(d, ^3\text{He})^6\text{He}$ \quad $Q_m = -4.482$ 

As summarized in the previous review (1988AJ01), angular distributions of the $^3\text{He}$ ions to $^6\text{He}^*(0, 1.8)$ have been measured at $E_d = 14.4$ and 22 MeV: they have an $l_p = 1$ character and therefore these two states have $J^e = (0-3)^+$. There is no evidence for any other states of $^6\text{He}$ with $E_x < 10.7$ MeV: see (1979AJ01). (1987BO39) $[E_d = 30.7$ MeV] deduce that the branching ratio of $^6\text{He}^*(1.8)$ into a dineutron [$n^2$: $T = 1$, $S = 0$] and an $\alpha$-particle is 0.75 ± 0.10. See also (1985BO55) and (1987DA31). More recently, the energy spectrum of neutrons from the $^6\text{He}$ excited state at $E_x = 1.8$ MeV populated in this reaction was measured at $E_d = 23$ MeV (1994BO46).

22. $^7\text{Li}(t, \alpha)^6\text{He}$ \quad $Q_m = 9.838$
As summarized in (1988AJ01), the energy of the first-excited state is $1.797 \pm 0.025$ MeV, $\Gamma = 113 \pm 20$ keV. $^6\text{He}^*(1.80)$ decays into $^4\text{He} + 2n$. The branching ratio $\Gamma_\gamma/\Gamma_\alpha \leq 2 \times 10^{-6}$: for $\Gamma_{cm} = 113 \pm 20$ keV, $\Gamma_\gamma \leq 0.23$ eV. Angular distributions of the $\alpha_0$ and $\alpha_1$ groups have been measured at $E_t = 13$ and 22 MeV. No other $\alpha$-groups are reported corresponding to $^6\text{He}$ states with $E_x < 24$ MeV (region between $E_x \approx 13$ and 16 MeV was obscured by the presence of breakup $\alpha$-particles): see (1979AJ01). Angular distributions were reported at $E_t = 0.151$ and 0.272 MeV ($^1\text{H}$; $\alpha_0$, $\alpha_1$) and at $E(^7\text{Li}) = 31$ MeV (1987AL23; to $^6\text{He}^*(0, 1.8, 13.6)$).

In more recent work, differential cross sections were measured at $E_t = 38$ MeV (1992CL04). DWBA calculations are presented and spectroscopic factors are deduced.

The resonance theory of threshold phenomena was used to analyze differential cross sections for $^7\text{Li}(t, \alpha)^6\text{He}^*(1.8)$ for $\theta < 90^\circ$ at $E_t = 80–500$ keV in a study of $^{10}\text{Be}$ levels (1991LA1D).

23. $^7\text{Li}(^3\text{He}, p^3\text{He})^6\text{He}$

\[ Q_m = -9.975 \]

At $E(^3\text{He}) = 120$ MeV the missing mass spectra show $^6\text{He}^*(0, 1.8)$ and a strong, broad peak corresponding to $^6\text{He}^*(16)$ [possibly due to unresolved states]. There is no indication of a state near 23.7 MeV but there is some evidence of structures at $E_x = 32.0$ and 35.7 MeV, with $\Gamma \leq 2$ MeV (1985FR01).

24. (a) $^7\text{Li}(^6\text{Li}, ^7\text{Be})^6\text{He}$

\[ Q_m = -4.370 \]

(b) $^7\text{Li}(^7\text{Li}, ^8\text{Be})^6\text{He}$

\[ Q_m = 7.280 \]

In reaction (a) at $E(^6\text{Li}) = 93$ MeV a broad peak ($\Gamma = 5.5$ MeV) was reported at $E_x = 14$ MeV. A second structure may also be present at 15.5 MeV (1987GLZW, 1988BUZH). $^6\text{He}^*(0, 1.8)$ are also populated (1988BUZH). For reaction (b) see $^8\text{Be}$ in (1988AJ01). See also $^7\text{Be}$, (1984AJ01) and (1988BU1Q, 1984BA53), and see (1996SO17) which involves $^{10}\text{Be}$ excited states. Measurements of differential cross sections at $E(^7\text{Li}) = 22$ MeV were reported in (1988BO18).

25. $^9\text{Be}(\gamma, ^3\text{He})^6\text{He}$

\[ Q_m = -21.178 \]

Measurements of ground-state cross sections and angular distributions are reported in (1999SH05). See (1999ZHZN) for a compilation and evaluation of cross section data for $E_\alpha \leq 30$ MeV.

26. $^9\text{Be}(n, \alpha)^6\text{He}$

\[ Q_m = -0.600 \]
Angular distributions have been reported for $E_n = 12.2$ to 18.0 MeV ($\alpha_0$, $\alpha_1$). No other states are observed with $E_x \leq 7$ MeV: see (1979AJ01). For a study of possible dineutron breakup of $^6$He*(1.8) see (1983OT02). An analysis of the alpha and neutron spectra observed in this reaction for $E_n \approx 14$ MeV is presented in (1988FE06). See also $^{10}$Be in (1988AJ01) and (1983SH1J).

27. $^9$Be($^6$He, $^6$He)$^9$Be

$E_b = 19.069$

Elastic scattering measurements for $E(^6$He) = 8.8–9.3 MeV were reported in (1991SM01). The data are well reproduced with calculations using $^6$Li or $^7$Li optical model parameters. See also $^9$Be in (1988AJ01).

28. $^9$Be($^6$Li, $^9$B)$^6$He

$Q_m = -4.576$

Differential cross sections were measured at $E(^6$Li) = 34, 62 MeV, and spectroscopic factors were deduced (1985CO09). Vector and tensor analyzing powers were measured for detection of the $^6$He nuclei at $\theta_{cm} = 14^\circ$–$80^\circ$ at $E(^6$Li) = 32 MeV (1993RE04). See $^9$B in (1988AJ01).

29. $^9$Be($^7$Li, $^6$He)$^{10}$B

$Q_m = -3.390$

This reaction has been used as a source of $^6$He beams for elastic scattering experiments at $E(^6$He) = 8.8–9.3 MeV (1991SM01) and at $E(^6$He) = 10.2 MeV (1995WA01).

30. $^9$Be($^9$Be, $^6$He)$^{12}$C

$Q_m = 5.101$

Angular distributions were measured at $E(^9$Be) = 40 MeV (1992CO05). See $^9$Be in (1988AJ01) and $^{12}$C in (1990AJ01).

31. $^{11}$B($^7$Li, $^{12}$C)$^6$He

$Q_m = 5.982$

At $E(^{11}$B) = 88 MeV the population of the ground state and the first-excited state at $E_x = 1.8 \pm 0.3$ MeV ($\Gamma \leq 0.2$ MeV) is reported (1987BEY1). See also (1988BEYJ).

32. $^{12}$C($\mu^+$, $^6$He)X
Measurements of the energy dependence at $E = 100, 190$ GeV were reported by (2000HA33).

33. $^{12}$C($^6$He, n)X

Peripheral fragmentation of $^6$He at 240 MeV/A was studied (1997CH24, 1997CH47, 1998AL10) in a kinematically complete experiment. It was found that one-neutron stripping to $^5$He is the dominant mechanism. A continuation of the analysis described in (2000AL04) indicates excitation of the $^6$He first $2^+$ state and associates it with E1 dipole oscillation. See also (1993FE02). Model calculations are discussed in (1998BE09, 1998GA37).

34. $^{12}$C($^6$He, $^\alpha$)X

Measurements at 240 MeV/A are described in (1998AL10, 1998AN02, 1999AU01, 2000AL04). Fragmentation cross sections of $^6$He were analyzed in the Glauber theory to investigate the importance of neutron correlation (1994SU02). Fragmentation reaction data and beta-delayed particle emission data are reproduced successfully. Detailed structure is described with a multicluster model and halo-like structure is discussed in (1995SU13). See also (1998BE09, 1998GA37).

35. $^{12}$C($^6$He, $^6$He)$^{12}$C

Elastic and quasielastic scattering of $^6$He on $^{12}$C was studied at $E(^6$He) = 10.2 MeV (1995WA01). See also (1995PE1D). Measurements of cross sections were made at 41.6 MeV/A (1996AL11). The results were successfully analyzed within a 4-body ($\alpha + n + n + ^{12}$C) eikonal scattering model. Potential parameters were deduced and differential cross sections were calculated for $^6$He scattering at 50 and 100 MeV/A (1993GO06). The possibility of studying the structure of the neutron halo in $^6$He elastic rainbow scattering is discussed. See also (1989SI02, 1992CL04, 1993FE02, 1995GA24). Calculations of cross sections at $E = 20$–60 MeV/A were reported in (2000BO45). Proton, neutron and matter r.m.s. distributions were also calculated.

36. $^{208}$Pb($^6$He, 2n$\alpha$)X

Measurements and analyses of a three-body breakup experiment at 240 MeV/A are described in (1999AU01, 2000AL04). Two-neutron interferometry measurements at 50 MeV/A are discussed in (2000MA12).
${}^{6}\text{Li}$
(Figs. 5 and 7)

GENERAL: References to articles on general properties of $^{6}\text{Li}$ published since the previous review (1988AJ01) are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for $^{6}\text{Li}$ located on our website at (www.tunl.duke.edu/NuclData/General_Tables/6li.shtml).

Ground State Properties:

$$\mu = +0.8220473(6) \text{ nm}, +0.8220567(3) \text{ nm}: \text{see (1989RA17)},$$

$$Q = -0.818(17) \text{ mb (1998CE04)}.$$ 

The interaction nuclear radius of $^{6}\text{Li}$ is $2.09 \pm 0.02$ fm (1985TA18). These authors have also derived nuclear matter, charge and neutron r.m.s. radii.

Quadrupole moment: The tiny quadrupole moment of $^{6}\text{Li}$ poses a difficult task for theoretical calculations. Except for a phenomenological (1985ME02), a microscopic cluster (1986ME13), and a Greens-Function Monte-Carlo (1997PU03) calculation, the models fail even to predict the sign. See the discussion of three-body models in (1993SC30). In (1991UN02), this failure of the three-body models is blamed on the missing antisymmetrization of the valence nucleons with the nucleons in the alpha-core. Another microscopic cluster calculation (1992CS04) considers the findings of (1986ME13) to be due to a fortuitous choice of the model space.

Asymptotic D/S ratio $^1$: The ratio of the D- and S-state asymptotic normalization constants, referred to in the literature as $\eta$, has been used widely to quantify the properties of the D-state wave function. There is general agreement in the $A = 2–4$ systems between theoretical calculations and empirical determinations of the normalization constants. See (1988WE20, 1990EI01, 1990LE24). The S-state $\alpha + d$ normalization constant for $^{6}\text{Li}$ appears to be well determined (1993BL09, 1999GE02), but both the magnitude and sign of $\eta$ are uncertain.

In a two-body $\alpha + d$ model it was found (1984NI01) that in order to reproduce the experimental quadrupole moment $Q$, the wave functions must have $\eta < 0$. However, three-body ($\alpha + n + p$) models consistently result in predictions of $\eta > 0$ (1990LE24, 1995KU08). Recent microscopic six-body calculations using realistic NN potentials predict $\eta = -0.07$ (1996FO04).

The asymptotic D/S ratio has been probed empirically by studying scattering processes, transfer reactions, and $^{6}\text{Li}$ breakup. These determinations usually rely on an underlying assumption as to the scattering or reaction mechanism. The S- and D-state asymptotic normalization constants were determined in a study of d-\alpha scattering (1978BO43) from which $\eta$ was found to be $+0.005 \pm 0.014$. Several $^{6}\text{Li} + ^{58}\text{Ni}$ elastic scattering studies (1984NI01, 1995DE06, 1995RU14) have described polarization observables with $\eta \approx -0.01$, while an investigation of the breakup of $^{6}\text{Li}$ on $^1\text{H}$ suggests $\eta > 0$ (1992PU03). A study of the $^{6}\text{Li}(d, \alpha)^4\text{He}$ reaction (1990SA47) found that $\eta$

$^1$ We are very grateful to K.D. Veal and C.R. Brune for providing these comments on the asymptotic D/S ratio for $^{6}\text{Li}$.
should lie in the range $-0.010$ to $-0.015$. Recently, a phase-shift analysis of $^6\text{Li} + ^4\text{He}$ scattering determined $\eta = -0.025 \pm 0.006 \pm 0.010$ (1999GE02) while an analysis of ($^6\text{Li}$, d) transfer reactions resulted in a near zero value of $\eta = +0.0003 \pm 0.0009$ (1998VE03).

Based on these theoretical and empirical results, we conclude that both the magnitude and sign of $\eta$ for the $^6\text{Li} \rightarrow \alpha + d$ wave function are not well determined. See also (1998VE03, 1999GE02).

Isotopic abundance: (7.5 ± 0.2)% (1984DE53). See also (1987LA1J, 1988LA1C).

For estimates of the parity-violating $\alpha$-decay width of $^6\text{Li}^*$(3.56) $[0^+; T = 1]$ see (1983RO12, 1984BU01, 1986BU07).

1. $^1\text{H}(^6\text{Li}, ^6\text{Li})^1\text{H}$

   Differential cross sections were measured at $E = 0.7 \text{ GeV}/A$ by (2000DOZY, 2001EG02). Matter distribution radii and halo features of $^6\text{Li}^*(3.56)$ were deduced.

2. $^2\text{H}(\alpha, \pi^0)^6\text{Li}$

   Measurements of cross sections at $E_\alpha = 418, 420 \text{ MeV}$ are reported by (2000AN15, 2000AN31). Halo features of $^6\text{Li}^*$ were deduced.

3. (a) $^3\text{He}(^3\text{H}, \gamma)^6\text{Li}$
   $Q_m = 15.7947$

   (b) $^3\text{He}(^3\text{H}, n)^5\text{Li}$
   $Q_m = 10.41$

   (c) $^3\text{He}(^3\text{H}, d)^4\text{He}$
   $Q_m = 14.32037$

   (d) $^3\text{He}(^3\text{H}, ^3\text{H})^3\text{He}$

$E_b = 15.80$

Figure 5: Energy levels of $^6\text{Li}$. In these diagrams, energy values are plotted vertically in MeV, based on the ground state as zero. Uncertain levels or transitions are indicated by dashed lines; levels which are known to be particularly broad are cross-hatched. Values of total angular momentum $J$, parity, and isobaric spin $T$ which appear to be reasonably well established are indicated on the levels; less certain assignments are enclosed in parentheses. For reactions in which $^6\text{Li}$ is the compound nucleus, some typical thin-target excitation functions are shown schematically, with the yield plotted horizontally and the bombarding energy vertically. Bombarding energies are indicated in laboratory coordinates and plotted to scale in cm coordinates. Excited states of the residual nuclei involved in these reactions have generally not been shown; where transitions to such excited states are known to occur, a brace is sometimes used to suggest reference to another diagram. For reactions in which the present nucleus occurs as a residual product, excitation functions
Table 6.4: Energy levels of $^6$Li

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV) $^a$</th>
<th>$J^\pi; T$</th>
<th>$\Gamma_{cm}$ (MeV) $^a$</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>$1^+; 0$</td>
<td></td>
<td>stable</td>
<td>3, 4, 5, 6, 9, 10, 11, 12, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 36, 37, 38, 39, 40, 42, 43, 44, 45, 47, 48, 49, 50, 51, 52, 53, 54, 55, 57, 59, 60, 61, 64, 67</td>
</tr>
<tr>
<td>2.186 ± 2</td>
<td>$3^+; 0$</td>
<td>0.024 ± 0.002</td>
<td>$\gamma$, d, $\alpha$</td>
<td>3, 4, 5, 8, 9, 10, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 29, 30, 33, 34, 36, 37, 38, 42, 44, 45, 46, 47, 48, 49, 55, 57</td>
</tr>
<tr>
<td>3.56288 ± 0.10</td>
<td>$0^+; 1$</td>
<td>$(8.2 \pm 0.2) \times 10^{-6}$</td>
<td>$\gamma$</td>
<td>3, 5, 12, 15, 17, 18, 20, 21, 22, 23, 25, 34, 37, 38, 39, 42, 44, 67</td>
</tr>
<tr>
<td>4.312 ± 22 $^b$</td>
<td>$2^+; 0$</td>
<td>1.30 ± 0.10 $^b$</td>
<td>$\gamma$, d, $\alpha$</td>
<td>3, 8, 17, 18, 20, 21, 29, 37, 39, 42, 55</td>
</tr>
<tr>
<td>5.366 ± 15</td>
<td>$2^+; 1$</td>
<td>0.541 ± 0.020 $^b$</td>
<td>$\gamma$, n, p, $\alpha$</td>
<td>3, 17, 20, 37, 38, 39</td>
</tr>
<tr>
<td>5.65 ± 50</td>
<td>$1^+; 0$</td>
<td>1.5 ± 0.2</td>
<td>d, $\alpha$</td>
<td>8, 20, 39, 42</td>
</tr>
<tr>
<td>17.985 ± 25 $^b$, $^c$, $^e$</td>
<td>$2^−; 1$ $^b$</td>
<td>3.012 ± 0.007 $^b$</td>
<td>$\gamma$, t, $^3$He</td>
<td>3</td>
</tr>
<tr>
<td>24.779 ± 54 $^b$, $^c$, $^f$</td>
<td>$3^−; 1$ $^b$</td>
<td>6.754 ± 0.110 $^b$</td>
<td>$\gamma$, n, t, $^3$He</td>
<td>3, 8</td>
</tr>
<tr>
<td>24.890 ± 55 $^b$, $^c$</td>
<td>$4^−; 1$ $^b$</td>
<td>5.316 ± 0.112 $^b$</td>
<td>$\gamma$, n, t, $^3$He</td>
<td>3</td>
</tr>
<tr>
<td>26.590 ± 65 $^b$, $^c$, $^g$</td>
<td>$2^−; 1$ $^b$, $^g$</td>
<td>8.684 ± 0.125 $^b$, $^g$</td>
<td>$\gamma$, n, d, t, $^3$He</td>
<td>3, 8</td>
</tr>
</tbody>
</table>

$^a$ See also Table 6.12.

