Energy Levels of Light Nuclei
\[ A = 5, 6, 7 \]

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Abstract: A review of the evidence on the properties of the nuclei \( A = 5, 6 \) and 7, with emphasis on material about the structures of the \( A = 5, 6, 7 \) systems.

About this evaluation: This prepublication version of \( A = 5\text{--}7 \) includes figures and introductory tables. There are also hyperlinks for references (in TUNL/NNDC format) and General Tables (when mentioned within the text). Unlike our other PDF documents, there are no hyperlinks for the Tables.

(References closed 29 August 2000)

This work is supported by the US Department of Energy, Office of High Energy and Nuclear Physics, under: Contract No. DEFG02-97-ER41042 (North Carolina State University); Contract No. DEFG02-97-ER41033 (Duke University).
Table 1: Energy Levels of Light Nuclei – previous evaluations

<table>
<thead>
<tr>
<th>Reference key</th>
<th>Mass chains covered (A)</th>
<th>Reference</th>
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<tr>
<td><strong>Early Evaluations:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>37LI1A</td>
<td>7–38</td>
<td>M.S. Livingston and H.A. Bethe, Rev. Mod. Phys. 9 (1937) 245</td>
</tr>
<tr>
<td>48HO1A</td>
<td>7–20</td>
<td>W.F. Hornyak and T. Lauritsen, Rev. Mod. Phys. 20 (1948) 191</td>
</tr>
<tr>
<td>49LA1A</td>
<td>unavailable</td>
<td>T. Lauritsen, N.R.C. Preliminary Report No. 5 (1949)</td>
</tr>
<tr>
<td>52AJ38</td>
<td>5–23</td>
<td>F. Ajzenberg and T. Lauritsen, Rev. Mod. Phys. 24 (1952) 321</td>
</tr>
<tr>
<td>55AJ61</td>
<td>5–23</td>
<td>F. Ajzenberg and T. Lauritsen, Rev. Mod. Phys. 27 (1955) 77</td>
</tr>
<tr>
<td>59AJ76</td>
<td>5–24</td>
<td>F. Ajzenberg and T. Lauritsen, Nucl. Phys. 11 (1959) 1</td>
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<td><strong>The Ajzenberg-Selove $A = 5–20$ Series:</strong></td>
<td></td>
<td></td>
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<tr>
<td>66LA04</td>
<td>5–10</td>
<td>T. Lauritsen and F. Ajzenberg-Selove, Nucl. Phys. 78 (1966) 1</td>
</tr>
<tr>
<td>79AJ01</td>
<td>5–10</td>
<td>F. Ajzenberg-Selove, Nucl. Phys. A320 (1979) 1</td>
</tr>
<tr>
<td>68AJ02</td>
<td>11–12</td>
<td>F. Ajzenberg-Selove, Nucl. Phys. A114 (1968) 1</td>
</tr>
<tr>
<td>75AJ02</td>
<td>11–12</td>
<td>F. Ajzenberg-Selove, Nucl. Phys. A248 (1975) 1</td>
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<td>85AJ01</td>
<td>11–12</td>
<td>F. Ajzenberg-Selove, Nucl. Phys. A433 (1985) 1</td>
</tr>
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<td>90AJ01</td>
<td>11–12</td>
<td>F. Ajzenberg-Selove, Nucl. Phys. A506 (1990) 1</td>
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<td>71AJ02</td>
<td>16–17</td>
<td>F. Ajzenberg-Selove, Nucl. Phys. A166 (1971) 1</td>
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<td>72AJ02</td>
<td>18–20</td>
<td>F. Ajzenberg-Selove, Nucl. Phys. A190 (1972) 1</td>
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<tr>
<td>78AJ03</td>
<td>18–20</td>
<td>F. Ajzenberg-Selove, Nucl. Phys. A300 (1978) 1</td>
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<tr>
<td><strong>TUNL Evaluations:</strong></td>
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Introduction

In this article, The Triangle Universities Nuclear Laboratory Nuclear Data Evaluation Project continues the series of reviews summarizing experimental information on the properties of the nuclei with mass numbers five through twenty. This $A = 5–20$ series began with a 1966 review of $A = 5–10$ nuclei by T. Lauritsen and Fay Ajzenberg-Selove and was continued by Professor Ajzenberg-Selove with separate review papers for $A = 11–12, 13–15, 16–17$, and $18–20$. It comprised a total of 23 “Energy Levels of Light Nuclei” papers which extended over a period from 1966 through 1991 and which played a very significant role in nuclear physics research worldwide during these years. A complete list of these $A = 5–20$ papers is given in Table 1 along with several earlier reviews and the more recent TUNL $A = 16–17, 18–19$ and 20 reviews. In form, arrangement and purpose, this present paper summarizing $A = 5–7$ is similar to the previous review papers dealing with the nuclei $A = 5–20$. In a break with the earlier practice of Fay Ajzenberg-Selove of grouping $A = 5–10$ for publication, TUNL has chosen to publish the $A = 5–7$ review separately.

Arrangement of the Material

Following earlier practice, each nucleus is represented by a diagram and a master table exhibiting the known properties of the energy levels as adopted in this evaluation or retained from the previous “Energy Levels of Light Nuclei” reviews. A listing of the nuclear reactions for which the information derives is also provided. The accompanying text contains an abbreviated discussion and a selected bibliography for each relevant reaction. In addition to discussion of experimental work we have continued the TUNL practice of including a brief discussion of new theoretical work for each reaction, or in some cases, a table listing theoretical references with a one-line description of each. Since most nuclear reactions provide information on more than one nucleus, each reaction is listed under both the compound and the residual nucleus, with differently oriented discussions and partially overlapping bibliographies. With bombarding energies in the tens of MeV, where direct interactions predominate, it is frequently the target nucleus which is mainly concerned, and here, a third type of listing has been necessary. Generally speaking, in a reaction such as $X(a, b)Y$, information relating to resonances, yields and angular distributions in the resonance region will be found under the listing for the the nucleus $(X + a)$; particle spectra, angular correlations involving secondary decays, and results from stripping reactions are listed under $Y$; pickup reactions, high-energy elastic scattering, or quasi-elastic scattering studies are discussed under $X$. Where they appear to be relevant to compound nucleus levels, selected excitation functions have been schematically indicated on the diagrams; lack of space has severely limited both the faithfulness and the number of such reproductions.

Extensive use has been made of tabular presentations of numerical data. Where it has seemed appropriate to do so, we have added “mean” or “best” values, generally calculated with inverse square weighting of the cited errors. For the means, both internal and external errors have been computed, and the larger is quoted. In both the text and the tables, numbers or parameters with uncertain identifications are enclosed in parentheses. On the
diagrams, uncertain levels are indicated by dashed lines.

Electromagnetic transitions are only occasionally exhibited in the diagrams; where more information is available, it has been summarized in a table.

At the beginning of the text material for each nucleus, previous evaluations by Fay Ajzenberg-Selove, as well as those by TUNL, have provided a “general” bibliography consisting of a listing of mainly theoretical papers dealing with the nucleus as well as some experimental papers not otherwise classifiable. Previous TUNL evaluations have listed these publications by key number and a one-line description of each under appropriate categorical headings, e.g., shell model, cluster model, astrophysics, etc. Because the lists have become quite lengthy for \( A = 5, 6, 7 \), the authors of the present review have chosen to omit them in the published review and instead will provide them on the TUNL Data Evaluation Project’s website at (www.tunl.duke.edu/NuclData/General_Tables/ General_Tables.shtml) along with the abridged version of this and other reviews (see Electronic Data Services below).

Isobar Diagrams and Tables

To facilitate comparison of level structures of isobars, skeletonized level diagrams for each mass number are included. In each instance, the energy scales have been shifted to take into account the neutron-proton mass difference and the Coulomb energies, the latter calculated from \( E_C = 0.60Z(Z−1)/A^{1/3} \) MeV corresponding to a uniform charge distribution in a sphere of radius \( R = 1.44A^{1/3} \) fm. This admittedly arbitrary adjustment ignores such matters as proton correlations and other structural details, but has the virtues of uniformity and simplicity.

Conventions and Symbols

The notations in the literature are reasonably uniform and unambiguous, but for the sake of definiteness we list here the principal symbols which we have used:

- \( E \): energy in MeV, in lab coordinates unless otherwise specified; subscripts p, d, t, etc refer to protons, deuterons, tritons, etc;
- \( E_h \): the separation energy, in MeV;
- \( E_x \): excitation energy, in MeV, referred to the ground state;
- \( E_{cm} \): energy in the center-of-mass system;
- \( E_{brem} \): energy of bremsstrahlung photons;
- \( E_{res} \): projectile energy corresponding to a reaction resonance;
- \( \Gamma \): full width at half maximum intensity of a resonance excitation function or of a level; subscripts when shown indicate partial widths for decay via channel shown by the subscript;
$\theta^2$: dimensionless reduced width, $\gamma^2 2\mu R^2/3\hbar^2$;

$\epsilon$-capture: electron capture;

$S(E)$: astrophysical factor for center-of-mass energy $E$;

$\sigma(E)$: reaction cross section for center-of-mass energy $E$;

$^AX*(E)$: excited state of the nucleus $^AX$, at energy $E$;

PWBA: plane-wave Born approximation;

DWBA: distorted-wave Born approximation.

The reader is reminded of the following abbreviations: $1\text{ MeV} = 10^{-6}\text{ eV}$; $1\text{ meV} = 10^{-3}\text{ eV}$; $1\text{ psec} = 10^{-12}\text{ sec}$; $1\text{ fsec} = 10^{-15}\text{ sec}$; $1\text{ W.u.} = 1\text{ Weisskopf unit}$.

Other Review Papers on Light Nuclei

We wish to remind the readers of the papers on $A=3$ (87TI07) and $A=4$ (92TI02) and $A=21–44$ (90EN08). Higher mass chains are discussed in Nuclear Data Sheets.

Electronic Data Services

National Nuclear Data Center

Adopted levels, decay data and reaction data for $A=3–20$ have been entered by the TUNL Nuclear Data Evaluation Group into the Evaluated Nuclear Structure Data Files (ENSDF) maintained by the National Nuclear Data Center (NNDC) at Brookhaven National Laboratory. ENSDF files of adopted levels and decay data for the other $A=3–20$ nuclei as well as higher mass nuclei are also available. Access to these files is available through the World Wide Web (www.nndc.bnl.gov/).

Nuclear Physics Electronic

TUNL Nuclear Data Evaluation Group WWW Server

The TUNL Nuclear Data Evaluation Group maintains WWW pages at (www.tunl.duke.edu/NuclData) which provide:


(ii) Abridged versions of TUNL’s published evaluations for $A=3, 4, 5, 6, 7, 16, 17, 18, 19, 20$.

(iii) General Tables for the most recent TUNL evaluations of $A=5–7$. Beginning with $A=5–7$, the General Tables will no longer be included in the publications of “Energy Levels of Light Nuclei”. The tables can be found online at our website (www.tunl.duke.edu/NuclData/General_Tables/General_Tables.shtml). The tables consist mainly of theoretical papers dealing with nuclei, although some experimental papers not otherwise classifiable are also included. The tables contain NNDC or TUNL key numbers for each publication, along
with a one-line description for each.
(iv) Abridged versions of Fay Ajzenberg-Selove’s $A = 5$–15 compilations (most recent versions); PDF versions of $A = 13$–15 (86AJ01) and $A = 18$–20 (87AJ02) to be completed soon.
(v) Postscript ENSDAT output of the $A = 3$–20 ENSDF files.
(vi) A preliminary posting of our new HTML project that will provide HTML documents for individual nuclides found within the Fay Ajzenberg-Selove and TUNL evaluations. The HTML documents contain dynamic links to the NSR database, as well as dynamic links for references, tables, and links to previous FAS or TUNL publications whenever mentioned within the text.
(vii) Update Lists of references for $A = 5$–12 nuclei, which provide brief descriptions of important research bearing on level information published since the last full evaluation. References for the Update Lists are given for each nuclide with experimental and theoretical subdivisions for each, and include links to the NSR database.
(viii) A new posting of our Palm Pilot page that utilizes PalmOS technology and applications ready for easy access and download that is of interest to the nuclear physics community.
(ix) A short version ($A = 1$–20) of the Tables of Isotopes, provided by the Berkeley Isotopes Project.
(x) A brief but complete list that provides links to all of the available TUNL, FAS, HTML documents, figures, Update Lists, etc that is provided by our website.
(xi) Links to the National Nuclear Data Center and other useful sites, as well as to the online electronic journals most useful to the nuclear physics community.
(xii) Information about the status of the project and our publications.
Table 2
Parameters of the ground state of the light nuclei with $A = 5, 6, 7$

<table>
<thead>
<tr>
<th></th>
<th>Atomic mass $^a$ excess (keV)</th>
<th>$\tau_{1/2}$ or $\Gamma_{c.m.}^b$</th>
<th>Decay $^b$</th>
<th>$J^\pi$; $T$ $^b,c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^5\text{n}$</td>
<td>see text</td>
<td></td>
<td>n</td>
<td>$T = \frac{5}{2}$</td>
</tr>
<tr>
<td>$^5\text{H}$</td>
<td>(32.2 ± 0.7) $\times 10^3$ $^b,e$</td>
<td></td>
<td>n, t</td>
<td>$(\frac{1}{2}^+); \frac{3}{2}$</td>
</tr>
<tr>
<td>$^5\text{He}$</td>
<td>11294 $^b$</td>
<td>648 keV</td>
<td>n, $\alpha$</td>
<td>$\frac{3}{2}^-; \frac{1}{2}$</td>
</tr>
<tr>
<td>$^5\text{Li}$</td>
<td>11404 $^b$</td>
<td>1.23 MeV</td>
<td>p, $\alpha$</td>
<td>$\frac{3}{2}^-; \frac{1}{2}$</td>
</tr>
<tr>
<td>$^5\text{Be}$</td>
<td>&gt; 33700 $^h$</td>
<td></td>
<td>p, $^3\text{He}$</td>
<td>$(\frac{1}{2}^+); \frac{3}{2}$</td>
</tr>
<tr>
<td>$^6\text{n}$</td>
<td>see text</td>
<td></td>
<td>n</td>
<td>(0$^+$); 3</td>
</tr>
<tr>
<td>$^6\text{H}$</td>
<td>41860 ± 260 $^d$</td>
<td>1.6 ± 0.4 MeV</td>
<td>n</td>
<td>(2$^-$); 2</td>
</tr>
<tr>
<td>$^6\text{He}$</td>
<td>17594.1 ± 1.0 $^d$</td>
<td>806.7 ± 1.5 ms</td>
<td>0$^+$; 1</td>
<td></td>
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<tr>
<td>$^6\text{Li}$</td>
<td>14086.3 ± 0.5 $^d$</td>
<td>stable</td>
<td>1$^+$; 0</td>
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<tr>
<td>$^6\text{Be}$</td>
<td>18374 ± 5 $^d$</td>
<td>92 ± 6 keV</td>
<td>p, $\alpha$</td>
<td>0$^+$; 1</td>
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<tr>
<td>$^6\text{B}$</td>
<td>see text</td>
<td></td>
<td></td>
<td>$T = 2$</td>
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<td>$^6\text{C}$</td>
<td>see text</td>
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<td></td>
</tr>
<tr>
<td>$^7\text{H}$</td>
<td>see text</td>
<td></td>
<td></td>
<td>$T = \frac{5}{2}$</td>
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<tr>
<td>$^7\text{He}$</td>
<td>26110 ± 30 $^d$</td>
<td>160 ± 30 keV</td>
<td>n</td>
<td>$(\frac{3}{2}^-); \frac{3}{2}$</td>
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<tr>
<td>$^7\text{Li}$</td>
<td>14907.7 ± 0.5 $^d$</td>
<td>stable</td>
<td>$\frac{3}{2}^-; \frac{1}{2}$</td>
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<tr>
<td>$^7\text{Be}$</td>
<td>15769.5 ± 0.5 $^d$</td>
<td>53.22 ± 0.06 d</td>
<td>$\epsilon$</td>
<td>$\frac{3}{2}^-; \frac{1}{2}$</td>
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<tr>
<td>$^7\text{B}$</td>
<td>27870 ± 70 $^d$</td>
<td>1.4 ± 0.2 MeV</td>
<td>p, $\alpha$</td>
<td>$(\frac{3}{2}^-); \frac{3}{2}$</td>
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</tbody>
</table>

$^a$ The values of the mass excesses shown here were used to calculate $Q_m$. Mass excesses of nuclei not included in this table, but also used in $Q_m$ calculations were obtained from (95AU04). The mass excesses of $\pi^\pm$, $\pi^0$ and $\mu$ were taken to be 139570.18 ± 0.35, 134976.6 ± 0.6 and 105658.357 ± 0.005 keV (00GR22).

$^b$ From data reviewed in this article.

$^c$ $J^\pi$ values in parentheses are derived from systematics.

$^d$ (95AU04). Uncertainties include combined statistical and systematic errors.

$^e$ (78LEZA). $\mu = +0.8220467$ (6) nm, $Q = -0.818$ (17) mb (98CE04).

$^f$ (78LEZA). $\mu = +3.256424$ (2) nm, $Q = -(40.6 ± 0.8)$ mb (88DI1B).

$^h$ (88AJ01).
Table 3

Electromagnetic transitions in $A = 5–7$ $^a$

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$E_{xi} \rightarrow E_{xf}$ (MeV)</th>
<th>$J_i^\pi \rightarrow J_f^\pi$ $^b$</th>
<th>$\Gamma_\gamma$ (eV)</th>
<th>Mult.</th>
<th>$S$ (W.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^5$He</td>
<td>16.84 → 0 3/2 $^+$ → 3/2 $^-$</td>
<td>2.1 ± 0.4</td>
<td>E1</td>
<td>(2.2 ± 0.4) $\times 10^{-3}$</td>
<td></td>
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<tr>
<td>$^5$Li</td>
<td>16.87 → 0 3/2 $^+$ → 3/2 $^-$</td>
<td>5 ± 1</td>
<td>E1</td>
<td>(5 ± 1) $\times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>$^6$Li $^c$</td>
<td>2.19 → 0 3/2 $^+$ → 1 $^+$</td>
<td>(4.40 ± 0.34) $\times 10^{-4}$</td>
<td>E2</td>
<td>16.5 ± 1.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.56 → 0 3/2 $^+$ → 1 $^+$; 0</td>
<td>8.19 ± 0.17</td>
<td>M1</td>
<td>8.62 ± 0.18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.31 → 0 2/2 $^+$ → 1 $^+$</td>
<td>(5.4 ± 2.8) $\times 10^{-3}$</td>
<td>E2</td>
<td>6.8 ± 3.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.37 → 0 2/2 $^+$ → 1 $^+$; 0</td>
<td>0.27 ± 0.05</td>
<td>M1</td>
<td>(8.3 ± 1.5) $\times 10^{-2}$</td>
<td></td>
</tr>
<tr>
<td>$^7$Li $^d$</td>
<td>0.48 → 0 3/2 $^-$ → 3/2 $^-$</td>
<td>(6.30 ± 0.31) $\times 10^{-3}$</td>
<td>M1</td>
<td>2.75 ± 0.14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.63 → 0 5/2 $^-$ → 3/2 $^-$</td>
<td>(3.3 ± 0.2) $\times 10^{-7}$</td>
<td>E2</td>
<td>19.7 ± 1.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.30 → 0 1/2 $^-$ → 3/2 $^-$</td>
<td>6 $\times 10^{-3}$</td>
<td>E2</td>
<td>4.3</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ The last column gives the $\gamma$-ray strengths expressed in Weisskopf units [see D.H. Wilkinson, in Nuclear Spectroscopy B, ed. F. Ajzenberg-Selove (Academic Press, NY, 1960)]. The Weisskopf estimates ($\Gamma_W$ in eV, $E_\gamma$ in MeV) are: $\Gamma_W(E1) = 6.8 \times 10^{-2} A^{2/3} E_\gamma^5$, $\Gamma_W(E2) = 4.9 \times 10^{-8} A^{1/3} E_\gamma^5$, $\Gamma_W(E3) = 2.3 \times 10^{-14} A^2 E_\gamma^5$, $\Gamma_W(E4) = 6.8 \times 10^{-21} A^{3/3} E_\gamma^5$, $\Gamma_W(M1) = 2.1 \times 10^{-2} E_\gamma^2$, $\Gamma_W(M2) = 1.5 \times 10^{-8} A^{2/3} E_\gamma^5$.

The values for these $\gamma$-ray strengths are occasionally different from those listed in other tables of this paper because different values of $r_0$ were used. In this table $r_0 = 1.2$ fm is used consistently. The multipolarities in the next to the last column were used to calculate the $\Gamma_W$. See also (79EN05). Except for the $^5$He and $^5$Li transitions, the values in the table were obtained from Table 2 of (88AJ01).

$^b$ $T$ shown in usual convention [$J^\pi$; $T$] only if transitions from the initial state involve a change in $T$.

$^c$ See Table 6.10.

$^d$ See Table 7.5. See also (84MO1D).
A = 5 resonance parameters:

The resonance parameters tabulated here are based on comprehensive multichannel R-matrix analyses of reactions in the $^5$He and $^5$Li systems (97HA1A). These analyses include data from all possible reactions for the two-body channels d+t (or d+$^3$He in the case of $^5$Li) and N+$^4$He at cm energies corresponding to $E_x < 23$ MeV. In addition, N+$^4$He$^*$ channels are included to approximate the effects of three-body breakup processes. The fits obtained to the measurements for the two-body reactions are generally quite good. In the $^5$He analysis, for example, the $\chi^2$ per degree of freedom for the fit is 1.6, and it includes more than 2600 data points. Similar results were obtained for the $^5$Li analysis, which includes even more data.

The level information has been obtained from the $A = 5$ R-matrix parameters using two different prescriptions, given in separate tables. The recommended prescription, called the “extended” R-matrix method (87HA20, 97CS01), comes from the complex poles and residues of the $S$ matrix. This prescription has been found to give resonance parameters that are free, both formally and practically, of all dependence on the “geometric” parameters of R-matrix theory, such as boundary conditions and channel radii. The parameters are listed in Table 5.1 for $^5$He and in Table 5.3 for $^5$Li. Positions and widths for the lowest two $A = 5$ states have already been given in (97CS01), and for the second excited state of $^5$He ($^3_2^+$) in (87HA20), using this prescription.

For comparison, we also list in Tables 5.2 and 5.4 the more standard R-matrix resonance parameters that were used in the $A = 4$ level compilation (92TI02), as defined in the Appendix there. This multi-level generalization of the single-level resonance prescription given by Lane and Thomas (58LA73) is based on the real poles and residues of the “resonant” reactance matrix ($K_R$), which, because it is not truly an asymptotic quantity as is the $S$ matrix, retains dependence on the channel radii, and on the specification of the “non-resonant” phase shift. Our prescription is based on the usual assumption that the non-resonant phase shifts are the “hard-sphere” phases associated with the complete reflection of ingoing waves at the nuclear surface.

The single-level prescription of Lane and Thomas was used recently by Barker (97BA72) to obtain an interpretation of the behavior of the cross sections near the $J^p = 3/2^+$ resonance in $A = 5$ equivalent to that of the complex $S$-matrix pole and shadow pole description of (87HA20).

A comparison of the tables for a given system shows that the resonance parameters from the two prescriptions can be quite different, however. The widths for the resonant reactance-matrix pole prescription tend to be much larger than those of the $S$-matrix pole prescription, and they do not usually correspond with the experimental values. For that reason, reaction numbers were not given in the Tables (5.2 and 5.4) listing the $K_R$-based parameters, as defined in (92TI02).

In some cases, resonances seen using the recommended method are not present in the usual prescription, even though the input R-matrix parameters are identically the same.
These differences, which are most evident for light systems having broad resonances, stem from the fact that the resonant $K$-matrix prescription is based on the apparent positions of the $S$-matrix poles as seen from the real axis of the physical sheet. For broad resonances, as is known from the complex-eigenvalue expansion of the level matrix (58LA73), the apparent pole positions can change rapidly (or even disappear entirely) as the vantage point is varied, causing significant differences with the actual positions (and residues) of the poles in the complex energy plane.

**GENERAL:** References to articles on general properties of $A=5$ nuclei published since the previous review (88AJ01) are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for $A=5$ located on our website at (www.tunl.duke.edu/NuclData/General_Tables/05.shtml).

$^5n$
(Not illustrated)

$^5n$ has not been observed. It is suggested that it is unbound by 10 MeV; see (84AJ01). See also (84DE52).

$^5H$
(Not illustrated)

The previous review (88AJ01) noted that the $^9$Be($^{11}$B, $^{15}$O) reaction at $E(^{11}$B) = 52–76 MeV showed no evidence for the formation of $^5$H (86BE35, 87BO40). For the earlier work see (84AJ01). See also (87KO47, 88SEZJ). In several experiments on $\pi^-$ absorption at rest there is some evidence for the formation of a very broad (8 ± 3 MeV) resonance in the $^5$H system with $E_r = 7.4 \pm 0.7$ MeV in the $^9$Be($\pi^-$, X) reaction [see (87GO25) and the more recent work of (91GO19, 92AM1H)]. Measurements reported in (90AM04, 92AM1H) provide evidence for a state at $E_r = 11.8 \pm 0.7$ MeV, $\Gamma = 5.6 \pm 0.9$ MeV from $^6$Li($\pi^-$, p) and a state at $E_r = 9.1 \pm 0.7$ MeV, $\Gamma = 7.4 \pm 0.6$ MeV from $^7$Li($\pi^-$, p). In an experiment on $^6$Li($\pi^-$, p) at $E_x = 125$ MeV (80SE1A) a broad $^5$H state with $E_r = 11.1 \pm 1.5$, $\Gamma \simeq 14$ MeV was observed. Evidence for a dineutron-containing breakup channel was reported in (91SE06). Work on an experiment on $^7$Li($^6$Li, $^8$B)$^5$H described in (95ALZU) reported evidence for an unstable $^5$H nucleus at 5.2 ± 0.4 MeV above the t + 2n dissociation threshold. See also (95AU04). A recent study of the $^1$H($^6$He, 2p)$^5$H reaction (97KO07) reports a $^5$H resonance with decay energy into $^3$H + 2n of 1.1 ± 0.4 ± 0.3 MeV (0.3 MeV is the systematic error).

$^5$H is calculated to have $J^\pi = \frac{1}{2}^+$, to be unstable with respect to two neutron emission and to have excited states at $E_x = 2.44, 4.29$ and 7.39 MeV with $J^\pi = \frac{5}{2}^+, \frac{3}{2}^+$ and $\frac{3}{2}^+$ [(0 + 1)$\hbar \omega$ model space], and at $E_x = 2.85, 3.46$ and 6.02 MeV with $J^\pi = \frac{3}{2}^+, \frac{5}{2}^+$ and $\frac{3}{2}^+$ [(0 + 2)$\hbar \omega$ model space] (85PO10). A recent three-body calculation (00SH23) predicts states in the $^3$H + n + n continuum with $J^\pi = \frac{1}{2}^+$, $E_x = 2.5$–3.0 MeV, $\Gamma = 3$–4 MeV; $J^\pi = \frac{3}{2}^+$,
$E_x = 6.4$–$6.9 \text{ MeV}, \Gamma = 8 \text{ MeV}; J^\pi = \frac{5^+}{2}, E_x = 4.6$–$5.0 \text{ MeV}, \Gamma = 5 \text{ MeV. See also (82SM09, 83ANZQ, 86BE44, 87PE1C).}$

\[ ^5\text{He} \]
(Figs. 1 and 3)

**GENERAL:** References to articles on general properties of $^5\text{He}$ published since the previous review (88AJ01) are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for $^5\text{He}$ located on our website at [www.tunl.duke.edu/NuclData/General_Tables/5he.shtml](http://www.tunl.duke.edu/NuclData/General_Tables/5he.shtml).

1. $^1\text{H}$(\(^6\text{He}, \text{np})^5\text{He} \quad Q_m = -1.771$

   The quasi-free neutron knockout reaction was studied with $^6\text{He}$ beams produced by 115 MeV $^{15}\text{N}$ primary beams (97KOZV, 97KO07). $^5\text{He}$ was observed in the separation energy spectra. The $^5\text{He} \rightarrow ^4\text{He} + \text{n}$ decay energy is reported to be consistent with the “known mass of $^5\text{He}$” and is given as 0.97 MeV.

2. $^3\text{H}(\text{d, } \gamma)^5\text{He} \quad Q_m = 16.792$

   At low energies the reaction is dominated by a resonance at $E_d = 107$ keV; the mirror reaction shows resonance at $E_d = 430$ keV. The branching ratio $\Gamma_\gamma/\Gamma_n$ integrated over the resonance from 0 to 275 keV is $(5.6 \pm 0.6) \times 10^{-5}$ (86MO05), in very good agreement with the earlier value of $(5.4 \pm 1.3) \times 10^{-5}$ for $E_d = 45$ to 146 keV (84CE08). Assuming $\Gamma_n$ of $^5\text{He}^*(16.7)$ is $37 \pm 5$ keV (see reaction 7), then $\Gamma_\gamma = 2.1 \pm 0.4$ eV. (86MO05) also report branching ratios up to $E_d = 0.72$ MeV and summarize the earlier work to 5 MeV. More recently, a measurement (93KA01) at $E_d = 100$ keV of the $^3\text{H}(\text{d, } \gamma)^5\text{He}/^3\text{H}(\text{d, } \alpha)n$ ratio gave $(1.2 \pm 0.3) \times 10^{-4}$ which is larger than the results of (86MO05) and (84CE08) but includes contribution from decay to both the ground and first excited states.

   Differential cross sections, vector- and tensor-analyzing powers were measured at $E_d = 400$ keV for $^3\text{H}(\text{d, } \gamma)^5\text{He}$ (89RI04) and at $E_d = 0.1$, 0.45 and 8.6 MeV for $^3\text{H}(\text{d, } \gamma)$ and $^3\text{He}(\text{d, } \gamma)$ by (94BA02). These results were compared with coupled channels resonating group model (CCRGM) calculations. See also the shell model description of the $\frac{3}{2}^+$ resonance presented in (93KU02).