$^b$ Newly adopted in this evaluation or revised from the previous evaluation (1988AJ01).

$^c$ See remarks under reaction 3, and see Table 6.5.

$^d$ For possible states at high $E_x$ see reactions 8, 37, 39 and 45 and Table 6.9.

$^e$ $E_x = 17.985 \pm 25$ was previously reported in (1988AJ01) as $E_x = 21.0$ MeV.

$^f$ $E_x = 24.779 \pm 54$ MeV was previously reported as $E_x = 26.6 \pm 0.4$ MeV with $T = 0$ in (1988AJ01). See (1990MO10).

$^g$ (1990MO10).
have not been shown. Further information on the levels illustrated, including a listing of the reactions in which each has been observed, is contained in the master table, entitled “Energy levels of $^6$Li”.

In the previous review (1988AJ01), information on radiative capture of $^3$H on $^3$He was summarized as follows: “Capture $\gamma$-rays (reaction (a)) to the first three states of $^6$Li [$\gamma_0$, $\gamma_1$, $\gamma_2$] have been observed for $E(^3\text{He}) = 0.5$ to 25.8 MeV, while the yields of $\gamma_3$ and $\gamma_4$ have been measured for $E(^3\text{He}) = 12.6$ to 25.8 MeV. The $\gamma_2$ excitation function does not show resonance structure. However, the $\gamma_0$, $\gamma_1$, $\gamma_3$ and $\gamma_4$ yields do show broad maxima at $E(^3\text{He}) = 5.0 \pm 0.4$ [$\gamma_0$, $\gamma_1$], $20.6 \pm 0.4$ [$\gamma_1$], $\approx 21$ [$\gamma_3$] and $21.8 \pm 0.8$ [$\gamma_4$] MeV. The magnitude of the ground-state-capture cross section is well accounted for by a direct-capture model; that for the $\gamma_1$ capture indicates a non-direct contribution above $E(^3\text{He}) = 10$ MeV, interpreted as a resonance due to a state with $E_x = 25 \pm 1$ MeV, $\Gamma_{cm} = 4$ MeV, $T = 1$ (because the transition is E1, to a $T = 0$ final state) [the E1 radiative width $|M|^2 \geq 5.2/(2J + 1)$ W.u.], $J^\pi = (2, 3, 4)^-$, $\alpha + p + n$ parentage. The $\gamma_4$ resonance is interpreted as being due to a broad state at $E_x = 26.6$ MeV with $T = 0$. $J^\pi = 3^-$ is consistent with the measured angular distribution. The ground and first excited state reduced widths for $^3\text{He} + t$ parentage, $\theta_0^2 = 0.8 \pm 0.2$ and $\theta_t^2 = 0.6 \pm 0.3$: see (1974AJ01). See also (1985MOZZ, 1986MOZQ, 1987MOI1).

Since the previous review (1988AJ01), a new resonance analysis (1988MO11, 1990HE20, 1990MO10, 1992HE1E) has been applied to the $^3\text{He} + ^3\text{H}$ elastic scattering in odd parity states and to the $^3\text{He}(^3\text{H}, \gamma)$ data. This analysis explains the shape of the capture cross sections and angular distributions in terms of very wide overlapping resonances. See Table 6.5. These correspond to $^6$Li states at $E_x = 17.985 \pm 0.025$ MeV, $\Gamma_{cm} = 3.012 \pm 0.007$ MeV, $J^\pi = 2^-$; $E_x = 24.779 \pm 0.054$ MeV, $\Gamma_{cm} = 6.754 \pm 0.110$ MeV, $J^\pi = 3^-$; $E_x = 24.890 \pm 0.055$ MeV, $\Gamma_{cm} = 5.316 \pm 0.112$ MeV, $J^\pi = 4^-$; $E_x = 26.590 \pm 0.065$ MeV, $\Gamma_{cm} = 8.684 \pm 0.125$ MeV, $J^\pi = 2^-$ (all with $S = 1$, $T = 1$). The analysis is compatible with an almost pure $^3\text{He} – ^3\text{H}$ cluster structure of the negative parity unbound $^6$Li states with $S = 1$, $T = 1$. These results are supported by calculations described in (1995OH03) which utilize a complex-scaled $^3\text{He} + t$ resonating group method to calculate the energies and widths of the $^6$Li $^3\text{He} + t$ states. Note, however, that the calculated scattering phase shifts rise only gradually with energy and stay well below 90°. Consequently the stated precision on the extracted level parameters is a point of controversy between the authors of (1990MO10, 1990HE20) and one of the authors [H.M.H.] of this review. The radiative capture reaction as a source of $^6$Li production in Big Bang nucleosynthesis is discussed in (1990FU1H, 1990MA1O, 1997NOO4). See also (1995DU12).

The angular distribution and polarization of the neutrons in reaction (b) have been measured at $E(^3\text{He}) = 2.70$ and 3.55 MeV. The excitation function for $E(^3\text{He}) = 0.7$ to 3.8 MeV decreases monotonically with energy. The excitation function for $n_0$ has been measured for $E(^3\text{He}) = 2$ to 6 MeV and for $E(^3\text{He}) = 14$ to 26 MeV; evidence for a broad structure at $E(^3\text{He}) = 20.5 \pm 0.8$ MeV is reported [$^6$Li*(26.1)]: see (1979AJ01).

Angular distributions of deuterons (reaction (c)) have been measured for $E_t = 1.04$ to 3.27 MeV and at $E(^3\text{He}) = 0.29$ to 32 MeV. Polarization measurements are reported for $E_t = 9.02$ to 17.27 MeV [see (1979AJ01)], as well as at $E(^3\text{He}) = 18.0$ and 33.0 MeV (1986RA1C). See also (1986KO1K) and (1985CA41). A microscopic calculation for reaction (c) and its inverse with special emphasis on isospin breaking in the analyzing power is described in (1990BR09). See also
Table 6.5: Levels of $^6\text{Li}$ from $^3\text{He}^\left(^3\text{H},^3\text{H}\right)^3\text{He}$ and $^3\text{He}^\left(^3\text{H},\gamma\right)^6\text{Li}^*(2.18)^{\text{a}}$

<table>
<thead>
<tr>
<th>State</th>
<th>$J^\pi; T$</th>
<th>$E_{3\text{He}}$ (MeV)</th>
<th>$E_x$ (MeV)</th>
<th>$\Gamma_{cm}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{33}\text{P}_2$</td>
<td>$2^-; 1$</td>
<td>$2.190 \pm 0.025$</td>
<td>$17.985 \pm 0.025$</td>
<td>$3.012 \pm 0.007$</td>
</tr>
<tr>
<td>$^{33}\text{F}_3$</td>
<td>$3^-; 1$</td>
<td>$8.984 \pm 0.054$</td>
<td>$24.779 \pm 0.054$</td>
<td>$6.754 \pm 0.110$</td>
</tr>
<tr>
<td>$^{33}\text{F}_4$</td>
<td>$4^-; 1$</td>
<td>$9.095 \pm 0.055$</td>
<td>$24.890 \pm 0.055$</td>
<td>$5.316 \pm 0.112$</td>
</tr>
<tr>
<td>$^{33}\text{P}_2$</td>
<td>$2^-; 1$</td>
<td>$10.795 \pm 0.065$</td>
<td>$26.590 \pm 0.065$</td>
<td>$8.684 \pm 0.125$</td>
</tr>
</tbody>
</table>


the calculations of (1990BLZW, 1993DU02, 1993FI06).

Elastic scattering (reaction (d)) angular distributions were measured at $E(3\text{He}) = 5.00$ to 32.3 MeV and excitation functions were reported for $E(3\text{He}) = 4.3$ to 33.4 MeV see (1979AJ01). At the lower energies the elastic yield is structureless and decreases monotonically with energy. Polarization measurements were reported for $E_t = 9.02$ to 33.3 MeV. A strong change occurs in the analyzing power angular distributions at $E_t = 15$ MeV. See (1988AJ01) for a description of earlier analyses of these data. More recently a new resonance analysis (1990HE20, 1990MO10) of these same data along with $^3\text{He}^\left(^3\text{H},\gamma\right)$ data led to the $^6\text{Li} S = 1, T = 1$ states discussed above under reaction 3(a). See Table 6.5. A coupled-channels variational model calculation of the $^3\text{He}$(total) cross section for $E_t = 9$ MeV has been reported by (2001TH12).


4. (a) $^3\text{H}(\alpha, n)^6\text{Li}$
   
   $Q_m = -4.7829$

   (b) $^3\text{H}(\alpha, \alpha d)n$
   
   $Q_m = -6.25725$

   (c) $^3\text{H}(\alpha, t^3\text{He})n$
   
   $Q_m = -20.57762$

$^6\text{Li}^*(0, 2.19)$ have been populated with reaction (a): see (1974AJ01). See also $^7\text{Li}$ (1983CO1E) and (1983FU11). Cross sections for $E_\alpha < 20$ MeV were calculated with a resonating group method by (1991FU02). A kinematically complete experiment on reaction (b) at $E_\alpha = 67.2$ MeV is described in (2000GO35). $^6\text{Li}$ excited states at $E_x = 14.5$ and 16.0 MeV with widths $\approx 1$ MeV are reported. In a similar experiment (1999GO36) at $E_\alpha = 67.2$ MeV on reaction (c) a $^6\text{Li}$ level at $E_x \approx 20–21$ MeV was reported based on the energy of the final state between $^3\text{H}$ and $^3\text{He}$.

5. $^3\text{He}^\left(^3\text{He}, \pi^+\right)^6\text{Li}$
   
   $Q_m = -123.7941$
Differential cross sections were measured for the transitions to \(^6\text{Li}^*(0, 2.19)\) for \(E(\text{^3\text{He}) = 350, 420, 500 \text{ and 600 MeV (1983LE26). See also (1984AJ01), (1983BR31, 1983JA13) and (1984GE05). Analyses of data for \(E(\text{^3\text{He}) = 295–810 \text{ MeV and microscopic reaction model calculations are reported by (1991HA22). See also the calculations of (1999VO01).}}\)

\[ Q_m = 1.4743 \]

The previous review (1988AJ01) summarized the information on this reaction as follows: “No resonance has been observed corresponding to formation of \(^6\text{Li}^*(3.56) [0^+; T = 1]\): the parity-forbidden \(\Gamma_\alpha \leq 6 \times 10^{-7} \text{ eV (1984RO04)\". See also (1984BU01, 1986BU07). \n
“The cross section for the capture cross section has been measured for \(E_\alpha = 3 \text{ to 25 MeV by detecting the recoiling \(^6\text{Li ions: the direct capture is overwhelmingly E2 with a small E1 contribution. The spectroscopic overlap between the \(^6\text{Li}_g.s. and \(\alpha + d is 0.85 \pm 0.04: see (1984AJ01). See also (1982KI1A, 1985CA41, 1986LA22, 1986LA27) and theoretical work presented in (1984AK01, 1985AK1B, 1986AK1C, 1986BA1R).\”\n
Since the previous review (1988AJ01), measurements of the cross section at energies \(E_\alpha \approx 2 \text{ MeV corresponding to the 3^+ resonance at } E_\kappa = 2.186 \text{ MeV in } ^6\text{Li have been reported (1994MO17). Values extracted for the total width } \Gamma \text{ and the radiative width } \Gamma_\gamma \text{ confirm the adopted value (1988AJ01). An experimental search for the reaction at } E_{\text{cm}} \approx 53 \text{ keV (1996CE02) gave an upper limit for the } S \text{ factor of } 2 \times 20^{-7} \text{ MeV} \cdot \text{b at the 90\% confidence level. Implications for Big Bang nucleosynthesis of } ^6\text{Li are discussed. Thermonuclear reaction rates for this reaction calculated from evaluated data are presented in the compilation (1999AN35).} \n
A considerable amount of theoretical work has been devoted to this reaction – much of it related to its importance in astrophysics. A list of references with brief descriptions is provided in Table 6.6.

\[ Q_m = -2.224 \quad E_b = 1.475 \]

\[ Q_m = -14.320 \]

Reaction (a) has been studied to \(E_\alpha = 165 \text{ MeV and to } E_d = 21.0 \text{ MeV: see (1979AJ01, 1984AJ01). Measurements are also reported at } E_d = 5.4, 6.0 \text{ and 6.8 MeV (1985LU08), 6 to 11 \text{ MeV (1985OS02), 10.05 MeV (1983BR23) and 12.0 and 21.0 MeV (1983IS10) and at } E_\alpha = 11.3 \text{ MeV (1987BR07). See also (1986DO1K). \n
More recently, measurements of the cross section and transverse tensor analyzing power at \(E_d = 7 \text{ MeV were made (1988GA14) with kinematic conditions chosen to correspond to production of the singlet deuteron. Coulomb and nuclear field effects in these reactions are discussed in (1987KO1X, 1988KA38). Cross sections and polarization observables from data at } E_d < 12, 17 \text{ MeV are compared with three-body model predictions in (1988SU12).} \n
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Table 6.6: $^4$He(d, $\gamma$)$^6$Li – Theoretical work

<table>
<thead>
<tr>
<th>Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1989CR01</td>
<td>D-state effects in the $^4$He(d, $\gamma$)$^6$Li reaction</td>
</tr>
<tr>
<td>1989SC25</td>
<td>The reaction rate at $T = 300$ K for $^2$H($\alpha$, $\gamma$)$^6$Li and other reactions</td>
</tr>
<tr>
<td>1990CR04</td>
<td>Tensor interaction effects in $^4$He(d, $\gamma$)$^6$Li</td>
</tr>
<tr>
<td>1990KRZX</td>
<td>Polarization observables for $^4$He(d, $\gamma$)$^6$Li and the D state of $^6$Li</td>
</tr>
<tr>
<td>1990SC22</td>
<td>The extended elastic model II applied to $^2$H($\alpha$, $\gamma$)$^6$Li</td>
</tr>
<tr>
<td>1991SC23</td>
<td>A simple expression for the cross-section factor in nuclear fusion</td>
</tr>
<tr>
<td>1991TY02</td>
<td>Low-energy $^2$H($\alpha$, $\gamma$)$^6$Li and $^{208}$Pb($^6$Li, d$\alpha$)$^{208}$Pb cross sections</td>
</tr>
<tr>
<td>1993JA02</td>
<td>Polarizability and E1 radiation in $^4$He(d, $\gamma$)$^6$Li</td>
</tr>
<tr>
<td>1993MU12</td>
<td>Calculation of the $^6$Li $\rightarrow \alpha + d$ vertex constant</td>
</tr>
<tr>
<td>1994MO17</td>
<td>Direct capture in the $3^+$ resonance of $^2$H($\alpha$, $\gamma$)$^6$Li</td>
</tr>
<tr>
<td>1995DU12</td>
<td>Cluster model descriptions of $^6$Li photodisintegration</td>
</tr>
<tr>
<td>1995IG06</td>
<td>Analysis of the nuclear astrophysical reaction $^5$He(d, $\gamma$)$^6$Li</td>
</tr>
<tr>
<td>1995MU21</td>
<td>Astrophysical factor for $^4$He(d, $\gamma$)$^6$Li</td>
</tr>
<tr>
<td>1995MU11J</td>
<td>Peripheral astrophysical radiative capture processes, a survey</td>
</tr>
<tr>
<td>1995RY01</td>
<td>$^4$He(d, $\gamma$)$^6$Li capture and the isoscalar E1 multipole</td>
</tr>
<tr>
<td>1997NO04</td>
<td>Nuclear reaction rates and primordial $^6$Li</td>
</tr>
<tr>
<td>1998KH06</td>
<td>Microscopic study of $^2$H($\alpha$, $\gamma$)$^6$Li in a multicluster model</td>
</tr>
<tr>
<td>2000IG03</td>
<td>Coulomb breakup &amp; astrophys. $S$-factor of $^2$H($\alpha$, $\alpha$) at extremely low energies</td>
</tr>
<tr>
<td>2001NO01</td>
<td>Six-body calculation of the $^2$H($\alpha$, $\gamma$)$^6$Li cross section</td>
</tr>
</tbody>
</table>

For reaction (b), measurements of vector and tensor analyzing power at $E_d = 35, 45$ MeV have been reported (1986BR1N, 1986VA23, 1986VUZZ, 1987VU1A). Cross sections and polarization observables were measured at $E_d = 32.1, 35.15, 39.6, 49.7$ MeV to investigate $^3$H and $^3$He asymptotic normalization constants (1987VU1B) and charge symmetry breaking (1988VU01). Cross sections and polarization observables measured at $E_{cm} = 14–33$ MeV (1989BR23) were compared with microscopic-model predictions in a study of isospin violation. See also (1990BR09). The role of tensor force was explored in (1988BR18).

For earlier work and other breakup channels, see (1988AJ01).

8. $^4$He(d, d)$^4$He $E_b = 1.4743$

Elastic differential cross-section and polarization measurements have been carried out up to $E_\alpha = 166$ MeV and $E_d = 45$ MeV; see (1974AJ01, 1979AJ01, 1984AJ01). Measurements were also reported at $E_d = 0.87$ to 1.43 MeV (1984BA19, 1985BAYZ), at $E_d = 11.9$ MeV (1988EL01), 21 MeV (1986M11E), 24.0 and 38.2 MeV (1986GR1D), 31.8 to 39.0 MeV (1986KO1M), 40 MeV (1989DE1A), 56 MeV (1985NI01) and at $E_\alpha = 7.0$ GeV/c (1984SA39). A compilation of data
Table 6.7: Levels of $^6$Li from $^4$He(d, d)$^4$He $^a$

<table>
<thead>
<tr>
<th>$E_d$ (MeV)</th>
<th>$J^\pi; T$</th>
<th>$E_x$ (MeV)</th>
<th>$\Gamma_{cm}$ (MeV)</th>
<th>$\Gamma_d/\Gamma$ $^b$</th>
<th>$\gamma_2^2$ $^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.070 ± 0.003</td>
<td>3$^+$; 0</td>
<td>2.187</td>
<td></td>
<td></td>
<td>0.27</td>
</tr>
<tr>
<td>4.34 ± 0.04</td>
<td>2$^+$; 0</td>
<td>4.36</td>
<td>1.32 ± 0.04</td>
<td>0.967</td>
<td>0.511</td>
</tr>
<tr>
<td>5.7 ± 0.1 $^d$</td>
<td>1$^+$; 0</td>
<td>5.3</td>
<td>1.9 ± 0.1</td>
<td>0.74</td>
<td>0.34</td>
</tr>
<tr>
<td>(19.3 ± 1.3)</td>
<td>3$^+$; 0</td>
<td>(14.3)</td>
<td>26.7 ± 1.0</td>
<td>0.34</td>
<td>1.69</td>
</tr>
<tr>
<td>(21.6 ± 1.1)</td>
<td>3$^+$; 0</td>
<td>(15.8)</td>
<td>17.8 ± 0.8</td>
<td>0.76</td>
<td>0.77</td>
</tr>
<tr>
<td>33 ± 2</td>
<td>4$^+$</td>
<td>23</td>
<td>12 ± 2</td>
<td>0.15</td>
<td>0.14</td>
</tr>
<tr>
<td>34 ± 5</td>
<td>3$^-$</td>
<td>24</td>
<td>16 ± 3</td>
<td>0.30</td>
<td>0.24</td>
</tr>
<tr>
<td>39$^{+3}_{-0}$</td>
<td>2$^-$</td>
<td>27</td>
<td>22 ± 7</td>
<td>0.43</td>
<td>0.42</td>
</tr>
</tbody>
</table>

$^a$ The data in this table are mostly from the S-matrix analysis of (1983JE03). The results are unique up to $E_d = 15$ MeV. See also Table 6.4 in (1974AJ01), and Tables 6.3 in (1979AJ01) and (1984AJ01).

$^b$ The errors in $\Gamma_d/\Gamma$ are typically 0.03.

$^c$ In units of the Wigner limit $\gamma_2^2 = 2.93$ MeV for a radius of 4.0 fm. See (1988AJ01).

$^d$ 6.26 MeV ($R$-matrix analysis): $E_x = 5.65$ MeV.


Phase-shift analyses, particularly that by (1983JE03) which uses all available differential cross section, vector and tensor analyzing power measurements and $L \leq 5$, in the range $E_d = 3$ to 43 MeV lead to the results displayed in Table 6.7. It is found that the d-wave shifts are split and exhibit resonances at $E_x = 2.19$ ($^3$D$_3$), 4.7 ($^3$D$_2$) and 5.65 MeV ($^3$D$_1$). (1983JE03) suggest very broad $G_3$ and $G_4$ resonances at $E_d = (19.3)$ and 33 MeV, a $D_3$ resonance at 22 MeV and $F_3$ and $F_2$ resonances at $\approx 34$ and $\approx 39$ MeV, corresponding to states which are primarily of $(d + \alpha)$ parentage.

(1985JE04) have investigated the points where $A_{yy} = 1$ and report four such points at $E_d = 4.30$ [$\theta_{cm} = 120.7^\circ$, 4.57 ($58.0^\circ$), 11.88 ($55.1^\circ$) and 36.0 ± 1.0 MeV (150.1 ± 0.3$^\circ$)]. [For the latter see also (1986KO1M)]. The correspondence of these polarization maxima to $^6$Li states is discussed by (1985JE04). For a discussion of the $M$-matrix see (1988EL01). For work on $(\alpha + d)$ correlations involving $^6$Li*$(0, 2.19, 4.31 + 5.65)$ see (1987CH08, 1987CH33, 1987PO03) and (1987FO08).

For additional references to early work see references cited in (1988AJ01).

A considerable body of theoretical work on the $^4$He + d channel has been done since the previous review (1988AJ01). A list of references with brief descriptions is provided in Table 6.8.

9. (a) $^4$He($^3$He, p)$^6$Li $\quad Q_m = -4.0192$
### Table 6.8: $^4$He(d, d)$^4$He – Theoretical work

<table>
<thead>
<tr>
<th>Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988BE58</td>
<td>Polarization phenomena in $^4$He(d, d) at intermediate energies</td>
</tr>
<tr>
<td>1988KA25</td>
<td>Convergence features in the pseudostate theory of the $d + \alpha$ system</td>
</tr>
<tr>
<td>1988WE20</td>
<td>Manifestations of the D-state in light nuclei</td>
</tr>
<tr>
<td>1989ET05</td>
<td>Description of diffraction scattering on nuclei</td>
</tr>
<tr>
<td>1989FI1E</td>
<td>Microscopic theory of collective resonances of light nuclei</td>
</tr>
<tr>
<td>1989KR08</td>
<td>Padé approximation technique for processing scattering data</td>
</tr>
<tr>
<td>1990BL13</td>
<td>Analysis of higher partial waves in $^4$He(d, d) in 3-body framework</td>
</tr>
<tr>
<td>1990DA1H</td>
<td>Two body phase space in $\alpha$-d breakup at 40 MeV</td>
</tr>
<tr>
<td>1990GU23</td>
<td>D-wave effect in $\alpha$-d elastic scattering at intermediate energies</td>
</tr>
<tr>
<td>1990HO1R</td>
<td>Microscopic study of clustering phenomena</td>
</tr>
<tr>
<td>1990HU09</td>
<td>A geometric model for nucleus-nucleus scattering at high energies</td>
</tr>
<tr>
<td>1990KU06</td>
<td>Reconstruction of interaction potential from scattering data</td>
</tr>
<tr>
<td>1990KU16</td>
<td>Padé-approximation techniques for processing scattering data</td>
</tr>
<tr>
<td>1990LI11</td>
<td>Further study of $\alpha$ elastic scattering on light nuclei</td>
</tr>
<tr>
<td>1991BL04</td>
<td>Manifestation of Pauli-forbidden states in $^4$He(d, d) at low energies</td>
</tr>
<tr>
<td>1991KR02</td>
<td>Energy-dependent phase-shift analysis of $^4$He(d, d) at low energies</td>
</tr>
<tr>
<td>1991KU09</td>
<td>d-$\alpha$ scattering in a three-body model</td>
</tr>
<tr>
<td>1991KU27</td>
<td>Recovering $\alpha + d$ potential from Faddeev and measured phase shifts</td>
</tr>
<tr>
<td>1992ES04</td>
<td>$\alpha$-d resonances and the low-lying states of $^6$Li</td>
</tr>
<tr>
<td>1992FU10</td>
<td>Reaction mechanisms in $A = 6$ with the multiconfiguration RGM</td>
</tr>
<tr>
<td>1992KU16</td>
<td>Supersymmetric potentials and the Pauli Principle in $^4$He(d, d)</td>
</tr>
<tr>
<td>1992KU1G</td>
<td>Deuteron size effects in d-$\alpha$ scattering</td>
</tr>
<tr>
<td>1993BL09</td>
<td>Determination of $^6$Li $\rightarrow \alpha + d$ vertex constant for d-$\alpha$ phase-shifts</td>
</tr>
<tr>
<td>1993FI06</td>
<td>Study of continuous spectrum of $^6$Li in RGM</td>
</tr>
<tr>
<td>1994CS01</td>
<td>Microscopic description of beta-delayed deuteron emission in $^6$He</td>
</tr>
<tr>
<td>1995DU12</td>
<td>Cluster model description of photonuclear processes in $^6$Li</td>
</tr>
<tr>
<td>1997DU15</td>
<td>Electromagnetic effects in light nuclei and the cluster potential</td>
</tr>
<tr>
<td>1997KU14</td>
<td>Reconstruction of analytic $S$ matrix from experimental d-$\alpha$ data</td>
</tr>
<tr>
<td>1998DU03</td>
<td>Potential cluster model description of the d-$\alpha$ interaction</td>
</tr>
<tr>
<td>1999CO11</td>
<td>An $S$-matrix inversion technique applied to $\alpha$-d scattering</td>
</tr>
</tbody>
</table>
Angular distributions have been measured at $E(\text{^3He}) = 8$ to 18 MeV and $E_\alpha = 42, 71.7$ and 81.4 MeV: see (1974AJ01). More recently, proton polarization was measured as a function of angle at $E_{cm} = 12.6$ MeV (1989GR02). At $E_\alpha = 28, 63.7, 71.7$ and 81.4 MeV the $\alpha$-spectra show that the sequential decay (reaction (b)) involves $^6\text{Li}^*(2.19)$ and possibly $^5\text{Li}$: see (1979AJ01). See also the recent theoretical work of (1993GO16) and the multiconfiguration RGM calculations of (1995FU16).

10. (a) $^4\text{He}(\alpha, \text{d})^6\text{Li}$
   \[ Q_m = -22.3722 \]
   (b) $^4\text{He}(\alpha, \text{pn})^6\text{Li}$
   \[ Q_m = -24.5968 \]
   (c) $^4\text{He}(\alpha, \alpha\text{d})^2\text{H}$
   \[ Q_m = -23.84653 \]

Reactions (a) and (b) have been studied to $E_\alpha = 158.2$ MeV [see (1979AJ01, 1984AJ01)] and at 198.4 MeV (1985WO11). The dependence of the cross section on energy shows that the $\alpha + \alpha$ process does not contribute significantly to $^6\text{Li}$ (and $^7\text{Li}$) synthesis above $E_\alpha = 250$ MeV (1985WO11) [and see for additional comments on astrophysical problems]. A more recent measurement of the cross section for reaction (b) (2001AU06, 2001ME13) at $E_\alpha = 159.3, 279.6$ and 619.8 MeV found cross sections which differ significantly from tabulated values commonly used in cosmic-ray production calculations and lead to lower predicted production of $^6\text{Li}$. For reaction (c) [and excited states of $^4\text{He}$] see (1984AJ01): $^6\text{Li}^*(2.19)$ is involved in the process.

11. $^6\text{He}(\beta^-)^6\text{Li}$
   \[ Q_m = 3.508 \]
   See $^6\text{He}$, reaction 1.

12. (a) $^6\text{He}(\text{p, n})^6\text{Li}$
   \[ Q_m = 2.7254 \]
   (b) $^6\text{He}(\text{p, p})^6\text{He}$

The (p, n) reaction has been studied in inverse kinematics by $^1\text{H}(^6\text{He}, ^6\text{Li})\text{n}$ experiments with secondary $^6\text{He}$ beams. An experiment utilizing a secondary $^6\text{He}$ beam with $E(^6\text{He}) = 42$ MeV/A was reported by (1995CO05, 1998CO1M, 1998CO19, 1998CO28). The $^6\text{Li}$ ground state and $E_x = 3.56$ MeV state were observed. Angular distributions were reported and the ratio of the cross section for the Gamow-Teller transition to the ground state and the Fermi transition to the isobaric analog state was measured. The reaction was also studied at $E/A = 93$ MeV (1996BR30). The $0^\circ$ ground state cross section was measured to be \( \frac{d\sigma}{d\Omega} = 43 \pm 16 \text{ mb/sr} \). The ratio of Gamow-Teller to Fermi strength was found to be $(87 \pm 6)\%$ of that expected from p, n systematics and
beta decay. Differential cross sections at $E/A = 41.6$–68 MeV were measured by (1997CO04) to study the effects of halo structure. Measurements on reactions (a) and (b) utilizing a secondary $^6$He beam at 36 MeV/A are reported by (2001DE19).

The status of theoretical and experimental research on nuclei featuring a two-particle halo was reviewed in (1996DA31).

13. $^6$Li*$(0^+; 1) \rightarrow \alpha + d$ $Q_m = 2.0886$

A theoretical study in a microscopic three-cluster model of the parity-violating $\alpha + d$ decay of the lowest $0^+$ state in $^6$Li ($E_x = 3.5629$ MeV) is described in (1996CS03). A phase shift analysis of $^4$He + d was used in a determination of the vertex constant for the $^6$Li$(1^+; 0)_{g.s.} \rightarrow \alpha + d$ virtual decay by (1992BLZX, 1993BL09, 1997KU14). See also (1990RY07, 1991KR02, 1993BO38).

14. (a) $^6$Li($\gamma$, n)$^5$Li $Q_m = -5.389$
   (b) $^6$Li($\gamma$, p)$^5$He $Q_m = -4.497$
   (c) $^6$Li($\gamma$, d)$^4$He $Q_m = -1.4743$
   (d) $^6$Li($\gamma$, np)$^4$He $Q_m = -3.6989$
   (e) $^6$Li($\gamma$, t)$^3$He $Q_m = -15.7947$

The previous review (1988AJ01) summarizes the information on these reactions as follows: “The ($\gamma$, n) and ($\gamma$, Xn) cross sections increase from threshold to a maximum at $E_\gamma \approx 12$ MeV then decrease to $E_\gamma = 32$ MeV: see (1984AJ01) and (1988DI02). (1984DY01) also report a broad peak at 16 MeV. The cross section for photoproton production (reaction (b)) is generally flat up to 90 MeV. [The previously reported hump at $E_\gamma \approx 16$ MeV is almost certainly due to oxygen contamination: see (1984AJ01).] See also (1988CA11) and $^5$He. The cross section for reaction (c) is $\leq 5 \mu$b in the range $E_\gamma = 2.6$ to 17 MeV consistent with the expected inhibition of dipole absorption by isospin selection rules: see (1966LA04). The onset of quasideuteron photodisintegration between 25 and 65 MeV is suggested by the study of (1984WA18; $E_\gamma$(bremsstrahlung) = 67 MeV). The $90^\circ$ differential cross section for reaction (e) decreases monotonically for $E_\gamma = 18$ to 70 MeV: reaction (e) contributes $\approx \frac{1}{3}$ of the total cross section for $^6$Li + $\gamma$, consistent with a $^3$H + $^3$He cluster description of $^6$Li$_{g.s.}$ with $\theta^2 \approx 0.68$. The agreement with the inverse reaction, $^3$H($^3$He, $\gamma$) [see reaction 3] is good: see (1984AJ01). See also (1986LI1F).”

“The absorption cross section has been studied in the range $E_\gamma \approx 100$ to 340 MeV; it shows a broad bump centered at $\approx 125$ MeV and a fairly smooth increase to a maximum at $\approx 320$ MeV: see (1984AJ01). For spallation studies see (1974AJ01, 1984AJ01). For pion production see (1986GL07, 1987GL01) and (1984AJ01).”

Since the previous review (1988AJ01) tagged photons were used to study $^6$Li($\gamma$, p) at $\theta_p = 0^\circ$ for $E_\gamma \approx 59$ and 75 MeV. Strong evidence for the photo-deuteron mechanism was found.
Table 6.9: $^6$Li($\gamma$, X) – Theoretical work

<table>
<thead>
<tr>
<th>Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988DU04</td>
<td>Calculation of the $^6$Li($\gamma$, d$\gamma'$) cross section at $E_\gamma = 2.23$ MeV</td>
</tr>
<tr>
<td>1989AR02</td>
<td>Quark degrees of freedom and nuclear photoabsorption</td>
</tr>
<tr>
<td>1990BU29</td>
<td>Possibility (?) of observing an isoscalar E1 multipole in $^6$Li($\gamma$, d)</td>
</tr>
<tr>
<td>1990VA16</td>
<td>Cluster effects in $^6$Li photodisintegration</td>
</tr>
<tr>
<td>1990ZH19</td>
<td>Manifestations of cluster structure in $^6$Li($\gamma$, d)</td>
</tr>
<tr>
<td>1991BE05</td>
<td>$^6$Li $\to \alpha + d$ break-up — astrophysical significance</td>
</tr>
<tr>
<td>1995DU12</td>
<td>Description of photonuclear processes in $^6$Li</td>
</tr>
</tbody>
</table>

Measurements made for angles between $30^\circ$ and $150^\circ$ (1995DI01) showed most of the strength occurring in three-body breakup channels. Studies at these same energies of the ($\gamma$, d) and ($\gamma$, t) reaction were reported in (1997DI01). See also (1994RY01). Measurements of $^6$Li($\gamma$, d) at $E_\gamma \approx 60$ MeV indicated strict non-violation of the isospin selection rule for E1 absorption.

The ($\gamma$, pn) reaction was also studied at $E_\gamma = 55$–$100$ MeV with bremsstrahlung photons and with linearly polarized tagged photons for $E_\gamma = 0.3$–$0.9$ GeV. See also (1990RIZX).

Linearly polarized photons were used to measure the cross section asymmetry in $^6$Li($\gamma$, t)$^3$He up to $E_\gamma \approx 70$ MeV (1989BU10) and differential cross sections up to $E_\gamma \approx 90$ MeV (1993DE07, 1995BU08). Results of a measurement of the absolute total photoabsorption cross section for $E_\gamma = 300$–$1200$ MeV are presented in (1994BI06).

A list of theoretical references relating to $^6$Li photonuclear reactions with brief descriptions is provided in Table 6.9.

15. $^6$Li($\gamma$, $\gamma$)$^6$Li

The width, $\Gamma_\gamma$, of $^6$Li*(3.56) = $8.1 \pm 0.5$ eV: see (1974AJ01) and Table 6.4 in (1979AJ01); $E_x = 3562.88 \pm 0.10$ keV: see (1984AJ01). See also (1987PI06). The results of an absolute measurement of the total photoabsorption cross section are described in (1994BI06). Photon absorption and photon scattering for light elements is discussed in terms of a collective resonance phenomenon in (1990ZI03).

16. (a) $^6$Li($\gamma$, $\pi^0$)$^6$Li $\quad Q_m = -134.97660$
(b) $^6$Li($\gamma$, $\pi^+$)$^6$He $\quad Q_m = -143.0780$
(c) $^6$Li($\gamma$, $\pi^-$)$^6$Be $\quad Q_m = -143.8579$

Measurements of neutral-pion photoproduction yield (reaction (a)) for $E < 10$ MeV above threshold were reported in (1989NA23). The total cross section was measured in the energy region
from the reaction threshold to \( E_\gamma \approx 146.5 \) MeV (1989GL07) and analyzed in the impulse approximation. The cross section increases monotonically to \( \sigma = 6.50 \pm 0.96 \) \( \mu b \) at \( E_\gamma = 146.5 \) MeV. See also (1986GL07, 1987GL01) and (1984AJ01). An analysis (1991TR1C) of early measurements suggests that anomalously large measured values of the cross section are due to target impurities. The differential cross section at small angles at energies \( E \approx 300-450 \) MeV has been measured by (1991BE16). Total and differential cross sections were measured within 23 MeV of threshold with tagged photons by (1999BE14). Differential cross sections for reaction (b) leading to the \(^6\)He ground state have been measured at \( E_\gamma = 200 \) MeV (1991SH02) and analyzed by DWBA. See also the measurements of (1991GA26). The energy distributions of electroproduced \( \pi^+ \) at \( E_e \approx 200 \) MeV were measured and \((\gamma, \pi^+)\) cross sections were deduced (1994SH38). For reaction (c) see (1988KA41, 1991GA26).