   The $^3\text{H}(\text{d, } \gamma)^5\text{He}$ and $^3\text{He}(\text{d, } \gamma)^5\text{Li}$ reactions were used in a measurement (91BA02) of the ground state widths of $^5\text{He}$ and $^5\text{Li}$. The results were $\Gamma_n = 1.36 \pm 0.19$ MeV in $^5\text{He}$ and $\Gamma_p = 2.44 \pm 0.21$ MeV for $^5\text{Li}$. The ground-state widths given by the conventional $R$-matrix prescription in Table 5.2 and 5.4 are 0.963 MeV and 2.11 MeV for $^5\text{He}$ and $^5\text{Li}$, respectively.
Figure 1: Energy levels of \(^5\text{He}\), extended R-matrix prescription (see Table 5.1). For notation see Fig. 2.
Table 5.1
Energy levels of $^5$He, extended $R$-matrix prescription $^a$

<table>
<thead>
<tr>
<th>$E_n$ (MeV)</th>
<th>$J^\pi; T$</th>
<th>$\Gamma_{c.m.}$ (MeV)</th>
<th>$\Gamma_n$ (MeV)</th>
<th>$\Gamma_d$ (MeV)</th>
<th>$\Gamma_{n^*}$ (MeV)</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s. $^b$</td>
<td>$\frac{1}{2}^-$; $\frac{1}{2}$</td>
<td>0.648</td>
<td>0.578</td>
<td>8.80 $^c$</td>
<td>66.0 $^c$</td>
<td>n, $\alpha$</td>
<td>5, 7, 12, 22, 23, 24</td>
</tr>
<tr>
<td>1.27</td>
<td>$\frac{1}{2}^-$; $\frac{1}{2}$</td>
<td>5.57</td>
<td>3.18</td>
<td>38.0 $^c$</td>
<td>1.27 $^c$</td>
<td>n, $\alpha$</td>
<td>5, 7, 20, 23, 24</td>
</tr>
<tr>
<td>16.84</td>
<td>$\frac{3}{2}^+$; $\frac{3}{2}$</td>
<td>0.0745</td>
<td>0.040</td>
<td>0.025 $^d$</td>
<td>$\gamma$, n, d, t, $\alpha$</td>
<td>2, 3, 6, 7, 9, 12, 13, 22, 23, 24</td>
<td></td>
</tr>
<tr>
<td>19.14</td>
<td>$\frac{3}{2}^+$; $\frac{1}{2}$</td>
<td>3.56</td>
<td>0.003</td>
<td>1.62 $^e$</td>
<td>n, d, t, $\alpha$</td>
<td>4, 9, 13, 22</td>
<td></td>
</tr>
<tr>
<td>19.26</td>
<td>$\frac{3}{2}^+$; $\frac{1}{2}$</td>
<td>3.96</td>
<td>0.014</td>
<td>1.83 $^e$</td>
<td>n, d, t, $\alpha$</td>
<td>4, 9, 13, 22</td>
<td></td>
</tr>
<tr>
<td>19.31</td>
<td>$\frac{3}{2}^+$; $\frac{1}{2}$</td>
<td>3.02</td>
<td>0.045</td>
<td>1.89 $^e$</td>
<td>n, d, t, $\alpha$</td>
<td>4, 9, 13</td>
<td></td>
</tr>
<tr>
<td>19.96</td>
<td>$\frac{3}{2}^-$; $\frac{1}{2}$</td>
<td>1.92</td>
<td>0.003</td>
<td>0.325 $^f$</td>
<td>0.862</td>
<td>n, p, d, t, $\alpha$</td>
<td>3, 16, 23, 24</td>
</tr>
<tr>
<td>21.25</td>
<td>$\frac{3}{2}^+$; $\frac{1}{2}$</td>
<td>4.61</td>
<td>0.098</td>
<td>2.38 $^g$</td>
<td>n, d, t, $\alpha$</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>21.39</td>
<td>$\frac{3}{2}^+$; $\frac{1}{2}$</td>
<td>3.95</td>
<td>0.091</td>
<td>2.12 $^g$</td>
<td>n, d, t, $\alpha$</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>21.64</td>
<td>$\frac{3}{2}^+$; $\frac{1}{2}$</td>
<td>4.03</td>
<td>0.050</td>
<td>0.878 $^h$</td>
<td>0.726</td>
<td>n, p, d, t, $\alpha$</td>
<td>20</td>
</tr>
<tr>
<td>23.97</td>
<td>$\frac{5}{2}^+$; $\frac{1}{2}$</td>
<td>5.44</td>
<td>0.053</td>
<td>2.85 $^e$</td>
<td>n, d, t, $\alpha$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24.06</td>
<td>$\frac{5}{2}^-$; $\frac{1}{2}$</td>
<td>5.23</td>
<td>0.013</td>
<td>2.18 $^i$</td>
<td>n, d, t, $\alpha$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(35.7 ± 0.4)</td>
<td>$\approx$ 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20, 24</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ This prescription, based on the complex poles and residues of the $S$-matrix, is the recommended one (see Introduction). The channel radii are: $a_n = 3.0$ fm, $a_d = 5.1$ fm.

$^b$ Situated 798 keV above the n + $\alpha$ threshold.

$^c$ Large partial widths in closed channels that have no meaning as decay widths, but rather as asymptotic normalization constants.

$^d$ Entirely $^4S(d)$.

$^e$ Primarily $^4D(d)$.

$^f$ Primarily $^2P(d)$.

$^g$ Primarily $^2D(d)$.

$^h$ Primarily $^2S(d)$.

$^i$ Primarily $^4P(d)$.
Table 5.2
Energy levels of $^5$He, $R$-matrix prescription $^a$

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$J^\pi; T$</th>
<th>$\Gamma_{\text{cm}}$ (MeV)</th>
<th>$\Gamma_n$ (MeV)</th>
<th>$\Gamma_d$ (MeV)</th>
<th>$\Gamma_{n^*}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s. $^b$</td>
<td>$\frac{3}{2}^-; \frac{1}{2}$</td>
<td>0.963</td>
<td>0.963</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6.17</td>
<td>$\frac{1}{2}^-; \frac{1}{2}$</td>
<td>20.61</td>
<td>20.61</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>16.66</td>
<td>$\frac{3}{2}^+; \frac{1}{2}$</td>
<td>0.889</td>
<td>0.691</td>
<td>0.198 $^c$</td>
<td>0.508</td>
</tr>
<tr>
<td>19.97</td>
<td>$\frac{3}{2}^+; \frac{1}{2}$</td>
<td>3.49</td>
<td>0.127</td>
<td>2.85 $^d$</td>
<td>0.508</td>
</tr>
<tr>
<td>20.32</td>
<td>$\frac{1}{2}^+; \frac{1}{2}$</td>
<td>6.64</td>
<td>0.273</td>
<td>5.08 $^e$</td>
<td>1.29</td>
</tr>
<tr>
<td>20.48</td>
<td>$\frac{3}{2}^+; \frac{1}{2}$</td>
<td>4.43</td>
<td>0.066</td>
<td>4.37 $^f$</td>
<td></td>
</tr>
<tr>
<td>21.67</td>
<td>$\frac{3}{2}^+; \frac{1}{2}$</td>
<td>6.87</td>
<td>0.156</td>
<td>6.72 $^f$</td>
<td></td>
</tr>
<tr>
<td>21.77</td>
<td>$\frac{5}{2}^+; \frac{1}{2}$</td>
<td>6.58</td>
<td>0.247</td>
<td>6.33 $^f$</td>
<td></td>
</tr>
<tr>
<td>23.52</td>
<td>$\frac{5}{2}^+; \frac{1}{2}$</td>
<td>25.21</td>
<td>0.028</td>
<td>25.18 $^f$</td>
<td></td>
</tr>
<tr>
<td>24.10</td>
<td>$\frac{5}{2}^-; \frac{1}{2}$</td>
<td>57.3</td>
<td>0.177</td>
<td>44.8 $^d$</td>
<td>12.3</td>
</tr>
<tr>
<td>24.58</td>
<td>$\frac{5}{2}^-; \frac{1}{2}$</td>
<td>5.56</td>
<td>0.020</td>
<td>5.54 $^g$</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ See the Introduction for a discussion of the two prescriptions. The prescription used here is defined in (92TI02). The channel radii are: $a_n = 3.0$ fm, $a_d = 5.1$ fm.

$^b$ Situated 985 keV above the $n + \alpha$ threshold.

$^c$ Entirely $^4S(d)$.

$^d$ Primarily $^2P(d)$.

$^e$ Primarily $^2S(d)$.

$^f$ Primarily $^4D(d)$.

$^g$ Primarily $^4P(d)$. 

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The data of (91BA02) were used by (96EF03) in a single-level $R$-matrix analysis to obtain values of the ground-state energies and widths of $^3\text{He}$ and $^5\text{Li}$, close to those given by the extended $R$-matrix prescription in Tables 5.1 and 5.3.

3. (a) $^3\text{H(d, n)}^4\text{He}$
   
   \[ Q_m = 17.589 \]
   \[ E_b = 16.792 \]

   (b) $^3\text{H(d, 2n)}^3\text{He}$
   
   \[ Q_m = -2.988 \]

   (c) $^3\text{H(d, pn)}^3\text{H}$
   
   \[ Q_m = -2.225 \]

The cross section for reaction (a) has been measured in the range $E_t = 12.5$ to 117 keV (84JA08) [0.525$(\pm 4.8\%)$ mb to 3.739$(\pm 1.4\%)$ b] and in the range $E_d = 79.913$ to 115.901 keV (± 0.015 keV) (87BR10) [3.849 to 4.734 b (± 1.6%)]. See also (85FI1G; $E_d = 13.8$ to 114.3 keV). A strong resonance, $\sigma$ (peak) = 4.88 b, appears at $E_d = 105$ keV; see Table 5.2 in (79AJ01) and (87BR10). For a discussion of $R$-matrix analysis and evidence for a “shadow” pole, see (87BR10, 87HA20). See also (87HA44, 87MO1K). The related work of (91BO23) uses a resonance coupled channels model to interpret the $^5\text{He}$ $(3^+)$ resonance as a coupled channel pole associated predominantly with the d-t system. A later study by (93CS02) uses a realistic dynamical microscopic reaction approach and reaches the same conclusion. A more recent analysis of cross section data for $E_d = 8$–116 keV is described in (95LA33).

Resonance parameters for the $^5\text{He}$ $3^+$ second excited state were determined.

From $E_d = 10$ to 500 keV, the cross section is well fitted with the assumption of s-wave formation of a $J^p = \frac{1}{2}^+$ state. (See however the discussion below.) Measurements of cross sections and angular distributions for reaction (a) have been reported to $E_d = 21$ MeV and $E_t = 20.0$ MeV [see (74AJ01, 79AJ01, 84AJ01)] as well as at 1.0, 1.5 and 2.0 MeV (87LI07). Neutron yields from reaction (a) above have been measured at $E_d = 140$–300 keV (89SH17). Measurements to determine the intensity of intermediate energy neutrons are described in (89GA21). An absolute measurement of the polarization of 50 MeV neutrons at $\theta_{\text{lab}} = 29.7^\circ$ was reported in (91SA18).

A study of reaction (a) with polarized deuterons at $E_d = 0.2$ to 1.0 MeV indicates intervention of the s-wave, $J^p = \frac{1}{2}^+$ channel, as well as possible p-waves above $E_d = 0.3$ MeV. The polarization increases monotonically from 0.03 at $E_d = 3$ MeV to $\approx 0.5$ at $E_d = 6.5$ MeV and then with a lower slope to 0.69 at $E_d = 13$ MeV. The change in the slope may be caused by excited states of $^3\text{He}$ near 20 MeV. Comparison with the $^3\text{He(d, p)}^4\text{He}$ mirror reaction at corresponding c.m. energies shows excellent agreement between the polarization values in the two reactions up to $E_d = 6$ MeV, but then the proton polarization becomes $\approx 15\%$ higher, converging back to the neutron values at $E_d \approx 12$–13 MeV. This may be due to experimental factors. Vector polarization transfer coefficients, $K_y^v$ (0$^\circ$) have been measured for $E_d = 5$ to 11 MeV (85HOZU, 86HO1E, prelim.). For earlier polarization work see (84AJ01).

An R-matrix formalism was used in a phase shift analysis of d + $^3\text{H}$ below 1 MeV to obtain the contribution of $^2S_{1/2}$- and P-wave channels near the $^5\text{He}$ $(3^+$) resonance. See also the recent work (97BA72) in which properties of the $3^+$ levels of $^5\text{He}$ and $^5\text{Li}$ are discussed
in terms of conventional $R$-matrix parameters. The multichannel resonating group model has been used in a study (90BL08) of partial wave contributions in this energy region.

Improved formulae for fusion cross sections and thermal reactivities utilizing new data and $R$-matrix techniques are presented in (92BO47). See also (89SC1F, 89SC41, 89SC19, 89AB21, 89SC25).

The $^3\text{H}(d, n)$ reactivity in fusion reactors and screening-effect corrections needed for low energy data are discussed in (89LA29).

(87BR10) have derived astrophysical $S$-factors in the range $E_d = 8.3$ to 115.9 keV [$S(0) = 11.71 \pm 0.08$ MeV · b; multilevel fit], as well as reactivities. See (84AJ01) for the earlier work, and (85CA41, 87VA36). Angular distributions of $\alpha$ particles were measured for $E_d < 200$ keV (97BE59) and evidence for a D-wave contribution to the cross section in the vicinity of the $^3\text{H}^+$ s-wave resonance in $^5\text{He}$ was reported. Thermomuclear reaction rates for this reaction calculated from evaluated data are presented in the compilation (99AN35).

Reaction (b) has been studied for $E_d = 10.9$ to 83 MeV. A study of reaction (c) leads to the suggestion of a resonance at $E_{\text{c.m.}} = 2.9 \pm 0.3$ MeV [$E_x = 19.7$ MeV], $\Gamma_{\text{c.m.}} = 1.9 \pm 0.2$ MeV, consistent with $J^\pi = \frac{3}{2}^-$ [see Table 5.1]: see (74AJ01, 79AJ01). See also (83BAZP, 84SLZZ, 87GOZF), (86BR20, 86RA21) and (84SHZK, 85FIZW, 86CO1J, 86ILZZ, 86KO21, 86VAZU). For applications and developments in muon-catalyzed fusion see the references cited in (88AJ01) and the General Table for $^5\text{He}$ located on our website at (www.tunl.duke.edu/NuclData/General_Tables/5he.shtml).

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

$$E_h = 16.792$$

The elastic scattering has been studied for $E_d = 2.6$ to 11.0 MeV; see (84AJ01). For earlier measurements at other energies see (66LA04). The excitation curves show an interference at $E_x \approx 19$ MeV and a broad ($\Gamma > 1$ MeV) resonance corresponding to $E_x = 20.0 \pm 0.5$ MeV, similar to that seen in $^3\text{He}(d, d)$ [see $^5\text{Li}$]. Together with data from $^3\text{H}(d, n)^4\text{He}$, this work favors an assignment $D_{3/2}$ or $D_{5/2}$ with a mixture of doublet and quartet components (channel spin $\frac{1}{2}$ and $\frac{3}{2}$) if only one state is involved [any appreciable doublet component would, however, be in conflict with results from $^7\text{Li}(p, ^3\text{He})^5\text{He}$]. Measurements of differential cross section and analyzing power using polarized deuterons with $E_d = 3.2$ to 12.3 MeV show resonance-like behavior in the vector analyzing power near $E_d = 5$ MeV. The anomaly appears in the odd Legendre coefficients and is interpreted in terms of an $^3\text{He}(d, d)$ resonance of state of $^5\text{He}$ with $E_x \approx 19.7$ MeV. Broad structure in the differential cross section near 6 MeV, principally in the even Legendre coefficients, corresponds to an even parity state $^5\text{He}^e(20.0)$. Elastic scattering data is also utilized in the S-matrix studies of the $^5\text{He}(\frac{3}{2}^+, \frac{1}{2}^+)$ resonance at $E_x = 16.84$ MeV (88BE1U, 91BO23, 93CS02). (See reaction 3.) See also the effective-range expansion and Coulomb renormalization for d + t and related systems (91KA31, 96PO26). For earlier references see (79AJ01, 88AJ01). For d-t correlations see (87PO03). See also “Complex reactions” in the General section of (88AJ01) and (81PL1A, 83HAYX, 86BO01).
See also (97BA72) in which properties of the $^{3}_{2}^{+}$ levels of $^{5}$He and $^{5}$Li are discussed in terms of conventional $R$-matrix parameters.

5. $^3\text{H}(t, n)^5\text{He}$

At $E_t = 0.5$ MeV, the reaction appears to proceed via three channels: (i) direct breakup into $^4\text{He} + 2n$, the three-body breakup shape being modified by the n-n interaction; (ii) sequential decay via $^5\text{He}(0)$; (iii) sequential decay via a broad excited state of $^5\text{He}$. The width of $^5\text{He}(0)$ is estimated to be $0.74 \pm 0.18$ MeV. Some evidence is also shown for $^5\text{He}^*$ at $E_x \approx 2$ MeV, $\Gamma \approx 2.4$ MeV: see (79AJ01). See also $^6\text{He}$ in (88AJ01) and (86BA73).

6. $^3\text{He}(t, p)^5\text{He}$

Some evidence is reported at $E_t = 22.25$ MeV for a broad state of $^5\text{He}$ at $E_x \approx 20$ MeV, in addition to a sharp peak corresponding to $^5\text{He}^*(16.7)$: see (79AJ01). See also $^6\text{Li}$ in (88AJ01).

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

The coherent scattering length (thermal, bound) is $3.07 \pm 0.02$ fm, $\bar{s}_b = 0.76 \pm 0.01$ b. Total cross sections have been measured for $E_n = 4 \times 10^{-4}$ eV to 150.9 MeV and at 10 GeV/c [see (84AJ01)] and at $E_n = 1.5$ to 40 MeV (83HA20).

The total cross section has a peak of 7.6 b at $E_n = 1.15 \pm 0.05$ MeV, $E_{c.m.} = 0.92 \pm 0.04$ MeV, with a width of about 1.2 MeV: see (74AJ01). A second resonance is observed at $E_n = 22.133 \pm 0.010$ MeV [$\sigma_{\text{peak}} = 0.9$ b] with a total width of 76$\pm$12 keV and $\Gamma_n = 37\pm 5$ keV (83HA20). Attempts to detect additional resonances in the total cross section have been unsuccessful: see (74AJ01). For curves and tables of neutron cross sections see (88MCZT, 90NAZH, 90SH1C).

The $P_{3/2}$ phase shift shows strong resonance behavior near 1 MeV, while the $P_{1/2}$ phase shift changes more slowly, indicating a broad $P_{1/2}$ level at several MeV excitation. (66HO07) have constructed a set of phase shifts for $E_n = 0$ to 31 MeV, $l = 0, 1, 2, 3$, using largely p-α phase shifts. At the $^{3}_{2}^{+}$ state the best fit to all data is given by $E_{\text{res}} = 17.669$ MeV $\pm 10$ keV, $\gamma_{d}^{3} = 2.0$ MeV $\pm 25\%$, $\gamma_{n}^{3} = 50$ keV$\pm 20\%$ (see Table 5.2 in 79AJ01). See also (97BA72) in which properties of the $^{3}_{2}^{+}$ levels of $^{5}$He and $^{5}$Li are discussed in terms of conventional $R$-matrix parameters.

An $R$-function analysis of the $^4\text{He} + n$ data below 21 MeV (including absolute neutron analyzing power measurement and accurate cross section measurements) has led to a set of phase shifts and analyzing powers which are based on the $^4\text{He} + n$ data alone (rather than
also including the $^4\text{He} + p$ data). At $a = 3.3$ fm the values obtained for the $P_{1/2}$ and $P_{3/2}$ resonances are, respectively, $E_{\text{cm}} = 1.97$ and 0.77 MeV, $\Gamma_{\text{cm}} = 5.22$ and 0.64 MeV: see (84AJ01). Angular distributions of $A_y$ have been studied by (84KL05, 84KR23, 86KL04) for $E_n = 15$ to 50 MeV: see also for phase-shift analysis and comparison with $^4\text{He}(p, p)$.

The excitation energies and the spectroscopic factors for $^5\text{He}$ states are obtained by (85BA68) from 2-level $R$-matrix fits to the phase shifts, as functions of the channel radius. For $a \approx 5.1$ fm a very broad state with $J^\pi = \frac{1}{2}^+$ is found to lie at $E_x \approx 7$ MeV in both $^5\text{He}$ and $^5\text{Li}$, in agreement with the shell-model calculation by (84VA06). Broad $\frac{3}{2}^+$ and $\frac{5}{2}^+$ states then lie at $\approx 14$ MeV and the $\frac{1}{2}^-$ state is at about 2.6 MeV. (85BA68) suggest that the phase-shift analysis should be redone with values of $a$ larger than those previously used ($a \approx 3$ fm). See also references cited in (88AJ01). In more recent work $S$-matrix studies of the low energy $\frac{3}{2}^-$ and $\frac{1}{2}^-$ states are described in (97CS01, 98CS02). See also the calculations of (99AO01, 99FI10).

Nucleon-$\alpha$ potentials have been derived from phase shifts by (91CO05) and constructed from experimental data by the Marchenko inversion method as discussed in (93HO09). The scattering amplitude in the vicinity of the $^5\text{He}$ ($\frac{3}{2}^+$) resonance is expressed in terms of the scattering length and the effective range by (94MU07). A study of the two-pole structure of the $\frac{3}{2}^+$ resonance is discussed in (93CS02). See also the discussion of Pauli blocking in this reaction (90AM07) and an application of an algebraic cluster approach to n-$\alpha$ scattering (89US02).

8. $^4\text{He}(p, \pi^+)^5\text{He}$

As reported in (88AJ01), differential cross sections were measured at $E_p = 201$ MeV (85LE19) and at $E_p = 800$ MeV (84HO01; also $A_y$). See also (87SO1C) and (85GE06).

More recently differential cross section and analyzing powers were measured at incident proton energies between 240 and 507 MeV, spanning the region of the $\Delta_{1232}$ resonance (94FU06). These results were compared with the prediction of a microscopic $(p, \pi^+)$ model and with a phenomenological model. See (94FA10).

9. (a) $^4\text{He}(d, p)^5\text{He}$
(b) $^4\text{He}(d, pn)^4\text{He}$

A typical proton spectrum (reaction (a)) consists of a peak corresponding to the formation of the ground state of $^5\text{He}$, plus a continuum of protons ascribed to reaction (b). A study of the latter reaction shows evidence for sequential decay via $^5\text{He}^+(0, 16.7 \pm 0.1 \ [\Gamma = 80 \pm 30 \ \text{keV}])$ and suggests some fine structure near $E_x = 19$ MeV [see also reactions 14 and 22]: see (79AJ01). Differential cross sections and VAP have been measured for the ground
state group at \(E_d = 5.4, 6.0,\) and 6.8 MeV (85LU08; also TAP) and at 6 to 11 MeV (85OS02). Measurements of differential cross sections, analyzing powers, and polarization transfer coefficients at \(E_d = 56\) MeV were reported in (90YOZZ). At \(E_\alpha = 28.3\) MeV tensor polarization measurements involving the ground state transitions to \(^5\)He (and \(^5\)Li) deviate from theoretical predictions which assume charge symmetry (85WI15). See also \(^6\)Li (88PUZZ; \(E_d = 2.1\) GeV) and other references cited in (88AJ01).

Cross sections and transverse tensor analyzing powers for reaction (b) at \(E_d = 7\) MeV were measured with kinematic conditions chosen to correspond to singlet deuteron production (88GA14).

Theoretical studies relevant to reaction (b) include a study of effects of the proton Coulomb field on \(^\alpha, n\) resonance peaks (88KA38), comparisons of measured cross sections and polarization observables at \(E_d = 12, 17\) MeV with a three-body model (88SU12), a study of the influence of three-particle Coulomb dynamics on the cross section (91AS02), a study of the effects of the internal structure of the \(\alpha\) particle on the reaction (90KU27), and a multiconfiguration resonating group study of the six-nucleon system (91FU01, 95FU16).

10. \(^4\)He\(^4\)He, \(^3\)He\(^5\)He \hspace{2cm} Q_m = -21.375

Differential cross sections for this reaction to \(^5\)He(g.s.) were measured at \(E(\^4\)He\) = 118 MeV, and compared with DWBA predictions (94WA06). Measurements of angular distributions at \(E_\alpha = 158\) and 200 MeV were reported by (96ST25).

11. \(^4\)He\(^7\)Li, \(^6\)Li\(^5\)He \hspace{2cm} Q_m = -8.048

A study of this reaction and of the \(^4\)He\(^7\)Li, \(^6\)He\(^5\)Li reaction at \(E(\^7\)Li\) = 50 MeV, and of the \(^6\)Li\(^{12}\)C, \(^{13}\)N\(^5\)He and \(^6\)Li\(^{13}\)C, \(^{14}\)C\(^5\)Li reactions at \(E(C) = 90\) MeV was reported by (88WO10). Properties of the two lowest states of \(^5\)He and \(^5\)Li, from \(R\)-matrix parameters \((a = 5.5\) fm\) are displayed in Table 5.2 of (88AJ01). As noted there, positive parity states are then predicted to lie at \(E_x \approx 5\) MeV \((\frac{1}{2}^+\) and 12 MeV \((\frac{3}{2}^+, \frac{5}{2}^+)\) in \(^5\)He–\(^5\)Li (88WO10). See also the analysis in (88BA75).

12. (a) \(^6\)Li(\(\gamma, p\))^5He \hspace{2cm} Q_m = -4.497

(b) \(^6\)Li(e, ep)^5He \hspace{2cm} Q_m = -4.497

(c) \(^6\)Li(\(\pi^+, \pi^+\)p)\(^5\)He \hspace{2cm} Q_m = -4.497

(d) \(^6\)Li(\(\pi^-, \pi^-\)p)\(^5\)He \hspace{2cm} Q_m = -4.497

At \(E_\gamma = 60\) MeV, the proton spectrum shows two prominent peaks. In this early work cited in (79AJ01) these are attributed to \(^5\)He*\((0 + 4.0, 20 \pm 2)\): see (79AJ01). The \((\gamma, p_{0+1})\)
cross section has been reported for $E_\gamma = 34.5$ to 98.8 MeV. A broad secondary structure is also observed (88CA11). A review of photodisintegration data for energies up to $E_\gamma = 50$ MeV was presented in (90VA16). More recently, measurements were made at $E_\gamma = 60$ MeV (94RY01), at $E_\gamma = 61$, 77 MeV (94NI04), and at $E_\gamma = 59$–75 MeV (95DI01). In reaction (b) the missing energy spectrum show strong peaks due to $^5\text{He}^*(0, 16.7)$ and possibly some strength in the region $E_x = 5$–15 MeV (86LAZH; prelim.). See also $^6\text{Li}$ in (88AJ01), and see the recent triple cross section measurements of (99HO02). Reviews of $(e, e'p)$ data are presented in (90DE16, 91VA05). See also (89LA13, 90DE06, 90LA06). A microscopic cluster model used to interpret these experiments is discussed in (90LO14). For reaction (c) at $E_{x^+} = 130$ and 150 MeV, $^5\text{He}^*(0, 16.7)$ are populated (87HU02). Measurements at $E_{x^+} = 500$ MeV were made by (98PA31) to search for Delta components. Reaction (d) was studied at GeV energies by (00AB25) to deduce Fermi momentum distributions.

13. $^6\text{Li}(n, d)^5\text{He}$  
$Q_m = -2.272$

Angular distributions of $d_0$ have been studied at $E_n = 6.6$ to 56.3 MeV. At $E_n = 56.3$ MeV angular distributions have also been obtained to $^5\text{He}^*(16.7)$ and, possibly, to two higher states: see (79AJ01, 84AJ01). Measured cross sections and analysis for $E_n = 14.1$ MeV are presented in (89SHZS). See also (86BOZG). A Multiconfiguration Resonating-Group Method calculation applied to this reaction is discussed in (95FU16).

14. $^6\text{Li}(p, 2p)^5\text{He}$  
$Q_m = -4.497$

At $E_p = 100$ MeV the population of $^5\text{He}^*(0, 16.7)$ and possibly of a broad structure at $E_x \approx 19$ MeV is observed: momentum distributions for $^5\text{He}^*(0, 16.7)$ and angular correlation measurements are also reported. Measurements were reported at $E_p = 47$ and 70 MeV (83VD03), 70 MeV (83GO06), 392 MeV (96KAZZ, 97HA15, 98NO04), and 1 GeV (85BE30, 85DO16, 00MI17). See also (84AJ01). Experimental and theoretical studies for $E_p = 30$–150 MeV were reviewed in (87VD1A). See also (87VD01). The influence of noncoplanarity on information obtained from these reactions was studied by (90GO34).

15. $^6\text{Li}(d, ^3\text{He})^5\text{He}$  
$Q_m = 0.997$

$^5\text{He}_{g.s.}$ has been observed at $E_d = 14.5$ MeV: see (79AJ01).

16. $^6\text{Li}(\alpha, \alpha p)^5\text{He}$  
$Q_m = -4.497$

20
At $E_{\alpha} = 140$ MeV $^{5}$He$^\ast$(0, 20.0) are populated: see (84AJ01).

17. $^{6}$Li($^{6}$Li, $^{7}$Be)$^{5}$He $Q_m = 1.109$

Angular distributions have been obtained at $E^{(6}\text{Li}) = 156$ MeV to $^{5}\text{He}_{\text{g.s.}}$. Unresolved states at $E_x = 16$–20 MeV are also populated (87MI34).

18. $^{6}$Li($^{12}$C, $^{13}$N)$^{5}$He $Q_m = -2.553$

See reaction 11 (88WO10).

19. $^{7}$Li($\gamma$, d)$^{5}$He $Q_m = -9.522$

Cross sections and excitation functions were calculated by (88DU04). Also see $^{7}$Li in (88AJ01).

20. (a) $^{7}$Li($\pi^+$, 2p)$^{5}$He $Q_m = 128.606$
(b) $^{7}$Li($\pi^-$, 2n)$^{5}$He $Q_m = 127.041$

Reaction (a) at $E_{\pi^+} = 59.4$ MeV involves $^{5}$He$^\ast$(0, 4.) and a broad peak centered at $E_x \approx 21$ MeV with $\Gamma \approx 4$ MeV. It is not clear whether $^{5}$He$^\ast$(16.7) is populated (86RI01). See also (79AJ01, 84AJ01).

DWIA calculations of cross sections and analyzing powers for population of $^{5}$He($\frac{3}{2}^-$, g.s.) are described in (92KH04).

21. $^{7}$Li(n, t)$^{5}$He $Q_m = -3.265$

The angular distribution of t$_0$ has been measured at $E_n = 14.4$ MeV: see (79AJ01) and $^{8}$Li. See also (86BOZG, 89SHZS).

22. (a) $^{7}$Li(p, $^3$He)$^{5}$He $Q_m = -4.029$
(b) $^{7}$Li(p, pd)$^{5}$He $Q_m = -9.522$

21
At $E_p = 43.7$ MeV, angular distributions of the $^3\text{He}$ groups to the ground state of $^5\text{He}$ ($\Gamma = 0.80 \pm 0.04$ MeV; $L = 0 + 2$) and to levels at 16.7 MeV ($L = 1$) and 19.9 $\pm$ 0.4 MeV ($\Gamma = 2.7$ MeV) have been studied. Since no transitions are observed in the $^7\text{Li}(p, t)^5\text{Li}$ reaction to the analog 20 MeV state in $^5\text{Li}$ [see $^5\text{Li}$], the transition is presumably $S$-forbidden and the states in $^5\text{He}$ near 20 MeV are $^4\text{D}_3/2$ or $^4\text{D}_5/2$ [compare $^3\text{H}(d, d)$]. Particle-particle coincidence data have been obtained at $E_p = 43.7$ MeV. They suggest the existence of $^5\text{He}^*(20.0)$ with $\Gamma = 3.0 \pm 0.6$ MeV and of a broad state at $\approx 25$ MeV. No $T = \frac{3}{2}$ states decaying via $T = 1$ states in $^4\text{He}$ were observed: see (79AJ01). Measurements of angular distributions at $E_p = 29.1$–44.6 MeV are reported in (89BA88). In reaction (b) $^5\text{He}^*(0 + 4, 16.7, 25)$ appear to be involved at $E_p = 670$ MeV (81ER10) while at 200 MeV some structure at $E_x \approx 20$ MeV is reported in addition to the ground state (86WA11).

23. (a) $^7\text{Li}(d, \alpha)^5\text{He}$ $Q_m = 14.325$
(b) $^7\text{Li}(d, n)^4\text{He}^4\text{He}$ $Q_m = 15.1223$

At $E_d = 24$ MeV, the $\alpha$-particle spectrum from reaction (a) shows structures corresponding to the ground and 16.7 MeV states and to states at $E_x \approx 20.2$ and 23.8 MeV with $\Gamma \approx 2$ MeV and $\approx 1$ MeV, respectively. Measurements of the $\alpha$-particle energy spectra at $E_d = 13.6$ MeV were reported in (93PAZP). An analysis of cross section data measured at $E_d = 0$–12 MeV is reported in (97HAZX). Astrophysical $S$ factors were measured at $E_{cm} = 57$–141 keV by (97YA08). Reaction (b) proceeds mainly via excited states of $^8\text{Be}$ and $^5\text{He}_{g.s.}$ and possibly as well $^5\text{He}^*(4.)$: see (79AJ01). See also (87WA21) and $^8\text{Be}$.

Measurements of $\sigma(\theta)$ at $E_d = 6.8$ MeV were reported in (89AR04). Parameters of the resonance for the $^5\text{He}$ state at $E_x = 16.76$ MeV were extracted. Analysis (91AR10, 93FA12) of coincidence measurements at $E_d = 1.4$, 2.1 and 2.5 MeV gave $E_x = 4.1 \pm 0.2$ MeV, $\Gamma = 2.9 \pm 0.4$ MeV for the $^5\text{He} p_{1/2}$ first excited state.

24. (a) $^7\text{Li}(^3\text{He}, \alpha)^5\text{He}$ $Q_m = 8.831$
(b) $^7\text{Li}(^3\text{He}, ^3\text{He}d)^5\text{He}$ $Q_m = -9.522$

A kinematically complete experiment is reported at $E(^3\text{He}) = 120$ MeV. The cross section for reaction (b) is an order of magnitude greater than that for reaction (a). The missing mass spectrum for the composite of both reactions suggests the population of several states of $^5\text{He}$, in addition to $^5\text{He}^*(0, 16.7, 20.0)$, including a state at 35.7 $\pm$ 0.4 MeV with a width of $\approx 2$ MeV (85FR01).

25. $^8\text{Li}(p, \alpha)^5\text{He}$ $Q_m = 14.516$
Differential cross sections were measured at $E_{cm} = 1.5$ MeV with a $^8$Li beam, and the data were used to calculate thermonuclear reaction rates for $^8$Li destruction (92BEZZ, 92BE46).

26. (a) $^9$Be(p, po)$^5$He $Q_m = -2.371$
   (b) $^9$Be(p, d$^3$He)$^5$He $Q_m = -20.724$

Both reactions have been studied at $E_p = 26.0$ to 101.5 MeV [see (84AJ01)]. Reaction (a) was studied at $E_p = 150.5$ MeV (85WA13) and at $E_p = 200$ MeV (89NA10), who analyzed the data in terms of DWIA. Absolute spectroscopic factors were derived. See also (85VD03). More recently, cross sections and polarization observables were measured at $E_p = 296$ MeV by (96YOZZ, 97YOZQ, 98YO09). Alpha spectroscopic factors were deduced.

27. $^9$Be(d, $^6$Li)$^5$He $Q_m = -0.897$

The angular distribution to $^5$He$_{g.s.}$ has been measured at $E_d = 13.6$ MeV (84SH1F; prelim.). See also (89VAZJ).

28. (a) $^9$Be($^3$He, $^7$Be)$^5$He $Q_m = -0.785$
   (b) $^9$Be($^3$He, $\alpha$)$^4$He$^4$He $Q_m = 19.0041$

See (84AJ01) and (90MAYW). A coupled-channel model analysis of data at $E_{^3$He} = 60 MeV is described in (96RU13). For reaction (b) see $^8$Be in (88AJ01) and (87WA25).

29. $^9$Be($\alpha$, 2$\alpha$)$^5$He $Q_m = -2.371$

Measurements at $E_\alpha = 197$ MeV of energy-sharing distributions were reported by (94CO16). Spectroscopic factors were extracted. See (84AJ01) for earlier work. Cross section measurements at $E_\alpha = 580$ MeV with DWIA calculations are described in (99NA05).

30. $^9$Be($^7$Li, $^7$Li$\alpha$)$^5$He $Q_m = -2.371$

This reaction was studied at $E_{^7$Li} = 52$ MeV (98SO05, 98SO26), and decay from $^9$Be excited state into the $\alpha + ^5$He channel was observed.
31. $^9\text{Be}({}^{18}\text{O}, {}^{22}\text{Ne})^5\text{He}$ \hspace{1cm} $Q_m = 7.296$

Cross sections were measured and the mass excess was extracted by (90BEYY).

32. $^{10}\text{B}(n, {}^5\text{He})^6\text{Li}$ \hspace{1cm} $Q_m = -5.258$

See $^6\text{Li}$ in (88AJ01).

33. $^{10}\text{B}(d, {}^7\text{Be})^5\text{He}$ \hspace{1cm} $Q_m = -1.877$

An angular distribution has been measured at $E_d = 13.6$ MeV involving $^5\text{He}_{g.s.}$ and $^7\text{Be}^*(0.43)$ (83DO10).

34. (a) $^{11}\text{B}({}^7\text{Li}, {}^{13}\text{C})^5\text{He}$ \hspace{1cm} $Q_m = 9.155$
(b) $^{11}\text{B}({}^9\text{Be}, {}^{15}\text{N})^5\text{He}$ \hspace{1cm} $Q_m = 8.618$

At $E(^{11}\text{B}) = 88$ MeV a broad structure is observed at $E_x = 5.2 \pm 0.3$ MeV, $\Gamma = 2.0 \pm 0.5$ MeV (88BE34). For reaction (b) see (90BEYX).

35. $^{12}\text{C}({}^6\text{He}, {}^5\text{He} n)^{12}\text{C}$ \hspace{1cm} $Q_m = -1.771$

Peripheral fragmentation of 240 MeV/nucleon $^6\text{He}$ was studied by (97CH24, 97CH1P). It was found that one-neutron stripping to $^5\text{He}$ is the dominant mechanism.
5Li
(Figs. 2 and 3)

GENERAL: References to articles on general properties of 5Li published since the previous review (88AJ01) are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for 5Li located on our website at (www.tunl.duke.edu/ NuclData/General_Tables/5li.shtml).

1. \( ^1H(\alpha, \gamma)^5Li \rightarrow ^1H + \alpha \) \( Q_m = -1.69 \)

Gamma rays were measured over a large dynamic range for \( E_\alpha = 200 \text{ MeV} \) (00HO18). Both inclusive and exclusive (coincidence with either \( \alpha \) particle, proton or both) measurements were performed. A pronounced contribution from capture into the unbound ground and first excited states of 5Li was observed. For the measured parameters of the 5Li resonances, see Table 5.5.

2. \( ^2H(^3\text{He}, ^3\text{He})^2H \) \( E_b = 16.66 \)

Angular distribution and analyzing powers for polarized \(^3\text{He}\) on \(^2\text{H}\) at \( E_{^3\text{He}} = 22.5, 24, 27, 30, 33 \text{ MeV} \) were measured and analyzed by (00OK01). Based on the phase shifts, they report the following resonances identified with 5Li with excitation energies between 15 and 30 MeV: (i) the well-established (88AJ01) \( ^4S_{3/2} \) state at 16.7 MeV; (ii) a broad \( ^2S_{1/2} \) state around 19 MeV; (iii) quartet D states around 20 MeV, \( ^3\!^2\!^2\!^2\) and \( ^3\!^1\!^1\!^1\) assigned before (88AJ01); (iv) two doublet P states (\( ^3\!^2\) and \( ^1\!^1\) ) around 25 MeV; and (v) at least one negative parity state around 29 MeV.

The results are compared with shell model calculations. See also reaction 5 below.

Figure 2: Energy levels of 5Li, extended R-matrix prescription (see Table 5.3). In these diagrams, energy values are plotted vertically in MeV, based on the ground state as zero. For the \( A = 5 \) diagrams all levels are represented by discrete horizontal lines. 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 5Li 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. For reactions in which the present nucleus occurs as a residual product, excitation functions have not been shown. \( Q \) values and threshold energies are based on atomic masses from (95AU04) except for the ground state energies of the \( A = 5 \) nuclei for which the values from Tables 5.1 and 5.3 are used. Further information on the levels illustrated, including a listing of the reactions in which each has been observed, is contained in Table 5.3.
Table 5.3
Energy levels of $^5$Li, extended $R$-matrix prescription $^a$

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$J^\pi; T$</th>
<th>$\Gamma_{cm}$ (MeV)</th>
<th>$\Gamma_p$ (MeV)</th>
<th>$\Gamma_d$ (MeV)</th>
<th>$\Gamma_{p^*}$ (MeV)</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\frac{3}{2}^-; \frac{1}{2}$</td>
<td>1.23</td>
<td>1.06</td>
<td>43.1 $^c$</td>
<td>0.009 $^c$</td>
<td>p, $\alpha$</td>
<td>3, 6, 9, 13, 18, 20, 23</td>
</tr>
<tr>
<td>1.49</td>
<td>$\frac{1}{2}^-; \frac{1}{2}$</td>
<td>6.60</td>
<td>3.78</td>
<td>16.4 $^c$</td>
<td></td>
<td>p, $\alpha$</td>
<td>3, 9, 13, 18, 20</td>
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<tr>
<td>16.87</td>
<td>$\frac{3}{2}^+; \frac{1}{2}$</td>
<td>0.267</td>
<td>0.055</td>
<td>0.134 $^d$</td>
<td>0.741</td>
<td>$\gamma$, p, d, $^3$He, $\alpha$</td>
<td>3, 4, 5, 18, 20</td>
</tr>
<tr>
<td>19.28</td>
<td>$\frac{3}{2}^-; \frac{1}{2}$</td>
<td>0.959</td>
<td>0.001</td>
<td>0.040 $^e$</td>
<td></td>
<td>n, p, d, $^3$He, $\alpha$</td>
<td>4, 5, 9</td>
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<tr>
<td>19.45</td>
<td>$\frac{3}{2}^+; \frac{1}{2}$</td>
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<td>0.040</td>
<td>1.82 $^f$</td>
<td></td>
<td>p, d, $^3$He, $\alpha$</td>
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<tr>
<td>19.71</td>
<td>$\frac{5}{2}^+; \frac{1}{2}$</td>
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<td>0.011</td>
<td>2.03 $^f$</td>
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<td>p, d, $^3$He, $\alpha$</td>
<td>3, 5</td>
</tr>
<tr>
<td>20.53</td>
<td>$\frac{1}{2}^+; \frac{1}{2}$</td>
<td>5.00</td>
<td>0.026</td>
<td>1.53 $^g$</td>
<td>0.196</td>
<td>n, p, d, $^3$He, $\alpha$</td>
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<tr>
<td>22.06</td>
<td>$\frac{5}{2}^+; \frac{1}{2}$</td>
<td>15.5</td>
<td>0.928</td>
<td>2.33 $^h$</td>
<td></td>
<td>p, d, $^3$He, $\alpha$</td>
<td>23, 24</td>
</tr>
<tr>
<td>23.74</td>
<td>$\frac{5}{2}^+; \frac{1}{2}$</td>
<td>5.43</td>
<td>0.234</td>
<td>2.49 $^i$</td>
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<td>p, d, $^3$He, $\alpha$</td>
<td></td>
</tr>
<tr>
<td>25.42</td>
<td>$\frac{3}{2}^+; \frac{1}{2}$</td>
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<td>0.023</td>
<td>0.467 $^j$</td>
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<td>25.44</td>
<td>$\frac{7}{2}^+; \frac{1}{2}$</td>
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<td>1.94 $^f$</td>
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<td>32.53</td>
<td>$\frac{1}{2}^+; \frac{1}{2}$</td>
<td>35.7</td>
<td>8.75</td>
<td>0.013 $^k$</td>
<td></td>
<td>p, d, $^3$He, $\alpha$</td>
<td>23, 24</td>
</tr>
</tbody>
</table>

$^a$ This prescription, based on the complex poles and residues of the $S$-matrix, is the recommended one (see Introduction). The channel radii are $a_p = 2.9$ fm, $a_d = 4.8$ fm.

$^b$ Situated 1.69 MeV above the p + $\alpha$ threshold.

$^c$ Partial widths in closed channels that have no meaning as decay widths, but rather as asymptotic normalization constants.

$^d$ Primarily $^4S(d)$.

$^e$ Primarily $^2P(d)$.

$^f$ Primarily $^4D(d)$.

$^g$ Primarily $^2S(d)$.

$^h$ Primarily $^2F(d)$.

$^i$ Primarily $^2D(d)$.

$^j$ Mixture of $^4S(d)$ and $^4D(d)$.

$^k$ Mixture of $^4P(d)$ and $^2P(d)$. 

---

27
3. $^3$He(d, $\gamma$)$^6$Li  \hspace{1cm} Q_m = 16.66

The previous review (88AJ01) describes the earlier work as follows: “The ratio $\Gamma_\gamma/\Gamma_{po}$ has been determined for $E(^3$He) = 63 to 150 keV [$E_{c.m.} = 25 to 60$ keV] by (85CE13) by measuring simultaneously the $\gamma$-rays and the charged particles. Because of the large widths of the final states, $\gamma_0$ and $\gamma_1$ could not be resolved but the results are consistent with $E_x = 3.0 \pm 1.0$ MeV for the excited state. $\Gamma_\gamma/\Gamma_{po}$ is roughly constant for $E_{c.m.} = 25 to 60$ keV at $(4.5 \pm 1.2) \times 10^{-5}$ and $\Gamma_\gamma/\Gamma_{po} = (8 \pm 3) \times 10^{-5}$ at $E(^3$He) = 150 keV (85CE13)”.

For applications see (85CE13, 85CE16, 88CE04, 92LI32).

“Excitation curves and angular distributions have been measured for $E_d = 0.2 to 5$ MeV and $E(3^\text{He}) = 2 to 26$ MeV. A broad maximum in the cross section is observed at $E_d = 0.45 \pm 0.04$ MeV [$^5$Li*(16.7)]. $\sigma_{\gamma_0} = 21 \pm 4 \mu b$, $\Gamma_{\gamma_0} = 5 \pm 1$ eV. The radiation at resonance is isotropic, consistent with s-wave capture. Study of $\gamma_0$ and $\gamma_1$ yields $\Gamma = 2.6 \pm 0.4$ MeV for the ground-state width (but see below), and $E_x = 7.5 \pm 1.0$ MeV, $\Gamma = 6.6 \pm 1.2$ MeV for the $\frac{1}{2}^+$ state: see (74AJ01, 88AJ01). An excess in the cross section at higher bombarding energies is interpreted as being due to a state at $E_x \approx 18$ MeV: even parity is deduced from the relative intensity of $\gamma_0$ and $\gamma_1$. A broad peak is also observed at $E_x \approx 20.7$ MeV in the $\gamma_0$ cross section. The cross section for $\gamma_1$ is $\approx 0$. The observations are consistent with $J^p = \frac{5}{2}^+$: angular distributions appear to require at least one other state with significant strength near 19 MeV: see (74AJ01)”.

In more recent measurements at $E_d = 8.6$ MeV a ground state width $\Gamma_{\gamma} = 2.44 \pm 0.21$ MeV was extracted from the $\gamma_0$ spectrum (91BA02). An analysis of these data with single level R-matrix fits (96EF03) gave values for the energies and widths of the ground states of $^5$Li and $^5$He. Cross section and analyzing power measurements in the $\frac{3}{2}^+$ fusion resonance region ($E_d = 0.45$ MeV) and $E_d = 8.6$ MeV were reported by (91WE11, 92BA04, 94BA02, 98WE07), and comparisons with the results of coupled-channels resonating group model calculations were discussed. See also the shell model description of the $\frac{3}{2}^+$ resonance discussed in (93KU02). Potential model descriptions of this reaction are discussed in (90NE14, 92LI32, 92NE03, 95DU13). Analyzing power formulae derived in a model-independent way are presented in (96TA09).

Measurements of high-energy (> 20 MeV) gamma ray production in the reaction are described in (92PI04).

4. (a) $^3$He(d, p)$^4$He  \hspace{1cm} Q_m = 18.35304 \hspace{1cm} E_b = 16.66
(b) $^3$He(d, np)$^3$He  \hspace{1cm} Q_m = -2.22457
(c) $^3$He(d, 2p)$^3$H  \hspace{1cm} Q_m = -1.46081
(d) $^3$He(d, 2d)$^1$H  \hspace{1cm} Q_m = -5.49349
(e) $^3$He(d, tp)$^1$H  \hspace{1cm} Q_m = -1.46081

Excitation functions and angular distributions have been measured for $E_{c.m.} = 6.95 to 171.3$ keV, and values of $S(E)$ have been deduced: $S(0) = 6.3 \pm 0.6$ MeV · b (87KR18).
also (84AJ01, 88AJ01). $S$-factors have been obtained down to $E_{cm} = 5.88$ keV. The effect on $S$ of electron screening at low energies has been studied by (88EN03, 88SCZG, 88SC1F). See also the calculations of (89BE08, 90BR12).

A pronounced resonance occurs at $E_d = 430$ keV, $\Gamma \approx 450$ keV. The peak cross section is $695 \pm 14$ mb: see Table 5.2 in (79AJ01). The recent work of (97BA72) discusses a description of the $\frac{3}{2}^+$ levels of $^5$Li and $^5$He in terms of conventional $R$-matrix parameters. Excitation functions for ground-state protons have also been reported for $E(^3\text{He}) = 0.39$ to 2.15 MeV and 18.7 to 44.1 MeV and for $E_d = 2.8$ to 17.8 MeV [see (74AJ01)]. Angular distributions have been measured for $E_d = 0.25$ to 27 MeV and $E(^3\text{He}) = 18.7$ to 44.1 MeV [see Table 5.6 in (74AJ01) and (79AJ01)]. Resonance-like behavior has been suggested at $E_x = 16.6, 17.5, 20.0, 20.9$ and 22.4 MeV: see (79AJ01).

In early work, tensor analyzing power measurements were reported for $E_d = 0.48$ to 6.64 MeV (80DR01). [See, however, (80GR14) for a discussion of the (80DR01) results and for a summary of $T_{20}(0^\circ)$ for $E_d = 0$ to 40 MeV.] Measurements of angular distributions and analyzing powers at $E(^3\text{He}) = 27$ and 33 MeV have suggested the presence of a broad resonance(s) at $E_x \approx 28$ MeV. Vector and tensor analyzing powers have been studied at $E_d = 1.0$ to 13.0 MeV (86BI1C, 86BI2P; prelim.) and 18, 20 and 22 MeV (86SA1L; prelim.). See also (86RO1J) and Tables 5.6 in (74AJ01) and 5.4 in (79AJ01). In recent work of (99GE19), angular distribution and complete sets of analyzing powers were measured at five energies between $E_d = 60$ and 641 keV. The data were included in an $R$-matrix analysis of the $^5$Li system (see Table 5.6). Multichannel resonating group model calculations for this reaction are presented in (88GU07, 90BL02, 90BL08). A model-independent description of the $d + ^3\text{He}$ system near the low energy $\frac{3}{2}^+$ resonance using the effective range expansion is described in (96PO26).

Differential cross sections for reaction (b) were measured at $E_d = 23.08$ MeV (88BR27, 90BR14). Triple differential cross sections and vector analyzing powers were measured at $E_d = 17$ MeV (89AYZZ, 90AYZW) and at $E(^3\text{He}) = 32.25$ MeV (88DA18, 91DA06).

The $d - ^3\text{He}$ fusion process in reactors is discussed in (88DA26, 88MI29, 88MO36). Applications of the reaction in studying deuterium diffusion behavior in materials is discussed in (89PA26, 90QIZZ). See also (90LE30, 90WI1L).

It is suggested that at low energies [$E_d = 2.2$ to 6 MeV] reaction (c) goes primarily via a $J^\pi = \frac{3}{2}^-$, $T = \frac{1}{2}$ state of $^5$Li located 0.8 ± 0.2 MeV above threshold [i.e., $E_x = 18.9 \pm 0.2$ MeV]: see (79AJ01). Other studies of the breakup have been reported at $E_d = 23.08$ MeV (86BR19J, reaction (c)) and 60 MeV (85OK03; reaction (d)). For the earlier work see (84AJ01). See also other references cited in (88AJ01). For a descriptive list of theoretical work on this reaction see the General Table for $^5\text{Li}$ located on our website at (www.tnml.duke.edu/NuclData/GeneralTаблицes/5Li.shtml).

5. $^3\text{He}(d, d)^3\text{He} \quad E_b = 16.66$

In the range $E_d = 380$ to 570 keV, the scattering cross section is consistent with s-wave
Table 5.4
Energy levels of $^5$Li, conventional $R$-matrix prescription $^a$

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$J^T; T$</th>
<th>$\Gamma_{cm}$ (MeV)</th>
<th>$\Gamma_p$ (MeV)</th>
<th>$\Gamma_d$ (MeV)</th>
<th>$\Gamma_{p^*}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s. $^b$</td>
<td>$\frac{3}{2}^+; \frac{1}{2}^-$</td>
<td>2.11</td>
<td>2.11</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6.18</td>
<td>$\frac{1}{2}^-; \frac{1}{2}^-$</td>
<td>19.8</td>
<td>19.8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>16.63</td>
<td>$\frac{3}{2}^+; \frac{1}{2}^-$</td>
<td>2.09</td>
<td>0.570</td>
<td>1.52 $^c$</td>
<td></td>
</tr>
<tr>
<td>19.17</td>
<td>$\frac{1}{2}^+; \frac{1}{2}^-$</td>
<td>1.50</td>
<td>0.0006</td>
<td>0.136 $^d$</td>
<td>1.36</td>
</tr>
<tr>
<td>20.30</td>
<td>$\frac{1}{2}^+; \frac{1}{2}^-$</td>
<td>4.64</td>
<td>0.208</td>
<td>3.72 $^e$</td>
<td>0.709</td>
</tr>
<tr>
<td>21.09</td>
<td>$\frac{1}{2}^+; \frac{1}{2}^-$</td>
<td>7.47</td>
<td>0.115</td>
<td>7.36 $^f$</td>
<td></td>
</tr>
<tr>
<td>22.60</td>
<td>$\frac{5}{2}^+; \frac{3}{2}^-$</td>
<td>12.5</td>
<td>0.010</td>
<td>12.5 $^f$</td>
<td></td>
</tr>
<tr>
<td>24.27</td>
<td>$\frac{5}{2}^+; \frac{3}{2}^-$</td>
<td>8.15</td>
<td>1.11</td>
<td>7.04 $^g$</td>
<td></td>
</tr>
<tr>
<td>26.86</td>
<td>$\frac{3}{2}^+; \frac{1}{2}^-$</td>
<td>24.2</td>
<td>0.009</td>
<td>24.2 $^f$</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ See the Introduction for a discussion of the two prescriptions. The channel radii are $a_p = 2.9$ fm, $a_d = 4.8$ fm.

$^b$ Situated 2.08 MeV above the $p + \alpha$ threshold.

$^c$ Entirely $^4S(d)$.

$^d$ Primarily $^2P(d)$.

$^e$ Primarily $^2S(d)$.

$^f$ Primarily $^4D(d)$.

$^g$ Primarily $^2D(d)$.
Table 5.5
Parameters of $^5\text{Li}$ resonances deduced from $\alpha + \text{p}$ gamma spectra

<table>
<thead>
<tr>
<th>$J^\pi$</th>
<th>Quantity</th>
<th>Experimental result $^a$</th>
<th>Conventional $^b$ $R$-matrix</th>
<th>Extended $^b$ $R$-matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{3}{2}^-$</td>
<td>$\sigma$ ($\mu$b)</td>
<td>8.0 ± 0.7</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>$E_x$ (MeV) $^c$</td>
<td>2.9 ± 0.2</td>
<td>2.08</td>
<td>1.69</td>
</tr>
<tr>
<td></td>
<td>$\Gamma$ (MeV)</td>
<td>1 ± 0.2</td>
<td>2.11</td>
<td>1.23</td>
</tr>
<tr>
<td>$\frac{1}{2}^-$</td>
<td>$\sigma$ ($\mu$b)</td>
<td>4.5 ± 0.4</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>$E_x$ (MeV) $^c$</td>
<td>9.3 ± 0.4</td>
<td>8.26</td>
<td>3.18</td>
</tr>
<tr>
<td></td>
<td>$\Gamma$ (MeV)</td>
<td>10 ± 1</td>
<td>19.8</td>
<td>6.60</td>
</tr>
</tbody>
</table>

$^a$ From Table I of (00HO18). These results were obtained by fitting the photon spectrum to a background plus two Gaussian peaks representing the two resonances.

$^b$ See Tables 5.3 and 5.4.

$^c$ These energies are relative to the $\alpha + \text{p}$ threshold.

Table 5.6
A scheme of $^5\text{Li}$ levels below $E_x = 17$ MeV obtained from an $R$-matrix analysis $^a$ of $^3\text{He}(d, d)^3\text{He}$, $^3\text{He}(d, \text{p})^4\text{He}$, and $^4\text{He}(\text{p, p})^4\text{He}$ data and comparison with previous scheme $^a$

<table>
<thead>
<tr>
<th>Present scheme $^b$</th>
<th>Previous scheme $^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_x$ (MeV)</td>
<td>$J^\pi$</td>
</tr>
<tr>
<td>g.s.</td>
<td>$\frac{3}{2}^-$</td>
</tr>
<tr>
<td>1.28</td>
<td>$\frac{1}{2}^-$</td>
</tr>
<tr>
<td>16.86</td>
<td>$\frac{3}{2}^+$</td>
</tr>
<tr>
<td>16.88 $^c$</td>
<td>$\frac{1}{2}^+$</td>
</tr>
<tr>
<td>17.65 $^{c,d}$</td>
<td>$\frac{3}{2}^-$</td>
</tr>
<tr>
<td>19.45</td>
<td>$\frac{3}{2}^+$</td>
</tr>
</tbody>
</table>

$^a$ See Table 5.3.

$^b$ From Tables II and III of (99GE19).

$^c$ Weak resonance.

$^d$ Above the range of the analysis.
formation of the $J^\pi = \frac{3}{2}^+$ state at 16.66 MeV. The excitation curves for $E_d = 1.96$ to 10.99 MeV show a broad resonance ($\Gamma > 1$ MeV) corresponding to $E_x = 20.0 \pm 0.5$ MeV. From the behavior of the angular distributions an assignment of $^2\!D_{3/2}$ or ($^2\!D$, $^4\!D_{5/2}$ is favored, if only one state is involved: see (79AJ01). A phase-shift analysis of the angular distribution and VAP data below 5 MeV suggests several MeV broad states $^2\!P_{3/2}$, $^4\!D_{7/2}$, $^4\!D_{5/2}$, $^4\!D_{3/2}$ and, possibly, $^4\!D_{1/2}$: see (84AJ01). See also (87KR18).

Angular distributions and analyzing powers have been measured at many energies to $E = 44$ MeV; see (79AJ01, 84AJ01) for the earlier work, (82COZO, 83COZR; $E_d = 10$ MeV; TAP) and (87YAZJ; $E_d = 29.5$ MeV on polarized $^3\!He$; prelim.). For $d-^3\!He$ correlations see (87PO03). See also “Complex reactions” in the $^5\!Li$ General section of (88AJ01). The $R$-matrix formalism was used by (90TR08) to calculate the $S(\frac{1}{2}^+)$-wave cross section for $d+^3\!He$, using $p+^4\!He$ cross section data and $d+^3\!He$ analyzing power data from the $^5\!Li(\frac{3}{2}^-)$ region. See also the work of (91NE01). A generalized potential model description of $^3\!He + d$ scattering is discussed in (91NE01). For earlier theoretical work see references cited in (88AJ01).

6. $^3\!He(t, n)^5\!Li$  
$Q_m = 10.41$

At $E(\!^3\!He) = 14$ to 26 MeV $^5\!Li^*(0, 20.5 \pm 0.8)$ are populated: see (79AJ01). See also $^6\!Li$ in (88AJ01).

7. $^3\!He(^3\!He, p)^5\!Li$  
$Q_m = 11.17$

The spectrum of protons at $E(\!^3\!He) = 3$ to 18 MeV shows a pronounced peak corresponding to $^5\!Li_{g.s.}$ superposed on a continuum: see (74AJ01). The angular distribution of $p_0$ has been measured at $E(\!^3\!He) = 26$ MeV (83KI10; polarized target). See also $^6\!Be$ in (88AJ01) and (86OS1D).

8. $^3\!He(\alpha, d)^5\!Li$  
$Q_m = -7.18$

The contribution of unbound $^6\!Li$ nuclear states to deuteron spectra from this reaction was studied by (93GO16).

9. $^4\!He(p, p)^4\!He$  
$E_b = -1.69$

Differential cross sections and polarization measurements have been carried out at many energies: see (66LA04, 74AJ01, 79AJ01, 84AJ01) for the earlier work. More recent measurements were reported (88AJ01) at $E_p = 65$ MeV (86FU05; $A_y$), 100 MeV (83NAZV,
Phase shifts below \( E_p = 18 \) MeV have been determined by (77DO01) based on all the available cross-section and polarization measurements, using an \( R \)-matrix analysis program. The \( P_{3/2} \) phase shift shows a pronounced resonance corresponding to \( ^5\text{Li}_{g.s.} \) while the \( P_{1/2} \) shift changes slowly over a range of several MeV, suggesting that the first excited state is very broad and located 5–10 MeV above the ground state. The reduced widths of the \( P \)-wave resonance states are nearly the same. The \( D_{5/2}, D_{3/2}, F_{7/2} \) and \( F_{5/2} \) phase shifts become greater than \( 1^\circ \) at \( E_p \approx 11, 13, 14 \) and 16 MeV, respectively (77DO01). \( 86\text{TH1C}, \text{prelim.} \) have measured \( A_y \) for \( 1.1 \leq E_p \leq 2.15 \) MeV: \( A_y = 1 \) for \( E_p = 1.89 \) MeV, \( \theta_{\text{cm}} = 87.0^\circ \).

A phase-shift analysis for \( E_p = 21.8 \) to 55 MeV is presented by (78HO17) [see also analyzing-power contour diagram for \( E_p = 20 \) to 65 MeV]. A striking anomaly is seen in the analyzing power at \( E_p = 23 \) MeV and the \( 2D_{3/2} \) phase shift clearly shows the \( \frac{3}{2}^+ \) state at \( E_x = 16.7 \) MeV [see also (79AJ01)]. The other phase shifts \( 2S_{1/2}, 2P_{3/2}, 2P_{1/2}, 2D_{5/2}, 2F_{7/2}, 2F_{5/2}, 2G_{9/2} \) and \( 2G_{7/2} \) are smooth functions of energy. Both the \( 2P_{3/2} \) and \( 2P_{1/2} \) inelastic parameters show a somewhat anomalous behavior at \( E_p \approx 30 \) MeV; the absorption first increases then decreases to stay rather constant at \( E_p > 40 \) MeV. These results are consistent with broad and overlapping states with \( J^p = \frac{1}{2}^- \) and \( \frac{3}{2}^- \) at \( E_x \approx 22 \) MeV. There is very little splitting of the real parts of the \( F \)-wave phase shifts up to 40 MeV. There is some indication (from the \( 2G_{7/2} \) phase shifts) of a \( \frac{1}{2}^+ \) level around \( E_p = 29 \) MeV \( [E_x \approx 21 \text{ MeV}] \). The G-waves are necessary to fit the detailed shape of the angular distributions for \( E_p = 20 \) to 55 MeV (78HO17). For a contour diagram of the analyzing power for \( E_p = 130 \) to 1800 MeV see (80MO09). For a measurement of the spin rotation parameter, \( R \), at \( E_p = 500 \) MeV see (83MO01). See also (86SA1J; prelim.; \( E_p = 65 \) MeV).”

Theory and analyses reported since the previous review (88AJ01) include the S-matrix studies of resonances in the \( A = 5 \) system of (98CS02), the S-matrix and \( R \)-matrix determination of the \( \frac{3}{2}^- \) and \( \frac{5}{2}^- \) states of \( ^5\text{Li} \) of (97CS01), and the study of the \( \frac{3}{2}^+ \) levels of \( ^5\text{Li} \) on \( ^3\text{He} \) based on conventional \( R \)-matrix parameters (97BA72). See also the study of the cluster potential model (97DU15), and the calculation of interaction potentials by inversion of scattering phase shifts (96AL01). See also (96CO20).