Theoretical studies of pion photoproduction include: an impulse-approximation calculation for \((\gamma, \pi^0)\) at \( E_\gamma = 300 \) MeV (1989TR09); an impulse approximation and shell model study of inelastic photoproduction of pions (1991TR02); a DWIA Feynman-diagram production-operator-based calculation of \((\gamma, \pi^+)\) at \( E_\gamma = 200 \) MeV (1990BE49); and multicluster dynamic-model calculation of \( \pi^+ \) photoproduction off \(^6\)Li (1995ER1B); and an exclusive \((\gamma, \pi^+)\) production calculation for \( E_\gamma = 200 \) MeV (1995DO24).

17. (a) \(^6\)Li(e, e)\(^6\)Li
(b) \(^6\)Li(e, ep)\(^5\)He \(Q_m = -4.497\)
(c) \(^6\)Li(e, ed)\(^4\)He \(Q_m = -1.4743\)
(d) \(^6\)Li(e, et)\(^3\)He \(Q_m = -15.7947\)

The previous review (1988AJ01) summarized the information then available on electron scattering as follows: “The elastic scattering has been studied for \( E_e = 85 \) to 600 MeV: see (1974AJ01, 1979AJ01, 1984AJ01). The results appear to require that the ground state be viewed as an \( \alpha\)-d cluster in which the deuteron cluster is deformed and aligned. The ground-state M1 current density has also been calculated (1982BE11). A model-independent analysis of the elastic scattering yields \( r_{\text{r.m.s.}} = 2.51 \pm 0.10 \) fm. See also the discussion in (1984DO20).”

“Table 6.10 summarizes the results obtained in the inelastic scattering of electrons. Form factors have been measured for \(^6\)Li*\((2.19, 3.56, 5.37)\) as well as for the t+\(^3\)He continuum up to 4 MeV above threshold [no narrow structures corresponding to \(^6\)Li states are observed]: see (1984AJ01)”. In more recent work, nucleon spin structure functions were extracted from measurements of deep inelastic scattering on polarized targets by (1999RO13).

For reaction (b) see \(^5\)He and (1987VA08) and (1987VA1N). Angular distributions for the \( d_0 \) group in the \((e, d_0)\) reaction have been measured for \( E_x = 10 \) to 28 MeV. The deduced E1 and E2 components of the \((\gamma, d_0)\) cross section show no structure. The E1 strength implies non-negligible isospin mixing in this energy region (1986TA06). Triple differential cross sections were measured for \( E_x = 27-49 \) MeV in a search for GDR evidence (1999HO02). At \( E_e = 480 \) MeV (reaction (c)) the \( \alpha\)-d momentum distribution in the ground state of \(^6\)Li has been studied. The results are well
Table 6.10: Levels of $^6$Li from $^6$Li(e, $e'$) and $^6$Li(γ, $\gamma'$) $^a$

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$J^\pi; T$</th>
<th>$\Gamma_\gamma$ (eV)</th>
<th>Multipolarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.183 ± 0.009</td>
<td>3$^+$; 0</td>
<td>$(4.40 ± 0.34) \times 10^{-4}$ $^b$</td>
<td>E2</td>
</tr>
<tr>
<td>3.56288 ± 0.00010c</td>
<td>0$^+$; 1</td>
<td>8.19 ± 0.17 $^d$</td>
<td>M1</td>
</tr>
<tr>
<td>4.27 ± 0.04</td>
<td>2$^+$; 0</td>
<td>$(5.4 ± 2.8) \times 10^{-3}$</td>
<td>E2</td>
</tr>
<tr>
<td>5.379 ± 17 $^d$, $^e$</td>
<td>2$^+$; 1</td>
<td>0.27 ± 0.05</td>
<td>M1</td>
</tr>
</tbody>
</table>

$^a$ See Tables 6.4 in (1979AJ01, 1984AJ01) for references and for the earlier work.

$^b$ (1969EI06), $B$(E2)$\dagger = 25.6 \pm 2.0$ $e^2 \cdot $fm$^4$. The value given in (1988AJ01) was incorrect. We are grateful to Dr. John Millener for pointing out this error.

$^c$ (1981RO02).

$^d$ Weighted mean of values shown in Table 6.4 in (1979AJ01).

$^e\Gamma = 540 \pm 20$ keV.

accounted for by an $\alpha$NN model. The $\alpha$-d probability in the ground state of $^6$Li is 0.73 [estimated $\pm 0.1$]. The data are consistent with the expected 2$S$ character of the $\alpha$-d relative wave function (1986EN05). See also (1986EV1A). $\pi^0$ production involving $^6$Li*(2.19, 3.56, 5.37) is reported at $E_e = 500$ MeV (1987NA1I).

For the earlier work see (1979AJ01, 1984AJ01) and the references cited in (1988AJ01). Since the previous review (1988AJ01), experimental results on quasielastic response have been reviewed (1988LO1E). Measurements of the quasielastic scattering cross section for electrons on $^6$Li are reported at momentum transfer 0.85–2.3 fm$^{-1}$ (1988BU25). See also the measurements at $E_e = 80–680$ MeV by (1989LI09). Cross sections for $^6$Li(e, ep) were measured in the missing energy region $0 \leq E_m \leq 30$ MeV and in the range $-100 \leq p_m \leq 200$ MeV/c of missing momentum (1989LA22). The $^6$Li $\rightarrow p + (n\alpha)$ spectral function was measured (1989LA13). The ratio of transverse and longitudinal response function was investigated in (1990LA06). See also the review (1990DE16) of proton spectral functions and momentum distributions in (e, $e'p$) experiments and see the report (1990GH1E) on nuclear density dependence of electron proton coupling in $^6$Li(e, $e'p$).

Reaction (c) was used (1990JO1D) in a study of correlation functions in $^6$Li. A measurement in parallel kinematics to study the mechanism of the $^6$Li(e, $e'\alpha$)$^3$H reaction is reported in (1991MI19, 1994EN04). Cross sections for $^6$Li(e, $e'\alpha$)$^3$He (reaction (d)) at $E_e = 523$ MeV and the momentum-transfer dependence of the $^3$H and $^3$He knockout reaction was measured by (1998CO06).

A list of references to theoretical work related to electron scattering on $^6$Li is provided, along with brief descriptions, in Table 6.11.

18. (a) $^6$Li($\pi^\pm$, $\pi^\pm$)$^6$Li
   (b) $^6$Li($\pi^+$, $\pi^-$)
<table>
<thead>
<tr>
<th>Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1987KR07</td>
<td>EM properties of $^6\text{Li}$ in cluster model</td>
</tr>
<tr>
<td>1987LE1N</td>
<td>Coincidence reactions and the 3-body structure of $^6\text{Li}$</td>
</tr>
<tr>
<td>1988AL1J</td>
<td>Second Born approximation correction to $^6\text{Li}$ electron scattering</td>
</tr>
<tr>
<td>1988ES01</td>
<td>Elastic electromagnetic form factors of $^6\text{Li}$ from 3-body models</td>
</tr>
<tr>
<td>1989ER07</td>
<td>Exchange and correlation effects in EM structure of $^6\text{Li}$</td>
</tr>
<tr>
<td>1989ES05</td>
<td>Inelastic $(1^+ \rightarrow 0^+)$ EM form factor of $^6\text{Li}$ with 3-body models</td>
</tr>
<tr>
<td>1989KU21</td>
<td>Correlation and exchange effects in EM form factors</td>
</tr>
<tr>
<td>1990BE54</td>
<td>Analysis of $^6\text{Li}(e,e')^6\text{Li}$ transitions to the low-lying $^6\text{Li}$ levels</td>
</tr>
<tr>
<td>1990DE1V</td>
<td>NN correlations, evidence from $^6\text{Li}(e,e'p)^5\text{He}$</td>
</tr>
<tr>
<td>1990KU12</td>
<td>Detailed study of EM structure of $^6\text{Li}$ from 3-body model</td>
</tr>
<tr>
<td>1990LU06</td>
<td>Calculation of the magnetic form factor of $^6\text{Li}$</td>
</tr>
<tr>
<td>1990RE1I</td>
<td>Parity-invariance violation in $^6\text{Li}(e,e'd)^4\text{He}$</td>
</tr>
<tr>
<td>1990WA1J</td>
<td>Occupation probabilities of shell-model orbitals</td>
</tr>
<tr>
<td>1991LU07</td>
<td>Magnetic form factor of $^6\text{Li}$</td>
</tr>
<tr>
<td>1991UN02</td>
<td>$^6\text{Li}$ elastic form factors and antisymmetrization</td>
</tr>
<tr>
<td>1992JO02</td>
<td>Two-body correlations in $^6\text{Li}$ through the $(e, e'd)$ reaction</td>
</tr>
<tr>
<td>1992LO09</td>
<td>Multiquark configuration effect on nuclear charge form factor</td>
</tr>
<tr>
<td>1992LOZX</td>
<td>Short-range correlation in the 6-body $^6\text{Li}$ wave function</td>
</tr>
<tr>
<td>1992RYZY</td>
<td>EM properties of $^6\text{Li}$ in multicluster dynamic model</td>
</tr>
<tr>
<td>1992ZH18</td>
<td>Calculation of $^6\text{Li}(e, ed)$ cross section in $\alpha 2\text{N}$ model</td>
</tr>
<tr>
<td>1993KU27</td>
<td>Prohibition and suppression of multicluster states by Pauli principle</td>
</tr>
<tr>
<td>1993RY01</td>
<td>$^6\text{Li}$ properties — multicluster dynamic model</td>
</tr>
<tr>
<td>1993SC30</td>
<td>Nucleon polarization in 3-body models of polarized Li</td>
</tr>
<tr>
<td>1994BO04</td>
<td>Shell model calculation of magnetic electron scattering</td>
</tr>
<tr>
<td>1994WE10</td>
<td>$^6\text{Li}$ inelastic form factors in a cluster model</td>
</tr>
<tr>
<td>1995AR10</td>
<td>Halo structure in $^6\text{Li}$ $E_x = 3.563$ 0$^+$ state</td>
</tr>
<tr>
<td>1995DO23</td>
<td>Phenomenological transition amplitudes in selected p-shell nuclei</td>
</tr>
<tr>
<td>1995KU08</td>
<td>Cluster structure of $^6\text{Li}$ low-lying states</td>
</tr>
<tr>
<td>1995MA59</td>
<td>Finite-size effects in quasi-elastic scattering — Fermi gas model</td>
</tr>
<tr>
<td>1998WI10</td>
<td>Quantum Monte Carlo calculations for light nuclei</td>
</tr>
<tr>
<td>1998WI28</td>
<td>Microscopic calculation of $^6\text{Li}$ elastic &amp; transition form factors</td>
</tr>
<tr>
<td>1999GN01</td>
<td>Multicluster calculation of $^6\text{Li}(e,e')$ asymmetric &amp; polarization ratios</td>
</tr>
</tbody>
</table>
Elastic angular distributions have been measured at $E_{\pi^+} \approx 50$ MeV [see (1984AJ01)] and at $E_{\pi^\pm} = 100, 180$ and 240 MeV (1986AN04; also to $^6\text{Li}^*(2.19)$). Differential cross sections are also reported for $E_{\pi^+} = 100$ to 260 MeV to $^6\text{Li}^*(0, 2.19, 3.56, 4.25)$. The excitation function for the unnatural-parity transition to $^6\text{Li}^*(3.56)$ has an anomalous energy dependence (1984KI16).

A number of experimental studies with polarized targets have been reported for elastic and inelastic ($E_\pi(^6\text{Li}) = 2.19$ MeV, $J^\pi = 3^+$) scattering. Measurements of polarization observables are reported at $E_{\pi^+} = 134, 164$ MeV (1989TA21, 1990TA1L, 1991BO1R), $E_{\pi^+} = 160$–219 MeV (1991RI01, 1994RI06). Comparison of these data with a coupled channels model is discussed in (1995BO1H). See also the $\Delta$-hole model analysis of (1992JU1B) and the multicluster dynamic model analysis by (1995RY1C). Calculations of cross sections and polarization observables at $E_{\pi^+} = 80$–260 MeV are presented in (1988ER06, 1988NA06). A theoretical study in terms of a strong absorption model is described in (1998AH06). Quantum Monte-Carlo calculations of cross sections for $E_\pi = 100$–240 MeV are reported in (2001LE01). Transition densities and $B(E2)$ transition strengths were also calculated.

Measurements of pion double-charge exchange cross section (reactions (b) and (c)) at incident pion energies $E_\pi = 180, 240$ MeV are reported in (1989GR06, 1995FO1J). In (1991SE06) it is shown that continuum missing mass spectra from reaction (c) can be explained in terms of the presence of dineutrons in the products of the breakup.

Cross section measurements for reaction (d) at $E_{\pi^+} = 130, 150$ MeV are reported in (1987HU02). For a study of reaction (i) at $E_{\pi^+} = 130$ MeV, see (1987HU13).

Pion absorption followed by nucleon emission (reactions (e), (f), (g), (h), (j), (k), (l)) has been studied in a number of experiments. For reaction (k) see (1983BA26, 1983LO10, 1985MC05, 1986MC11). Measurements have been reported for cross sections for reaction (g) at $E_{\pi^+} = 30, 50, 80, 115$ MeV (1989ROZY); reactions (g) and (h) angular distributions at $E_\pi = 70, 130, 165$ MeV (1989Y005); reactions (g) and (h) angular correlations at $E_\pi = 165$ MeV (1989YO07); cross sections for reaction (g) at $E_{\pi^+} = 115, 140, 165, 190, 220$ MeV (1989ZHZZ); angular distributions for reaction (h) at $E_\pi = 70, 130, 165$ MeV (1989YO03); two-particle coincidences for reactions (g) and (h) at low energies (1991YO1C); cross sections at $E_{\pi^+} = 50, 100, 150, 200$
MeV (1990RA05, 1990RA20, 1992RA01, 1992RA11); differential and total cross sections for reaction (g) at $E_{\pi^+} = 100, 165$ MeV (1995PA22, 1996LO04); inclusive spectra of $^3$He produced in reaction (l) (1992AM1H, 1993AM09); total reaction cross sections for $(\pi^+, X), (\pi^-, X)$ at $E_{\pi^+} = 42–65$ MeV (1996SA08). See also the earlier work on reaction (g) at $E_{\pi^+} = 59.4$ MeV (1986RI01), and see the compilation and review of (1992BA57, 1993IN01).

Analysis of particle emission following $\pi^+$ absorption on $^6$Li (1990RA20) has produced evidence for a three-nucleon absorption model. Distorted-wave impulse approximation calculations of cross sections and analyzing powers have been made (1992KH04) for two-nucleon pion absorption on polarized $^6$Li targets. A model based solely on isospin was used (1993MA14) in a calculation of ratios of pion absorption on three nucleons and agreement with experiment suggest a one-step process.

19. (a) $^6$Li(n, n)$^6$Li
   (b) $^6$Li(n, nd)$^4$He
   (c) $^6$Li(n, p)$^6$He
   (d) $^6$Li(n, d)$^5$He
   (e) $^6$Li(n, t)$^4$He
   (f) $^6$Li(n, $\alpha$)$^3$H

Angular distributions involving the groups to $^6$Li*$(0, 2.19)$ have been reported at $E_n = 1.0$ to 14.6 MeV [see (1984AJ01)], 4.2, 5.4 and 14.2 MeV (1985CH37; $n_0$, $n_1$), 7.5 to 14 MeV (1983DA22; $n_0$), 8.9 MeV (1984FE1A; $n_0$), 8.0 and 24 MeV (1986HAZR; $n_0$, $n_1$), $E_n = 5$ to 17 MeV (1986PF1A; $n_0$), 11.5, 14.1 and 18 MeV (1998CH33; $n_0$, $n_1$), and at 11.5 and 18.0 MeV (1998IB02; $n_0$, $n_1$).

An analysis (1988HA25) of (n, n) and (n, n') data at $E_n = 24$ MeV indicated that neutron and proton transition densities were approximately equal ($\rho_n \approx \rho_p$) in $^6$Li. Cross sections and analyzing powers for $E_n = 8–40$ MeV were analyzed (1989HAZV) with microscopic optical model potentials. Secondary neutron spectra induced by 14.2 MeV neutrons on $^6$Li were measured by (1993XI04).

An analysis of (n, n') data at $E_n = 7.45–14$ MeV is discussed in (1990BE54). See also the calculation for elastic coherent and incoherent scattering of thermal neutrons on $^6$Li (1990GO26) and the multi-cluster dynamic model calculation for $^6$Li(n, n) at $E_n = 12$ MeV (1992KA06).


For reaction (b) see (1984AJ01, 1985CH37, 1993XI04, 1994EL08).

A number of experiments on the (n, p) charge exchange (reaction (c)) have been reported. They include: measurements of $\sigma(E_p)$ and $\sigma(\theta)$ at $E_n \approx 198$ MeV (1987HE22); $\sigma(\theta, E_p)$ at $E_n \approx 118$ MeV (1987PO18, 1988HA12, 1998HA24); $\sigma(\theta)$ at $E_n = 198$ MeV (1988JA01); $\sigma(\theta)$ to explore
the Gamow-Teller sum rule (1988WA24); \(\sigma(\theta), \sigma(E)\) at \(E_n = 280\) MeV for an isospin symmetry test (1990MI10); \(\sigma(\theta, E)\) at \(E_n = 60–260\) MeV (1992SO02); and polarization observables at \(E_n = 0.88\) GeV (1996BB23).