Other theoretical work reported since the previous review (88AJ01) includes calculations for p-\( \alpha \) potentials derived from phase shifts for \( E_p \leq 23 \) MeV (91CO05) and at \( E_p = 495 \) MeV (88STZZ) and at \( E_p = 695, 793, 890, 991 \) MeV (85VE13, \( \sigma(\theta) \)) and 1 GeV (85AL09, \( \sigma(\theta) \)). Cross sections and \( A_y \) at \( E_p = 98.7 \) and 149.3 MeV for the continuum were reported by (85WE06). In experimental work reported since the previous review (88AJ01), differential cross sections were measured for \( E_p = 695, 793, 890, 991 \) MeV by (89GR20) with phase shift analysis and at 607 MeV/c by (91BA1V). Differential cross sections and analyzing powers at 71.9 MeV were measured (89BU01) and combined with existing data for \( E_p = 30–65 \) MeV for a phase shift analysis. Measurements of analyzing power at \( E_p = 180 \) MeV were reported by (90WEZY). Cross sections for the p+\( ^4\text{He} \) interaction at GeV energies have been measured at 2.7 GeV/c (93AB07), at 8.6 and 13.6 GeV/c (89BR30, 93GL09), and at \( \sqrt{s} = 31.5 \) GeV (89AK05). For earlier work at very high energies, see references cited in (88AJ01). The previous review (88AJ01) summarizes the analyses reported prior to 1988 as follows:
64.9 MeV (89CO11). Multichannel resonating group calculations are presented in (89KA39, 90BL02). The resonating group method was applied in the region \(E_p = 50-120\) MeV by (93KA47). See also the dynamic microscopic model calculation reported by (93CS02). Glauber theory calculations of cross sections at intermediate energies were reported by (93MA47). Other theoretical work related to \(^4\)He+\(p\) scattering is included in the descriptive list in the General Table for \(^5\)Li located on our website at (www.tunl.duke.edu/NuclData/General_Tables/5li.shtml).

In earlier work PNC effects were studied via the elastic scattering of 46 MeV longitudinally polarized protons on \(^4\)He: the longitudinal power \(A_z = -(3.3 \pm 0.9) \times 10^{-7}\). This was obtained by measuring \(\sigma^+\) and \(\sigma^-\) for the positive and negative helicity of the incident protons (85LA01, 86LA29): the conclusion reached by the authors from this, and all other experiments, is that there does not exist any evidence for a non-zero value of \(f_\pi\), the weak isovector coupling constant. See also (84AJ01) and (86ADZT, 86HA1Q, 88NA18). For \(\alpha+p\) correlations see (87PO03).

In application-related work, a method for precise absolute calibration of polarization effects is applied to \(p\)-\(\alpha\) scattering at \(E_p = 25.68\) MeV by (89CL04). Measurements of recoil cross sections for \(\alpha\) particles in connection with depth profiling were reported at \(E(\text{\(^3\)He}) = 0.9-3.4\) MeV (89SZ04) and at \(E(\text{\(^3\)He}) = 1.3-2.1\) MeV (88WA22).

10. (a) \(^4\)He(p, d)\(^3\)He \(Q_m = -18.35304\) \(E_b = -1.69\)
(b) \(^4\)He(p, pn)\(^3\)He \(Q_m = -20.57762\)
(c) \(^4\)He(p, 2p)\(^3\)H \(Q_m = -19.81385\)
(d) \(^4\)He(p, pd)\(^2\)H \(Q_m = -23.84653\)

As reported in (88AJ01) angular distributions of deuterons and of \(^3\)He ions (reaction (a)) have been measured for \(E_p = 27.9\) to 770 MeV and at \(E_\alpha = 3.98\) GeV/c [see (79AJ01, 84AJ01)]. Angular distributions and analyzing powers were measured at \(E_p = 100\) MeV (83NAZV, prelim.), 200 and 400 MeV (86AL01). Excitation functions are reported at several energies in the range \(E_p = 38.5\) to 44.6 MeV and 200 to 500 MeV. Continuum yields and analyzing powers have been studied at \(E_p = 98.7\) and 149.3 MeV by (85WE06). For polarization measurements to 500 MeV see above and (79AJ01, 84AJ01, 88BAZH). More recently, analyzing powers and differential cross sections were measured at \(E_p = 32, 40, 50\) and 52.5 MeV by (91SA17).

For reactions (b), (c) and (d) see (74AJ01, 79AJ01, 84AJ01). The breakup of \(^4\)He via reaction (c) has been studied by (86FU05): large values of \(A_y\) in the FSI region were reported. In more recent work on reactions (b), (c) and (d), quasifree knockout of charged particles for \(^4\)He was studied at \(E_p = 100\) MeV by (90WH01). For astrophysics-related theoretical work see (89GU28, 90BI06). For breakup processes at high energies, including pion production, see references cited in (88AJ01).
11. $^4\text{He}(\bar{p}, \bar{p})^4\text{He}$

In early work, antiproton interactions with $^4\text{He}$ were studied by (84BA60, 85BA76, 87BA12, 87BA47, 87BA69). See also (83FA16, 84BA74, 84FA14, 86DO20, 87NA23). More recently, the production rate of $^1\text{H}$, $^2\text{H}$, $^3\text{H}$ in $\bar{p}^4\text{He}$ annihilation was studied between 0–600 MeV/c by (88BA62), the annihilation cross section near 45 MeV/c was measured (89BA59), and the cross section for production of $\Lambda$ hyperons and $K^0_s$ mesons at 600 MeV/c was measured by (89BA94).

Calculations for the knockout and annihilation reactions were presented by (89NA16), and a study of the change of the branching ratio of channels for $\bar{p}^4\text{He}$ annihilation in the nuclear medium is discussed in (89NA16).

12. (a) $^4\text{He}(d, n)^5\text{Li}$ $Q_{m} = -3.91$

(b) $^4\text{He}(d, np)^4\text{He}$ $Q_{m} = -2.22457$

For reaction (a) see reaction 9 in $^5\text{He}$, (85WI15) and (87KA1ZL; $E_d = 15$ MeV; $n_0$; prelim.). Early work on reaction (b) reported in (88AJ01) includes measurements at $E_d = 12$ to 17 MeV and at $E_\alpha = 18.0$ to 140 MeV: see (79AJ01, 84AJ01), $^6\text{Li}$ in (88AJ01) and (85DO03, 87KUZI).

More recently, measurements of cross section and analyzing power at $E_d = 7$ MeV were reported by (88GA14). Comparison of data at $E_d = 12$ and 17 MeV with predictions of the three-body model are made by (88SU12). The effects of the internal structure of the $\alpha$ particle in a three-body description of the $d + \alpha$ reaction are explored by (90KU27). Multi-configuration resonating group calculations are discussed in (91FU01, 92FU10).

13. (a) $^4\text{He}(^3\text{He}, d)^5\text{Li}$ $Q_{m} = -7.18$

(b) $^4\text{He}(^3\text{He}, pd)^4\text{He}$ $Q_{m} = -5.49349$

At $E_\alpha = 26.3$ MeV, $^5\text{Li}_{g.s.}$ is reported to have a width of $1.9 \pm 0.25$ MeV while the first excited state is suggested to lie at $E_x = 2.82 \pm 0.35$ MeV, $\Gamma = 1.64 \pm 0.25$ MeV [reaction (b)]: see (82NE09, 86YA01). See also (85NEZW).

14. $^4\text{He}(\alpha, t)^5\text{Li}$ $Q_{m} = -21.50$

Measurements were made at $E_\alpha = 120, 160$ and 200 MeV (98ST07). Differential cross sections were extracted from measured triton energy spectra. Line shapes of the $^5\text{Li}$ ground state resonance was well reproduced by DWBA calculations.
15. $^4\text{He}(^7\text{Li}, ^6\text{He})^5\text{Li}$

$Q_m = -11.67$

See reaction 11 in $^5\text{He}$ and (88WO10).

16. $^6\text{Li}(\gamma, n)^5\text{Li}$

$Q_m = -5.39$

Available experimental data at energies up to $E_\gamma = 50$ MeV are reviewed and analyzed (90VA16) to explore cluster effects and final-state interactions.

17. $^6\text{Li}(\pi^+, \text{p})^5\text{Li}$

$Q_m = 134.96$

In early work, differential cross sections have been measured at $T_\pi = 75$ and 150 MeV for $p_0$: see (84AJ01). More recently cross section measurements at $E_\pi = 50, 100, 150$ and 200 MeV were reported by (92RA01). DWIA calculations presented in (92KH04) provide predictions of cross sections at $T_\pi = 115, 165$ and 255 MeV.

18. (a) $^6\text{Li}(\text{p, d})^5\text{Li}$

$Q_m = -3.16$

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

$Q_m = -1.4743$

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

$Q_m = -5.39$

Angular distributions have been measured at $E_p = 18.6$ to 185 MeV. At the highest energy, the spectra are characterized by a broad asymmetric peak corresponding to $^5\text{Li}_{g.s.}$, a narrow peak [$^5\text{Li}^* (16.7)$] and a broad peak at $E_x \approx 20$ MeV. DWBA analysis leads to $C^2S = 0.64$ and 0.57 for $^5\text{Li}^*(0, 16.7)$. The first excited state of $^5\text{Li}$ is also reported to be populated: see (84AJ01).

Reaction (b) has been studied at $E_p = 9$ to 50 MeV: the p-$\alpha$ FSI corresponding to $^5\text{Li}_{g.s.}$ is observed [see (79AJ01)]. See also (83CA13, 86NI1B). At 1 GeV (reaction (c)) the separation energy between 4–5 MeV broad 1$\text{D}_{3/2}$ and 1$s_{1/2}$ peaks is reported to be $17.7 \pm 0.5$ MeV (85BE30, 85DO16). See also (85PA03; $E_p = 70$ MeV).

19. (a) $^6\text{Li}(\text{d, t})^5\text{Li}$

$Q_m = 0.87$

(b) $^6\text{Li}(\text{d, pt})^4\text{He}$

$Q_m = 2.5583$
In early work, angular distributions of the t_0 group were measured at E_d = 15 and 20 MeV; see (74AJ01). More recently the production cross section for triton was measured by radiochemical methods (97ABZY). Calculations of differential cross sections for E_d < 30 MeV are described in (97HAZK, 97HAZY). Reaction (b) has been studied at E_d = 0.12 to 10.5 MeV: see (84AJ01). See also $^6$Be.

20. (a) $^6$Li($^3$He, a)$^5$Li $Q_m = 15.19$
(b) $^6$Li($^3$He, p)$^4$He $Q_m = 16.8787$

In early work reviewed in (88AJ01) at $E(^3$He) = 25.5 MeV, $^5$Li*(0, 16.7) and two broad peaks at $E_x \approx 19.8$ and 22.7 MeV [$\Gamma_{c.m.} = 2$ and 1 MeV] are populated: see (79AJ01). At $E(^3$He) = 33.3 MeV angular distributions and analyzing powers have been studied for $^5$Li*(0, 16.7) [$\Gamma \approx 1.6$ and $\approx 0.4$ MeV]; see (84AJ01). More recently, in experiments at $E(^3$He) = 8, 11, 13 and 14 MeV (89ARZI, 90AR17), the $^5$Li state at $E_x = 16.7$ MeV was observed and the width measured to be $\Gamma = 150 \pm 40$ keV.

In reaction (b) an analysis (89AR20) of data at $E(^3$He) = 2.5 MeV gave $\Gamma = 1.55 \pm 0.2$ MeV for $^5$Li_{g.s.}. Measurements at $E(^3$He) = 1.6, 3.5, 7.0 and 9.0 (92AR20) found the $^5$Li_{g.s.} width consistent with (88AJ01) and independent of $^3$He incident energy. Work reported for $E(^3$He) = 1.6 MeV (91AR25) and $E(^3$He) = 7 and 9 MeV (93AR12) determined that the ground state width is independent of detector angle. In early work reviewed in (88AJ01) the parameters of the first excited state are deduced to be $E_x = 5.0 \pm 0.7$ MeV, $\Gamma_{c.m.} = 5.7 \pm 0.7$ MeV (84AR17 $E(^3$He) = 1.7 and 2.3 MeV), $E_x = 5.8 \pm 0.5$ MeV, $\Gamma_{c.m.} = 5.2 \pm 0.5$ MeV (87FA11; $E(^3$He) = 1.65 MeV). More recently an experiment at $E(^3$He) = 2.0 and 2.2 MeV (92DA1K) found values in line with those measured at $E(^3$He) = 1.65 and 1.7 MeV. Measurements at $E(^3$He) = 11, 13 and 14 MeV reported by (89AR08) determined parameters for $E_x \approx 18$ MeV and found a level at $E_x = 17.9 \pm 0.4$ MeV, $\Gamma = 3.5 \pm 0.8$ MeV. Angular distribution of protons from the decay of $^5$Li_{g.s.} are reported by (88BU04; $E(^3$He) = 1.5 MeV). See also references cited in (88AJ01).

A recent theoretical study (96FA05) of the properties of resonance scattering in two fragment systems calculates parameters for the $E_x = 16.66$ MeV states formed in reaction (b).

21. $^6$Li($^6$Li, $^7$Li)$^5$Li $Q_m = 1.86$

Angular distributions have been measured at $E(^6$Li) = 156 MeV to $^5$Li_{g.s.}. Unresolved states at $E_x = 16$–20 MeV are also populated (87MI34).

22. $^6$Li($^{13}$C, $^{14}$C)$^5$Li $Q_m = 2.79$
See reaction 11 in $^5$He and (88WO10).

23. (a) $^7$Li(p, t)$^5$Li
   \[ Q_m = -4.16 \]
   (b) $^7$Li(p, nd)$^5$Li
   \[ Q_m = -10.41 \]

At $E_p = 43.7$ MeV, a triton group is observed to $^5$Li(0) ($\Gamma = 1.55 \pm 0.15$ MeV): the angular distribution is consistent with a substantial mixing of $L = 0$ and 2 transfer. There is some evidence also for a very broad excited state between $E_x = 2$ and 5 MeV. $^5$Li*(16.7, 20.0) were not observed. The formation of $^5$Li*(16.7)(^4S_{3/2}) would be $S$-forbidden: the absence of $^5$Li*(20.0) would indicate that this state(s) is also of quartet character [see reaction 22 in $^5$He]. Weak, broad states at $E_x = 22.0 \pm 0.5$ MeV and 25.0 $\pm 0.5$ MeV and possibly 34 MeV are reported in a coincidence experiment in which three- and four-particle breakup was analyzed: see (79AJ01). Measurements of angular distributions and differential cross sections at $E_p = 29.1$ and 35 MeV are reported in (89BA88). See also (88BAZH). For reaction (b) at $E_p = 670$ MeV see (84AJ01). See also (85NEZW).

24. $^7$Li($^3$He, dt)$^5$Li
   \[ Q_m = -9.65 \]

A kinematically complete experiment is reported at $E(^3$He) = 120 MeV. The missing mass spectrum shows the ground-state peak and a 4 MeV wide bump at $E_x \approx 34$ MeV, and some slight indication of a small bump at 22.0 $\pm 0.5$ MeV (85FR01).

25. $^7$Li($^6$Li, $^8$Li)$^5$Li
   \[ Q_m = -3.36 \]

See (84KO25).

26. $^9$Be($\alpha$, $^8$Li)$^5$Li
   \[ Q_m = -18.58 \]

At $E_\alpha = 90$ MeV differential cross sections have been measured for the transitions to $^5$Li_{g.s.} + $^8$Li_{g.s.}: see (84AJ01).

27. $^{10}$B(d, $^7$Li)$^5$Li
   \[ Q_m = -1.13 \]

An angular distribution is reported at $E_d = 13.6$ MeV (83DO10). See also (84SH1E).
### Table 5.7
Mirror states in $A = 5$ nuclei $^a$

<table>
<thead>
<tr>
<th>$^5$He $E_x$ (MeV)</th>
<th>$J^*$</th>
<th>$^5$Li $E_x$ (MeV)</th>
<th>$J^*$</th>
<th>$\Delta E_x$ (MeV) $^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$^3_2^-$</td>
<td>0</td>
<td>$^3_2^-$</td>
<td>—</td>
</tr>
<tr>
<td>1.27</td>
<td>$^1_2^-$</td>
<td>1.49</td>
<td>$^3_2^-$</td>
<td>+0.22</td>
</tr>
<tr>
<td>16.84</td>
<td>$^4_3^+$</td>
<td>16.87</td>
<td>$^4_3^+$</td>
<td>+0.03</td>
</tr>
<tr>
<td>19.14</td>
<td>$^5_3^+$</td>
<td>19.71</td>
<td>$^4_3^+$</td>
<td>+0.57</td>
</tr>
<tr>
<td>19.26</td>
<td>$^3_3^+$</td>
<td>25.42</td>
<td>$^3_3^+$</td>
<td>+6.16</td>
</tr>
<tr>
<td>19.31</td>
<td>$^3_3^+$</td>
<td>19.45</td>
<td>$^3_3^+$</td>
<td>+0.14</td>
</tr>
<tr>
<td>19.96</td>
<td>$^3_3^-$</td>
<td>19.28</td>
<td>$^3_3^-$</td>
<td>-0.68</td>
</tr>
</tbody>
</table>

$^a$ As taken from Table 5.1 and 5.3.

$^b$ Defined as $E_x(^5\text{Li}) - E_x(^5\text{He})$.

28. $^{10}\text{B}^{(3}\text{He, 2}\alpha)^5\text{Li}$

$Q_m = 10.73$

At $E(^3\text{He}) = 2.3$ and 5.0 MeV the reaction is reported to proceed via $^9\text{B}^*(4.9)$ to $^5\text{Li}_{gs}$.

(86AR14). See also (88AR05) and $^9\text{B}$ in (88AJ01).

$^5\text{Be}$

(Fig. 3)

The absence of any group structure in the neutron spectrum in the reaction $^3\text{He}^{(3}\text{He, n})^5\text{Be}$ at $E(^3\text{He}) = 18.0$ to 26.0 MeV indicates that $^5\text{Be}(0)$ is at least 4.2 MeV unstable with respect to $^3\text{He} + 2p [(M - A) > 33.7 \text{ MeV}]$. With Coulomb corrections adjusted to match the 16.7 MeV states of $^5\text{He} - ^5\text{Li}$, this observation places the first $T = \frac{1}{2}$ level in these nuclei above $E_x = 21.4 \text{ MeV}$: see (79AJ01).
Figure 3: Isobar diagram, $A = 5$. The diagrams for individual isobars have been shifted vertically to eliminate the neutron-proton mass difference and the Coulomb energy, taken as $E_C = 0.60Z(Z - 1)/A^{1/3}$. Energies in square brackets represent the (approximate) nuclear energy, $E_N = M(Z, A) - ZM(H) - NM(n) - E_C$, minus the corresponding quantity for $^5\text{He}$: here $M$ represents the atomic mass excess in MeV. Levels which are presumed to be isospin multiplets are connected by dashed lines.
GENERAL: References to articles on general properties of $A = 6$ nuclei published since the previous review (88AJ01) 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 (79AJ01, 88AJ01) and references cited there. More recently (90AL40) 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 (89GO18) 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 (97SM07).

$^6\text{H}$

(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 (84AL1F, 85AL1G) [$\sigma(\theta) \approx 60 \text{ nb/sr at } \theta = 10^\circ$] and in the $^{9}\text{Be}(^{11}\text{B}, ^{14}\text{O})^6\text{H}$ reaction at $E(^{11}\text{B}) = 88$ MeV (86BE35) [$\sigma(\theta) \approx 16 \text{ nb/sr at } \theta \approx 8^\circ$]. $^6\text{H}$ is unstable with respect to breakup into $^3\text{H} + 3\text{n}$ by $2.7 \pm 0.4 \text{ MeV, } \Gamma = 1.8 \pm 0.5 \text{ MeV (84AL1F), } 2.6 \pm 0.5 \text{ MeV, } \Gamma = 1.3 \pm 0.5 \text{ MeV (86BE35).}$ The value adopted in the previous review (88AJ01) is $2.7 \pm 0.3 \text{ MeV, } \Gamma = 1.6 \pm 0.4 \text{ MeV.}$ See also (87BO40). The atomic mass excess of $^6\text{H}$ using the (95AU04) masses for $^3\text{H}$ and n, is then $41.9 \pm 0.3 \text{ MeV.}$ However, there is no evidence for the formation of $^6\text{H}$ in the $^{6}\text{Li}(\pi^-, \pi^+)$ reaction at $E_{\pi^-} = 220$ MeV (90PA25). An analysis of the proton spectra for the $^{7}\text{Li}(\pi^-, p)$ reaction (90AM04) 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 $1^+ [(0 + 1) \hbar \omega \text{ model space}]$ (85PO10) [see also for $(0 + 2) \hbar \omega \text{ calculations].}$ See also the additional references cited in (88AJ01).

$^6\text{He}$

(Figs. 4 and 7)

GENERAL: References to articles on general properties of $^6\text{He}$ published since the previous review (88AJ01) are grouped into categories and listed, along with brief descriptions of each
Table 6.1
Energy levels of $^6$He

<table>
<thead>
<tr>
<th>$E_x$</th>
<th>$J^\pi; T$</th>
<th>$\tau_{1/2}$ or $\Gamma_{cm}$</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>(MeV ± keV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>g.s.</td>
<td>$0^+; 1$</td>
<td>$\tau_{1/2} = 806.7 \pm 1.5$ ms</td>
<td>$\beta^-$</td>
<td>1, 5, 8, 9, 10, 11, 12,</td>
</tr>
<tr>
<td>1.797 ± 25</td>
<td>$2^+; 1$</td>
<td>$\Gamma = 113 \pm 20$ keV</td>
<td>$n, \alpha$</td>
<td>13, 14, 15, 19, 20, 21,</td>
</tr>
<tr>
<td>5.6 ± 300</td>
<td>$(2^+, 1^-, 0^+); 1$</td>
<td>12.1 ± 1.1 MeV</td>
<td></td>
<td>22, 23, 24, 26, 30, 31</td>
</tr>
<tr>
<td>14.6 ± 0.7</td>
<td>$(1^-, 2^-); 1$</td>
<td>7.4 ± 1.0 MeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(15.5 ± 500)</td>
<td></td>
<td>4 ± 2 MeV</td>
<td>14</td>
<td>8, 14, 19, 22, 24</td>
</tr>
<tr>
<td>23.3 ± 1.0</td>
<td></td>
<td>14.8 ± 2.3 MeV</td>
<td>9, 10, 15, 19, 23, 24</td>
<td></td>
</tr>
<tr>
<td>(32)</td>
<td></td>
<td>$\leq 2$ MeV</td>
<td>10, 14, 19</td>
<td></td>
</tr>
<tr>
<td>(36)</td>
<td></td>
<td>$\leq 2$ MeV</td>
<td>23</td>
<td></td>
</tr>
</tbody>
</table>

Ground State Properties

The interaction radius of $^6$He, obtained from measurements of the total interaction cross section, is $2.18 \pm 0.02$ fm (85TA13, 85TA18). These authors have also derived nuclear matter, charge and neutron rms 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 (85TA13, 85TA18), 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 (93ZH1J, 95HI15), cluster-orbital shell models (91SU03, 94FU04), no-core microscopic shell models (96NA24), and microscopic cluster models for various effective nucleon-nucleon interactions (93CS04, 97WU01). See also (92TA18). 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 (95HA2B).
Figure 4: Energy levels of $^6\text{He}$. For notation see Fig. 5.
Table 6.2

$^6$He($\beta^-$)$^6$Li – Theoretical work

<table>
<thead>
<tr>
<th>Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>89DO1B</td>
<td>Meson exchange corrections to the $^6$He$<em>{g.s.}$-$^6$Li$</em>{g.s.}$ beta decay</td>
</tr>
<tr>
<td>89SA20</td>
<td>Polarisation effects of second-class currents in the direct and inverse decay of nuclei</td>
</tr>
<tr>
<td>89TE04</td>
<td>Neutral current effect in nuclear $\beta$-decays</td>
</tr>
<tr>
<td>90DA1H</td>
<td>Two body phase space in alpha-deuteron breakup at 40 MeV</td>
</tr>
<tr>
<td>90DAZR</td>
<td>Beta-decay of the ground state of $^6$He in three-particle $\alpha + 2n$ model</td>
</tr>
<tr>
<td>90DO04</td>
<td>Particle-hole symmetry and meson exchange corrections to the $^6$He beta decay amplitude</td>
</tr>
<tr>
<td>90HA29</td>
<td>A review of recent results on nuclear structure at the drip lines</td>
</tr>
<tr>
<td>91DA24</td>
<td>Decay of the ground state of the $^6$He nucleus in the three-particle $\alpha + 2n$ model</td>
</tr>
<tr>
<td>92DAZV</td>
<td>Static electromagnetic characteristics and beta-decay of $^6$He</td>
</tr>
<tr>
<td>92DE12</td>
<td>Beta-delayed deuteron emission of $^6$He in a potential model</td>
</tr>
<tr>
<td>93CH06</td>
<td>Gamow-Teller beta-decay rates for $A \leq 18$ nuclei, a comprehensive analysis</td>
</tr>
<tr>
<td>93ZH09</td>
<td>$^6$He beta decay to the $\alpha + d$ channel in a three-body model</td>
</tr>
<tr>
<td>94BA11</td>
<td>Deuteron emission following $^6$He beta decay</td>
</tr>
<tr>
<td>94BB03</td>
<td>Evidence for halo in quenching of $^6$He $\beta$-decay into alpha and deuteron</td>
</tr>
<tr>
<td>94CS01</td>
<td>Microscopic description of the beta delayed deuteron emission from $^6$He</td>
</tr>
<tr>
<td>94SK01</td>
<td>Improved limits on time-reversal-violating, tensor weak couplings in $^6$He</td>
</tr>
<tr>
<td>94SU02</td>
<td>Glauber theory microscopic analysis of fragmentation and beta-delayed particle emission</td>
</tr>
<tr>
<td>95SU13</td>
<td>Study of halo structure in light nuclei with a multicluster model</td>
</tr>
<tr>
<td>98GL01</td>
<td>Order-$\alpha$ radiative correction to $^6$He $\beta$-decay recoil spectrum</td>
</tr>
<tr>
<td>99ER02</td>
<td>Antisymmetrization in multicluster model &amp; nucleon exchange effects</td>
</tr>
</tbody>
</table>

1. $^6$He($\beta^-$)$^6$Li $Q_m = 3.508$

The half-life is 806.7 ± 1.5 ms (84AJ01). The decay to the ground state of $^6$Li ($J^g = 1^+$) is via a super-allowed Gamow-Teller transition; log $ft = 2.910 \pm 0.002$ (88AJ01, 84AJ01). A second beta-decay branch leading to an unbound final state consisting of a deuteron and an $\alpha$ particle was reported (90RI01) based on the observation of beta-delayed deuterons. The branching ratio for $E_d > 350$ keV was measured (93BO24, 93RIZY) to be $(7.6 \pm 0.6) \times 10^{-6}$. 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 (94BA11) 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 distribution for elastic scattering and 1n and 2n transfer were measured at 25
MeV/nucleon, and spectroscopic amplitudes were extracted by (99WO13). An analysis of elastic scattering data at 700 MeV/nucleon is described in (98AL05). See also the more recent analyses (00DE43) of data at $E = 25, 40$ MeV and that of (00GU19) at $E = 25–70$ MeV.

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 (95BE26). Cross sections for $E = 151$ MeV were calculated by (00AV02), and density distribution features were deduced. See also the discussion of (99EG02).

3. (a) $^3$H(t, n)$^5$He $Q_m = 10.534$ $E_b = 12.306$
(b) $^3$H(t, 2n)$^4$He $Q_m = 11.333$
(c) $^3$H(t, t)$^3$H

The cross section for reaction (b) was measured for $E_t = 30$ to 115 keV by (86BR20, 85JA16) who also calculated the astrophysical $S$-factors [the extrapolated $S(0) \approx 180$ keV·b] and discussed the earlier measurements. See also (74AJ01, 79AJ01) and (86JA1E). Calculations have also been made within the framework of the two-channel resonating group method (89VA20), the microscopic multichannel resonating group method (91TY01) and the generator coordinate method (90FU1H). For muon-catalyzed fusion see (88MA1V, 89BR23, 89CH2F, 90HA46). For earlier work see (88AJ01).

4. $^4$He(2n, $\gamma$)$^6$He $Q_m = 0.974$

A mechanism for this reaction in astrophysical processes is suggested, and a reaction rate is calculated (96EF02).

5. $^4$He(t, p)$^6$He $Q_m = -7.508$

Angular distributions of the protons to $^6$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 (79AJ01). Cross sections and angular distributions for the reaction products of the $^3$H($\alpha$, p)$^6$He reaction were measured at $E_\alpha = 27.2$ MeV (92GO21). A potential description of $^3$H + $^4$He elastic scattering is discussed in (93DU09).

6. $^4$He($^6$He, $^6$He)$^4$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. (98TE1D, 98TE03). Measurements at $E_{\text{c.m.}} = 11.6$ and 15.9 MeV (99RA15) also show evidence for the 2n transfer process in the elastic scattering. However, a couple-discretized-continuum channel analysis discussed in (00RU03) suggests a smaller 2n transfer process than commonly assumed. See also the analyses and calculations of (98GO1J, 99OG06, 99OG09). A microscopic multicluster model description of the elastic scattering process is discussed in (99FU03).

7. $^{6}\text{He}(p, p)^{6}\text{He}$ $E_{b} = 9.975$

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 (92GA27). A folding model with target densities which reproduce the rms radii and a range of electroweak data was used.

A calculation of the expansion of the Glauber amplitude described in (99AB37) 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 (00TI02). A theoretical study (00WE03) with four differential nuclear structure models concluded that elastic scattering at $< 100$ MeV/nucleon does not provide good constraints on the structure of the $^{6}\text{He}$ ground state.

8. $^{6}\text{Li}(e, \pi^{+})^{6}\text{He}$ $Q_{m} = -143.078$

(86SH14) report breaks in $(e, \pi^{+})$ 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 (90SH11). For the earlier work see (84AJ01). [Note: The states reported here at 7, 9 and 12 MeV are inconsistent with the work reported in reactions 11, 12, 22 and 23, and with the work on the analog region in $^{6}\text{Be}$].

9. (a) $^{6}\text{Li}(\pi^{-}, \gamma)^{6}\text{He}$ $Q_{m} = 136.062$
(b) $^{6}\text{Li}(\pi^{-}, \pi^{0})^{6}\text{He}$ $Q_{m} = 1.086$

The excitation of $^{6}\text{He}^{*}(0, 1.8)$ 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 (79AJ01). A study of capture branching ratios to $^{6}\text{He}^{*}(0, 1.8)$ was reported in (86PE05). For reaction (b) see (84AJ01).
10. $^6$Li(n, p)$^6$He

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 (79AJ01, 84AJ01)] and at 118 MeV (87PO18, 88HA2C, 88WA24). 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 (83BR1C, 84BR03) [see for discussions of the GDR strength]. The ground state reaction has also been studied at $E_n = 198$ MeV (88JA01). Proton spectra were measured at $E_n = 118$ MeV by (98HA24).

An angular distribution of the proton group corresponding to population of the $E_x = 1.8$ MeV $J^p = 2^+$ state in $^6$He was also reported (88WA24). See also (89WA1F). 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 (90MI10). Cross sections for $\theta_{lab} = 1^\circ$–$10^\circ$ for $E_n = 60$–$260$ MeV were measured to obtain the energy dependence of the Gamow Teller strength (91SOZZ, 92SO02).

Several theoretical studies have been reported since the previous review. A dynamical multicluster model was used to generate transition densities for $^6$He and $^6$Li (91DA08). A microscopic calculation in the framework of the $\alpha + 2N$ model (93SH1G) 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 (97DA01). Halo excitation of $^6$He in $^6$Li(n, p)$^6$He were studied using four-body distorted wave theory (97ER05); see also (97VA06). The status of experimental and theoretical research on nuclei featuring a two-particle halo is reviewed in (96DA31).

11. $^6$Li(d, 2p)$^6$He

The previous review (88AJ01) notes that at $E_d = 55$ MeV, $^6$He*(0, 1.8) [the latter weak] are populated: no other states are observed with $E_x \lesssim 25$ MeV [see (84AJ01)]. More recently cross sections at $0^\circ$ were measured at $E_d = 260$ MeV (93OH01) and at $E_d = 125.2$ MeV (95XU1A). In both studies the cross section for (d, $^3$He) showed a linear relationship with Gamow Teller strength from $\beta$ decay or (p, n) reactions.

12. $^6$Li(t, $^3$He)$^6$He

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 (79AJ01). Differential cross sections for the transition to $^6$He*(1.8) are reported at $E(^6$Li) = 65 MeV (87AL1L).

13. $^6$Li($^6$Li, $^6$Be)$^6$He

$$Q_m = -2.726$$
Table 6.3
Levels in $^6\text{He}$ from $^6\text{Li}(^7\text{Li}, ^7\text{Be})^6\text{He}$ $^a$

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$J^\pi$</th>
<th>$\Gamma$ (MeV)</th>
<th>$d\sigma/d\Omega$ $^b$ (mb/sr)</th>
<th>$G$ $^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>0$^+$</td>
<td></td>
<td></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$^+$) $^d$</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>

$^a$ (96JA11). $E(\text{Li}) = 350$ MeV.

Angular distributions have been studied for $E(^6\text{Li}) = 32$ and 36 MeV for the transitions to $^6\text{He}_{\text{g.s.}}$, $^6\text{Be}_{\text{g.s.}}$, and, in inelastic scattering of $^6\text{Li}$ [see $^6\text{Li}]$, to the analog state $^6\text{Li}^*(3.56)$: for a discussion of these see the references quoted in (79AJ01).

14. $^6\text{Li}(^7\text{Li}, ^7\text{Be})^6\text{He}$

$Q_m = -4.370$

Measurements of differential cross sections at $E(^7\text{Li}) = 82$ MeV are reported in (92GLZX, 93GLZZ, 94SAZZ) and at $E(^7\text{Li}) = 78$ MeV in (93SA35, 94RUZZ). The $^6\text{He}$ levels at $E_x = 0$ $J^\pi = 0^+$ and $E_x = 1.80$ $J^\pi = 2^+$ were identified. A maximum at $E_x = 6$ MeV is interpreted as consistent with a soft-dipole response expected in neutron-halo nuclei. A study (96JA11, 99AN13) at $E(^7\text{Li}) = 350$ 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 (96JA11). See Table 6.3. In experiments at $E = 65$ MeV/nucleon with this reaction, isovector spin-flip and spin non-flip resonance were deduced (98NAZP, 98NAZR). See also the more recent measurements described in (00NA22).

A theoretical study of $^6\text{He}$ structure with an extended microscopic three-cluster model is described in (99AR08).

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

$Q_m = -9.975$

(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 (79AJ01). Reactions (a) and (b) have been studied by (85SE17). See also $^7\text{Li}$, (84AJ01) and (86BA2G). An analysis of the available experimental data on $^7\text{Li}$ photodisintegration at energies up to $E_\gamma = 50$ MeV is presented in (90VAZM, 90VA16). See also the discussion of reactions involving scattering of polarized electrons from polarized targets (93CA11). In more recent work (99LA13, 00LA17) momentum distributions from transitions to the $^6\text{He}$ ground and first excited state were measured via reaction (b). The deduced spectroscopic factor for both is $0.58 \pm 0.05$ in agreement with variational Monte Carlo calculations.

16. $^7\text{Li}(\pi^+, 2p)^5\text{He}$ \hspace{1cm} $Q_m = 128.606$

Pion and proton spectra were measured at $E_p = 500$ MeV to deduce $\Delta$ components in the ground state wave function (98PA31).

17. $^7\text{Li}(\pi^-, \pi^-p)^6\text{He}$ \hspace{1cm} $Q_m = 128.813$

The results of measurements of inclusive spectra made with $\pi^-$ mesons with momentum 90 MeV/c are presented in (93AM09). The probability of one-neutron emission was found to be $Y = (1.1 \pm 0.2) \times 10^{-3}$ per stopped $\pi^-$. 

18. $^7\text{Li}(\pi^-, \pi^-p)^6\text{He}$ \hspace{1cm} $Q_m = -9.975$

Pion and proton spectra were measured at 0.7, 0.9, 1.25 GeV/c by (00AB25). Fermi-momentum distributions were deduced.

19. $^7\text{Li}(n, d)^6\text{He}$ \hspace{1cm} $Q_m = -7.751$

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 ($\pm 0.5$ 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 $S(1p_{1/2}) = 0.35$ for $^6\text{He}^*(1.8)$; see (79AJ01). Measurements of the cross section as a function of energy for $E_x = 10$–30 MeV were reported in (89CO22). See also the measurements at $E_n = 14.1$ MeV (89SHHZS).
20. $^7\text{Li}(p, 2p)^6\text{He}$ \hspace{1cm} $Q_m = -9.975$

From measurements at $E_p = 1$ GeV ([85BE30, 85DO16]), 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 ([83GO06] and (79AJ01)). Differential cross section measurements at $E_p = 70$ MeV are reported in ([88PA26, 98SH33]). Contributions from 1p and 1s nucleons in $^7\text{Li}$ were distinguished. Proton spectra measurements for $E_p = 1$ GeV were reported by ([00MI17]). Effective proton polarizations were deduced. See also the review of experimental and theoretical nucleon and cluster knockout reactions in light nuclei presented in ([87VD1A]).

21. $^7\text{Li}(d, ^3\text{He})^6\text{He}$ \hspace{1cm} $Q_m = -4.481$

As summarized in the previous review ([88AJ01]), 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 $J^p = (0-3)^+$. There is no evidence for any other states of $^6\text{He}$ with $E_x < 10.7$ MeV; see ([79AJ01]). ([87BO39]) $[E_d = 30.7$ 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 ([85BO55] and [87DA1N]). 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 ([94BO46]).

22. $^7\text{Li}(t, \alpha)^6\text{He}$ \hspace{1cm} $Q_m = 9.839$

As summarized in ([88AJ01]), the energy of the first-excited state is 1.797 ± 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 $\Gamma_{\text{c.m.}} = 113 \pm 20$ 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 ([79AJ01]). Angular distributions were reported at $E_t = 0.151$ and 0.272 MeV ([87AB09; $\alpha_0, \alpha_1$]) and at $E(^7\text{Li}) = 31$ MeV. ([87AL1L; to $^6\text{He}^*(0, 1.8, 13.6)$]).

In more recent work, differential cross sections were measured at $E_t = 38$ MeV ([92CL04]). 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 ([91LA1D]).

23. $^7\text{Li}(^3\text{He}, p^3\text{He})^6\text{He}$ \hspace{1cm} $Q_m = -9.975$
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 (85FR01).

24. (a) $^7\text{Li}(^6\text{Li}, ^7\text{Be})^6\text{He}$ \hspace{1cm} $Q_m = -4.370$
    (b) $^7\text{Li}(^7\text{Li}, ^8\text{Be})^6\text{He}$ \hspace{1cm} $Q_m = 7.281$

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 (87GLZW, 88BUZH). $^6\text{He}^*(0, 1.8)$ are also populated (88BUZH). For reaction (b) see $^8\text{Be}$. See also $^7\text{Be}$, (84AJ01) and (88BU1Q, 84BA53), and see (96SO17) which involves $^{10}\text{Be}$ excited states. Measurements of differential cross sections at $E(^7\text{Li}) = 22$ MeV were reported in (88BO18).

25. $^9\text{Be}(\gamma, ^3\text{He})^6\text{He}$ \hspace{1cm} $Q_m = -21.177$

Measurements of ground-state cross sections and angular distributions are reported in (99SH05). See (99ZHZN) for a compilation and evaluation of cross section data for $E_\alpha \leq 30$ MeV.

26. $^9\text{Be}(n, \alpha)^6\text{He}$ \hspace{1cm} $Q_m = -0.600$

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 (79AJ01). For a study of possible dineutron breakup of $^6\text{He}^*(1.8)$ see (83OT02). An analysis of the alpha and neutron spectra observed in this reaction for $E_n \approx 14$ MeV is presented in (88FE06). See also $^{10}\text{Be}$ and (83SH1J).

27. $^9\text{Be}(^6\text{He}, ^6\text{He})^9\text{Be}$ \hspace{1cm} $E_b = 19.069$

Elastic scattering measurements for $E(^6\text{He}) = 8.8$–9.3 MeV were reported in (91SM01). The data are well reproduced with calculations using $^6\text{Li}$ or $^7\text{Li}$ optical model parameters. See also $^9\text{Be}$.

28. $^9\text{Be}(^6\text{Li}, ^9\text{B})^6\text{He}$ \hspace{1cm} $Q_m = -4.576$
Differential cross sections were measured at $E(^{6}\text{Li}) = 34, 62$ MeV, and spectroscopic factors were deduced (85CO09). Vector and tensor analyzing powers were measured for detection of the $^{6}\text{He}$ nuclei at $\theta_{\text{cm}} = 14^\circ$–$80^\circ$ at $E(^{6}\text{Li}) = 32$ MeV (93RE04). See $^9\text{B}$.

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

$$Q_m = -3.389$$

This reaction has been used as a source of $^6\text{He}$ beams for elastic scattering experiments at $E(^{6}\text{He}) = 8.8$–$9.3$ MeV (91SM01) and at $E(^{6}\text{He}) = 10.2$ MeV (95WA01).

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

$$Q_m = 5.102$$

Angular distributions were measured at $E(^{9}\text{Be}) = 40$ MeV (92CO05). See $^9\text{Be}$ and $^{12}\text{C}$.

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

$$Q_m = 5.982$$

At $E(^{11}\text{B}) = 88$ 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 (87BEYI). See also (88BEYJ).

32. $^{12}\text{C}(\mu^+, X)^{6}\text{He}$

Measurements of the energy dependence at $E = 100, 190$ GeV were reported by (00HA33).

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

Peripheral fragmentation of $^6\text{He}$ at 240 MeV/$A$ was studied (97CH24, 97CH47, 98AL10) in a kinematically complete experiment. It was found that one-neutron stripping to $^5\text{He}$ is the dominant mechanism. A continuation of the analysis described in (00AL04) indicates excitation of the $^6\text{He}$ first $2^+$ state and associates it with E1 dipole oscillation. See also (93FE02). Model calculations are discussed in (98BE09, 98GA37).

34. $^{12}\text{C} (^{6}\text{He}, \alpha)X$
Measurements at 240 MeV/A are described in (98AL10, 98AU02, 99AU01, 00AL04). Fragmentation cross sections of \(^6\)He were analyzed in the Glauber theory to investigate the importance of neutron correlation (94SU02). 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 (95SU13). See also (98BE09, 98GA37).

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

\[ E_b = 18.376 \]

Elastic and quasielastic scattering of \(^6\)He on \(^{12}\)C was studied at \(E(\(^6\)He) = 10.2\) MeV (95WA01). See also (95PE1D). Measurements of cross sections were made at 41.6 MeV/A (96AL11). 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 (93GO06). The possibility of studying the structure of the neutron halo in \(^6\)He elastic rainbow scattering is discussed. See also (89SI02, 92CL04, 93FE02, 95GA24). Calculations of cross sections at \(E = 20–60\) MeV/nucleon were reported in (00BO45). Proton, neutron and matter rms distributions were also calculated.

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

Measurements and analyses of a three-body breakup experiment at 240 MeV/A are described in (99AU01, 00AL04). Two-neutron interferometry measurements at 50 MeV/A are discussed in (00MA12).
GENERAL: References to articles on general properties of $^6\text{Li}$ published since the previous review (88AJ01) 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

\[ \mu = +0.8220467(6) \text{ nm}, +0.8220560(4) \text{ nm}; \text{ see (78LEZA)}, \]
\[ Q = -0.818(17) \text{ mb} \ (98CE04). \]

The interaction nuclear radius of $^6\text{Li}$ is 2.09 ± 0.02 fm (85TA18). These authors have also derived nuclear matter, charge and neutron rms radii.

Quadrupole moment: The tiny quadrupole moment of $^6\text{Li}$ poses an difficult task for theoretical calculations. Except for a phenomenological (85ME02), a microscopic cluster (86ME13), and a Greens-Function Monte-Carlo (97PU03) calculation, the models fail to even predict the sign. See the discussion of three-body models in (93SC30). In (91UN02), 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 (92CS04) considers the findings of (86ME13) 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 (88WE1C, 90EI01, 90LE24). The S-state \(\alpha+d\) normalization constant for $^6\text{Li}$ appears to be well determined (93BL09, 99GE02), but both the magnitude and sign of \(\eta\) are uncertain.

In a two-body \(\alpha+d\) model it was found (84NI01) 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 \(\eta > 0\) (90LE24, 95KU08). Recent microscopic six-body calculations using realistic NN potentials predict \(\eta = -0.07\) (96FO04).

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 (78BO1A) from which \(\eta\) was found to be \(+0.005\pm0.014\). Several $^6\text{Li}+^{58}\text{Ni}$ elastic scattering studies (84NI01, 95DE06, 95RU14) have described polarization observables with \(\eta \approx -0.01\), while an investigation of the breakup of $^6\text{Li}$ on $^1\text{H}$ suggests \(\eta > 0\) (92PU03). A study of the $^6\text{Li}(\vec{d}, \alpha)^4\text{He}$ reaction

\(^1\) We are very grateful to K.D. Veal and C.R. Brune for providing these comments on the asymptotic D/S ratio for $^6\text{Li}$.

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Table 6.4
Energy levels of $^6$Li

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

$^a$ See also Table 6.12.

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

$^c$ For possible states at high $E_x$ see reactions 8, 37, 39 and 45 and Table 6.9.
(90SA47) found that $\eta$ should lie in the range $-0.010$ to $-0.015$. Recently, a phase shift analysis of $^6\text{Li} + ^4\text{He}$ scattering determined $\eta = -0.025 \pm 0.006 \pm 0.010$ (99GE02) while an analysis of $(^6\text{Li}, d)$ transfer reactions resulted in a near zero value of $\eta = +0.0003 \pm 0.0009$ (98VE03).

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 (98VE03, 99GE02).

Isotopic abundance: $(7.5 \pm 0.2)\%$ (84DE1A). See also (87LA1J, 88LA1C).

For estimates of the parity-violating $\alpha$-decay width of $^6\text{Li}^*(3.56) [0^+; T = 1]$ see (83RO12, 84BU01, 86BU07).

1. $^1\text{H}(^6\text{Li}, ^6\text{Li})^3\text{H}$ 
   \[ E_b = 5.605 \]

   Differential cross sections were measured at $E = 0.7$ GeV/A by (00DOZY). Matter distribution radii and halo features were deduced.

2. $^2\text{H}(\alpha, \pi^0)^6\text{Li}$ 
   \[ Q_m = -133.502 \]

   Measurements of cross sections at $E_\alpha = 418, 420$ MeV are reported by (00AN15). Halo features were deduced.

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 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 $^6\text{Li}$”.

56
\[
\begin{align*}
\frac{22.052}{^3\text{He} + \text{d} + \text{n}} &= \frac{21.289}{^3\text{H} + \text{d} + \text{p}} \\
\frac{13.328}{^7\text{Li} + ^3\text{He} - \alpha} \\
\frac{5.389}{^6\text{Li} + \text{n}} &= \frac{4.497}{^3\text{He} + \text{p}} \\
\frac{3.898}{^3\text{He} + \text{p}} &= \frac{3.699}{^4\text{He} + \text{n} + \text{p}} \\
\frac{3.563}{^6\text{Li}} &= 2.186 \\
\frac{-0.992}{^7\text{Li} + \text{d} - \text{t}} = 0.9 \text{~s} \text{r}
\end{align*}
\]
3. (a) $^3\text{He}(^3\text{H}, \gamma)^6\text{Li}$
(b) $^3\text{He}(^3\text{H}, n)^5\text{Li}$
(c) $^3\text{He}(^3\text{H}, d)^4\text{He}$
(d) $^3\text{He}(^3\text{H}, ^3\text{H})^3\text{He}$

In the previous review (88AJ01), information on radiative capture of $^3\text{H}$ on $^3\text{He}$ was summarized as follows: “Capture $\gamma$-rays (reaction (a)) to the first three states of $^6\text{Li}$ [$\gamma_0$, $\gamma_1$, $\gamma_2$] 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 ± 0.4 [$\gamma_1$], $\approx 21$ [$\gamma_3$] and 21.8 ± 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 $\theta_1^2 = 0.6 \pm 0.3$: see (74AJ01). See also (85MO1C, 86MO1G, 87MO1I).”

Since the previous review (88AJ01), a new resonance analysis (88MO1I, 90HE20, 90MO10 92HE1E) 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 distribution in terms of very wide overlapping resonances. See Table 6.5. These correspond to $^6\text{Li}$ 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 $^6\text{Li}$ states with $S = 1$, $T = 1$. These results are supported by calculations described in (95OH03) which utilize a complex-scaled $^3\text{He} + t$ resonating group method to calculate the energies and widths of the $^6\text{Li} ^3\text{He} + t$ 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 (90MO10, 90HE20) and one of the authors [H.M.H.] of this review. The radiative capture reaction as a source of $^6\text{Li}$ production in big bang nucleosynthesis is discussed in (90FU1H, 90MA1O, 97NO04). See also (95DU12).

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 [6Li*(26.1)]: see (79AJ01).

Angular distributions of deuterons (reaction (c)) have been measured for $E_l = 1.04$
Table 6.5
Levels of $^6\text{Li}$ from $^3\text{He}^{(3}\text{H}, \gamma)_{^3\text{H}}$ and $^3\text{He}^{(3}\text{H}, \gamma_1)_{^6\text{Li}^*(2.18)}$ $^a$

<table>
<thead>
<tr>
<th>State</th>
<th>$J^\pi; T$</th>
<th>$E_{^3\text{He}}$ (MeV)</th>
<th>$E_x$ (MeV)</th>
<th>$\Gamma_{\text{c.m.}}$ (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>$^{33}\text{F}_2$</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>

$^a$ From the analysis (90HE20, 90MO10) of data from (68BL10, 73VE09, 77VL01).

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 (79AJ01)], as well as at $E(^3\text{He}) = 18.0$ and 33.0 MeV (86RA1C). See also (86KO1K) and (85CA41). A microscopic calculation for reaction (c) and its inverse with special emphasis on isospin breaking in the analyzing power is described in (90BR09). See also the calculations of (90BLZW, 93DU02, 93FI06).

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 (79AJ01). 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 (88AJ01) for a description of earlier analyses of these data. More recently a new resonance analysis (90HE20, 90MO10) of these same data along with $^3\text{He}^{(3}\text{H}, \gamma)$ data led to the $^6\text{Li}$ $S = 1$, $T = 1$ states discussed above under reaction 3(a). See Table 6.5.

For other channels see (84AJ01). See also (84KR1B). For thermonuclear reaction rates see (88CA26).

4. $^3\text{H}(\alpha, n)^6\text{Li}$ $Q_m = -4.783$

$^6\text{Li}^*(0, 2.19)$ have been populated: see (74AJ01). See also $^7\text{Li}$, (83CO1E) and (83FU11). Cross sections for $E(^3\text{H}) < 20$ MeV were calculated with a resonating group method by (91FU02).

5. $^3\text{He}^{(3}\text{He}, \pi^+)^6\text{Li}$ $Q_m = -123.794$

Differential cross sections are reported for the transitions to $^6\text{Li}^*(0, 2.19)$ for $E(^3\text{He}) = 350, 420, 500$ and 600 MeV (83LE26). See also (84AJ01), (83BR1B, 83JA13) and (84GE05).
More recently, analyses of data for $E(^{3}\text{He}) = 295–810$ MeV and microscopic reaction model calculations have been done (91HA22). See also the calculations of (99VO01).

6. $^{4}\text{He}(d, \gamma)^{6}\text{Li}$ $Q_m = 1.475$

The previous review (88AJ01) summarized the information on this reaction as follows: “No resonance has been observed corresponding to formation of $^{6}\text{Li}^\ast(3.56)$ $[0^+; T = 1]$; the parity-forbidden $\Gamma_\alpha \leq 6 \times 10^{-7}$ eV (84RO04). See also Table 6.4.”

“The cross section for the capture cross section has been measured for $E_\alpha = 3$ 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 $^{6}\text{Li}_{\text{g.s.}}$ and $\alpha + d$ is $0.85 \pm 0.04$: see (84AJ01). See also (82KI1A), (85CA41, 86LA22, 86LA27) and theoretical work presented in (84AK01, 85AK1B, 86AK1C, 86BA1R).”

Since the previous review (88AJ01), measurements of the cross section at energies $E_\alpha \approx 2$ MeV corresponding to the $3^+$ resonance at $E_x = 2.186$ MeV in $^{6}\text{Li}$ have been reported (94MO17). Values extracted for the total width $\Gamma$ and the radiative width $\Gamma_\gamma$ confirm the adopted value (88AJ01). An experimental search for the reaction at $E_{cm} \approx 53$ keV (96CE02) gave an upper limit for the $S$ factor of $2 \times 20^{-7}$ MeV \cdot 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 (99AN35).

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.

7. (a) $^{4}\text{He}(d, np)^{4}\text{He}$ $Q_m = -2.224$ $E_b = 1.475$

(b) $^{4}\text{He}(d, t)^{3}\text{He}$ $Q_m = -14.320$

Reaction (a) has been studied to $E_\alpha = 165$ MeV and to $E_d = 21.0$ MeV: see (79AJ01, 84AJ01). Measurements are also reported at $E_d = 5.4, 6.0$ and $6.8$ MeV (85LU08; VAP, TAP), 6 to 11 MeV (85OS02; VAP), 10.05 MeV (83BR23; VAP, TAP) and 12.0 and 21.0 MeV (83IS10; VAP, TAP) and at $E_\alpha = 11.3$ MeV (87BR07). See also (86DO1K).

More recently, measurements of the cross section and transverse tensor analyzing power at $E_d = 7$ MeV were made (88GA14) with kinematic conditions chosen to correspond to production of the singlet deuteron. Coulomb and nuclear field effects in these reactions are discussed in (87KO1X, 88KA38). Cross sections and polarization observables from data at $E_d < 12, 17$ MeV are compared with three-body model predictions in (88SU12).

For reaction (b), measurements of vector and tensor analyzing power at $E_d = 35, 45$ MeV have been reported (86BR1N, 86VA1B, 86VU1A, 87VU1A). Cross sections and polarization observables were measured at $E_d = 32.1, 35.15, 39.6, 49.7$ MeV to investigate
<table>
<thead>
<tr>
<th>Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>89CR01</td>
<td>D-state effects in the $^4$He($d, \gamma$)$^6$Li reaction</td>
</tr>
<tr>
<td>89SC25</td>
<td>The reaction rate at $T = 300$ K for $^2$H($\alpha, \gamma$)$^6$Li and other reactions</td>
</tr>
<tr>
<td>90CR04</td>
<td>Tensor interaction effects in $^4$He($d, \gamma$)$^6$Li</td>
</tr>
<tr>
<td>90KRZX</td>
<td>Polarization observables for $^4$He($d, \gamma$)$^6$Li and the D state of $^6$Li</td>
</tr>
<tr>
<td>90SC22</td>
<td>The extended elastic model II applied to $^2$H($\alpha, \gamma$)$^6$Li</td>
</tr>
<tr>
<td>91SC23</td>
<td>A simple expression for the cross-section factor in nuclear fusion</td>
</tr>
<tr>
<td>91TY02</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>93JA02</td>
<td>Polarizability and E1 radiation in $^4$He($d, \gamma$)$^6$Li</td>
</tr>
<tr>
<td>93MU12</td>
<td>Calculation of the $^6$Li $\rightarrow$ $\alpha + d$ vertex constant</td>
</tr>
<tr>
<td>94MO17</td>
<td>Direct capture in the $3^+$ resonance of $^2$H($\alpha, \gamma$)$^6$Li</td>
</tr>
<tr>
<td>95DU12</td>
<td>Cluster model descriptions of $^6$Li photodisintegration</td>
</tr>
<tr>
<td>95IG06</td>
<td>Analysis of the nuclear astrophysical reaction $^4$He($d, \gamma$)$^6$Li</td>
</tr>
<tr>
<td>95MU21</td>
<td>Astrophysical factor for $^4$He($d, \gamma$)$^6$Li</td>
</tr>
<tr>
<td>95MU1J</td>
<td>Peripheral astrophysical radiative capture processes, a survey</td>
</tr>
<tr>
<td>95RY01</td>
<td>$^4$He($d, \gamma$)$^6$Li capture and the isoscalar E1 multipole</td>
</tr>
<tr>
<td>97NO04</td>
<td>Nuclear reaction rates and primordial $^6$Li</td>
</tr>
<tr>
<td>98KH06</td>
<td>Microscopic study of $^3$H($\alpha, \gamma$)$^6$Li in a multicenter model</td>
</tr>
<tr>
<td>00IG03</td>
<td>Coulomb breakup &amp; astrophys. S-factor of $^2$H($\alpha, \alpha$) at extremely low energies</td>
</tr>
</tbody>
</table>
3H and 3He asymptotic normalization constants (87VU1B) and charge symmetry breaking (88VU01). Cross sections and polarization observables measured at $E_{\text{cm}} = 14–33$ MeV (89BR23) were compared with microscopic-model predictions in a study of isospin violation. See also (90BR09). The role of tensor force was explored in (88BR18).

For earlier work and other breakup channels, see references cited in (88AJ01).

8. $^4$He(d, d)$^4$He $E_b = 1.475$

Elastic differential cross-section and polarization measurements have been carried out up to $E_a = 166$ MeV and $E_d = 45$ MeV; see (74AJ01, 79AJ01, 84AJ01). Measurements were also reported at $E_d = 0.87$ to 1.43 MeV (84BA19, 85BA1K), at $E_d = 11.9$ MeV (88EL01; TAP), 21 MeV (see 86MI1E; VAP, TAP), 24.0 and 38.2 MeV (86GR1D; TAP), 31.8 to 39.0 MeV (86KO1M; TAP), 40 MeV (89DE1A), 56 MeV (85NI1A; VAP, TAP) and at $E_a = 7.0$ GeV/c (84SA1C). A compilation of data for energies $E_d = 1–56$ MeV is presented in (87GR08). For a study of the inclusive inelastic scattering at $E_a = 7.0$ GeV/c see (87BA13).

Phase-shift analyses, particularly that by (83JE03) 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 $E_x = 2.19$ ($^3D_3$), 4.7 ($^3D_2$) and 5.65 MeV ($^3D_1$). (83JE03) 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 + α) parentage.

(85JE04) have investigated the points where $A_{2\gamma} = 1$ and report four such points at $E_d = 4.30$ [$\theta_{\text{cm}} = 120.7^\circ$], 4.57 (58.0$^\circ$), 11.88 (55.1$^\circ$) and 36.0 $\pm$ 1.0 MeV (150.1 $\pm$ 0.3$^\circ$). [For the latter see also (86KO1M)]. The correspondence of these polarization maxima to $^6$Li states is discussed by (85JE04). For a discussion of the M-matrix see (88EL01). For work on $(\alpha + d)$ correlations involving $^6$Li$^\pi$($0, 2.19, 4.31 + 5.65$) see (87CH08, 87CH33, 87PO03) and (87FO08).

For additional references to early work see references cited in (88AJ01).

A considerable body of theoretical work on the $^4$He + d channel has been done since the previous review (88AJ01). A list of references with brief descriptions is provided in Table 6.8.

9. (a) $^4$He($^3$He, p)$^6$Li $Q_m = -4.019$

(b) $^4$He($^3$He, pd)$^4$He $Q_m = -5.494$

Angular distributions have been measured at $E(^3\text{He}) = 8$ to 18 MeV and $E_a = 42$, 71.7 and 81.4 MeV: see (74AJ01). More recently, proton polarization was measured as a
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>$\gamma_d^2$ $^c$</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$^{+3}$</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 (83JE03). The results are unique up to $E_d = 15$ MeV. See also Table 6.4 in (74AJ01), and Tables 6.3 in (79AJ01) and (84AJ01).

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

$^c$ In units of the Wigner limit $\gamma_w^2 = 2.93$ MeV for a radius of 4.0 fm. See (88AJ01).

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

function of angle at $E_{cm} = 12.6$ MeV (89GR02). At $E_\alpha = 28, 63.7, 71.7$ and 81.4 MeV the $\alpha$-spectra show that the sequential decay (reaction (b)) involves $^6$Li$^*$ (2.19) and possibly $^5$Li: see (79AJ01). See also the recent theoretical work of (93GO16) and the multiconfiguration RGM calculations of (95FU16).

10. (a) $^4$He($\alpha$, d)$^6$Li

(b) $^4$He($\alpha$, pn)$^6$Li

(c) $^4$He($\alpha$, $\alpha$d)$^2$H

$Q_m = -22.372$

$Q_m = -24.596$

$Q_m = -23.847$

Reactions (a) and (b) have been studied to $E_\alpha = 158.2$ MeV [see (79AJ01, 84AJ01)] and at 198.4 MeV (85WO11). The dependence of the cross section on energy shows that the $\alpha + \alpha$ process does not contribute significantly to $^6$Li (and $^7$Li) synthesis above $E_\alpha = 250$ MeV (85WO11) [and see for additional comments on astrophysical problems]. For reaction (c) [and excited states of $^4$He] see (84AJ01): $^6$Li$^*$ (2.19) is involved in the process.

11. $^6$He($\beta^-$)$^6$Li

$Q_m = 3.508$

See $^6$He, reaction 1.
<table>
<thead>
<tr>
<th>Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>88BE58</td>
<td>Polarization phenomena in $^4$He(d, d) at intermediate energies</td>
</tr>
<tr>
<td>88KA25</td>
<td>Convergence features in the pseudostate theory of the d + α system</td>
</tr>
<tr>
<td>88WE1C</td>
<td>Manifestations of the D-state in light nuclei</td>
</tr>
<tr>
<td>89ET1A</td>
<td>Description of diffraction scattering on nuclei</td>
</tr>
<tr>
<td>89KI1E</td>
<td>Microscopic theory of collective resonances of light nuclei</td>
</tr>
<tr>
<td>89KR08</td>
<td>Padé approximation technique for processing scattering data</td>
</tr>
<tr>
<td>90BL13</td>
<td>Analysis of higher partial waves in $^4$He(d, d) in 3-body framework</td>
</tr>
<tr>
<td>90DA1H</td>
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</tr>
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<td>90HU06</td>
<td>A geometric model for nucleus-nucleus scattering at high energies</td>
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<tr>
<td>90LU16</td>
<td>Padé-approximation techniques for processing scattering data</td>
</tr>
<tr>
<td>90LU11</td>
<td>Further study of α elastic scattering on light nuclei</td>
</tr>
<tr>
<td>91BL04</td>
<td>Manifestation of Pauli-forbidden states in $^4$He(d, d) at low energies</td>
</tr>
<tr>
<td>91KR02</td>
<td>Energy-dependent phase-shift analysis of $^4$He(d, d) at low energies</td>
</tr>
<tr>
<td>91LU09</td>
<td>d-α scattering in a three-body model</td>
</tr>
<tr>
<td>91LU27</td>
<td>Recovering α+d potential from Faddeev and measured phase shifts</td>
</tr>
<tr>
<td>92CE01</td>
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</tr>
<tr>
<td>92FU10</td>
<td>Reaction mechanisms in $A = 6$ with the multiconfiguration RGM</td>
</tr>
<tr>
<td>92LU16</td>
<td>Supersymmetric potentials and the Pauli Principle in $^4$He(d, d)</td>
</tr>
<tr>
<td>92LU16</td>
<td>Deuteron size effects in d-α scattering</td>
</tr>
<tr>
<td>93BL09</td>
<td>Determination of $^6$Li $\rightarrow$ α + d vertex constant for d-α phase-shifts</td>
</tr>
<tr>
<td>93FU06</td>
<td>Study of continuous spectrum of $^6$Li in RGM</td>
</tr>
<tr>
<td>94CS01</td>
<td>Microscopic description of beta-delayed deuteron emission in $^6$He</td>
</tr>
<tr>
<td>95DU12</td>
<td>Cluster model description of photonuclear processes in $^6$Li</td>
</tr>
<tr>
<td>97DU16</td>
<td>Electromagnetic effects in light nuclei and the cluster potential</td>
</tr>
<tr>
<td>97LU14</td>
<td>Reconstruction of analytic S matrix from experimental d-α data</td>
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<tr>
<td>98DU03</td>
<td>Potential cluster model description of the d-α interaction</td>
</tr>
<tr>
<td>99CO11</td>
<td>An S-matrix inversion technique applied to α-d scattering</td>
</tr>
</tbody>
</table>
12. $^6$He(p, n)$^6$Li

$$Q_m = 2.726$$

An experiment utilizing a secondary $^6$He beam with $E(^6$He) = 42 MeV/nucleon was reported by (95CO05, 98CO1M, 98CO19, 98CO28). The $^6$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 (96BR30). The $0^\circ$ ground state cross section was measured to be $\frac{d\sigma}{d\Omega} = 43 \pm 16$ 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 (97CO04) to study the effects of halo structure.