For reaction (e), measurements were reported at thermal neutron energies (1994IT04) and at \(E_n < 10\) MeV (1994DR11). For reaction (f), measurements of parity violation with cold polarized neutrons are described in (1990VE16, 1993VE1A, 1996VE02). A discussion of nuclear reaction rates and primordial \(^6\)Li is presented in (1997NO04). See also the application-related calculation of (1993FA01).

Theoretical work related to reactions (b), (c), (d), (e), (f) includes: dynamical cluster-model calculation (1991DA08); microscopic calculation in a 3-particle \(\alpha + 2N\) model (1993SH1G); supermultiplet-symmetry-approximation calculation at \(E_n = 6.77\) MeV (1993DU09); multiconfiguration RGM calculation (1995FU16); and three-body cluster model calculations of \(^6\)Li(n, p) at \(E_n = 50\) MeV (1997DA01, 1997ER05).

20. (a) \(^6\)Li(p, p)\(^6\)Li
(b) \(^6\)Li(p, 2p)\(^5\)He \(Q_m = -4.497\)
(c) \(^6\)Li(p, pd)\(^4\)He \(Q_m = -1.4743\)
(d) \(^6\)Li(p, p\(^3\)H)\(^3\)He \(Q_m = -15.7947\)
(e) \(^6\)Li(p, pn)\(^5\)Li \(Q_m = -5.39\)

Proton angular distributions have been measured for \(E_p = 0.5\) to 800 MeV [\(p_0, p_1, p_2, p_3\)] [see (1966LA04, 1974AJ01, 1984AJ01)] and at \(E_p = 5\) to 17 MeV (1986PF1A; \(p_0\)).

Double-differential cross sections for the continuum yield [\(E_x = 1.5–3.5\) MeV] are reported at \(E_p = 65\) MeV (1987TO06). See also (1983GLZZ, 1983PO1B, 1983POZX). More recently differential cross sections and/or polarization observables have been measured at \(E_p = 6–10\) MeV (1989HA17) [optical model analysis]; \(E_p = 1.6–10\) MeV (1989HA18) [phase shift analysis]; \(E_p = 65, 80\) MeV (1989TO04) [DWIA analysis]; \(E_p = 200\) MeV (1990GL04); \(E_p = 65\) MeV (1992NA02) [microscopic DWBA analysis]; \(E_p = 72\) MeV (1994HE11) [depolarization parameters]; \(E_p < 2.2\) MeV (1995SK01) [deduced resonance parameters]; \(E_p = 0.88\) GeV (1996BB23) [polarized target]; \(E_p = 250–460\) keV (1997BR37); \(E_p = 280\) MeV (1990MI10) [deduced isospin symmetry test]; \(E_p = 14\) MeV [optical model, coupled channels]; \(E(\(^6\)Li) = 62, 72, 75\) MeV/A, \(\(^1\)H(\(^6\)Li, p)\) [neutron halo states] (1996KUZU); \(E_p = 1.6–2.4\) GeV (1999BB21, 1999DE47). For a summary of the results on excited states see Table 6.12.

Reaction (b) was studied at 70 MeV (1983GO06), at 50–100 MeV (1984PA1B, 1985PA1B) and 1 GeV (1985BE30, 1988BE2B, 2000MI17); see \(^3\)He and (1984AJ01) for the earlier work. Reaction (c) has been studied at \(E_p = 9\) MeV to 1 GeV [see (1974AJ01, 1979AJ01, 1984AJ01)] and at 20 and 42 MeV (1983CA13) [report involvement of \(^6\)Li*\((4.31, 5.65)\)] at 70 MeV (1983GO06, 1985PA1C, 1985PA04) and at 119.6 and 200.2 MeV (1984WA09, 1985WA25). In the latter experiments the spectroscopic factors for \(^6\)Li_{g.s.} are deduced to be 0.76 [at 119.6 MeV] and 0.84

Work on reaction (d) has suggested that the \(^4\)He + t parentage of \(^6\)Li is comparable with the \(\alpha + d\) parentage: see (1984AJ01). See also (1985PA1C). Reaction (e) was studied at \(E_p = 70\) MeV (1988PA27). See also \(^5\)Li, \(^6\)Be and (1985BE30, 1993ST06). The \((p, 3p)\) reaction has been studied by (1984NA17). The spectral function for pn pairs in \(^6\)Li was obtained in a study of the \(^6\)Li(p, p\(\alpha\))pn reaction at \(E_p = 200\) MeV (1990WA17). A measurement of tensor analyzing powers in \(^1\)H(\(^6\)Li, d or \(\alpha\) or t)X with 4.5 GeV polarized \(^6\)Li deuterons provided information on the \(^6\)Li D state (1992PU03). Systematic studies of electron screening effects on low energy reactions including \(^6\)Li + p are reported in (1992EN01, 1992EN04, 1995RO37). For antiproton studies see (1987AS06). See also (1984AJ01, 1988AJ01) for the earlier work.

Theoretical work on these reactions reported since the previous review (1988AJ01) is listed in Table 6.13 along with brief descriptions.

21. (a) \(^6\)Li(d, d)\(^6\)Li  
(b) \(^6\)Li(d, pn)\(^6\)Li  
(c) \(^6\)Li(d, 2d)\(^4\)He  
(d) \(^6\)Li(d, \(\alpha\)p)\(^3\)H  
(e) \(^6\)Li(d, \(\alpha\)n)\(^3\)He

Angular distributions of deuterons have been measured at \(E_d = 4.5\) to 19.6 MeV [see (1979AJ01)] and at 50 MeV (1988KO1C, 1996RU10). The \(0^+, T = 1\) state, \(^6\)Li* (3.56) is not appreciably populated. For a summary of the results on excited states see Table 6.12. Gaussian potentials were derived for the description of \(^6\)Li + d elastic scattering by (1992DU07).

At \(E_d = 21\) MeV reaction (b) shows spectral peaking (characteristic of \(^1\)S\(_0\) for the pn system [\(T = 1\)]) when \(^6\)Li* (3.56) is formed, in contrast with the much broader shape (characteristic of \(^3\)S\(_1\)) seen when \(^6\)Li* (0, 2.19) are populated. A study of reaction (c) at \(E_d = 52\) MeV shows that the \(\alpha\)-clustering probability, \(N_{\text{eff}} = 0.12^{+0.12}_{-0.06}\) if a Hankel function is used. The \(\alpha\)-particle and the deuteron clusters in \(^6\)Li have essentially a relative orbital momentum of \(l = 0\). The D-state probability of the ground state of \(^6\)Li is \(\approx 5\%\) of the S-state. Quasi-free scattering is an important process even for \(E_d = 6\) to 11 MeV. Interference effects are evident in reaction (c) proceeding through \(^6\)Li* (2.19, 4.31): this is due to the experiment being unable to determine whether the detected particle was emitted first or second in the sequential decay. Reactions (c) and (d) studied at \(E_d = 7.5\) to 10.5 MeV indicate that the three-body breakup of \(^6\)Li at these low energies is dominated by sequential decay processes (1979AJ01, 1990YA11). Differential cross sections for cluster pickup by 20 MeV/A deuterons on \(^6\)Li were measured by (1995MA57).

Calculation of Maxwellian rate parameters for reaction (d) and (e) are described in (2000VO08). See also \(^8\)Be and references cited in (1988AJ01).
Table 6.12: Parameters of levels of $^6\text{Li}$

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$\Gamma_{cm}$ (keV)</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.185 ± 3</td>
<td>20.0 ± 2.8</td>
<td>$^4\text{He}(d, d)^4\text{He}$</td>
</tr>
<tr>
<td>2.187 ± 3</td>
<td></td>
<td>$^4\text{He}(d, d)^4\text{He}$</td>
</tr>
<tr>
<td>2.188 ± 6</td>
<td>24 ± 2 $^b$</td>
<td>$^6\text{Li}(p, p'), (d, d'), ^7\text{Li}(d, t)^6\text{Li}$</td>
</tr>
<tr>
<td>2.203 ± 6</td>
<td></td>
<td>$^9\text{Be}(p, \alpha)^6\text{Li}$</td>
</tr>
<tr>
<td>2.186 ± 2</td>
<td>24 ± 2</td>
<td>“best” value</td>
</tr>
<tr>
<td>3.56288 ± 0.10 $^c$</td>
<td>$(8.2 \pm 0.2) \times 10^{-3} , ^c$</td>
<td>$^6\text{Li}(\gamma, \gamma')^6\text{Li}$</td>
</tr>
<tr>
<td>4.36 ± 40</td>
<td>1320 ± 40</td>
<td>$^4\text{He}(d, d)^4\text{He}$</td>
</tr>
<tr>
<td>4.27 ± 40</td>
<td></td>
<td>$^6\text{Li}(e, e')^6\text{Li}$</td>
</tr>
<tr>
<td>4.40 ± 120</td>
<td>1490 ± 150</td>
<td>$^6\text{Li}(p, p')^6\text{Li}$</td>
</tr>
<tr>
<td>4.32 ± 40</td>
<td>1820 ± 110</td>
<td>$^6\text{Li}(d, d')^6\text{Li}$</td>
</tr>
<tr>
<td>4.3 ± 100</td>
<td>600 ± 100</td>
<td>$^7\text{Li}(^3\text{He}, \alpha)^6\text{Li}$</td>
</tr>
<tr>
<td>4.3 ± 200</td>
<td>1600 ± 300</td>
<td>$^7\text{Li}(^3\text{He}, \alpha d)^4\text{He}$</td>
</tr>
<tr>
<td>4.3</td>
<td>1600 ± 120 $^e$</td>
<td>$^7\text{Li}(^3\text{He}, \alpha d)^4\text{He}$</td>
</tr>
<tr>
<td>4.30 ± 10</td>
<td>850 ± 50, 480 ± 80</td>
<td>$^9\text{Be}(p, \alpha)^6\text{Li}$</td>
</tr>
<tr>
<td>4.312 ± 22</td>
<td>1300 ± 100 $^f$</td>
<td>“best” value</td>
</tr>
<tr>
<td>5.379 ± 17 $^g$</td>
<td>540 ± 20 $^g$</td>
<td>$^6\text{Li}(e, e')^6\text{Li}$</td>
</tr>
<tr>
<td></td>
<td>546 ± 36 $^d$</td>
<td>$^6\text{Li}(e, e')^6\text{Li}$</td>
</tr>
<tr>
<td>5.33 ± 80</td>
<td>$560^{+340}_{-100}$</td>
<td>$^6\text{Li}(p, p')^6\text{Li}$</td>
</tr>
<tr>
<td>5.34 ± 20</td>
<td>560 ± 40 $^b$</td>
<td>$^7\text{Li}(^3\text{He}, \alpha)^6\text{Li}$</td>
</tr>
<tr>
<td>5.325 ± 5</td>
<td>270 ± 12</td>
<td>$^9\text{Be}(p, \alpha)^6\text{Li}$</td>
</tr>
<tr>
<td>5.366 ± 15</td>
<td>541 ± 20 $^h$</td>
<td>“best” value</td>
</tr>
<tr>
<td>5.65 ± 50 $^i$</td>
<td>1900 ± 100</td>
<td>$^4\text{He}(d, d)^4\text{He}$</td>
</tr>
<tr>
<td>5.7</td>
<td>$1000^{+600}_{-400}$</td>
<td>$^6\text{Li}(p, p')^6\text{Li}$</td>
</tr>
<tr>
<td>5.65 ± 200</td>
<td>1650 ± 300</td>
<td>$^7\text{Li}(^3\text{He}, \alpha d)^4\text{He}$</td>
</tr>
<tr>
<td>5.65 ± 40</td>
<td>$900 \pm 60, 1260 \pm 120$</td>
<td>$^9\text{Be}(p, \alpha)^6\text{Li}$</td>
</tr>
<tr>
<td>5.65 ± 50</td>
<td>1500 ± 200</td>
<td>“best” value</td>
</tr>
</tbody>
</table>
For references and other values see Tables 6.5 in (1979AJ01, 1984AJ01, 1988AJ01).


(1981RO02).

(1979BE38).

Average of measurements for $E(\text{He}) = 4, 5, 6$ MeV (1995AR14).

Weighted average of “best” values from (1988AJ01) and values of $1320 \pm 40$ keV (Table 6.7), $1044 \pm 58$ keV (1979BE38), and $1600 \pm 120$ keV from (1995AR14).

See Table 6.4 in (1979AJ01).

Weighted average of “best” values from (1988AJ01) and $546 \pm 36$ keV from (1979BE38).

See Table 6.3 in (1979AJ01).

See references (c) and (d) in Table 6.5 in (1979AJ01).

At $E_t = 17$ MeV angular distributions have been measured for the tritons to $^6\text{Li}*(0, 3.56)$: see (1979AJ01).

23. (a) $^6\text{Li}(^3\text{He}, ^3\text{He})^6\text{Li}$

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

$Q_m = 16.878$

Angular distributions have been measured at $E(^3\text{He}) = 8$ to $217$ MeV [see (1979AJ01, 1984AJ01)] and at $34, 50, 60$ and $72$ MeV (1986BR31; elastic).

More recently, differential cross sections were measured for elastic scattering at $E(^3\text{He}) = 93$ MeV (1994DO32), and at $E(^4\text{He}) = 60$ MeV (1995MA57), and for inelastic scattering to $^6\text{Li}*(E_x = 2.185$ MeV, $J^\pi = 3^+)$ at $E(^3\text{He}) = 50, 60, 72$ MeV (1995BU20). A microscopic-potential analysis of data at $E(^3\text{He}) = 34, 50, 60, 72$ MeV is described in (1993SI06). Differential cross section and energy spectra were compiled and analyzed by (1995MI16). For reaction (b), cross sections have been measured at $E(^3\text{He}) = 11, 13, 14$ MeV (1989ARZI, 1989AR08); $E(^3\text{He}) = 2.5$ MeV (1989AR20); $E(^3\text{He}) = 1.6$ MeV (1991AR25); $E(^3\text{He}) = 1.6$–$9$ MeV (1992AR20); $E(^3\text{He}) = 8$–$14$ MeV (1995KO51); $E(^3\text{He}) = 2.0, 22$ MeV (1992DA1K); $E(^3\text{He}) = 7, 9$ MeV (1993AR12). A calculation of near-threshold two-fragment resonance amplitudes and widths for this reaction at $E(^3\text{He}) = 8$–$14$ MeV was reported in (1995KO51). See also $^5\text{Li}$ (1984AR17, 1987ZA07) and see $^9\text{B}$ in (1988AJ01).

24. (a) $^6\text{Li}(\alpha, \alpha)^6\text{Li}$

(b) $^6\text{Li}(\alpha, 2\alpha)^2\text{H}$

$Q_m = -1.4743$

Angular distributions (reaction (a)) have been measured at $E_\alpha = 1.39$ to $166$ MeV [see (1974AJ01, 1979AJ01, 1984AJ01)] and at $E_\alpha = 36.6$ and $50.5$ MeV (1986BR31). See also (1986ROZK, 1987BU27). See also $^{10}\text{B}$ in (1988AJ01).
More recent measurements at \( E_\alpha = 50.5 \text{ MeV} \) of elastic and inelastic \( ^6\text{Li}^* (E_\chi = 2.185 \text{ MeV}, J^\pi = 3^+) \) were reported by (1994BUZY, 1996BU06). Tensor polarization for inelastic scattering to \( ^6\text{Li}^* (2.185, 3^+) \) has been measured at \( E_\alpha = 80 \text{ MeV} \) (1992KO19, 1993KO33). Angular distributions for (\( \alpha, \alpha' \)) in the continuum region were studied at \( E_\alpha = 50 \text{ MeV} \) (1992SA01) and at \( E_\alpha = 40 \text{ MeV} \) (1994SA32), at \( E_\alpha = 10 \text{ MeV} / A \) (1996SI13) and at \( E_\alpha = 119 \text{ MeV} \) (1993OK1A). Cross sections and analyzing powers for elastic scattering of polarized \( ^6\text{Li} \) by \( ^4\text{He} \) are reported for \( E(^6\text{Li}) = 50 \text{ MeV} \) (1995KE10) and \( E_{cm} = 11.1 \text{ MeV} \) (1996GR08).

Studies of continuum coupling effects in inelastic scattering are described in (1995KA1Y, 1995KA43, 1997RU06, 1998RU1C, 2000RU03). Folding-model potential analyses of elastic scattering are reported in (1993SI09, 1995SA12). Multiconfiguration resonating group methods applied to the \( ^6\text{Li} + \alpha \) system are discussed in (1994FU17, 1995FU11). Other recent theoretical studies include: a potential model description (1999MA02); analysis of density distribution influence (1998GO1J); a phase-shift-analysis determination of the asymptotic \( D- \) to \( S- \) state ratio (1999GE02); a calculation for \( E_\alpha = 16.3 \) and \( 48 \text{ MeV} \) with a modified Volkov-potential (2000KO52); and a calculation of the nuclear potential and polarization tensor for \( E_\alpha = 27.2 \text{ MeV} \) (2000KO67). See also (1988KO32, 1989LE07, 1999OG09).

Reaction (b) has been studied at \( E_\alpha = 6.6 \) to \( 700 \text{ MeV} \); see (1974AJ01, 1979AJ01, 1984AJ01). At the latter energy and using a width parameter of 60.6 MeV/c the effective number of \( \alpha + d \) clusters for \( ^6\text{Li}_{g.s.}, n_{\text{eff}} = 0.98 \pm 0.05 \). The results are very model dependent: see (1984AJ01). At \( E_\alpha = 27.2 \text{ MeV} \) \( ^6\text{Li}^* (2.19) \) is very strongly populated (1985KO29). See also references cited in (1988AJ01).

In more recent work, two dimensional coincidence spectra of charged particles were measured at \( E_\alpha \approx 100 \text{ MeV} \) (1992GA18). Quasi-free scattering processes were studied at \( E_\alpha = 77–119 \text{ MeV} \) (1992KO01), \( E_\alpha = 118 \text{ MeV} \) (1993KO1B), and \( E_\alpha = 118.4 \text{ MeV} \) (1997KO01). The four-body \( ^6\text{Li}(\alpha, 2\alpha)\text{pn} \) breakup reaction was measured at \( E_\alpha = 77–119 \text{ MeV} \) (1992WA18, breakup cross sections); \( E_\alpha = 118 \text{ MeV} \) (1988WA29, 1989WA26; spectral functions of pn pair).

25. (a) \( ^6\text{Li}(^6\text{Li}, ^6\text{Li})^6\text{Li} \)
   (b) \( ^6\text{Li}(^6\text{Li}, 2d)^4\text{He}^4\text{He} \) \( Q_m = -2.9487 \)
   (c) \( ^6\text{Li}(^6\text{Li}, \alpha)^4\text{He}^4\text{He} \) \( Q_m = 20.8979 \)

Angular distributions of \( ^6\text{Li} \) ions have been studied for \( E(^6\text{Li}) = 3.2 \) to \( 36 \text{ MeV} \) [see (1974AJ01, 1979AJ01, 1984AJ01)] and at \( E(^6\text{Li}) = 2.0 \) to \( 5.5 \text{ MeV} \) (1983NO08) and \( 156 \text{ MeV} \) (1985SA36; \( ^6\text{Li}^* (0, 2.19) \)), (1985MI05; elastic; \( ^6\text{Li}^* (2.19, 3.56) \) are also populated), (1987EY01; several states in \( ^{12}\text{C} \)). Reaction (b) has been studied for \( E(^6\text{Li}) = 36 \) to \( 47 \text{ MeV} \); enhancements in yield, due to double spectator poles, have been observed in d-d and \( \alpha-\alpha \) but not in \( \alpha-d \) double coincidence spectra. The widths of the peaks are smaller than those predicted from the momentum distribution of \( \alpha + d \) clusters in \( ^6\text{Li} \). \( ^6\text{Li}^* (2.19) \) was also populated. See references in (1984AJ01). Other work on reaction (b) is reported by (1984LA19: 2.4 and 4.2 MeV) and by (1985NO1A).

For reaction (c), the energy dependence of quasi-free effects were investigated in the range \( E(^6\text{Li}) = 2.4–6.7 \text{ MeV} \) (1987LA25, 1988LA11). An analysis (1996CH1C) used quasi-free data.
### Table 6.13: $^6$Li(p, p)$^6$Li – Theoretical work

<table>
<thead>
<tr>
<th>Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988HA25</td>
<td>$^6$Li proton and neutron transition densities from elastic scattering</td>
</tr>
<tr>
<td>1990ZH1R</td>
<td>Quasi resonating group method analysis of $^6$Li(p, p)$^6$Li</td>
</tr>
<tr>
<td>1992GA27</td>
<td>Folding-model study of elastic scattering in halo nuclei</td>
</tr>
<tr>
<td>1993DU09</td>
<td>Potential description of N + $^6$Li elastic scattering</td>
</tr>
<tr>
<td>1993KO44</td>
<td>Description of $^6$Li(p, p)$^6$Li with microscopic effective interaction</td>
</tr>
<tr>
<td>1993PE13</td>
<td>Folding model description of $^6$Li(p, p)$^6$Li at 25–50 MeV</td>
</tr>
<tr>
<td>1993SA10</td>
<td>DWBA analysis of $^6$Li(p, p)$^6$Li near the α-d breakup threshold</td>
</tr>
<tr>
<td>1994ZH28</td>
<td>Elastic and inelastic proton scattering on $^6$Li nucleus at intermediate energies</td>
</tr>
<tr>
<td>1994ZH34</td>
<td>Glauber-Sitenko diffraction theory calculation of $^6$Li(p, p)$^6$Li</td>
</tr>
<tr>
<td>1995GA24</td>
<td>Analysis of properties of exotic nuclei in elastic scattering</td>
</tr>
<tr>
<td>1995KA03</td>
<td>Folding-model analysis of $^6$Li(p, p)$^6$Li at $E_p = 10–136$ MeV</td>
</tr>
<tr>
<td>1995KA07</td>
<td>Continuum-continuum coupling in $^6$Li(p, p)$^6$Li at $E_p = 65$ MeV</td>
</tr>
<tr>
<td>1995KA43</td>
<td>Folding-model analysis of $^6$Li(p, p)$^6$Li at $E_p = 10–136$ MeV</td>
</tr>
<tr>
<td>1997DO01</td>
<td>Fully microscopic model analyses of $^6$Li(p, p)$^6$Li at $E_p = 200$ MeV</td>
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<tr>
<td>1997KA24</td>
<td>Shell model structures of $^6$Li states excited in $^6$Li(p, p)$^6$Li</td>
</tr>
<tr>
<td>1998DO16</td>
<td>Microscopic analysis of $^6$Li(p, p) at $E_p = 65$ MeV</td>
</tr>
<tr>
<td>2000TI02</td>
<td>Finite-range coupled channels calculation for $^6$He + p rxn</td>
</tr>
<tr>
<td>2000DE61</td>
<td>Microscopic model analysis of $^6$Li(p, p)$^6$Li for $E_p = 25, 30, 40$ MeV</td>
</tr>
<tr>
<td>2000LA40</td>
<td>Resonance optical model analysis for $^6$Li(p, p)$^6$Li for $E_p = 1–10$ MeV</td>
</tr>
<tr>
<td>2000ZQ40</td>
<td>Glauber-Sitenko diffraction theory calculation for $E_p = 0.16–1.04$ GeV</td>
</tr>
<tr>
<td>2001AR05</td>
<td>Microscopic multicluster calculation for $^6$He + p at $E_{cm} = 0–5$ MeV</td>
</tr>
</tbody>
</table>

from reaction (c) to extract the $^6$Li(d, α)$^4$He excitation function at astrophysical energies. See also $^{12}$C in (1985AJ01) and references cited in (1988AJ01).

More recently, elastic scattering angular distributions were measured for $E(^6$Li) = 5–40 MeV (1997PO03; optical model analysis). Eikonal-approximation calculations of differential cross sections and phase shifts for $E(^6$Li) = 156 MeV were reported in (1992EL1A).

26. $^6$Li($^7$Li, $^7$Li)$^6$Li

Angular distributions have been measured at $E(^7$Li) = 78 MeV to $^6$Li*(0, 2.19) (1986GLZU), and at $E(^7$Li) = 9–40 MeV (1998PO03).

27. $^6$Li($^9$Be, $^9$Be)$^6$Li

39
The elastic scattering has been studied in inverse kinematics at $E(\text{Li}) = 4.0, 6.0$ and 24 MeV [see (1979AJ01)], at 32 MeV (1985COO9) and at 50 MeV (1988TRZY): also inelastic. Recently angular distributions for elastic and inelastic scattering to $^6\text{Li}(2.186, 3^+)$ were measured (1995MU01) at $E_{\text{cm}} = 7, 10, 12$ MeV. Excitation functions for $E_{\text{cm}} \approx 4$–12 were also reported. See also $^9\text{Be}$ in (1988AJ01). For the interaction cross section at $E(\text{Li}) = 790$ MeV$A$ see (1985TA18).

28. $^6\text{Li}(^{10}\text{B}, ^{10}\text{B})^6\text{Li}$

The elastic scattering has been studied at $E(\text{Li}) = 5.8$ and 30 MeV: see (1979AJ01).

29. (a) $^6\text{Li}(^{12}\text{C}, ^{12}\text{C})^6\text{Li}$
   (b) $^6\text{Li}(^{13}\text{C}, ^{13}\text{C})^6\text{Li}$
   (c) $^6\text{Li}(^{14}\text{C}, ^{14}\text{C})^6\text{Li}$

The elastic and inelastic scattering (reaction (a)) has been studied at $E(\text{Li}) = 4.5$ to 156 MeV [see (1984AJ01)] and at $E(\text{Li}) = 19.2$ MeV (1983RU09), 36 and 45 MeV [and $E(^{12}\text{C}) = 72$ and 90 MeV] (1984VI02, 1985VI03; also to $^6\text{Li}*(2.19, 4.31)$ and to various states of $^{12}\text{C}$), at $E(^{12}\text{C}) = 58.4$ MeV (1987PA12), 90 MeV (1987DE02; also to various states of $^{12}\text{C}$), 123.5 and 168.6 MeV (1988KA09; and to various states of $^{12}\text{C}$), 150 MeV (1987TA21, 1988TA08), 156 MeV (1987EY01; and to various states in $^{12}\text{C}$) and at 210 MeV (1988NA02). See also (1986SHZP, 1987PA12). More recently, measurements of cross sections and/or analyzing power observables have been reported at $E(\text{Li}) = 93$ MeV (1989DE34); at $E_{\text{cm}} = 13.3$ MeV ((1989HN1A, 1995CA26) and to $^6\text{Li}*(3^+, 2.186)$ and $^{12}\text{C}*(2^+, 4.44)$; at $E(\text{Li}) = 210$ MeV (1989NA11, to $^{12}\text{C}*(2^+, 4.44)$; at $E(\text{Li}) = 30$ MeV (1989VA04, to $^{12}\text{C}*(2^+, 4.44)$; at 50 MeV (1990TR02, to $^{12}\text{C}*(2^+, 4.44; 0^+, 7.65; 3^-, 9.64)$); at $E(\text{Li}) = 30$ MeV (1994RE01); at $E(\text{Li}) = 30, 60$ MeV (1996KE09, to $^{12}\text{C}*(2^+, 4.44; 0^+, 7.65; 3^-, 9.64)$; at $E_{\text{cm}} = 20$ MeV (1996GA29, to $^6\text{Li}*(3^+, 2.18)$ and $^{12}\text{C}*(2^+, 4.44)$; at $E(\text{Li}) = 318$ MeV (1993NA01); at $E(\text{Li}) = 30$ MeV (1994RE15, to $^{12}\text{C}*(2^+, 4.44; 3^-, 9.64)$); and at $E(\text{Li}) = 50$ MeV (1995KE10). At $E(\text{Li}) = 34$ MeV the d-α angular correlations involve $^6\text{Li}*(0, 2.19)$ (1985CU04). See also (1988SE07), and see $^{12}\text{C}$ in (1985AJ01, 1990AJ01). An experimental study of the α+d breakup in $^6\text{Li}+^{12}\text{C}$ collision at $E(\text{Li}) = 156$ MeV is reported in (1989JE01). For pion production see (1984CH16). For the interaction cross section at $E(\text{Li}) = 790$ MeV$A$ see (1985TA18). For VAP measurements at $E(\text{Li})= 30$ MeV see (1988VAZY). Fusion cross sections for $E(\text{Li}) = 3.11$–12.07 MeV are reported by (1998MU12).

The elastic scattering (reaction (b)) has been studied for $E(\text{Li}) = 5.8$ to 40 MeV; see (1984AJ01). Measurements of differential cross sections for $E_{\text{cm}} = 26$ MeV and observations of a nuclear quasi rainbow were reported by (1994DE43). See also (1987CA30, 1988WO10). The elastic scattering (reaction (c)) has been measured for $E(\text{Li}) = 93$ MeV (1987DE02). See also $^{18}\text{F}$ and $^{19}\text{F}$ in (1987AJ02) and references cited in (1988AJ01).
Several theoretical studies relating to $^6$Li + $^{12}$C have been reported. The role of the Pauli Principle in heavy ion scattering has been studied (1988GR32). The dispersive contribution to the $^6$Li + $^{12}$C real potential was estimated (1990KA14). Elastic cross sections for $E(^6$Li) = 30 MeV were analyzed (1990SA05). A semimicroscopic analysis of inelastic scattering at $E(^6$Li) = 156 MeV is described in (1992GA17). Folding model analysis of $^6$Li + $^{12}$C scattering is discussed in (1994NA03, 1994SA10, 1995KH03). Differential cross sections were analyzed with an S-matrix approach by (1998PI02).

Other theoretical descriptions of $^6$Li + $^{12}$C scattering are discussed in (1994SA33; strong absorption model), (1995IS1F; multiple diffraction interaction), and (1996CA01; microscopic description).

30. $^6$Li($^{16}$O, $^{16}$O)$^6$Li

Elastic angular distributions have been reported at $E(^6$Li) = 4.5 to 50.6 MeV [see (1984AJ01)], at $E(^6$Li) = 35.3 and $E(^{16}$O) = 94.2 MeV (1984VI02) and at 50 MeV (1988TRZY; also inelastic). At $E(^{16}$Li) = 25.7 and $E(^{16}$O) = 68.6 MeV (1984VI01, 1985VI03) report some $\sigma(\theta)$ to $^6$Li*(2.19) [and to $^{16}$O*(6.13)]. See also (1987PA12). See (1985VI03, 1986SC28) for studies of the breakup. Polarization observables have been measured at $E(^6$Li) = 25.7 MeV, and also using $^{16}$O ions (1987VAZY, 1989VA04). Measurements of $E(^6$Li) = 50 MeV for elastic scattering and inelastic scattering to $^{16}$O*(2+, 6.05; 3−, 6.13; 2+, 6.92; 1−, 7.12) were reported (1990TR02). For fusion cross sections see (1986MA19). See also $^{16}$O in (1986AJ04), (1986MO1E, 1987PA12) and references cited in (1988AJ01). Theoretical work on this scattering reaction includes: $E(^6$Li) = 29.8 MeV, optical model description (1990SA05); $E(^6$Li) = 29.8–30.6 MeV, Pauli Principle rule (1988GR32); $E(^6$Li) = 30.6, optical model analysis (1990SA05); projectile effects (1991BO48); $E(^6$Li) = 154 MeV, 3-body cluster model (1991HI07); $E(^6$Li) = 22.8 MeV, nonresonant breakup states (1991HI11); and $E(^6$Li) = 30 MeV, double-folding model, role of Pauli Principle (1991SA26).

31. (a) $^6$Li($^{24}$Mg, $^{24}$Mg)$^6$Li
   (b) $^6$Li($^{25}$Mg, $^{25}$Mg)$^6$Li
   (c) $^6$Li($^{26}$Mg, $^{26}$Mg)$^6$Li
   (d) $^6$Li($^{27}$Al, $^{27}$Al)$^6$Li

Elastic scattering for reaction (a) was studied at $E(^6$Li) = 156 MeV (1995DE53). Reaction (c) has been studied at $E(^6$Li) = 88 MeV and 36 MeV (1984AJ01) and at 44 MeV (1989RU05; polarization observables), and $E(^6$Li) = 60 MeV (1994WA20; polarization observables). Reaction (d) was studied at $E(^6$Li) = 156 MeV by (1987NI04; particles and gammas from inelastic scattering). See also the measurements at $E(^6$Li) = 790 MeV/A (1985TA18).
Theoretical studies for these reactions include: analyzed non-Rutherford cross sections (1991BO48); effects of nonresonant breakup states (1991HI11); strong absorption model analysis (1994SA33); cluster folding interaction (1991HI07); coupled channels study (1992HI02); and cluster-folding analysis (1994RU11).

32. (a) $^6$Li($^{28}$Si, $^{28}$Si)$^6$Li
(b) $^6$Li($^{30}$Si, $^{30}$Si)$^6$Li

The elastic scattering has been studied at $E(^6$Li) = 13 to 154 MeV [see (1984AJ01)], at 27 and 34 MeV (1983VI03) and at 210 MeV (1988NAZX). For a study of the decay see (1987NI04). See also references cited in (1988AJ01).

More recent measurements have been reported at $E(^6$Li) = 210 MeV (inelastic $\sigma(\theta)$ to $^{28}$Si*(first 2$^+$ state) (1989NA11); elastic $\sigma(\theta)$, optical parameters (1989NA02); and $E(^6$Li) = 318 MeV ($\sigma(\theta)$, folding model potentials (1990NAZZ, 1993NA01)). Related analyses and other theoretical studies include: Pauli Principle role (1988GR32, 1991SA26); scattering matrix approach (1990KU23); deduced model parameters (1990SA05); non-Rutherford cross section thresholds (1991BO48); cluster-folding interactions (1991HI07); energy dependence, dispersion relation (1991TI04); strong absorption model (1994SA33); $E(^6$Li) = 210, 318 MeV, energy approximation (1995EM03); microscopic description (1996CA01); microscopic potentials, density matrix formalism (1996KN02); $E(^6$Li) = 35, 53 MeV/A, breakup effect (1997SA57); and $E(^6$Li) = 210, 315 MeV, S-matrix approach (1998PI02).

For reaction (b) see (1987AR13).

33. (a) $^6$Li($^{39}$K, $^{39}$K)$^6$Li
(b) $^6$Li($^{40}$Ca, $^{40}$Ca)$^6$Li
(c) $^6$Li($^{44}$Ca, $^{44}$Ca)$^6$Li
(d) $^6$Li($^{48}$Ca, $^{48}$Ca)$^6$Li

Elastic scattering has been studied for $E(^6$Li) = 26 to 99 MeV: see (1984AJ01, 1988AJ01), and at $E(^6$Li) = 34 MeV (reaction (b)) by (1987VA31) and at 210 MeV (1988NAZX, 1989NA02; reaction (b)). $^6$Li*(2.19) has been studied at $E(^{40}$Ca) = 227 MeV (1987VA31). Reaction (d) was studied at $E(^6$Li) = 150 MeV (1990KAZH). For fusion measurements (reaction (b)) see (1984BR04). For breakup measurements (reaction (b)) see (1984GR20, 1990YA09, 1992YAZW, 1993GU10, 1995AR15, 1996YA01).

For theoretical studies related to these reactions see: energy and target dependence of projectile breakup (1987SA21); sequential breakup cross sections (1987VA31); role of Pauli Principle (1988GR32); exchange effects (1988KH08, 1990DA23); imaginary part of channel-coupling potentials (1990TA11); $E(^6$Li) = 30 MeV, deduced optical model parameters (1990SA05); cluster folding interactions (1991HI07); strong absorption model (1994SA33); S-matrix approach

34. (a) $^7\text{Li}(\gamma, n)^6\text{Li}$

$$Q_m = -7.249$$

(b) $^7\text{Li}(\gamma, p\pi^-)^6\text{Li}$

$$Q_m = -146.038$$

Transitions to $^6\text{Li}^*(0, 2.19, 3.56)$ have been observed in reaction (a): see (1979AJ01, 1984AJ01). Differential cross sections are reported for $E_{\text{brem}} = 60$ to 120 MeV for the $n_0 + n_2$ groups (1985SE17). Bremsstrahlung yield for ($\gamma, n_0$) was measured for $E_{\gamma} = 7$–9 MeV (1989KA30). Reaction (b) at 0.9 GeV involves $^6\text{Li}^*(2.19)$ (1985RE1A). See also the measurements of $E_{\gamma} = 350$ MeV reported by (1991GA26), and see $^7\text{Li}$, (1985ST1A, 1986BA2G, 1986GO1M).