The current status of theoretical and experimental research on nuclei featuring a two-particle halo was reviewed in (96DA31).

13. $^6$Li $\rightarrow$ alpha + d

$$E_b = -1.475$$

A theoretical study in a microscopic three-cluster model of the parity-violating $\alpha + d$ decay of the lowest $0^+$ state is described in (96CS03). A phase shift analysis of $^4$He + d was used in a determination of the vertex constant for the $^6$Li$(1^+ 0) \rightarrow \alpha + d$ virtual decay by (92BLZX, 93BL09, 97KU14). See also (90RY07, 91KR02, 93BO38).

14. (a) $^6$Li$(\gamma, n)^5$Li
(b) $^6$Li$(\gamma, p)^3$He
(c) $^6$Li$(\gamma, d)^4$He
(d) $^6$Li$(\gamma, np)^4$He
(e) $^6$Li$(\gamma, t)^3$He

$$Q_m = -5.389$$
$$Q_m = -4.497$$
$$Q_m = -1.475$$
$$Q_m = -3.699$$
$$Q_m = -15.795$$

The previous review (88AJ01) 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 (84AJ01) and (88DI02). (84DY01) 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 (84AJ01).] See also (88CA11) and $^5$He. The cross section for reaction (c) is $\leq 5$ mb in the range $E_\gamma = 2.6$ to 17 MeV consistent with the expected inhibition of dipole absorption by isospin selection rules: see (66LA04). The onset of quasi-deuteron photodisintegration between 25 and 65 MeV is suggested by the study of (84WA18). $E_\gamma$(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 $^6\text{Li}+\gamma$, consistent with a $^3\text{H}+^3\text{He}$ cluster description of $^6\text{Li}_{g.s.}$ with $\theta^2 \approx 0.68$. The agreement with the inverse reaction, $^3\text{H}(^3\text{He}, \gamma)$ [see reaction 3] is good: see (84AJ01). See also (86LI1F).”

“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 (84AJ01). For spallation studies see (74AJ01, 84AJ01). For pion production see (86GL07, 87GL01) and (84AJ01).”

Since the previous review (88AJ01) tagged photons were used to study $^6\text{Li}(\gamma, p)$ at $\theta_p = 0^\circ$ for $E_\gamma \approx 59$ and 75 MeV. Strong evidence for the photo-deuteron mechanism was found. Measurements made for angles between 30° and 150° (95DI01) 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 (97DI01). See also (94RY01). Measurements of $^6\text{Li}(\gamma, d)$ at $E_\gamma \approx 60$ MeV indicated strict obedience 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 (90RIZX).

Linearly polarized photons were used to measure the cross section asymmetry in $^6\text{Li}(\gamma, t)^3\text{He}$ up to $E_\gamma \approx 70$ MeV (89BU10) and differential cross sections up to $E_\gamma \approx 90$ MeV (93DE07, 95BU08). Results of a measurement of the absolute total photoabsorption cross section for $E_\gamma = 300–1200$ MeV are presented in (94BI1B).

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

15. $^6\text{Li}(\gamma, \gamma)^6\text{Li}$

The width, $\Gamma_\gamma$, of $^6\text{Li}^*(3.56) = 8.1 \pm 0.5$ eV: see (74AJ01) and Table 6.4 in (79AJ01); $E_X = 3562.88 \pm 0.10$ keV: see (84AJ01). See also (87PI06). The results of an absolute measurement of the total photoabsorption cross section are described in (94BI1B). Photon
absorption and photon scattering for light elements is discussed in terms of a collective resonance phenomenon in (90ZI1C).

16. (a) $^6\text{Li}(\gamma, \pi^0)^6\text{Li}$  \hspace{1cm} $Q_m = -134.977$
(b) $^6\text{Li}(\gamma, \pi^+)^6\text{He}$  \hspace{1cm} $Q_m = -143.078$
(c) $^6\text{Li}(\gamma, \pi^-)^6\text{Be}$  \hspace{1cm} $Q_m = -143.858$

Measurements of neutral-pion photoproduction yield (reaction (a)) for $E < 10$ MeV above threshold were reported in (89NA23). The total cross section was measured in the energy region from the reaction threshold to $E_\gamma \approx 146.5$ MeV (89GL07) 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 (86GL07, 87GL01) and (84AJ01). An analysis (91TR1C) 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 (91BE16). Total and differential cross sections were measured within 23 MeV of threshold with tagged photons by (99BE14). Differential cross sections for reaction (b) leading to the $^6\text{He}$ ground state have been measured at $E_\gamma = 200$ MeV (91SH02) and analyzed by DWBA. See also the measurements of (91GA26). The energy distributions of electroproduced $\pi^+$ at $E_\gamma \approx 200$ MeV were measured and ($\gamma, \pi^+$) cross sections were deduced (94SH38). For reaction (c) see (88KA41, 91GA26).

Theoretical studies of pion photoproduction include an impulse-approximation calculation for ($\gamma, \pi^0$) at $E_\gamma = 300$ MeV (89TR09), an impulse approximation and shell model study of inelastic photoproduction of pions (91TR02), a DWIA Feynman-diagram production-operator-based calculation of ($\gamma, \pi^+$) at $E_\gamma = 200$ MeV (90BE49), and multicluster dynamic-model calculation of $\pi^+$ photoproduction off $^6\text{Li}$ (95ER1B), and an exclusive ($\gamma, \pi^+$) production calculation for $E_\gamma = 200$ MeV (95DO24).

17. (a) $^6\text{Li}(e, e)^6\text{Li}$  \hspace{1cm} $Q_m = -4.497$
(b) $^6\text{Li}(e, ep)^5\text{He}$  \hspace{1cm} $Q_m = -1.475$
(c) $^6\text{Li}(e, ed)^4\text{He}$  \hspace{1cm} $Q_m = -15.795$

The previous review (88AJ01) summarizes the information then available on electron scattering as follows: The elastic scattering has been studied for $E_e = 85$ to 600 MeV: see (74AJ01, 79AJ01, 84AJ01). 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 (82BE11). A model-independent analysis of the elastic scattering yields $r_{\text{rms}} = 2.51 \pm 0.10$ fm. See also the discussion in (84DO1A).
Table 6.10
Levels of $^6\text{Li}$ from $^6\text{Li}(e, e')$ and $^6\text{Li}(\gamma, \gamma')$ $^a$

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$J^\pi$; $T$</th>
<th>$\Gamma_{\gamma_0}$ (eV)</th>
<th>Multipolarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.183 ± 0.009</td>
<td>$3^+; 0$</td>
<td>$(4.40 \pm 0.34) \times 10^{-4}$ $^b$</td>
<td>E2</td>
</tr>
<tr>
<td>3.56288 ± 0.00010 $^c$</td>
<td>$0^+; 1$</td>
<td>$8.19 \pm 0.17$ $^d$</td>
<td>M1</td>
</tr>
<tr>
<td>4.27 ± 0.04</td>
<td>$2^+; 0$</td>
<td>$(5.4 \pm 2.8) \times 10^{-3}$</td>
<td>E2</td>
</tr>
<tr>
<td>5.379 ± 17 $^{d,e}$</td>
<td>$2^+; 1$</td>
<td>$0.27 \pm 0.05$</td>
<td>M1</td>
</tr>
</tbody>
</table>

$^a$ See Tables 6.4 in (79AJ01, 84AJ01) for references and for the earlier work.

$^b$ (69EI06), $B(E2) = 2.5 \pm 0.2 e^2 \cdot \text{fm}^4$.

$^c$ (81RO1D).

$^d$ Weighted mean of values shown in Table 6.4 in (79AJ01).

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

Table 6.10 summarizes the results obtained in the inelastic scattering of electrons. Form factors have been measured for $^6\text{Li}^*(2.19, 3.56, 5.37)$ as well as for the $t + ^3\text{He}$ continuum up to 4 MeV above threshold [no narrow structures corresponding to $^6\text{Li}$ states are observed]: see (84AJ01). In more recent work, nucleon spin structure functions were extracted from measurements of deep inelastic scattering on polarized targets by (99RO13).

For reaction (b) see $^5\text{He}$ and (87VA08) and (87VA1N). 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 (86TA06). Triple differential cross sections were measured for $E_x = 27$ to 49 MeV in a search for GDR evidence (99HO02). At $E_x = 480$ MeV (reaction (c)) the $\alpha$-d momentum distribution in the ground state of $^6\text{Li}$ has been studied. The results are well accounted for by an $\alpha NN$ model. The $\alpha$-d probability in the ground state of $^6\text{Li}$ is 0.73 [estimated $\pm 0.1$]. The data are consistent with the expected $2S$ character of the $\alpha$-d relative wave function (86EN05). See also (86EV1A). $\pi^0$ production involving $^6\text{Li}^*(2.19, 3.56, 5.37)$ is reported at $E_x = 500$ MeV (87NA11).

For the earlier work see (79AJ01, 84AJ01) and the references cited in (88AJ01).

Since the previous review (88AJ01), experimental results on quasielastic response have been reviewed (88LO1E). Measurements of the quasielastic scattering cross section for electrons on $^6\text{Li}$ are reported at momentum transfer 0.85 to 2.3 F$^{-1}$ (88BU04). See also the measurements at $E_e = 80$ to 680 MeV by (89LI09). Cross sections for $^6\text{Li}(e, ep)$ 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 (89LA22). The $^6\text{Li} \rightarrow p + (n\alpha)$ spectral function was measured (89LA13). The ratio of transverse and longitudinal response function was investigated in (90LA06). See also the review (90DE16) of proton spectral functions and momentum distributions in $(e, e'p)$ experiments and see the report (90GH1E) on nuclear density dependence of electron proton coupling in $^6\text{Li}(e, e'p)$.

Reaction (c) was used (90JO1D) in a study of correlation functions in $^6\text{Li}$. A measurement
in parallel kinematics to study the mechanism of the $^6$Li(e, $e'\alpha$)$^2$H reaction is reported in (91MI19, 94EN04). 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 (98CO06).

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($\pi^+$, $\pi^+p$)$^5$He
   (c) $^6$Li($\pi^+$, $^3$He)$^3$He
   (d) $^6$Li($\pi^+$, $\pi^+d$)$^4$He
   (e) $^6$Li($\pi^-$, $\pi^+$)$^6$H
   (f) $^6$Li($\pi^-$, $p$)$^5$H
   (g) $^6$Li($\pi^+$, 2p)$^4$He
   (h) $^6$Li($\pi^-$, $^3$He)$^3$n
   (i) $^6$Li($\pi^+$, p)$^5$Li
   (j) $^6$Li($\pi^+$, pd)$^3$He
   (k) $^6$Li($\pi^-$, pp)$^4$n
   (l) $^6$Li($\pi^+$, $\pi^-$)

Elastic angular distributions have been measured at $E_{\pi^\pm} \approx 50$ MeV [see (84AJ01)] and at $E_{\pi^\pm} = 100, 180$ and 240 MeV (86AN04 also to $^6$Li*(2.19)). Differential cross sections are also reported for $E_{\pi^\pm} = 100$ to 260 MeV to $^6$Li*(0, 2.19, 3.56, 4.25). The excitation function for the unnatural-parity transition to $^6$Li*(3.56) has an anomalous energy dependence (84KI16).

A number of experimental studies with polarized targets have been reported for elastic and inelastic ($E_x$($^6$Li) = 2.19 MeV, $J^\pi = 3^+$) scattering. Measurements of polarization observables are reported at $E_{\pi^\pm} = 134, 164$ MeV (89TA21, 90TA1L, 91BO1R), $E_{\pi^\pm} = 160–219$ MeV (91RI01, 94RI06). Comparison of these data with a coupled channels model is discussed in (95BO1H). See also the $\Delta$-hole model analysis of (92JU1B) and the multicluster dynamic model analysis by (95RY1C). Calculations of cross sections and polarization observables at $E_{\pi^\pm} = 80–260$ MeV are presented in (88ER06, 88NA06). A theoretical study in terms of a strong absorption model is described in (98AH06).

Cross section measurements for reaction (b) at $E_{\pi^\pm} = 130, 150$ MeV are reported in (87HU02). For a study of reaction (d) at $E_{\pi^\pm} = 130$ MeV, see (87HU13).

Measurements of pion double-charge exchange cross section (reactions (e) and (l)) at incident pion energies $E_{\pi} = 180, 240$ MeV are reported in (89GR06, 95FO1J). In (91SE06) it is shown that continuum missing mass spectra from reaction (e) can be explained in terms of the presence of dineutrons in the reaction products.
### Table 6.11
\(^6\text{Li}(e, e)^6\text{Li} – \text{Theoretical work}\)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
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<td>87KR07</td>
<td>EM properties of (^6\text{Li}) in cluster model</td>
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<tr>
<td>87LE1N</td>
<td>Coincidence reactions and the 3-body structure of (^6\text{Li})</td>
</tr>
<tr>
<td>88AL1J</td>
<td>Second Born approximation correction to (^6\text{Li}) electron scattering</td>
</tr>
<tr>
<td>88ES01</td>
<td>Elastic electromagnetic form factors of (^6\text{Li}) from 3-body models</td>
</tr>
<tr>
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<td>Exchange and correlation effects in EM structure of (^6\text{Li})</td>
</tr>
<tr>
<td>89ES05</td>
<td>Inelastic ((1^+ \rightarrow 0^+)) EM form factor of (^6\text{Li}) with 3-body models</td>
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<tr>
<td>89KU21</td>
<td>Correlation and exchange effects in EM form factors</td>
</tr>
<tr>
<td>90BE54</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>90DE1V</td>
<td>NN correlations, evidence from (^6\text{Li}(e, e'p)^6\text{He})</td>
</tr>
<tr>
<td>90KU12</td>
<td>Detailed study of EM structure of (^6\text{Li}) from 3-body model</td>
</tr>
<tr>
<td>90LO14</td>
<td>Cluster-model interpretation of (^6\text{Li}(e, e'p)^5\text{He})</td>
</tr>
<tr>
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</tr>
<tr>
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<tr>
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</tr>
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<td>Two-body correlations in (^6\text{Li}) through the ((e,e'd)) reaction</td>
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<tr>
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<td>Multiquark configuration effect on nuclear charge form factor</td>
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<td>92LZOX</td>
<td>Short-range correlation in the 6-body (^6\text{Li}) wave function</td>
</tr>
<tr>
<td>92RYZY</td>
<td>EM properties of (^6\text{Li}) in multicluster dynamic model</td>
</tr>
<tr>
<td>92ZH18</td>
<td>Calculation of (^6\text{Li}(e, ed)) cross section in (\alpha 2\text{N}) model</td>
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<td>Nucleon polarization in three-body models of polarized (\text{Li})</td>
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<td>Halo structure in (^6\text{Li}) (E_x = 3.563) (0^+) state</td>
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<td>Microscopic calculation of (^6\text{Li}) elastic &amp; transition form factors</td>
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<td>99GN01</td>
<td>Multicluster calculation of (^6\text{Li}(e, e')) asymmetric &amp; polarization ratios</td>
</tr>
</tbody>
</table>
Pion absorption followed by nucleon emission (reactions (c), (f), (g), (h), (j), (k)) has been studied in a number of experiments. For reaction (c) see \(83\text{BA26, 83LO10, 85MC05, 86MC11}\). Measurements have been reported for cross sections for reaction (g) at \(E_{\pi^+} = 30, 50, 80, 115\) MeV \((89\text{ROZY})\); reactions (b) and (g) angular distributions at \(E_{\pi} = 70, 130, 165\) MeV \((89\text{YO05})\); reactions (g) and (l) angular correlations at \(E_{\pi} = 165\) MeV \((89\text{YO07})\); cross sections for reaction (g) at \(E_{\pi^+} = 115, 140, 165, 220\) MeV \((89\text{ZHZZ})\); angular distributions for reaction (k) at \(E_{\pi^+} = 70, 130, 165\) MeV \((89\text{YO03})\); two-particle coincidences for reactions (g) and (k) at low energies \((91\text{YO0C})\); cross sections at \(E_{\pi^+} = 50, 100, 150, 200\) MeV \((90\text{RA05, 90RA20, 92RA01, 92RA11})\); differential and total cross sections for reaction (g) at \(E_{\pi^+} = 100, 165\) MeV \((95\text{PA22, 96LO04})\); inclusive spectra of \(^3\text{He}\) produced in reaction (h) \((92\text{AM1H, 93AM09})\); total reaction cross sections for \((n, X)\) at \(E_n = 12\) MeV \((93\text{IN01})\), and see the compilation and review of \((92\text{BA57, 93IN01})\).

Analysis of particle emission following \(^6\text{Li}\) absorption has produced evidence for a three-nucleon absorption model. Distorted-wave impulse approximation calculations of cross sections and analyzing powers have been made \((92\text{KH04})\) for two-nucleon pion absorption on polarized \(^6\text{Li}\) targets. A model based solely on isospin was used \((93\text{MA14})\) in a calculation of ratios of pion absorption on three nucleons and agreement with experiment suggest a one-step process.

19. (a) \(^6\text{Li}(n, n)^6\text{Li}\)
(b) \(^6\text{Li}(n, nd)^4\text{He}\) \(Q_n = -1.475\)
(c) \(^6\text{Li}(n, p)^6\text{He}\) \(Q_n = -2.726\)
(d) \(^6\text{Li}(n, d)^3\text{He}\) \(Q_n = -2.727\)
(e) \(^6\text{Li}(n, t)^4\text{He}\) \(Q_n = 4.782\)
(f) \(^6\text{Li}(n, \alpha)^3\text{H}\) \(Q_n = 4.782\)

Angular distributions involving the groups to \(^6\text{Li}^*(0, 2.19)\) have been reported at \(E_n = 1.0\) to \(14.6\) MeV \([\text{see } (84\text{AJ01})]\), 4.2, 5.4 and 14.2 MeV \((85\text{CH37}; n_0, n_1)\), 7.5 to 14 MeV \((83\text{DA22}; n_0)\), 8.9 MeV \((84\text{FE1A}; n_0)\), 8.0 and 24 MeV \((86\text{HA1S}; n_0, n_1)\), \(E_n = 5\) to 17 MeV \((86\text{PF1A}; n_0)\), 11.5, 14.1 and 18 MeV \((98\text{CH33}; n_0, n_1)\), and at 11.5 and 18.0 MeV \((98\text{IB02}; n_0, n_1)\).

An analysis \((88\text{HA25})\) 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 \(^6\text{Li}\). Cross sections and analyzing powers for \(E_n = 8\)–\(40\) MeV were analyzed \((89\text{HAZV})\) with microscopic optical model potentials. Secondary neutron spectra induced by 14.2 MeV neutrons on \(^6\text{Li}\) were measured by \((93\text{XI1A})\).

An analysis of \((n, n')\) data at \(E_n = 7.45\)–\(14\) MeV is discussed in \((90\text{BE54})\). See also the calculation for elastic coherent and incoherent scattering of thermal neutrons on \(^6\text{Li}\) \((90\text{GO026})\) and the multi-cluster dynamic model calculation for \(^6\text{Li}(n, n)\) at \(E_n = 12\) MeV \((92\text{KA06})\).
Theoretical studies of $^6\text{Li}(n, n)$ include multiconfiguration resonating group calculations (88FU09, 91FU02), folding model descriptions for $E_n = 25$–$50$ MeV (93PE13), study of antisymmetry in NN potentials (95CO18), study of optical model potentials for intermediate energies (96CH33).

For reaction (b) see (84AJ01, 85CH37, 93XI1A, 94EL08).

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 (87HE22), $\sigma(\theta, E_p)$ at $E_n \approx 118$ MeV (87PO18, 88HA12, 98HA24), $\sigma(\theta)$ at $E_n = 198$ MeV (88JA01), $\sigma(\theta)$ to explore Gamow Teller sum rule (88WA24), $\sigma(E_p)$ at $E_n = 280$ MeV for an isospin symmetry test (90MI10), $\sigma(\theta, E)$ at $E_n = 60$–$260$ MeV (92SO02), polarization observables at $E_n = 0.88$ GeV (96BB23).

For reaction (e), measurements were reported at thermal neutron energies (94IT04) and at $E_n < 10$ MeV (94DR11). For reaction (f), measurements of parity violation with cold polarized neutrons are described in (90VE16, 93VE1A, 96VE02). A discussion of nuclear reaction rates and primordial $^6\text{Li}$ is presented in (97NO04). See also the application-related calculation of (93FA01).

Theoretical work related to reactions (b), (c), (d), (e), (f) include: dynamical cluster-model calculation (91DA08); microscopic calculation in a 3-particle +2N model (93SH1G); supermultiplet-symmetry-approximation calculation at $E_n = 6.77$ MeV (93DU09); multiconfiguration RGM calculation (95FU16); three-body cluster model calculations of $^6\text{Li}(n, p)$ at $E_n = 50$ MeV (97DA01, 97ER05).

20. (a) $^6\text{Li}(p, p)^6\text{Li}$
   (b) $^6\text{Li}(p, 2p)^5\text{He}$
   (c) $^6\text{Li}(p, pd)^4\text{He}$
   (d) $^6\text{Li}(p, p^3\text{H})^3\text{He}$
   (e) $^6\text{Li}(p, pn)^5\text{Li}$

Proton angular distributions have been measured for $E_p = 0.5$ to 800 MeV [$p_0$, $p_1$, $p_2$, $p_3$] [see (66LA04, 74AJ01, 84AJ01)] and at $E_p = 5$ to 17 MeV (86PF1A, prelim.; $p_0$).

Double-differential cross sections for the continuum yield [$E_x = 1.5$–3.5 MeV] are reported at $E_p = 65$ MeV (87TO06; prelim.). See also (83GL1A, 83PO1B, 83POZX). More recently differential cross sections and/or polarization observables have been measured at $E_p = 6$–10 MeV (89HA17) [optical model analysis]; $E_p = 1.6$–10 MeV (89HA18) [phase shift analysis]; $E_p = 65$, 80 MeV (89TO04) [DWIA analysis]; $E_p = 200$ MeV (90GL04); $E_p = 65$ MeV (92NA02) [microscopic DWBA analysis]; $E_p = 72$ MeV (94HE11) [depolarization parameters]; $E_p < 2.2$ MeV (95SK01) [deduced resonance parameters]; $E_p = 0.88$ GeV (96BB23) [polarized target]; $E_p = 250$–460 keV (97BR37), $E_p = 280$ MeV (90MI10) [deduced isospin symmetry test]; $E_p = 14$ MeV [optical model, coupled channels]; $E(6\text{Li}) = 62, 72, 75$ MeV/A,
$^1$H($^6$Li, p) [neutron halo states] (96KUZU); $E_p = 1.6$–2.4 GeV (99BB21, 99DE47). For a summary of the results on excited states see Table 6.12.

Reaction (b) was studied at 70 MeV (83GO06), at 50–100 MeV (84PA1B, 85PA1B) and 1 GeV (85BE30, 88BE2B, 00MI17); see $^5$He and (84AJ01) for the earlier work. Reaction (c) has been studied at $E_p = 9$ MeV to 1 GeV [see (74AJ01, 79AJ01, 84AJ01)] and at 20 and 42 MeV (83CA13) [report involvement of $^6$Li*(4.31, 5.65)], at 70 MeV (83GO06, 85PA1C, 85PA04) and at 119.6 and 200.2 MeV (84WA09, 85WA25). 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 [at 200.2 MeV] using DWIA and a bound-state Woods-Saxon $2S$ wave function (84WA09, 85WA25).

Work on reaction (d) has suggested that the $^3$He + t parentage of $^6$Li is comparable with the $^3$He + d parentage: see (84AJ01). See also (85PA1C). Reaction (e) was studied at $E_p = 70$ MeV (88PA27). See also $^5$Li, $^6$Be and (85BE30, 93ST06). The (p, 3p) reaction has been studied by (84NA17). The spectral function for pn pairs in $^6$Li was obtained in a study of the $^6$Li(p, po)pn reaction at $E_p = 200$ MeV (90WA17). A measurement of tensor analyzing powers in $^1$H($^6$Li, d or p or t)$X$ with 4.5 GeV polarized $^6$Li deuterons provided information on the $^6$Li D state (92PU03). Systematic studies of electron screening effects on low energy reactions including $^6$Li + p are reported in (92EN01, 92EN04, 95RO37). For antiproton studies see (87AS06). See also (84AJ01, 88AJ01) for the earlier work.

Theoretical work on these reactions reported since the previous review (88AJ01) 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 $Q_m = -2.224$

(c) $^6$Li(d, 2d)$^4$He $Q_m = -1.475$

(d) $^6$Li(d, ap)$^3$H $Q_m = 2.558$

(e) $^6$Li(d, αn)$^3$He $Q_m = 1.795$

Angular distributions of deuterons have been measured at $E_d = 4.5$ to 19.6 MeV [see (79AJ01)] and at 50 MeV (88KO1C, 96RU1A). 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 (92DU07).

At $E_d = 21$ MeV reaction (b) shows spectral peaking (characteristic of $^3$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, $N_{\alpha\alpha} = 0.12^{+0.12}_{-0.06}$ if a Hankel function is used. The $\alpha$-particle and the deuterons 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
Table 6.12
Parameters of levels of $^6\text{Li}$

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$\Gamma_{c.m.}$ (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>$^6\text{Li}(p', (d, d')$, $^7\text{Li}(d, t)^6\text{Li}$</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” values</td>
</tr>
<tr>
<td>3.56288 ± 0.10 $^c$ (8.2 ± 0.2) × 10$^{-3}$ $^c$</td>
<td></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></td>
<td>1044 ± 58 $^d$</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” values</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” values</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></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 ± 60, 1260 ± 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” values</td>
</tr>
</tbody>
</table>

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for references and other values see Tables 6.5 in (79AJ01, 84AJ01, 88AJ01).

b See (88AJ01).

c (81RO1D).

d (79BE38).

e Average of measurements for $E(^{3}\text{He}) = 4, 5, 6$ MeV (95AR14).

f Weighted average of “best” values from (88AJ01) and values of 1320 ± 40 keV (Table 6.7), 1044 ± 58 keV (79BE38), and 1600 ± 120 keV from (95AR14).

g See Table 6.4 in (79AJ01).

h Weighted average of “best” values from (88AJ01) and 546 ± 36 keV from (79BE38).

i See Table 6.3 in (79AJ01).

j See references (c) and (d) in Table 6.5 in (79AJ01).

through $^{6}\text{Li}*(2.19, 4.31)$: 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 $^{6}\text{Li}$ at these low energies is dominated by sequential decay processes (79AJ01, 90YA11). Differential cross sections for cluster pickup by 20 MeV/nucleon deuterons on $^{6}\text{Li}$ were measured by (95MA57).

Calculation of Maxwellian rate parameters for reaction (d) and (e) are described in (00VO08). See also $^{8}\text{Be}$ and (82CH28, 83GO1J, 83LY04, 84BL21, 84KU15, 85LI1C, 86AV1C, 87AL1L).

22. $^{6}\text{Li}(t, t)^{6}\text{Li}$

At $E_t = 17$ MeV angular distributions have been measured for the tritons to $^{6}\text{Li}*(0, 3.56)$: see (79AJ01).

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

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

$Q_m = 16.878$

Angular distributions have been measured at $E(^{3}\text{He}) = 8$ to 217 MeV [see (79AJ01, 84AJ01)] and at 34, 50, 60 and 72 MeV (86BR1M; elastic).

More recently, differential cross sections were measured for elastic scattering at $E(^{3}\text{He}) = 93$ MeV (94DO32), and at $E(^{3}\text{He}) = 60$ MeV (95MA57), and for inelastic scattering to $^{6}\text{Li}^*$ ($E_x = 2.185$ MeV, $J^* = 3^+$) at $E(^{3}\text{He}) = 50, 60, 72$ MeV (95BU20). A microscopic-potential analysis of data at $E(^{3}\text{He}) = 34, 50, 60, 72$ MeV is described in (93SI06). Differential cross section and energy spectra were compiled and analyzed by (95MI16). For reaction (b), cross sections have been measured at $E(^{3}\text{He}) = 11, 13, 14$ MeV (89ARZR, 89AR08); $E(^{3}\text{He}) = 2.5$
<table>
<thead>
<tr>
<th>Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>88HA25</td>
<td>$^6$Li proton and neutron transition densities from elastic scattering</td>
</tr>
<tr>
<td>90ZH1R</td>
<td>Quasi resonating group method analysis of $^6$Li(p, p)$^6$Li</td>
</tr>
<tr>
<td>92GA27</td>
<td>Folding-model study of elastic scattering in halo nuclei</td>
</tr>
<tr>
<td>93DU09</td>
<td>Potential description of N+$^6$Li elastic scattering</td>
</tr>
<tr>
<td>93KO44</td>
<td>Description of $^6$Li(p, p)$^6$Li with microscopic effective interaction</td>
</tr>
<tr>
<td>93PE13</td>
<td>Folding model description of $^6$Li(p, p)$^6$Li at 25–50 MeV</td>
</tr>
<tr>
<td>93SA10</td>
<td>DWBA analysis of $^6$Li(p, p)$^6$Li near the α-d breakup threshold</td>
</tr>
<tr>
<td>94ZH34</td>
<td>Glauber-Sitenko diffraction theory calculation of $^6$Li(p, p)$^6$Li</td>
</tr>
<tr>
<td>94ZH28</td>
<td>Elastic and inelastic proton scattering on $^6$Li nucleus at intermediate energies</td>
</tr>
<tr>
<td>95GA24</td>
<td>Analysis of properties of exotic nuclei in elastic scattering</td>
</tr>
<tr>
<td>95KA07</td>
<td>Continuum-continuum coupling in $^6$Li(p, p)$^6$Li at $E_p = 65$ MeV</td>
</tr>
<tr>
<td>95KA03</td>
<td>Folding-model analysis of $^6$Li(p, p)$^6$Li at $E_p = 10$–136 MeV</td>
</tr>
<tr>
<td>93KA43</td>
<td>Folding-model analysis of $^6$Li(p, p)$^6$Li at $E_p = 10$–136 MeV</td>
</tr>
<tr>
<td>97DO01</td>
<td>Fully microscopic model analyses of $^6$Li(p, p)$^6$Li at $E_p = 200$ MeV</td>
</tr>
<tr>
<td>97KA24</td>
<td>Shell model structures of $^6$Li states excited in $^6$Li(p, p)$^6$Li</td>
</tr>
<tr>
<td>98DO16</td>
<td>Microscopic analysis of $^6$Li(p, p) at $E_p = 65$ MeV</td>
</tr>
<tr>
<td>98FUZP</td>
<td>Microscopic optical model calculation for $E_p = 60$–70 MeV</td>
</tr>
<tr>
<td>00TI02</td>
<td>Finite-range coupled channels calculation for $^6$He + p rxn</td>
</tr>
</tbody>
</table>
MeV (89AR20); $E(^3\text{He}) = 1.6$ MeV (91AR25); $E(^3\text{He}) = 1.6$–9 MeV (92AR20); $E(^3\text{He}) = 8$–14 MeV (95KO51); $E(^3\text{He}) = 2.0$, 22 MeV (92DA1K); $E(^3\text{He}) = 7$, 9 MeV (93AR12). 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 (95KO51). See also $^5\text{Li}$ (84AR17, 87ZA07) and see $^9\text{B}$.

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

(b) $^6\text{Li}(\alpha, 2\alpha)^2\text{H}$ $Q_m = -1.475$

Angular distributions (reaction (a)) have been measured at $E_\alpha = 1.39$ to 166 MeV [see (74AJ01, 79AJ01, 84AJ01)] and at $E_\alpha = 36.6$ and 50.5 MeV (86BR1M). See also (86RO1M, 87BU27). See also $^{10}\text{B}$.

More recent measurements at $E_\alpha = 50.5$ MeV of elastic and inelastic $^6\text{Li}^\ast(E_x = 2.185$ MeV, $J^\pi = 3^+$) were reported by (94BUZY, 96BU06). Tensor polarization for inelastic scattering to $^6\text{Li}^\ast(2.185, 3^+)$ has been measured at $E_\alpha = 80$ MeV (92KO19, 93KO33). Angular distributions for $(\alpha, \alpha')$ in the continuum region were studied at $E_\alpha = 50$ MeV (92SA01) and at $E_\alpha = 40$ MeV (94SA32), at $E_\alpha = 10$ MeV/A (96SI13) and $E_\alpha = 119$ MeV (93OK1A). Cross sections and analyzing powers for elastic scattering of polarized $^6\text{Li}$ by $^4\text{He}$ are reported for $E(^6\text{Li}) = 50$ MeV (95KE10) and $E_{cm} = 11.1$ MeV (96GR08).

Studies of continuum coupling effects in inelastic scattering are described in (95KA1Y, 95KA43, 97RU06, 98RU03). Folding-model potential analyses of elastic scattering are reported in (93SI09, 95SA12). Multiconfiguration resonating group methods applied to the $^6\text{Li} + \alpha$ system are discussed in (94FU17, 95FU11). Other recent theoretical states include a potential model description (99MA02), analysis of density distribution influence (98GO1J), and a phase-shift-analysis determination of the asymptotic D- to S-state ratio (99GE02). See also (88KO32, 89LE07, 99OG09).

Reaction (b) has been studied at $E_\alpha = 6.6$ to 700 MeV; see (74AJ01, 79AJ01, 84AJ01). At the latter energy and using a width parameter of 60.6 MeV/c the effective number of $\alpha + d$ clusters for $^6\text{Li}_{g.s.}$, $n_{eff} = 0.98 \pm 0.05$. The results are very model dependent: see (84AJ01). At $E_\alpha = 27.2$ MeV $^6\text{Li}^\ast(2.19)$ is very strongly populated (85KO29). See also (82CH28, 83AV1A, 83BE1H, 83BU15, 85BE60, 86GA1F, 86ZE01, 87KO1L, 88LE06).

In more recent work, two dimensional coincidence spectra of charged particles were measured at $E_\alpha \approx 100$ MeV (92GA18). Quasifree scattering processes were studied at $E_\alpha = 77$–119 MeV (92OK01), $E_\alpha = 118$ MeV (93OK1B), and $E_\alpha = 118.4$ MeV (97OK01). The four-body $^6\text{Li}(\alpha, 2\alpha)\text{pn}$ breakup reaction was measured at $E_\alpha = 77$–119 MeV (92WA18, breakup cross sections); $E_\alpha = 118$ MeV (88WA29, 89WA26, spectral functions of pn pair).

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

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

(c) $^6\text{Li}(^6\text{Li}, \alpha)^4\text{He}^4\text{He}$ $Q_m = 20.897$
Angular distributions of $^6\text{Li}$ ions have been studied for $E(^6\text{Li}) = 3.2$ to 36 MeV [see (74AJ01, 79AJ01, 84AJ01)] and at $E(^6\text{Li}) = 2.0$ to 5.5 MeV (83NO08) and 156 MeV (85SA36; $^6\text{Li}^*(0, 2.19)$), (85MI05; elastic; $^6\text{Li}^*(2.19, 3.56)$ are also populated), (87EY01; several states in $^{12}\text{C}$). Reaction (b) has been studied for $E(^6\text{Li}) = 36$ to 47 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 (84AJ01). Other work on reaction (b) is reported by (84LA19: 2.4 and 4.2 MeV) and by (85NO1A).

For reaction (c), the energy dependence of quasifree effects were investigated in the range $E(^6\text{Li}) = 2.4$–6.7 MeV (87LA25, 88LA1D). An analysis (96CH1C) used quasifree data from reaction (c) to extract the $^6\text{Li}(d, \alpha)^4\text{He}$ excitation function at astrophysical energies. See also $^{12}\text{C}$ in (85AJ01) and (83CH59, 84CH1E, 86KA1B, 86SA1D, 87AR13, 87SA1C).

More recently, elastic scattering angular distributions were measured for $E(^6\text{Li}) = 5$–40 MeV (97PO03 optical model analysis). Eikonal-approximation calculations of differential cross sections and phase shifts for $E(^6\text{Li}) = 156$ MeV were reported in (92EL1A).

26. $^6\text{Li}(^7\text{Li}, ^7\text{Li})^6\text{Li}$

Angular distributions have been measured at $E(^7\text{Li}) = 78$ MeV to $^6\text{Li}^*(0, 2.19)$ (86GL1D), and at $E(^7\text{Li}) = 9$–40 MeV (98PO03).

27. $^6\text{Li}(^9\text{Be}, ^9\text{Be})^6\text{Li}$

The elastic scattering has been studied in inverse kinematics at $E(^6\text{Li}) = 4.0, 6.0$ and 24 MeV [see (79AJ01)], at 32 MeV (85CO09) and at 50 MeV (88TRZY; prelim.; also inelastic). Recently angular distributions for elastic and inelastic scattering to $^6\text{Li}^*(3^+, 2.186)$ were measured (95MU01) at $E_{\text{cm}} = 7, 10, 12$ MeV. Excitation functions for $E_{\text{cm}} \approx 4$–12 were also reported. See also $^9\text{Be}$. For the interaction cross section at $E(^6\text{Li}) = 790$ MeV/A see (85TA18).

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

The elastic scattering has been studied at $E(^6\text{Li}) = 5.8$ and 30 MeV: see (79AJ01).

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 $E(^6\text{Li}) = 4.5$ to 156 MeV [see (84AJ01)] and at $E(^6\text{Li}) = 19.2$ MeV (83RU09), 36 and 45 MeV [and $E(^{12}\text{C}) = 72$ and 90 MeV] (84VI02, 85VI03) 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 (87PA12), 90 MeV (87DE02; also to various states of $^{12}\text{C}$), 123.5 and 168.6 MeV (88KA09; and to various states of $^{12}\text{C}$), 150 MeV (87TA21, 88TA08; also VAP), 156 MeV (87YE01; and to various states in $^{12}\text{C}$) and at 210 MeV (88NA02). See also (86SH1Q, 87PA12). More recently, measurements of cross sections and/or analyzing power observables have been reported at $E(^6\text{Li}) = 93$ MeV (89DE34), at $E_{cm} = 13.3$ MeV (89HN1A, 95CA26 and to $^6\text{Li}^*(3^+, 2.186)$ and $^{12}\text{C}^*(2^+, 4.44)$), at $E(^6\text{Li}) = 210$ MeV (89NA11, to $^{12}\text{C}^*(2^+, 4.44)$), at $E(^6\text{Li}) = 30$ MeV (89VA04, to $^{12}\text{C}^*(2^+, 4.44)$), at 50 MeV (90TR02 to $^{12}\text{C}^*(2^+, 4.44; 0^+, 7.65; 3^-, 9.64)$), at $E(^6\text{Li}) = 30$ MeV (94RE01), at $E(^6\text{Li}) = 30, 60$ MeV ($^{12}\text{C}^*(2^+, 4.44; 0^+, 7.65; 3^-, 9.64)$), to 20 MeV (96GA29, to $^6\text{Li}^*(3^+, 2.18)$ and $^{12}\text{C}^*(2^+, 4.44)$), at $E(^6\text{Li}) = 318$ MeV (93NA01), at $E(^6\text{Li}) = 30$ MeV ($^{12}\text{C}^*(2^+, 4.44; 0^+, 7.65; 3^-, 9.64)$), at $E(^6\text{Li}) = 30$ MeV (94RE15 to $^{12}\text{C}^*(2^+, 4.44; 0^+, 7.65; 3^-, 9.64)$), at $E(^6\text{Li}) = 50$ MeV ($^{12}\text{C}^*(2^+, 4.44; 3^-, 9.64)$), at $E(^6\text{Li}) = 34$ MeV the d-$\alpha$ angular correlations involve $^6\text{Li}^*(0, 2.19)$ (85CU04). See also (88SE1E), and see $^{12}\text{C}$ in (85AJ01, 90AJ01). An experimental study of the $\alpha + d$ breakup in $^6\text{Li} + ^{12}\text{C}$ collision at $E(^6\text{Li}) = 156$ MeV is reported in (89JE01). For pion production see (84CH16). For the interaction cross section at $E(^6\text{Li}) = 790$ MeV/A see (85TA18). For VAP measurements at $E(^6\text{Li}) = 30$ MeV see (88VAZY). Fusion cross section for $E(^6\text{Li}) = 3.11 - 12.07$ MeV are reported by (98MU12).

The elastic scattering (reaction (b)) has been studied for $E(^6\text{Li}) = 5.8$ to 40 MeV: see (84AJ01). Measurements of differential cross sections for $E_{cm} = 26$ MeV and observations of a nuclear quasi rainbow were reported by (94DE43). See also (87CA30, 88WO10). The elastic scattering (reaction (c)) has been measured for $E(^6\text{Li}) = 93$ MeV (87DE02). See also $^{18}\text{F}$ and $^{19}\text{F}$ in (87AJ02) and references cited in (88AJ01).

Several theoretical studies relating to $^6\text{Li} + ^{12}\text{C}$ have been reported. The role of the Pauli Principle in heavy ion scattering has been studied (88GR32). The dispersive contribution to the $^6\text{Li} + ^{12}\text{C}$ real potential was estimated (90KA14). Elastic cross sections for $E(^6\text{Li}) = 30$ MeV were analyzed (90SA05). A semimicroscopic analysis of inelastic scattering at $E(^6\text{Li}) = 156$ MeV is described in (92GA17). Folding model analysis of $^6\text{Li} + ^{12}\text{C}$ scattering is discussed in (94NA03, 94SA10, 95KH03). Differential cross sections were analyzed with an $S$-matrix approach by (98PI02).

Other theoretical descriptions of $^6\text{Li} + ^{12}\text{C}$ scattering are discussed in (94SA33, strong absorption model), (95IS1F, multiple diffraction interaction), and (96CA01, microscopic description).

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

Elastic angular distributions have been reported at $E(^6\text{Li}) = 4.5$ to 50.6 MeV [see (84AJ01)], at $E(^6\text{Li}) = 55.3$ and $E(^{16}\text{O}) = 94.2$ MeV (84VI02) and at 50 MeV (88TRZY; pre-lim.; also inelastic). At $E(^6\text{Li}) = 25.7$ and $E(^{16}\text{O}) = 68.6$ MeV (84VI01, 85VI03) report some
σ(θ) to $^6$Li*(2.19) [and to $^{16}$O*(6.13)]. See also (87PA12). See (85VI03, 86SC28) for studies of the breakup. Polarization observables have been measured at $E(^6$Li) = 25.7 MeV, and also using $^{16}$O ions (87VAZY, 89VA04). 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 (90TR02). For fusion cross sections see (86MA19). See also $^{16}$O in (86AJ04), (86MO1E, 87PA12) and (83BU15, 83JO1A, 84WI08, 85CO21, 85SA13, 86SAZS). Theoretical work on this scattering reaction includes (90SA05, $E(^6$Li) = 29.8 MeV, optical model description), (88GR32, $E(^6$Li) = 29.8–30.6 MeV, Pauli Principle rule), (90SA05, $E(^6$Li) = 30.6, optical model analysis), (91BO48, projectile effects), (91HI07, $E(^6$Li) = 154 MeV, 3-body cluster model), (91HI11, $E(^6$Li) = 22.8 MeV, nonresonant breakup states), (91SA26, $E(^6$Li) = 30 MeV, double-folding model, role of Pauli Principle).

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 (95DE53). Reaction (c) has been studied at $E(^6$Li) = 88 MeV and 36 MeV (84AJ01) and at 44 MeV (89RU05, polarization observables), and $E(^6$Li) = 60 MeV (94WA20, polarization observables). Reaction (d) was studied at $E(^6$Li) = 156 MeV by (87NI04, particles and gammas from inelastic scattering). See also the measurements at $E(^6$Li) = 790 MeV/A (85TA18).

Theoretical studies for these reactions include (91BO48, analyzed non-Rutherford cross sections), (91HI11, effects of nonresonant breakup states), (94SA33, strong absorption model analysis), (91HI07, cluster folding interaction), (92HI02, coupled channels study), (94RU11, cluster-folding analysis).

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 (84AJ01)], at 27 and 34 MeV (83VI03) and at 210 MeV (88NAZX). For a study of the decay see (87NI04). See also references cited in (88AJ01).

More recent measurements have been reported at $E(^6$Li) = 210 MeV (89NA11, inelastic σ(θ) to $^{28}$Si*(first 2+ state)), (89NA02, elastic σ(θ), optical parameters), $E(^6$Li) = 318 MeV (90NAZZ, 93NA01, σ(θ), folding model potentials). Related analyses and other theoretical studies include (88GR32, 91SA26, Pauli Principle role), (90KU23, scattering matrix approach), (90SA05, deduced model parameters), (91BO48, non Rutherford cross section...
thresholds), (91HI07, cluster-folding interactions), (91TI04, energy dependence, dispersion relation), (94SA33, strong absorption model), (95EM03, $E(^6\text{Li}) = 210, 318 \text{ MeV}$, energy approximation), (96CA01, microscopic description), (96KN02, microscopic potentials, density matrix formalism), (97SA57, $E(^6\text{Li}) = 35, 53 \text{ MeV/nucleon}$, breakup effect), (98PI02, $E(^6\text{Li}) = 210, 315 \text{ MeV}$, $S$-matrix approach).

For reaction (b) see (87AR13).

33. (a) $^6\text{Li}(^{30}\text{K}, ^{39}\text{K})^6\text{Li}$
(b) $^6\text{Li}(^{40}\text{Ca}, ^{40}\text{Ca})^6\text{Li}$
(c) $^6\text{Li}(^{44}\text{Ca}, ^{44}\text{Ca})^6\text{Li}$
(d) $^6\text{Li}(^{48}\text{Ca}, ^{48}\text{Ca})^6\text{Li}$

Elastic scattering has been studied for $E(^6\text{Li}) = 26$ to 99 MeV: see (84AJ01, 88AJ01), and at $E(^6\text{Li}) = 34 \text{ MeV}$ (reaction (b)) by (87VA31) and at 210 MeV (88NAZX, 89NA02; reaction (b)). $^6\text{Li}^*(2.19)$ has been studied at $E(^{40}\text{Ca}) = 227 \text{ MeV}$ (87VA31). Reaction (d) was studied at $E(^6\text{Li}) = 150 \text{ MeV}$ (90KAZH). For fusion measurements (reaction (b)) see (84BR04). For breakup measurements (reaction (b)) see (84GR20, 90YA09, 92YAZW, 93GU10, 95AR15, 96YA01).

For theoretical studies related to these reactions, see (87SA21, energy and target dependence of projectile breakup), (87VA31, sequential breakup cross sections), (88GR32, role of Pauli Principle), (88KH08, 90DA23, exchange effects), (90TA11, imaginary part of channel-coupling potentials), (91HI07, cluster folding interactions), (94SA33, strong absorption model), (95BE60, 98PI02, $S$-matrix approach), (96KN02, microscopic potentials). For earlier work see references cited in (88AJ01).

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

Transitions to $^6\text{Li}^*(0, 2.19, 3.56)$ have been observed in reaction (a): see (79AJ01, 84AJ01). Differential cross sections are reported for $E_\gamma$ (bremsstrahlung) = 60 to 120 MeV for the $n_0 + n_2$ groups (85SE17). Bremsstrahlung yield for $(\gamma, n_0)$ was measured for $E_\gamma = 7$–9 MeV (89KA30). Reaction (b) at 0.9 GeV involves $^6\text{Li}^*(2.19)$ (85RE1A). See also the measurements of $E_\gamma = 350 \text{ MeV}$ reported by (91GA26), and see $^7\text{Li}$, (85S11A 86BA2G, 86GO1M1).

An analysis of $^7\text{Li}(\gamma, n)$ data in the giant resonance energy region is described in (87VA05). Cluster effects were explored in (92VA12). Calculation with a potential two cluster model are reported in (97DU02).
35. $^7\text{Li}(\pi^-, \pi^- p)^6\text{He}$  

$Q_m = -9.975$

Quasielastic pion-proton backward scattering was measured at $E_\pi = 0.7, 0.9, 1.25$ GeV (00AB25). Fermi momentum distributions for $^6\text{Li}$ were deduced.

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

$Q_m = 133.103$

Differential cross sections have been measured at $E_{\pi^+} = 75$ and 175 MeV for the transitions to $^6\text{Li}^*(0, 2.19)$: see (84AJ01). Proton spectra measured at momentum exchange 660 MeV/c (89LIZO) provided evidence for an eta-meson nuclear bound state.

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

$Q_m = -5.025$

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

$Q_m = -7.249$

Angular distributions of deuterons (reaction (a)) have been studied for $E_p = 167$ to 800 MeV [see (79AJ01 84AJ01)] and at 18.6 MeV (86GO1N, 87GO27; $d_0$, $d_1$, $d_2$; see for spectroscopic factors), 200 and 400 MeV (85KR13; $d_0$, $d_1$; $d_2$ is weakly populated at 200 MeV) and at 800 MeV (84SM04; $d_0$, $d_1$). 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 (85KR13). 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 $E_x \approx 20$ MeV: see (79AJ01). The tensor analyzing power $T_{20}$ was measured for the $^1\text{H}(^7\text{Li}, d)^6\text{Li}$ reaction at $E(^7\text{Li}) = 70$ MeV to $^6\text{Li}^*(0, 2.186)$ (91DA07). Data at $E_p = 33.6$ MeV were analyzed by (91AB04) in a test for Cohen-Kurath wave functions. See also the analysis of data at $E_p = 698$ MeV by (93AL05, eta production). In reaction (b) at $E_p = 1$ GeV the separation energy between $\approx 6.5$ MeV broad 1p$_{3/2}$ and 1s$_{1/2}$ groups is reported to be 18.0 $\pm$ 0.8 MeV (85BE30, 85DO16). See also (83LY04, 88BE1I, 88GUZW). Differential cross sections were measured at $E_p = 70$ MeV (88PA26) and at $E_p = 2.7$–3.8 MeV (88BO37, application). See also the measurements for nuclear microprobe utilization (95RI14).

38. $^7\text{Li}(d, t)^6\text{Li}$  

$Q_m = -0.992$

A study at $E_d = 23.6$ MeV of the relative cross sections of the analog reactions $^7\text{Li}(d, t)^6\text{Li}$ (to the first two $T = 1$ states at 3.56 and 5.37 MeV) and $^7\text{Li}(d, ^3\text{He})^6\text{He}$ (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 (79AJ01). (87BO39) $[E_d = 30.7$ MeV] deduce that the branching ratio of $^6\text{Li}^*(4.31) [2^+]$ 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 (87GU1F; $E_d = 18$ MeV; angular distributions to $^6\text{Li}^*(0, 2.19, 3.56)$; prelim.) and (84BL21, 86AV1C, 88GUZW). See also the analysis method discussed in (95GU22, DWBA and dispersive theory).

39. (a) $^7\text{Li}(^3\text{He}, \alpha)^6\text{Li}$ $Q_m = 13.328$
(b) $^7\text{Li}(^3\text{He}, d\alpha)^4\text{He}$ $Q_m = 11.853$

Angular distributions have been reported at $E(^3\text{He}) = 5.1$ to $33.3$ MeV [see (74AJ01, 84AJ01); the lower energy work has not been published] and more recently at $E(^3\text{He}) = 60$ MeV (94BUZX). Excited states observed in this reaction are displayed in Table 6.12. See also (68CO07) 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. (86AN04) have analyzed unpublished data which suggest the involvement of several broad highly excited states of $^6\text{Li}$. See also (87AL1L).

Several attempts have been made to look at the isospin decay of $^6\text{Li}^*(5.37) [J^\pi; T = 2^+, 1]$ via $^7\text{Li}(^3\text{He}, \alpha)^6\text{Li}^* \to d + \alpha$: 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 (79AJ01). $^4\text{He} + d$ spectra suggest the excitation of $^6\text{Li}^*(4.3) [E_x = 4.3 \pm 0.2$ MeV, $\Gamma = 1.6 \pm 0.3$ MeV] and $^6\text{Li}^*(5.7) [E_x = 5.65 \pm 0.2$ MeV, $\Gamma = 1.65 \pm 0.3$ MeV]: see (84AJ01). See also (85DA29, 88BO1Y). A more recent measurement at $E(^3\text{He}) = 4, 5, 6$ MeV (95AR14) gave values for the width of of $^6\text{Li}^*(4.31)$ in agreement with the adopted value $\Gamma = 1700 \pm 200$ keV and found no dependence on incident energy. Measurements of d-$\alpha$ coincidence spectra at $E(^3\text{He}) = 11.5$ MeV (88AR20) and 5.0 MeV (91AR19) gave spectroscopic parameters for $^6\text{Li}^*(5.65)$ in agreement with adopted values (88AJ01). 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 (85FR01). See also $^{10}\text{B}$ and (83KU17, 88BO1J).

40. (a) $^7\text{Li}(^6\text{Li}, ^7\text{Li})^6\text{Li}$
(b) $^7\text{Li}(^7\text{Li}, ^8\text{Li})^6\text{Li}$ $Q_m = -5.216$

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 (87GLZW). See (84KO25) for reaction (b).

41. $^9\text{Be}(\gamma, t)^6\text{Li}$ $Q_m = -17.688$

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Cross section measurements were made with virtual photons with electrons at 21.0–39.0 MeV (99SH05). A compilation and evaluation of cross section data for $E_{\gamma} < 30$ MeV has been done by (99ZHZN).

42. (a) $^9$Be(p, $\alpha$)$^6$Li $Q_m = 2.126$
(b) $^9$Be(p, 2$\alpha$)$^2$H $Q_m = 0.651$
(c) $^9$Be(p, pt)$^6$Li $Q_m = -17.688$

Angular distributions of $\alpha$-particles (reaction (a)) have been measured at $E_p = 0.11$ to 45 MeV. [see (74AJ01, 79AJ01)] and at $E_p = 22.5, 31$ and 41 MeV (86HA27, $\alpha_0, \alpha_1, \alpha_2$; see for spectroscopic factors). See also Table 6.12 and (84AJ01). Recent measurements of angular distributions and analyzing power at $E_p = 77–321$ keV are reported by (98BR10). A study of possible reasons for non-observation of certain $^6$Li excited states in the reaction is discussed in (99TI07). $^6$Li*($3.56$) decays by $\gamma$-emission consistent with M1; $\Gamma_{\alpha}/\Gamma < 0.025$ [forbidden by spin and parity conservation]: see (84AJ01). At $E_p = 9$ MeV the yield of reaction (b) is dominated by FSI through $^8$Be*(0, 2.9) and $^6$Li*(2.19) with little or no yield from direct three-body decay: see (79AJ01). More recent measurements of cross sections and/or polarization observables have been reported at $E_p = 50$ MeV (89GU05), $E_p = 25, 30$ MeV (92PE12; determined spectroscopic strengths), $E_p = 40$ MeV (97FA17) [see also (89FA1B)], $E_p = 2–5$ MeV (88ABZW), $E_p = 16–390$ keV [deduced $S(E)$] (97ZA06), $E_p = 77–321$ keV [deduced stellar reaction rates] (98BR10), $E_p = 30–300$ keV (00ISZZ). See also application-related experiments (90RE09, 95RI14). Analyses of data for this reaction have been reported for $E_p = 45–50$ MeV [DWBA] (96YA09, 97YAZV) and $E_p < 2$ MeV [analyzed reaction rates, primordial $^6$Li] (97NO04). Reactions (b) and (c) at $E_p = 58$ MeV involve $^6$Li*(0, 2.19) (85DE17). See also $^{10}$B and (85MA1F, 86AN26, 86KA26).

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

See $^5$He.

44. $^9$Be(t, $^6$He)$^6$Li $Q_m = -5.382$

Angular distributions of $^6$He$_{g.s.}$+$^6$Li$_{g.s.}$ and $^6$He$_{g.s.}$+$^6$Li*$_{3.56}$ [both listed ions 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 \(^{6}\text{He}_{g.s.}\) + \(^{6}\text{Li}^*(2.19)\) and \(^{6}\text{Li}_{g.s.}\) + \(^{6}\text{He}^*(1.8)\) have also been measured. This reaction appears to proceed predominantly by means of the direct pickup of a triton or \(^{3}\text{He}\) from \(^{9}\text{Be}\). Differential cross sections are also reported at \(E_t = 17\) MeV: see (84AJ01) for references.

45. \(^{9}\text{Be}(^{3}\text{He}, ^{6}\text{Li})^{6}\text{Li}\) \hspace{1cm} \(Q_m = -1.893\)

Angular distributions of \(^{6}\text{Li}\) ions have been obtained at \(E(^{3}\text{He}) = 6\) to 10 MeV: see (74AJ01). A study of the continuum suggests the population of \(^{6}\text{Li}\) states at \(E_x = 8\)–12, \(\approx 21\) and 21.5 MeV: see (84AJ01). More recently, measurements at \(E(^{3}\text{He}) = 60\) MeV of differential cross sections have been reported (90MA1O, 90MAZG, 95MA57). Spectroscopic factors were deduced. Angular distributions at \(E(^{3}\text{He}) = 60\) MeV for transition to the \(^{6}\text{Li}\) ground state and to \(^{6}\text{Li}^*(3^+, 2.185; 2^+, 5.37; 1^+, 5.65)\) were measured (96RU13) and analyzed by coupled-channels methods.

46. \(^{10}\text{B}(n, ^{5}\text{He})^{6}\text{Li}\) \hspace{1cm} \(Q_m = -5.258\)

Differential cross sections are reported at \(E_n = 14.4\) MeV involving \(^{6}\text{Li}^*(2.19)\) and \(^{5}\text{He}_{g.s.}\) (84TU02).

47. \(^{10}\text{B}(d, ^{6}\text{Li})^{6}\text{Li}\) \hspace{1cm} \(Q_m = -2.985\)

Angular distributions involving \(^{6}\text{Li}^*(0, 2.19)\) have been studied at \(E_d = 13.6\) MeV (83DO10) and at 19.5 MeV [see (74AJ01)]. See also (84SH1E).

48. \(^{10}\text{B}(^{3}\text{He}, ^{7}\text{Be})^{6}\text{Li}\) \hspace{1cm} \(Q_m = -2.874\)

Angular distributions involving \(^{6}\text{Li}^*(0, 2.19)\) have been measured at \(E(^{3}\text{He}) = 30\) MeV: see (74AJ01).

49. \(^{10}\text{B}(\alpha, ^{8}\text{Be})^{6}\text{Li}\) \hspace{1cm} \(Q_m = -4.552\)

At \(E_\alpha = 72.5\) MeV only \(^{6}\text{Li}^*(0, 2.19)\) are observed: the latter is excited much more strongly than is the ground state [\(S_\alpha\) for the ground state is 0.4 that for \(^{6}\text{Li}^*(2.19)\)]. The angular distributions for both transitions are flat: see (79AJ01). See also (84AJ01). A more recent measurement of differential cross sections at \(E_\alpha = 27.2\) MeV is reported in (95FA21). Spectroscopic factors were deduced.
50. $^{11}\text{B}(d,\,^{7}\text{Li})^{6}\text{Li}$ \hspace{1cm} $Q_{m} = -7.190$

See (84AJ01).

51. $^{11}\text{B}(^{3}\text{He},\,^{8}\text{Be})^{6}\text{Li}$ \hspace{1cm} $Q_{m} = 4.571$

Angular distributions are reported at $E(^{3}\text{He}) = 71.8$ MeV involving several states in $^{8}\text{Be}$ (86JA02, 86JA14).

52. $^{12}\text{C}(p,\,^{7}\text{Be})^{6}\text{Li}$ \hspace{1cm} $Q_{m} = -22.567$

Angular distributions involving $^{7}\text{Be}*(0, 0.43)$ have been measured at $E_{p} = 40.3$ MeV (85DE05). For the earlier work at $E_{p} = 30.6$ to 56.8 MeV see (74AJ01, 79AJ01). See also (83DE1C, 84RE1A, 87KW01, 87KW03).

53. $^{12}\text{C}(d,\,^{8}\text{Be})^{6}\text{Li}$ \hspace{1cm} $Q_{m} = -5.892$

Angular distributions involving several states in $^{8}\text{Be}$ have been studied at $E_{d} = 19.5$ and 51.8 MeV [see (74AJ01)] and at 50 MeV (85GO1G, 89GO07, 89GO26), 54.2 MeV (84UM04) and 78 MeV (86TA07), as well as at $E_{d} = 18$ and 22 MeV (87TA07) and 51.7 MeV (86YA12). See also (84NE1A, 87GO1S) and the DWBA calculations at $E_{d} = 50$ MeV (88KA46) and $E_{d} = 15$ MeV (88RA27).

54. $^{12}\text{C}(^{3}\text{He},\,^{9}\text{B})^{6}\text{Li}$ \hspace{1cm} $Q_{m} = -11.571$

Angular distributions have been obtained at $E(^{3}\text{He}) = 28$ to 40.7 MeV [see (74AJ01)] and at $E(^{3}\text{He}) = 33$ MeV (89SI02), $E(^{3}\text{He}) = 33.4$ MeV (86CL1B, also $A_{y}$), $E(^{3}\text{He}) = 60$ MeV (90MAZG, 93MA48), $E(^{3}\text{He}) = 30$ to 60 MeV (95MA57). See also (89GL1D) and see $^{9}\text{B}$.

55. (a) $^{12}\text{C}(\alpha,\,^{10}\text{B})^{6}\text{Li}$ \hspace{1cm} $Q_{m} = -23.712$

(b) $^{12}\text{C}(\alpha,\,d\alpha)^{10}\text{B}$ \hspace{1cm} $Q_{m} = -25.187$
Angular distributions (reaction (a)) at \( E_\alpha = 42 \text{ MeV} \) involve \(^6\text{Li}^*(0, 2.19)\): see \(74\text{AJ01}\). Differential cross sections were measured at \( E_\alpha = 90 \text{ MeV} \) and cluster spectroscopic amplitudes were deduced \(91\text{GL03}\). At \( E_\alpha = 65 \text{ MeV} \) reaction (b) goes via \(^6\text{Li}^*(2.19, 4.31)\): see \(84\text{AJ01}\). See also \(^{10}\text{B}\) and \(87\text{GA20}\).

56. (a) \(^{12}\text{C}(\text{\textit{6}Li}, \alpha)^{14}\text{N} \) \hspace{1cm} \(Q_m = 8.798\)
(b) \(^{12}\text{C}(\text{\textit{6}Li}, \text{ad})^{12}\text{C} \) \hspace{1cm} \(Q_m = -1.475\)

An analysis involving excited states of \(^6\text{Li}\) and \(^{14}\text{N}\) was applied to cross section and analyzing power data at \(E(\text{\textit{6}Li}) = 33 \text{ MeV} \) by \(00\text{MA43}\).

Measurements of triple differential cross sections for elastic breakup of 156 MeV \(^6\text{Li}\) (reaction (b)) were reported in \(89\text{HE28, 89HE17, 89RE1G}\). A diffraction dissociation model analysis was used. See also reaction 70. Partial cross sections for the \(^6\text{Li} + \text{^{12}C}\) reaction were measured for \(E(\text{\textit{6}Li}) = 3.11-12.07 \text{ MeV} \) by \(98\text{MU12}\).