An analysis of $^7\text{Li}(\gamma, n)$ data in the giant resonance energy region is described in (1987VA05). Cluster effects were explored in (1992VA12). Calculation with a potential two cluster model are reported in (1997DU02).

35. $^7\text{Li}(\pi^-, \pi^- p)^6\text{He}$

$$Q_m = -9.9754$$

Quasielastic pion-proton backward scattering was measured at $E_{\pi} = 0.7, 0.9, 1.25$ GeV (2000AB25). Fermi momentum distributions for $^6\text{Li}$ were deduced.

36. $^7\text{Li}(\pi^+, p)^6\text{Li}$

$$Q_m = 133.1026$$

Differential cross sections have been measured at $E_{\pi^+} = 75$ and 175 MeV for the transitions to $^6\text{Li}^*(0, 2.19)$: see (1984AJ01). Proton spectra measured at momentum exchange 660 MeV/c (1989LIZO) provided evidence for an $\eta$-meson nuclear bound state.

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

$$Q_m = -5.0254$$

(b) $^7\text{Li}(p, pn)^6\text{Li}$

$$Q_m = -7.2499$$

Angular distributions of deuterons (reaction (a)) have been studied for $E_p = 167$ to 800 MeV [see (1979AJ01, 1984AJ01)] and at 18.6 MeV (1986GO23, 1987GO27; $d_0$, $d_1$, $d_2$; see for spectroscopic factors), 200 and 400 MeV (1985KR13; $d_0$, $d_1$; $d_2$ is weakly populated at 200 MeV) and at 800 MeV (1984SM04; $d_0$, $d_1$). The ratio of the intensities of the groups to $^6\text{Li}^*(2.19)$ and $^6\text{Li}_{g.s.}$ increases with energy. It is suggested that this can be understood in terms of a small admixture of 1f orbital in these states (1985KR13). A DWBA analysis of $E_p = 185$ MeV data leads to $C^2S = 0.87, 0.67, 0.24, (0.05), 0.14$, respectively for $^6\text{Li}^*(0, 2.19, 3.56, 4.31, 5.37)$. No
other states were seen below \( E_x \approx 20 \text{ MeV} \): see (1979AJ01). The tensor analyzing power \( T_{20} \) was measured for the \(^1\text{H}(^7\text{Li}, \text{d})^6\text{Li} \) reaction at \( E(^7\text{Li}) = 70 \text{ MeV} \) to \(^6\text{Li}^*(0, 2.186) \) (1991DA07). Data at \( E_p = 33.6 \text{ MeV} \) were analyzed by (1991AB04) in a test for Cohen-Kurath wave functions. See also the analysis of data at \( E_p = 698 \text{ MeV} \) by (1993AL05; \( \eta \) production). In reaction (b) at \( E_p = 1 \text{ GeV} \) the separation energy between \( \approx 6.5 \text{ MeV} \) broad \( 1p_{3/2} \) and \( 1s_{1/2} \) groups is reported to be \( 18.0 \pm 0.8 \text{ MeV} \) (1985DA29, 1985DO16). See also (1983LY04, 1988BE11, 1988GUZW). Differential cross sections were measured at \( E_p = 70 \text{ MeV} \) (1988PA26) and at \( E_p = 2.7–3.8 \text{ MeV} \) (1988BO37; application). See also the measurements for nuclear microprobe utilization (1995RI14).

38. \(^7\text{Li}(\text{d}, t)^6\text{Li} \quad Q_m = -0.9927\)

A study at \( E_d = 23.6 \text{ MeV} \) of the relative cross sections of the analog reactions \(^7\text{Li}(\text{d}, t)^6\text{Li} \) (to the first two \( T = 1 \) states at 3.56 and 5.37 MeV) and \(^7\text{Li}(\text{d}, ^3\text{He})^4\text{He} \) (to the ground and 1.80 MeV excited states) shows that \(^6\text{Li}^*(3.56, 5.37) \) have high isospin purity (\( \alpha^2 < 0.008 \)): this is explained in terms of antisymmetrization effects which prevent mixing with nearby \( T = 0 \) states: see (1979AJ01). (1987BO39) \([E_d = 30.7 \text{ MeV}]\) deduce that the branching ratio of \(^6\text{Li}^*(4.31) \) into a dinucleon \([T = 1, S = 0]\) is \( (85 \pm 10)\% \): see also reactions 21 in \(^6\text{He} \) and 4 in \(^6\text{Be} \). See also (1987GUZZ; \( E_d = 18 \text{ MeV} \); angular distributions to \(^6\text{Li}^*(0, 2.19, 3.56) \) and (1984BL21, 1986AV01, 1988GUZW). See also the analysis method discussed in (1995GU22; DWBA and dispersive theory).

39. (a) \(^7\text{Li}(^3\text{He}, \alpha)^6\text{Li} \quad Q_m = 13.3277\)
(b) \(^7\text{Li}(^3\text{He}, \text{d} \alpha)^4\text{He} \quad Q_m = 11.8534\)

Angular distributions have been reported at \( E(^3\text{He}) = 5.1 \) to 33.3 MeV [see (1974AJ01, 1984AJ01): the lower energy work has not been published] and more recently at \( E(^3\text{He}) = 60 \text{ MeV} \) (1994BUZX). Excited states observed in this reaction are displayed in Table 6.12. See also (1968CO07) which reported observation of \(^6\text{Li} \) states at 0.0, 2.17 \( \pm 0.02 \), 3.55 \( \pm 0.02 \) and 5.34 \( \pm 0.02 \) MeV. (1986AN04) have analyzed unpublished data which suggest the involvement of several broad highly excited states of \(^6\text{Li} \). See also (1987AL23).

Several attempts have been made to observe the isospin-forbidden decay of \(^6\text{Li}^*(5.37) \) \([2^+; 1]\) via \(^7\text{Li}(^3\text{He}, \alpha)^6\text{Li}^* \rightarrow \text{d} + \alpha \): the branching is \(< 1\% \), \( \Gamma_p / \Gamma = 0.35 \pm 0.10 \) and \( \Gamma_{p+n} / \Gamma = 0.65 \pm 0.10 \) for \(^6\text{Li}^*(5.37) \); see (1979AJ01). \(^4\text{He} + \text{d} \) spectra suggest the excitation of \(^6\text{Li}^*(4.3) \) \([E_x = 4.3 \pm 0.2 \text{ MeV}, \Gamma = 1.6 \pm 0.3 \text{ MeV}]\) and \(^6\text{Li}^*(5.7) \) \([E_x = 5.65 \pm 0.2 \text{ MeV}, \Gamma = 1.65 \pm 0.3 \text{ MeV}]\); see (1984AJ01). See also (1985DA29, 1988BO1Y). A more recent measurement at \( E(^3\text{He}) = 4, 5, 6 \text{ MeV} \) (1995AR14) gave values for the width of of \(^6\text{Li}^*(4.31) \) in agreement with the adopted value \( \Gamma = 1700 \pm 200 \text{ keV} \) and found no dependence on incident energy. Measurements of \( \text{d} - \alpha \) coincidence spectra at \( E(^3\text{He}) = 11.5 \text{ MeV} \) (1988AR20) and 5.0 MeV (1991AR19) gave spectroscopic
parameters for $^6\text{Li}^*(5.65)$ in agreement with adopted values (1988AJ01). At $E(^3\text{He}) = 120$ MeV the missing mass spectra for ($^3\text{He}$, 2d) and ($^3\text{He}$, pt) reflect the population of $^6\text{Li}^*(0, 2.19)$ and suggest broad structures at $E_x = 28.5$ and $32.9$ MeV (1985FR01). See also $^{10}\text{B}$ in (1988AJ01) and (1983KU17, 1988BO1J).

40. (a) $^7\text{Li}^6\text{Li}, ^7\text{Li}^6\text{Li}$
   (b) $^7\text{Li}^({^7}\text{Li}, ^8\text{Li})^6\text{Li}$ $Q_m = -5.2171$

At $E(^6\text{Li}) = 93$ MeV a broad group ($\Gamma \approx 11$ MeV) centered at $E_x = 20$ MeV is reported in addition to other peaks at $E_x = 17.1 \pm 0.3, 18.9 \pm 0.3$ and $21.2 \pm 0.3$ MeV (1987GLZW). See (1984KO25) for reaction (b).

41. $^9\text{Be}(\gamma, t)^6\text{Li}$ $Q_m = -17.6885$

Cross section measurements were made with virtual photons using electrons at 21.0–39.0 MeV (1999SH05). A compilation and evaluation of cross section data for $E_\gamma < 30$ MeV has been done by (1999ZHZN).

42. (a) $^9\text{Be}(p, \alpha)^6\text{Li}$ $Q_m = 2.1254$
   (b) $^9\text{Be}(p, 2\alpha)^2\text{H}$ $Q_m = 0.6510$
   (c) $^9\text{Be}(p, pt)^6\text{Li}$ $Q_m = -17.6885$

Angular distributions of $\alpha$-particles (reaction (a)) have been measured at $E_p = 0.11$ to 45 MeV. [see (1974AJ01, 1979AJ01)] and at $E_p = 22.5, 31$ and 41 MeV (1986HA27; $\alpha_0, \alpha_1, \alpha_2$; see for spectroscopic factors). See also Table 6.12 and (1984AJ01). Recent measurements of angular distributions and analyzing power at $E_p = 77$–321 keV are reported by (1998BR10). Measurements at $E_x = 1$ GeV are reported in (2000ANZX). Calculations of the cross section and polarization observables for $E_p = 40$ MeV are reported in (2000GA49, 2000GA59). A study of possible reasons for non-observation of certain $^6\text{Li}$ excited states in the reaction is discussed in (1999TI07). $^6\text{Li}^*(3.56)$ decays by $\gamma$-emission consistent with M1; $\Gamma_\alpha/\Gamma < 0.025$ [forbidden by spin and parity conservation]; see (1984AJ01). An analysis of the $^9\text{Be}(p, \alpha)$ cross section at $E_p = 16$–700 keV is described in (2001BA47). Astrophysical $S$-factor, analyzing powers and $R$-matrix parameters were deduced. At $E_p = 9$ MeV the yield of reaction (b) is dominated by FSI through $^8\text{Be}^*(0, 2.9)$ and $^6\text{Li}^*(2.19)$ with little or no yield from direct three-body decay: see (1979AJ01). More recent measurements of cross sections and/or polarization observables have been reported at $E_p = 50$ MeV (1989GU05), $E_p = 25, 30$ MeV (1992PE12; determined spectroscopic strengths), $E_p = 40$ MeV (1997FA17) [see also (1989FA1B)], $E_p = 2$–5 MeV (1988ABZW), $E_p = 16$–390 keV.
$E_p = 30–300$ keV (2000ISZZ). See also application-related experiments (1990RE09, 1995RI14). Analyses of data for this reaction have been reported for $E_p = 45–50$ MeV [DWBA] (1996YA09, 1997YA2V) and $E_p < 2$ MeV [analyzed reaction rates, primordial $^6$Li] (1997NO04). Reactions (b) and (c) at $E_p = 58$ MeV involve $^6$Li*(0, 2.19) (1985DE17). See also $^{10}$B in (1988AJ01) and (1985MA1F, 1986AN26, 1986KA26).

43. $^9$Be(d, $^5$He)$^6$Li $Q_m = -0.897$

See $^5$He.

44. $^9$Be(t, $^6$He)$^6$Li $Q_m = -5.3830$

Angular distributions of $^6$He$_{g.s.}$ + $^6$Li$_{g.s.}$ and $^6$He$_{g.s.}$ + $^6$Li*(3.56) [both ions listed were detected] have been measured at $E_t = 21.5$ and 23.5 MeV. In the latter case the final state is composed of two isobaric analog states: angular distributions are symmetric about 90° cm, within the overall experimental errors. In the reaction leading to the ground states of $^6$He and $^6$Li differences from symmetry of as much as 40% are observed at forward angles. Angular distributions involving $^6$He$_{g.s.} + ^6$Li*(2.19) and $^6$Li$_{g.s.} + ^6$He*(1.8) have also been measured. This reaction appears to proceed predominantly by means of the direct pickup of a triton or $^3$He from $^9$Be. Differential cross sections are also reported at $E_t = 17$ MeV: see (1984AJ01) for references.

45. $^9$Be($^3$He, $^6$Li)$^6$Li $Q_m = -1.8938$

Angular distributions of $^6$Li ions have been obtained at $E(^3$He) = 6 to 10 MeV: see (1974AJ01). A study of the continuum suggests the population of $^6$Li states at $E_x = 8–12$, ≈ 21 and 21.5 MeV: see (1984AJ01). More recently, measurements at $E(^3$He) = 60 MeV of differential cross sections have been reported (1990MA10, 1990MAZG, 1995MA57). Spectroscopic factors were deduced. Angular distributions at $E(^3$He) = 60 MeV for transition to the $^6$Li ground state and to $^6$Li*(3+, 2.185; 2+, 5.37; 1+, 5.65) were measured (1996RU13) and analyzed by coupled-channels methods.

46. $^{10}$B(n, $^5$He)$^6$Li $Q_m = -5.258$

Differential cross sections are reported at $E_n = 14.4$ MeV involving $^6$Li*(2.19) and $^5$He$_{g.s.}$ (1984TU02).
47. \(^{10}\)B(d, \(^6\)Li)\(^6\)Li

\[ Q_m = -2.9861 \]

Angular distributions involving \(^6\)Li*(0, 2.19) have been studied at \(E_d = 13.6\) MeV (1983DO10) and at 19.5 MeV [see (1974AJ01)]. See also (1984SH1E).

48. \(^{10}\)B\(^3\)He, \(^7\)Be)\(^6\)Li

\[ Q_m = -2.8738 \]

Angular distributions involving \(^6\)Li*(0, 2.19) have been measured at \(E(\^3\)He) = 30 MeV: see (1974AJ01).

49. \(^{10}\)B(\(\alpha\), \(^8\)Be)\(^6\)Li

\[ Q_m = -4.5522 \]

At \(E_\alpha = 72.5\) MeV only \(^6\)Li*(0, 2.19) are observed: the latter is excited much more strongly than is the ground state \([S_\alpha\text{ for the ground state is }0.4\text{ that for }^6\text{Li}*(2.19)]\). The angular distributions for both transitions are flat: see (1979AJ01). See also (1984AJ01). A more recent measurement of differential cross sections at \(E_\alpha = 27.2\) MeV is reported in (1995FA21). Spectroscopic factors were deduced.

50. \(^{11}\)B(d, \(^7\)Li)\(^6\)Li

\[ Q_m = -7.1903 \]

See (1984AJ01).

51. \(^{11}\)B\(^3\)He, \(^8\)Be)\(^6\)Li

\[ Q_m = 4.5712 \]

Angular distributions are reported at \(E(\^3\)He) = 71.8 MeV involving several states in \(^8\)Be (1986JA02, 1986JA14).

52. \(^{12}\)C(p, \(^7\)Be)\(^6\)Li

\[ Q_m = -22.5668 \]

Angular distributions involving \(^7\)Be*(0, 0.43) have been measured at \(E_p = 40.3\) MeV (1985DE05). For the earlier work at \(E_p = 30.6\) to 56.8 MeV see (1974AJ01, 1979AJ01). See also references cited in (1988AJ01).
53. $^{12}$C(d, $^{8}$Be)$^{6}$Li  

Angular distributions involving states in $^{8}$Be have been studied at $E_d = 19.5$ and 51.8 MeV [see (1974AJ01)] and at 50 MeV (1985GO1G, 1989GO07, 1989GO26), 54.2 MeV (1984UM04) and 78 MeV (1986JA14), as well as at $E_d = 18$ and 22 MeV (1987TA07) and 51.7 MeV (1986YA12). See also (1984NE1A, 1987GO1S) and the DWBA calculations at $E_d = 50$ MeV (1988KA46) and $E_d = 15$ MeV (1988RA27).

$Q_m = -5.8922$

54. $^{12}$C($^{3}$He, $^{9}$B)$^{6}$Li  

Angular distributions have been obtained at $E(^{3}$He) = 28 to 40.7 MeV [see (1974AJ01)] and at $E(^{3}$He) = 33 MeV (1989SI02), $E(^{3}$He) = 33.4 MeV (1986CL1B; also $A_y$), $E(^{3}$He) = 60 MeV (1990MAZG, 1993MA48), $E(^{3}$He) = 30–60 MeV (1995MA57). See also (1989GL1D) and see $^{9}$B in (1988AJ01).

$Q_m = -11.5708$

55. (a) $^{12}$C($^{6}$Li, $^{10}$B)$^{6}$Li  
(b) $^{12}$C($^{6}$Li, d$^{10}$B)

Angular distributions (reaction (a)) at $E_{^{6}$Li} = 42 MeV involve $^{6}$Li$^*$ (0, 2.19): see (1974AJ01). Differential cross sections were measured at $E_{^{6}$Li} = 90 MeV and cluster spectroscopic amplitudes were deduced (1991GL03). At $E_{^{6}$Li} = 65 MeV reaction (b) goes via $^{6}$Li$^*$ (2.19, 4.31): see (1984AJ01). See also $^{10}$B in (1988AJ01) and (1987GA20).

(a) $Q_m = -23.7122$
(b) $Q_m = -25.1865$

56. (a) $^{12}$C($^{6}$Li, $^{14}$N)  
(b) $^{12}$C($^{6}$Li, od)$^{12}$C

An analysis involving excited states of $^{6}$Li and $^{14}$N was applied to cross section and analyzing power data at $E(^{6}$Li) = 33 MeV by (2000MA43).

Measurements of triple differential cross sections for elastic breakup of 156 MeV $^{6}$Li (reaction (b)) were reported in (1989HE28, 1989HE17, 1989RE1G). A diffraction dissociation model analysis was used. See also reaction 70. Partial cross sections for the $^{6}$Li + $^{12}$C reaction were measured for $E(^{6}$Li) = 3.11–12.07 MeV by (1998MU12).

(a) $Q_m = 8.7980$
(b) $Q_m = -1.4743$

57. $^{12}$C($^{10}$B, $^{16}$O)$^{6}$Li  

$Q_m = 2.7015$
See $^{16}\text{O}$ in (1986AJ04).

58. $^{12}\text{C}$(\textsuperscript{\text{11}}\text{B}, \textsuperscript{6}\text{Li})\textsuperscript{17}\text{O}$ \hspace{1cm} $Q_m = -4.609$

Measurements of angular distributions at $E(\text{\textsuperscript{11}}\text{B}) = 25, 35, 40$ MeV have been reported by (1996JA12). Transfer mechanisms were studied.

59. $^{12}\text{C}$(\textsuperscript{\text{12}}\text{C}, \textsuperscript{\text{12}}\text{C})\textsuperscript{6}\text{Li}\textsuperscript{6}\text{Li}$ \hspace{1cm} $Q_m = -28.1726$

The fragmentation of $^{12}\text{C}$ into two $^{6}\text{Li}$ ions has been observed at $E(\text{\textsuperscript{12}}\text{C}) = 2.1$ GeV/A (1986LIZP).

60. $^{12}\text{C}$(\textsuperscript{\text{14}}\text{N}, \textsuperscript{\text{20}}\text{Ne})\textsuperscript{6}\text{Li}$ \hspace{1cm} $Q_m = -4.1810$

Angular distributions of reaction products were measured for $E(\text{\textsuperscript{14}}\text{N}) = 50$ MeV, and multi-nucleon transfer mechanisms were studied (1992ARZX). See also the analysis for $E(\text{\textsuperscript{14}}\text{N}) = 54$ MeV (1987GO12), and see $^{\text{20}}\text{Ne}$ in (1987AJ02, 1998TI06).

61. $^{13}\text{C}$(\textsuperscript{\text{8}}\text{Be})\textsuperscript{6}\text{Li}$ \hspace{1cm} Q_m = -8.6140$


62. $^{13}\text{C}$(\textsuperscript{\text{6}}\text{Li})\textsuperscript{10}\text{Be}$ \hspace{1cm} Q_m = -8.6181$

Measurements of differential cross sections and analyzing powers were reported by (1989SI02). Spectroscopic factors were extracted.

63. $^{13}\text{C}$(\textsuperscript{\text{3}}\text{He}, \textsuperscript{6}\text{Li})\textsuperscript{10}\text{B}$ \hspace{1cm} Q_m = -8.0809$

Differential cross sections at $E(\text{\textsuperscript{3}}\text{He}) = 60$ MeV have been reported (1990MAZG, 1995MA57). Cluster pick-up mechanisms were studied.
Angular distributions and polarization observables involving $^6$Li ions and several $^{12}$C states are reported at $E_d = 22$ MeV (1987TA07) and 51.7 MeV (1986YA12) and at $E_d = 54.2$ MeV (1984UM04). See also (1984NE1A), and $^{12}$C in (1990AJ01) for polarization studies.

Measurements and analyses of differential cross sections at $E(^3\text{He}) = 30$–60 MeV have been reported (1995MA57).

Differential cross sections at $E_d = 50$ MeV were reported (1990GO14).

Angular distributions have been measured at $E(^3\text{He}) = 11$ to 40.7 MeV involving $^6$Li*(0, 3.56) and various states of $^{16}$O: see (1974AJ01, 1977AJ02). Differential cross sections have been reported for $E(^3\text{He}) = 66$ MeV (1991MA56).

Measurement of the tensor analyzing power made at $E(^6\text{Li}) = 34$ MeV (1978VE03) were analyzed to obtain the $D$- and $S$-state ratio for the $<d\alpha|^6\text{Li}|\text{bound state overlap.}$

Angular distributions measured for $E(^6\text{Li}) = 21$–32 MeV are reported by (1999MA16).
For reaction (a) differential cross sections were measured at $E(^6\text{Li}) = 25$–60 MeV and analyzed by the optical model (1994KE08, 1998KE03).

For reaction (b) measurements of triple differential cross sections for elastic breakup of 156 MeV $^6\text{Li}$ were reported in (1989HE28, 1989HE17, 1989RE1G). Data were analyzed on the basis of a diffractive disintegration approach. Breakup measurements at $E(^6\text{Li}) = 60$ MeV were reported in (1988HE16). See also reaction 56, and see the theoretical study of angular correlation of breakup fragments in (1989BA25).

$^6\text{Be}$

(Figs. 6 and 7)

GENERAL: References to articles on general properties of $^6\text{Be}$ published since the previous review (1988AJ01) are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for $^6\text{Be}$ located on our website at (www.tunl.duke.edu/NuclData/General_Tables/6be.shtml).

<table>
<thead>
<tr>
<th>Reactions</th>
<th>$Q_m$ (MeV)</th>
<th>$E_b$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) $^3\text{He} (^3\text{He}, \gamma)^6\text{Be}$</td>
<td>11.4884</td>
<td>11.49</td>
</tr>
<tr>
<td>(b) $^3\text{He} (^3\text{He}, p)^7\text{Li}$</td>
<td>11.17</td>
<td></td>
</tr>
<tr>
<td>(c) $^3\text{He} (^3\text{He}, 2p)^4\text{He}$</td>
<td>12.8596</td>
<td></td>
</tr>
<tr>
<td>(d) $^3\text{He} (^3\text{He}, ^3\text{He})^3\text{He}$</td>
<td>-5.4935</td>
<td></td>
</tr>
</tbody>
</table>

The yield of $\gamma$-rays to $^6\text{Be}^*(1.7)$ (reaction (a)) increases smoothly from 0.4 to 9.3 $\mu$b (assuming isotropy) for $0.86 < E(^3\text{He}) < 11.8$ MeV ($90^\circ$). No transitions are observed to $^6\text{Be}_\text{g.s.}$

Table 6.14: Energy levels of $^6\text{Be}$

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$J^n; T$</th>
<th>$\Gamma_{cm}$</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
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<td>g.s.</td>
<td>0$^+$; 1</td>
<td>92 ± 6 keV</td>
<td>p, $\alpha$</td>
<td>2, 3, 4</td>
</tr>
<tr>
<td>1.67 ± 50 $^a$</td>
<td>(2)$^+$; 1</td>
<td>1.16 ± 0.06 MeV</td>
<td>p, $\alpha$</td>
<td>1, 2, 3, 4</td>
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<tr>
<td>23</td>
<td>4$^-$</td>
<td>broad</td>
<td>$\gamma$, $^3\text{He}$</td>
<td>1, 3</td>
</tr>
<tr>
<td>26</td>
<td>2$^-$</td>
<td>broad</td>
<td>$^3\text{He}$</td>
<td>1, 3</td>
</tr>
<tr>
<td>27</td>
<td>3$^-$</td>
<td>broad</td>
<td>$^3\text{He}$</td>
<td>1</td>
</tr>
</tbody>
</table>

$^a$ See Table 6.8 in (1974AJ01).
Figure 6: Energy levels of $^6$Be. For notation see Fig. 5.
[σ < 0.01 μb at E(3He) = 1.4 MeV]. This is understood in terms of a direct capture of 3He by 3He in the singlet spin state and with zero angular momentum: the 0+ → 0+ γ-transition is forbidden. Reaction (a) is thus of negligible astrophysical importance compared to reaction (c): see (1979AJ01). The capture cross section from E(3He) = 12 MeV to 27 MeV continues to increase smoothly with energy at first and then shows a broad structure centered at E(3He) = 23 ± 1 MeV [Eγ = 23.0 ± 0.5 MeV], Γem ≈ 5 MeV. This appears to be a 33F cluster resonance which decays by an E1 transition to 6Be*(1.7). The γ-ray angular distributions are consistent with Jπ = 3−: see (1979AJ01). See also (1989IS1B). Thermonuclear reaction rates for this reaction calculated from evaluated data are presented in the compilation (1999AN35).

Aγ has been measured for E(3He) = 14 to 30 MeV [reaction (b)] by (1983KI10) using a polarized target. See also 6Li.

Measurements of the total cross section for reaction (c) have been carried out for E(3He) = 60 keV to 2.2 MeV [see (1979AJ01)] and for 36 to 685 keV (1987KR09). The measurements are consistent with a non-resonant reaction mechanism, at least down to Ecm = 24.5 keV. Upper limits for ωγ for a resonance below that energy (and with Er (cm) as low as 16.2 keV) [which might help explain the low observed flux of solar neutrinos], are given in (1987KR09). [It should be noted that a corresponding mirror state in 6Li has not been observed.] The best fit to the data is given by S(0) = 5.57 ± 0.31 MeV · b (1987KR09). See (1979AJ01) for the earlier work. See also (1966LA04, 1974AJ01). For work on astrophysical considerations see references cited in (1988AJ01), and see also the following work: thermonuclear reaction rates calculated from evaluated data (1988CA26, 1999AN35); dynamic screening (1988CA11); neutrino astrophysics (1989BA2P); reaction rates (1989SC25); plasma fusion (1988PO1J); S factors, RGM (1989VA20); cross sections, extended elastic model (1990SC15); cross sections, microscopic study (1991TY01); phase shifts, generator coordinate method (1990KR12); astrophysical S-factor, potential model (1992WI09); cross sections, microscopic analysis (1994DE27); S factor, electron screening effects (1989BE08); and nucleosynthesis around black holes (1989JI1A). (1985SI12) report α-d correlation measurements at E(3He) = 13.6 MeV, which suggest the breakup of the diproton (2He) into 2H + e+ + ν.

The elastic scattering (reaction (d)) has been studied for E(3He) = 3 to 32 MeV and at 120 MeV. The excitation function shows a smooth monotonic behavior except for an anomaly at E(3He) = 25 MeV in the L = 3 partial wave corresponding to a broad state in 6Be at Eγ ≈ 24 MeV. Polarization measurements have been carried out at E(3He) = 17.9 to 32.9 MeV. A two level R-matrix analysis of the phase shifts (L ≤ 5) suggests three broad F-wave states at Eγ ≈ 23.4, 26.2 and 26.7 MeV [Jπ = 4−, 2− and 3−, respectively], in disagreement with the capture γ-ray results described above: see (1979AJ01). Calculations using the generator coordinate method have been reported for phase shifts (E(3He) < 5 MeV) (1990KR12), and for differential cross sections and astrophysical S factors (E(3He) = 2–6 MeV) (1994DE27). See also (1984AJ01) and (1986FO04).

A kinematically complete experiment (reaction (e)) has been performed at E(3He) = 120 MeV: large peaks were observed which appear to correspond to 3He-d quasi-free scattering followed by p-d FSI: see (1984AJ01).
The total reaction cross sections $\sigma_R = 156.7 \pm 3.8$, 250$\pm$14 and 296$\pm$12 mb at $E(^{3}\text{He}) = 17.9$, 21.7 and 24.0 MeV (1987BR02) [see also for partial cross sections for the breakup reactions and for unpublished results for $\sigma_R$ for $E(^{3}\text{He}) = 3.0$ to 17.9 MeV]. See also (1984AJ01) and references cited in (1988AJ01).

2. $^4\text{He}(^{3}\text{He}, n)^{6}\text{Be}$

Neutron groups to $^{6}\text{Be}^{*}(0, 1.7)$ have been observed at $E( ^{3}\text{He}) = 19.4$ to 38.61 MeV: see Table 6.8 in (1974AJ01) for the parameters of the first-excited state. There is no evidence for other states of $^{6}\text{Be}$ with $E_x \leq 5$ MeV, nor for a state near the $^{3}\text{He}$ threshold at 11.5 MeV: see (1979AJ01).

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

(b) $^6\text{Li}(p, pn)^5\text{Li}$

Neutron groups have been observed to $^{6}\text{Be}^{*}(0, 1.7)$ as has the ground-state threshold. The width of the ground state is $95 \pm 28$ keV. The parameters of $^{6}\text{Be}^{*}(1.7)$ are displayed in Table 6.8 of (1974AJ01). Angular distributions have been reported at $E_p = 8.3$ to 144 MeV [see (1979AJ01, 1984AJ01)] and at 800 MeV (1986KI12). The transverse spin transfer coefficient, $D_{NN}(0^\circ)$, at $E_p = 160$ MeV for the ground-state transition is $-0.37 \pm 0.04$ in agreement with results in other light nuclei (1984TA07). See also $^{7}\text{Be}$ and references cited in (1988AJ01).


In reaction (b) some evidence has been reported at $E_p = 47$ MeV for sequential decay via $^{6}\text{Be}^{*}(15.5 \pm 2, 24 \pm 2)$: see (1979AJ01). See also (1988MIZX).

4. $^6\text{Li}(^{3}\text{He}, t)^6\text{Be}$

Triton groups have been observed to $^{6}\text{Be}^{*}(0, 1.7)$. The width of the ground state is 89$\pm$6 keV. The parameters of the excited state are displayed in Table 6.8 of (1974AJ01). No other excited
states have been seen with $E_x < 13$ MeV. There is no evidence for a state near 11.5 MeV: see (1979AJ01). (1987BO39) have studied the decay of $^6$Be* (1.7) at $E(^3\text{He}) = 38.7$ MeV; they report that the branching ratio for decay via the emission of $^2$He [$T = 1, S = 0$] is $0.60 \pm 0.15$: see also reactions 21 in $^6$He and 38 in $^6$Li and (1984BO49, 1985BO56, 1988BO1J). See also (1984AJ01), (1987DA31; theor.) and $^9$B in (1988AJ01).

In more recent work, kinematically complete experiments for $^6$Li($^3$He, t)$^6$Be* (0, 1.7) $\rightarrow \alpha + p + p$ were reported in (1988BO38, 1989BO1N, 1989BO25, 1989BO42) and in (1992BO25, 1993BO38 [studied decay mechanism]). Measurements of differential cross sections at $E(^3\text{He}) = 93$ MeV are described in (1994DOZW).

$^6$B, $^6$C
(Not illustrated)

Not observed: see (1979AJ01, 1984AJ01, 1989GR06 [$^6$Li($\pi^+, \pi^-$) at $E_{x+} = 180, 240$ MeV], 93PO11 [properties of exotic light nuclei]) (1998SU18).

Table 6.15: Isospin triplet components $(T = 1)$ in $A = 6$ nuclei $^a$

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<th>$^6$He</th>
<th>$^6$Li</th>
<th>$^6$Be</th>
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<td>$E_x$ (MeV)</td>
<td>$J^\pi$</td>
<td>$E_x$ (MeV)</td>
</tr>
<tr>
<td>0</td>
<td>0$^+$</td>
<td>3.56</td>
</tr>
<tr>
<td>1.80</td>
<td>2$^+$</td>
<td>5.37</td>
</tr>
<tr>
<td>5.6</td>
<td>(2$^+$, 1$^-$, 0$^+$)</td>
<td>17.99</td>
</tr>
<tr>
<td>14.6</td>
<td>(1$^-$, 2$^-$)</td>
<td>24.78</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24.89</td>
</tr>
<tr>
<td></td>
<td></td>
<td>26.59</td>
</tr>
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</table>

$^a$ As taken from Tables 6.1, 6.4 and 6.14.

$^b$ Defined as $E_x(^7\text{Li}) - E_x(^6\text{He}) - 3.56$ MeV.

$^c$ Defined as $E_x(^6\text{Be}) - E_x(^6\text{He})$. 

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Figure 7: Isobar diagram, $A = 6$. 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.

1966LA04  T. Lauritsen and F. Ajzenberg-Selove, Nucl. Phys. 78 (1966) 1
1979AJ01  F. Ajzenberg-Selove, Nucl. Phys. A320 (1979) 1

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1984FE01  Fereh et al., INDC (CCP)-221/L (1984) 18


1984NE1A Nemets, Rudchik and Chuvilski, in Alma Ata (1984) 334


1984PA1B Pasechnik et al., in Alma Ata (1984) 288


1985GO1G Gorionov et al., in Leningrad (1985) 310


1985MA1F Mazitov and Rasulov, in Leningrad (1985) 298


1985PA1B Pasechnik, in Leningrad (1985) 265

1985PA1C Pasechnik et al., in Leningrad (1985) 296


1985RE1A Repenko et al., in Leningrad (1985) 342


1985ST1A Stibunov, in Leningrad (1985) 341

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1986EV1A Evseev, Buki, Likhachev and Shevchenko, in Kharkov (1986) 350
1986LI1F  Likhachev et al., in Kharkov (1986) 349
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1987GO1S  Goryunov et al., in Yurmala (1987) 474
1987KO1X  V.V. Komarov, A.M. Green, A.M. Popova and V.L. Shablov, Mod. Phys. Lett. A2 (1987) 81
1987NA1I  Naumenko et al., in Yurmala (1987) 370
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<td>1988B</td>
<td>Bekbaev et al., in Baku (1988) 442</td>
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1988MO1I A. Mondragń and E. Hernndez, in Belgium (1988) 794
1989FA1B  Falk et al., in Sao Paulo (1989) 297
1989GL1D  Glovatska et al., Tashkent (1989) 339
1989HN1A  Hnizdo et al., Sao Paulo (1989) 327

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1989RA1G  J. Rapaport, Santa Fe 88 (1989) 186
1989RE1G  H. Rebel, Calcutta (1989) 364
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<td>1989TR09</td>
<td>V.A. Tryasuchev, Yad. Fiz. 49 (1989) 1056</td>
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1990DAZR  B.V. Danilin and N.B. Shulgina, in Leningrad 90 (1990) 227
1990GH1E  Ghiò et al., in Panic XII (1990) Paper I-77
1990JO1D  Jodice et al., Panic XII (1990) Paper I-76
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1990WA1J Wagner, Prog. Part. Nucl. Phys. 24 (1990) 17

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1993SH1G  N.B. Shul’gina and B.V. Danilin, in Wein 92 (1993) 603
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