57. \(^{12}\text{C}(^{10}\text{B}, ^{16}\text{O})^{6}\text{Li} \) \hspace{1cm} \(Q_m = 2.702\)

See \(^{16}\text{O}\) in \(86\text{AJ04}\).

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

Measurements of angular distributions at \(E(\text{^{11}B}) = 25, 35, 40 \text{ MeV} \) have been reported by \(96\text{JA12}\). Transfer mechanisms were studied.

59. \(^{12}\text{C}(^{12}\text{C}, ^{12}\text{C})^{6}\text{Li}^{6}\text{Li} \) \hspace{1cm} \(Q_m = -28.172\)

The fragmentation of \(^{12}\text{C}\) into 2 \(^6\text{Li}\) ions has been observed at \(E(\text{^{12}C}) = 2.1 \text{ GeV}/A\) \(86\text{LI1D}\).

60. \(^{12}\text{C}(^{14}\text{N}, ^{20}\text{Ne})^{6}\text{Li} \) \hspace{1cm} \(Q_m = -4.181\)

Angular distributions of reaction products were measured for \(E(\text{^{14}N}) = 50 \text{ MeV}\), and multinucleon transfer mechanisms were studied \(92\text{ARZX}\). See also the analysis for \(E(\text{^{14}N}) = 54 \text{ MeV}\) \(87\text{GO12}\), and see \(^{20}\text{Ne}\) in \(87\text{AJ02, 98TI06}\).
61. $^{13}$C(p, $^8$Be)$^6$Li

$Q_m = -8.614$

See (74AJ01).

62. $^{13}$C(t, $^6$Li)$^{10}$Be

$Q_m = -8.618$

Measurements of differential cross sections and analyzing powers were reported by (89SI02). Spectroscopic factors were extracted.

63. $^{13}$C($^3$He, $^6$Li)$^{10}$B

$Q_m = -8.081$

Differential cross sections at $E(^3$He) = 60 MeV have been reported (90MAZG, 95MA57). Cluster pick-up mechanisms were studied.

64. $^{16}$O(d, $^{12}$C)$^6$Li

$Q_m = -5.687$

Angular distributions and polarization observables involving $^6$Li ions and several $^{12}$C states are reported at $E_d = 22$ MeV (87TA07) and 51.7 MeV (86YA12) and at $E_d = 54.2$ MeV (84UM04). See also (84NE1A), and $^{12}$C in (90AJ01) for polarization studies.

65. $^{16}$O($^3$He, $^6$Li)$^{13}$N

$Q_m = -9.237$

Measurements and analyses of differential cross sections at $E(^3$He) = 30–60 MeV have been reported (95MA57).

66. $^{19}$F(d, $^6$Li)$^{15}$N

$Q_m = -2.538$

Differential cross sections at $E_d = 50$ MeV were reported (90GO14).

67. $^{19}$F($^3$He, $^{16}$O)$^6$Li

$Q_m = 4.095$
Angular distributions have been measured at \( E(\text{^3He}) = 11 \) to 40.7 MeV involving \(^6\text{Li}^*(0, 3.56)\) and various states of \(^{16}\text{O}\): see (74AJ01, 77AJ02). Differential cross sections have been reported for \( E(\text{^3He}) = 66 \) MeV (91MA56).

68. \(^{58}\text{Ni}(\text{^6}\text{Li}, \text{d})\text{X}\)

Measurement of the tensor analyzing power made at \( E(\text{^6Li}) = 34 \) MeV (78VE03) were analyzed to obtain the \( D\)- and \( S\)-state ratio for the \(<a|\text{^6Li}|\) bound state overlap.

69. \(^{138}\text{Ba}(\text{^6Li}, \text{^9Li})\)

Angular distribution measured for \( E(\text{^6Li}) = 21-32 \) MeV are reported by (99MA16).

70. (a) \(^{208}\text{Pb}(\text{^6Li}, \text{^6Li})^{208}\text{Pb}\)
(b) \(^{208}\text{Pb}(\text{^6Li}, \text{d})^{208}\text{Pb}\) \(Q_m = -1.475\)

For reaction (a) differential cross sections were measured at \( E(\text{^6Li}) = 25-60 \) MeV and analyzed by the optical model (94KE08, 98KE03).

For reaction (b) measurements of triple differential cross sections for elastic breakup of 156 MeV \(^6\text{Li}\) were reported in (89HE28, 89HE17, 89RE1G). Data were analyzed on the basis of a diffractive disintegration approach. Breakup measurements at \( E(\text{^6Li}) = 60 \) MeV were reported in (88HE16). See also reaction 56, and see the theoretical study of angular correlation of breakup fragments in (89BA25).
GENERAL: References to articles on general properties of $^6\text{Be}$ published since the previous review (88AJ01) 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).

1. (a) $^3\text{He}(^3\text{He}, \gamma)^6\text{Be}$
   \[ Q_m = 11.488 \]
   \[ E_b = 11.488 \]

(b) $^3\text{He}(^3\text{He}, p)^5\text{Li}$
   \[ Q_m = 11.169 \]

(c) $^3\text{He}(^3\text{He}, 2p)^4\text{He}$
   \[ Q_m = 12.859 \]

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

(e) $^3\text{He}(^3\text{He}, pd)^3\text{He}$
   \[ Q_m = -5.494 \]

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°). No transitions are observed to $^6\text{Be}(0) [\sigma < 0.01 \mu$b at $E(^3\text{He}) = 1.4$ MeV]. This is understood in terms of a direct capture of $^3\text{He}$ by $^3\text{He}$ in the singlet spin state and with zero angular momentum: the $0^+ \rightarrow 0^+$ $\gamma$-transition is forbidden. Reaction (a) is thus of negligible astrophysical importance compared to reaction (c): see (79AJ01). The capture cross section from $E(^3\text{He}) = 12$ MeV to 27 MeV continues to increase smoothly with energy at first and then shows a broad structure centered at $E(^3\text{He}) = 23\pm1$ MeV [$E_x = 23.0\pm0.5$ MeV], $\Gamma_{cm} \approx 5$ MeV. This appears to be a $^{33}\text{F}$ cluster resonance which decays by an E1 transition to $^6\text{Be}^*(1.7)$. The $\gamma$-ray angular distributions are consistent with $J^e = 3^-$: see (79AJ01). See also (89IS1B). Thermoneural reaction rates for this reaction calculated from evaluated data are presented in the compilation (99AN35).

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

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$J^e; T$</th>
<th>$\Gamma_{cm}$</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<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>
</tr>
<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 (74AJ01).
Figure 6: Energy levels of $^6\text{Be}$. For notation see Fig. 5.
$A_y$ has been measured for $E(^{3}\text{He}) = 14$ to 30 MeV [reaction (b)] by (83KI10) using a polarized target. See also $^3\text{Li}$.

Measurements of the total cross section for reaction (c) have been carried out for $E(^{3}\text{He}) = 60\text{ keV}$ to 2.2 MeV [see (79AJ01)] and for 36 to 685 keV (87KR09). The measurements are consistent with a non-resonant reaction mechanism, at least down to $E_{cm} = 24.5\text{ keV}$. Upper limits for $\omega_\gamma$ for a resonance below that energy (and with $E_R$ (cm) as low as 16.2 keV) [which might help explain the low observed flux of solar neutrinos], are given in (87KR09). [It should be noted that a corresponding mirror state in $^6\text{He}$ has not been observed.]

The best fit to the data is given by $S(0) = 5.57 \pm 0.31\text{ MeV} \cdot b$ (87KR09). See (79AJ01) for the earlier work. See also (66LA04, 74AJ01). For work on astrophysical considerations see (82BA1J, 82KA1E, 83FO1A, 84DA1H, 84HA1M, 85CA41, 86FI1B, 87AS05, 87RO1D, 88BA1H, 88FO1A), and see (88CA1J, [thermonuclear reaction rates], 88CA26, 99AN35, [atomic screening], 88CA1J [dynamic screening], 89BA2P [neutrino astrophysics], 89SC25 [reaction rates], 88PO1J [plasma fusion], 89VA20 [S factors, RGM], 90SC15 [cross sections, extended elastic model], 91TY01 [cross sections, microscopic study], 90KR12, [phase shifts, generator coordinate method], 92WI09 [astrophysical S-factor, potential model], 94DE27 [cross sections, microscopic analysis], 89BE08 [S factor, electron screening effects], 89JI1A [nucleosynthesis around black holes]). (85SI12) report -d correlation measurements at $E(^{3}\text{He}) = 13.6\text{ MeV}$, which suggest the breakup of the diproton ($^2\text{He}$) into $^2\text{H} + e^+ + \nu$.

Thermonuclear reaction rates for this reaction calculated from evaluated data are presented in the compilation (99AN35). The elastic scattering (reaction (d)) has been studied for $E(^{3}\text{He}) = 3$ to 32 MeV and at 120 MeV. The excitation function shows a smooth monotonic behavior except for an anomaly at $E(^{3}\text{He}) = 25\text{ MeV}$ in the $L = 3$ partial wave corresponding to a broad state in $^6\text{Be}$ at $E_x \approx 24\text{ MeV}$. Polarization measurements have been carried out at $E(^{3}\text{He}) = 17.9$ to 32.9 MeV. A two level $R$-matrix analysis of the phase shifts ($L \leq 5$) suggests three broad F-wave states at $E_x \approx 23.4 (4^-), 26.2 (2^-)$ and 26.7 MeV ($3^-$), in disagreement with the capture $\gamma$-ray results described above: see (79AJ01). Calculations using the generator coordinate method have been reported for phase shifts ($E(^{3}\text{He}) < 5\text{ MeV}$) (90KR12), and for differential cross sections and astrophysical $S$ factors $E(^{3}\text{He}) = 2$–6 MeV) (94DE27). See also (84AJ01) and (86FO04).

A kinematically complete experiment (reaction (e)) has been performed at $E(^{3}\text{He}) = 120\text{ MeV}$: large peaks were observed which appear to correspond to $^3\text{He}$-d quasi-free scattering followed by p-d FSI: see (84AJ01).

The total reaction cross sections $\sigma_R = 156.7 \pm 3.8, 250 \pm 14$ and 296 $\pm 12\text{ mb}$ at $E(^{3}\text{He}) = 17.9, 21.7$ and 24.0 MeV (87BR02) [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 (84AJ01) and (83PR1A, 84HA25, 85HA14, 86GO1E, 86OS1D, 86WI1A, 87AS05, 88RYZW).

2. $^4\text{He}(^{3}\text{He}, n)^{6}\text{Be}$  \hspace{1cm}  $Q_m = -9.089$

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 (74AJ01) for the parameters of the first-excited state. There is no evidence for other states of $^6$Be with $E_x \leq 5$ MeV, nor for a state near the $^3$He threshold at 11.5 MeV: see (79AJ01).

3. (a) $^6$Li(p, n)$^6$Be $Q_m = -5.070$
(b) $^6$Li(p, pn)$^5$Li $Q_m = -5.389$

Neutron groups have been observed to $^6$Be*(0, 1.7) as has the ground-state threshold. The width of the ground state is $95 \pm 28$ keV. The parameters of $^6$Be*(1.7) are displayed in Table 6.8 of (74AJ01). Angular distributions have been reported at $E_p = 8.3$ to 144 MeV [see (79AJ01, 84AJ01)] and at 800 MeV (86KI12). 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 (84TA07). See also $^7$Be and (84TA1F, 85GO1F, 86SA1Q, 861A1E, 87RA32, 87SA46, 85SH1C, 88HE08).

In more recent work, evidence for a proportionality between $\sigma_{pn}(0^\circ)$ and Gamow-Teller transition strengths were examined (87TA13). See also (89RA1G). Measurements are reported at $E_p = 60$–200 MeV (90RA08 [D_{NN}(0^\circ)], $E_p = 256$, 800 MeV (93ST06 [double differential cross sections]), $E_p = 186$ MeV (93WAZX, 93YAZZ, 94RA23 [polarization observables], 94WA22 [quasifree excitations], 95YA12 [dipole excitations]), $E_p = 392$ MeV (94TO1C [\sigma(\theta), A_y(\theta)], $E_p = 300, 400$ MeV (94SA43 [quasifree excitations, D_{NN}(0^\circ)]), $E_p = 295$ MeV (95WA16 [spin-flip strength, D_{NN}(0^\circ)]), $E_p = 200$ MeV (95WAZW [A_y(\theta)]), $E_p = 35$ MeV (96ORZZ [\sigma(\theta)]), $E_p = 280$ MeV (90MI10 [\sigma(\theta), isospin-symmetry test]). For recent applications see (98HA24, 98WA12). Calculations with a dynamical multicluster model are discussed in (91DA08, 93SH1G). See also the review of two-particle neutron halo nuclei in (96DA31).

In reaction (b) some evidence has been reported at $E_p = 47$ MeV for sequential decay via $^6$Be*(15.5 ± 2, 24 ± 2): see (79AJ01). See also (88MIZX).

4. $^6$Li($^3$He, t)$^6$Be $Q_m = -4.307$

Triton groups have been observed to $^6$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 (74AJ01). No other excited states have been seen with $E_x < 13$ MeV. There is no evidence for a state near 11.5 MeV: see (79AJ01). (87BO39) have studied the decay of $^6$Be*(1.7) at $E(^3$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 (84BO49, 85BO56, 88BO1J). See also (84AJ01), (87DA1N; theor.) and $^9$B.

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 (88BO38, 89BO1N, 89BO25 89BO42) and in (92BO25, 93BO38...
Table 6.15
Isospin triplet components \((T = 1)\) in \(A = 6\) nuclei \(^a\)

<table>
<thead>
<tr>
<th>(\text{(^6)He})</th>
<th>(\text{(^6)Li})</th>
<th>(\text{(^6)Be})</th>
</tr>
</thead>
<tbody>
<tr>
<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>24.89</td>
</tr>
<tr>
<td>24.78</td>
<td>3(^-); 1</td>
<td>27</td>
</tr>
</tbody>
</table>

\(^a\) As taken from Tables 6.1, 6.4 and 6.14.

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

\(^c\) Defined as \(E_x\)\(^{(6}\)Be\) – \(E_x\)\(^{(6}\)He\).

[studied decay mechanism]). Measurements of differential cross sections at \(E(\text{\(^3\)He}) = 93\) MeV are described in (94DOZW).

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

Not observed: see (79AJ01, 84AJ01, 89GR06 [\(^6\)Li(\(\pi^+, \pi^-\)) at \(E_{\pi^+} = 180, 240\) MeV], 93PO11 [properties of exotic light nuclei]) (98SU18).
Figure 7: Isobar diagram, $A = 6$. For notation see Fig. 3.
A = 7

GENERAL: References to articles on general properties of A = 7 nuclei published since the previous review (88AJ01) are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for A = 7 located on our website at (www.tunl.duke.edu/NuclData/General_Tables/07.shtml).

\[ ^7\text{H} \]

(not illustrated)

\(^7\text{H}\) has not been observed. Attempts have been made to detect it in the spontaneous fission of \(^{252}\text{Cf}\) (82AL33) and in the \(^7\text{Li}(\pi^-, \pi^+)\) reaction [see (84AJ01)]. A study of \(^9\text{Be}(\pi^-, 2p)\) (87GO25) found no evidence for \(^7\text{H}\). See also the review of (89OG1B) and the \(^7\text{Li}(\pi^-, \pi^+)\) investigation reported in (89GR06). The ground state is calculated to have \(J^\pi = \frac{1}{2}^-\) and to be unstable with respect to 1n, 2n, 3n and 4n emission. Excited states are predicted at 4.84, 5.00 and 6.96 MeV, with \(J^\pi = \frac{3}{2}^+, \frac{5}{2}^+, \) and \(\frac{5}{2}^-\) [(0 + 1)\(\hbar\omega\) model space] and at 3.88, 3.94 and 5.99 MeV with \(J^\pi = \frac{3}{2}^+, \frac{5}{2}^+, \) and \(\frac{7}{2}^+\) [(0 + 2)\(\hbar\omega\) model space] (85PO10). See also (84BE1C, 85GA1C, 86GA1J, 87FL1A, 87GO1Z, 87PE1C).

\[ ^7\text{He} \]

(Figs. 8 and 11)

GENERAL: References to articles on general properties of \(^7\text{He}\) published since the previous review (88AJ01) are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for \(^7\text{He}\) located on our website at (www.tunl.duke.edu/NuclData/General_Tables/7he.shtml).

Mass of \(^7\text{He}\): The atomic mass excess of \(^7\text{He}\) is 26.11 ± 0.03 MeV: \(^7\text{He}\) is then unbound with respect to decay into \(^6\text{He}\) + n by 0.44 MeV: see (84AJ01). The ground state is calculated to have \(J^\pi = \frac{3}{2}^-\) and to be unstable with respect to decay into \(^6\text{He}\) + n by about 1 MeV (85PO10). See also (88AJ01).

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

\[ Q_m = -0.359 \]

This reaction was studied at \(E(^8\text{He}) = 50\) MeV/A (99KO14, 00KO46). Deuterons, neutrons, \(^4\text{He}\) and \(^6\text{He}\) were detected. Spectra indicate a level in \(^7\text{He}\) at \(E_x = 2.9 \pm 0.3\) MeV, \(\Gamma = 2.2 \pm 0.3\) MeV which decays mainly into \(3\text{n} + ^4\text{He}\), \(\Gamma_{3\text{n}}/\Gamma_{\text{tot}} = 0.7 \pm 0.2\). Arguments are given for a tentative assignment \(J^\pi = (\frac{3}{2}^-)\).
Table 7.1  
Energy levels of $^7$He \(^a\)

<table>
<thead>
<tr>
<th>$E_x$ (MeV) (^b)</th>
<th>$J^\pi$, $T$</th>
<th>$\Gamma_{c.m.}$ (keV)</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>((\frac{3}{2}))^(-), (\frac{3}{2})(^+)</td>
<td>160 ± 30</td>
<td>n</td>
<td>1, 2, 3, 4, 5, 6</td>
</tr>
<tr>
<td>2.9 ± 0.3</td>
<td>((\frac{5}{2}))^(-), (\frac{5}{2})(^+)</td>
<td>2200 ± 300</td>
<td>n</td>
<td>1, 6</td>
</tr>
</tbody>
</table>

\(^a\) Excited states are calculated at 4.27, 4.55 and 5.38 MeV with $J^\pi = \frac{1}{2}^+$, $\frac{1}{2}^-$ and $\frac{5}{2}^-$ ([0 + 1]h\(\omega\) model space). In the (0 + 2)h\(\omega\) model space the excited states are predicted at 3.43, 5.03 and 7.47 MeV with $J^\pi = \frac{3}{2}^+$, $\frac{5}{2}^-$ and $\frac{7}{2}^-$ (85PO10). See also (90WO10), the refined resonating group model calculation of (97WU01), and the quantum Monte Carlo calculation of (98WI10, 00WI09).

\(^b\) See also reactions 3, 5 and 6.

2. $^7$Li($\pi^-$, $\gamma$)$^7$He  
$Q_m = 128.37$

Capture $\gamma$-rays from the transition to $^7$He\(_{g.s.}\) are reported by (86PE05).

3. $^7$Li(n, p)$^7$He  
$Q_m = -10.42$

The proton group corresponding to $^7$He\(_{g.s.}\) has $\Gamma < 0.2$ MeV: see (79AJ01). At $E_n = 60$ MeV broad bumps in the spectra are ascribed to states at $E_x \approx 20 \pm 1$ MeV [$\Gamma = 9 \pm 2$ MeV] and, possibly, at $\approx 6$ MeV (83BR1C, 84BR03); see for discussion of the GDR). See also (87HE24) and (87BR32). Analyzing powers measured at $E_n = 0.88$ GeV are reported in (96BB23).

4. $^7$Li(t, $^3$He)$^7$He  
$Q_m = -11.18$

The $^3$He particles leading to the ground state of $^7$He have been observed at $E_t = 22$ MeV. The width of the ground state is 160 ± 30 keV; for a radius of 2.2 fm and $l_n = 1$, this width is 0.22 of the Wigner limit. The angular distribution is peaked in the forward direction. No other states of $^7$He were observed for $E_x < 2.4$ MeV: see (79AJ01).

5. (a) $^6$Li($^{14}$C, $^{13}$N)$^7$He  
$Q_m = -14.35$
(b) $^7$Li($^7$Li, $^7$Be)$^7$He  
$Q_m = -12.06$
(c) $^7$Li($^{11}$B, $^{11}$C)$^7$He  
$Q_m = -13.19$
(d) $^9$Be($^6$Li, $^8$B)$^7$He  
$Q_m = -23.60$

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Figure 8: Energy levels of $^7$He. For notation see Fig. 5.
\((e) \, ^{9}\text{Be} (^{9}\text{Be}, ^{11}\text{C})^{7}\text{He} \quad Q_{m} = -14.07\)
\((f) \, ^{9}\text{Be} (^{11}\text{B}, ^{13}\text{N})^{7}\text{He} \quad Q_{m} = -11.44\)
\((g) \, ^{9}\text{Be} (^{14}\text{C}, ^{16}\text{O})^{7}\text{He} \quad Q_{m} = -7.01\)
\((h) \, ^{9}\text{Be} (^{15}\text{N}, ^{17}\text{F})^{7}\text{He} \quad Q_{m} = -16.61\)

Reaction \((a)\) was investigated at \(E(^{14}\text{C}) = 24\ \text{MeV/A}\) (95BO10, 95VO05). The \(^{7}\text{He}\) ground state was populated strongly, but no excited states were observed. At \(E(^{6}\text{Li}) = 72\ \text{MeV}\) and at \(E(^{7}\text{Li}) = 70\ \text{MeV}\) (reactions \((b)\) and \((d)\)) there is no evidence for excited states with \(\Gamma \leq 2\ \text{MeV}\) for \(E_{x} < 10\ \text{MeV}\) (85AL1B, 85AL1G, 85AL29). The ground state of \(^{7}\text{He}\) is strongly populated. Reactions \((c)\), \((e)\), \((f)\) and \((g)\) have been investigated at \(E(^{11}\text{B}) = 88\), \(E(^{9}\text{Be}) = 106.7\) and \(E(^{14}\text{C}) = 152.6\ \text{MeV}\). The ground state of \(^{7}\text{He}\) is populated. There is some evidence for a second state in reaction \((g)\) at \(E_{x} = 2.9 \pm 0.5, \Gamma = 1.5 \pm 0.5\ \text{MeV}\) (88BE34). See also (79AJ01) and (88BEYJ). At \(E(^{15}\text{N}) = 2.40\ \text{MeV}\), reaction \((h)\) shows evidence for a level at \(E_{x} = 3.2 \pm 0.2\ \text{MeV}, \Gamma = 1.5 \pm 0.2\ \text{MeV}\) (98BO1M, 98BO38, 99BO26).

6. \(^{10}\text{B}(\pi^{-}, pd)^{7}\text{He}\) 

\[Q_{m} = 105.09\]

Stopped negative pion absorption on \(^{10}\text{B}\) was studied with detection of protons and deuterons (98GO30). The missing-mass spectra show evidence for a level in \(^{7}\text{He}\) with \(E_{x} = 2.8 \pm 0.2\ \text{MeV}, \Gamma \approx 2.0\ \text{MeV}\).
\( ^7\text{Li} \)

(Figs. 9 and 11)

**GENERAL:** References to articles on general properties of \(^7\text{Li}\) published since the previous review (88AJ01) are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for \(^7\text{Li}\) located on our website at (www.tunl.duke.edu/NuclData/General_Tables/7li.shtml).

\[ \mu = +3.25642(2) \text{ nm: see (78LEZA)}. \]

\[ Q = -40.6 \pm 0.8 \text{ mb (88DI1B)}. \text{ See (88DI1B) for a review of earlier determinations, particularly those of (84SU09, 84VE03, 84VE08, 85WE08).} \]

\[ B(E2): \frac{3^-}{2^-} \to \frac{1^-}{2^-} = 8.3 \pm 0.5 \text{ e}^2 \text{ fm}^4 \text{ (85WE08). See also (84VE08), (88TA1D) and (84AJ01).} \]

Isotopic abundance: \(92.5 \pm 0.2\%\) (84DE1A). See also (87LA1J, 88LA1C).

The interaction nuclear radius of \(^7\text{Li}\) is \(2.23 \pm 0.02 \text{ fm}\) (85TA18). [See also for derived nuclear matter, charge and neutron matter r.m.s. radii].

1. \(^3\text{H}(\alpha, \gamma)^7\text{Li}\) \hspace{1cm} \(Q_m = 2.467\)

Excitation functions and angular distributions have been studied for \(E_\alpha = 0.5\) to 2.0 MeV. The cross section rises smoothly as expected for a direct capture process: see (66LA04) and (87BU18, \(\gamma_0, \gamma_1\)). Measurements of the astrophysical \(S\)-factor, \(S(E)\), and the branching ratio \(R\) for direct capture to the 478 keV state compared to direct capture to the ground state were reported by (87SC18). They deduce \(S(0) = 0.14 \pm 0.02 \text{ keV b, } R = 0.32 \pm 0.01\). More recently, available data on \(^3\text{H} + \alpha\) scattering were analyzed (93MO11) in the optical model framework to predict \(S(0) = 0.10 \text{ keV b and branching ratio } R = 0.43\). Measurements of the cross section and angular distribution in the energy range \(50 \leq E \leq 1200 \text{ keV}\) were reported by (94BR25). They determined \(R \approx 0.45\) at low energies in disagreement with (87SC18). A recent analysis by (99BU10) estimated the uncertainties in Big Bang nucleosynthesis \(^7\text{Li}\) yields. For astrophysical calculations related to \(^3\text{H}(\alpha, \gamma)\) see the General Table for \(^7\text{Li}\) located on our website at (www.tunl.duke.edu/NuclData/General_Tables/7li.shtml). See also the references cited in (88AJ01).

Thermonuclear reaction rates for this reaction calculated from evaluated data are presented in the compilation (99AN35).

2. \(^3\text{H}(\alpha, n)^6\text{Li}\) \hspace{1cm} \(Q_m = -4.782\) \hspace{1cm} \(E_b = 2.467\)

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

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$J^\pi; T$</th>
<th>$\tau_m$ or $\Gamma_{c.m.}$ (keV)</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>$\frac{3}{2}^-$; $\frac{1}{2}$</td>
<td>stable</td>
<td>stable</td>
<td></td>
</tr>
<tr>
<td>0.477612 ± 0.003</td>
<td>$\frac{1}{2}^-$; $\frac{1}{2}$</td>
<td>$\tau_m = 105 \pm 3$ fsec $^a$</td>
<td>$\gamma$</td>
<td>4, 5, 6, 10, 11, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 48, 49, 50, 51, 53, 54, 55</td>
</tr>
<tr>
<td>4.630 ± 9</td>
<td>$\frac{7}{2}^-$; $\frac{1}{2}$</td>
<td>$\Gamma = 93 \pm 8$ keV</td>
<td>$t, \alpha$</td>
<td>3, 4, 10, 11, 16, 17, 18, 19, 20, 21, 22, 26, 38, 39, 41, 46, 50</td>
</tr>
<tr>
<td>6.68 ± 50</td>
<td>$\frac{5}{2}^-$; $\frac{1}{2}$</td>
<td>875$^{+200}_{-100}$</td>
<td>$t, \alpha$</td>
<td>3, 11, 16, 17, 18, 22, 39, 46, 54</td>
</tr>
<tr>
<td>7.4595 ± 1.0</td>
<td>$\frac{5}{2}^-$; $\frac{1}{2}$</td>
<td>89 ± 7</td>
<td>$n, t, \alpha$</td>
<td>2, 3, 7, 8, 9, 11, 16, 17, 18, 19, 22, 36, 38, 39, 46</td>
</tr>
<tr>
<td>9.67 ± 100</td>
<td>$\frac{7}{2}^-$; $\frac{1}{2}$</td>
<td>$\approx 400$</td>
<td>$n, t, \alpha$</td>
<td>2, 3, 11, 17, 19, 22, 39</td>
</tr>
<tr>
<td>9.85</td>
<td>$\frac{5}{2}^-$; $\frac{1}{2}$</td>
<td>$\approx 1200$</td>
<td>$n, \alpha$</td>
<td>7, 36</td>
</tr>
<tr>
<td>11.24 ± 30</td>
<td>$\frac{7}{2}^-$; $\frac{3}{2}$</td>
<td>260 ± 35</td>
<td>$n, p$</td>
<td>7, 8, 38</td>
</tr>
<tr>
<td>13.7</td>
<td>$\frac{3}{2}^-$; $\frac{1}{2}$</td>
<td>$\approx 500$</td>
<td>n</td>
<td>14</td>
</tr>
<tr>
<td>14.7 $^b$</td>
<td>$\frac{3}{2}^-$; $\frac{1}{2}$</td>
<td>$\approx 700$</td>
<td>n</td>
<td>14</td>
</tr>
</tbody>
</table>

$^a$ See Table 7.2 in (79AJ01), Table 7.5 here and reaction 39.

$^b$ See also reactions 7, 9, 14, 21 and 37 for possible additional states.
Figure 9: Energy levels of $^7\text{Li}$. For notation see Fig. 5.
Table 7.3

\(^7\text{Li} \text{ levels from } ^3\text{H} + ^4\text{He}^a\)

<table>
<thead>
<tr>
<th>(E_x \text{ (MeV }\pm\text{ keV)})</th>
<th>(J^\pi)</th>
<th>(l_o)</th>
<th>(LS) term</th>
<th>(R) (fm)</th>
<th>(\theta^2_{\alpha}) (^b)</th>
<th>(\theta^2_{\text{inv}}) (^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.65 \pm 20</td>
<td>(^2^1)(^{-})</td>
<td>3</td>
<td>(2F_{7/2})</td>
<td>4.0</td>
<td>0.57 \pm 0.04</td>
<td>0.000 \pm 0.002</td>
</tr>
<tr>
<td>6.64 \pm 100</td>
<td>(^4^2)(^{-})</td>
<td>3</td>
<td>(2F_{5/2})</td>
<td>4.0</td>
<td>1.36 \pm 0.13</td>
<td>0.000 \pm 0.002</td>
</tr>
<tr>
<td>6.79 \pm 90</td>
<td>(^4^2)(^{-})</td>
<td>3</td>
<td>(2F_{5/2})</td>
<td>4.4</td>
<td>0.52</td>
<td>0.000 \pm 0.002</td>
</tr>
<tr>
<td>7.47 \pm 30</td>
<td>(^4^2)(^{-})</td>
<td>3</td>
<td>(4P_{5/2})</td>
<td>4.0</td>
<td>0.011 \pm 0.001</td>
<td>0.26 \pm 0.02</td>
</tr>
<tr>
<td>9.67 \pm 100</td>
<td>(^2^2)(^{-})</td>
<td>3</td>
<td>(4D_{7/2})</td>
<td>4.0</td>
<td>0.53 \pm 0.22</td>
<td>2.3 \pm 0.7 (^d)</td>
</tr>
</tbody>
</table>

\(^a\) For references see Table 7.3 in (79AJ01).

\(^b\) \(\gamma^2 \alpha R^2/3\hbar^2\).

\(^c\) See reaction 2: \(^3\text{H}(\alpha, n)^6\text{Li}\).

\(^d\) \(\theta^2_{\text{inv}}\), to \(^6\text{Li}*(2.19)\).

The cross section for this reaction has been measured for \(E_\alpha = 11\) to 18 MeV: the data show the effect of \(^7\text{Li}*(7.46)\) and indicate a broad resonance near \(E_\alpha = 16.8\) MeV \([^7\text{Li}*(9.6)]\). The level parameters derived from this reaction and from reaction 3 are displayed in Table 7.3. The yield of \(^6\text{Li}\) ions at 0\(^\circ\) (lab) has also been measured for \(E_\alpha = 11.310\) to 11.930 MeV with 2–3% accuracy: the data were then reduced to obtain the cm differential cross sections at 0\(^\circ\) and 180\(^\circ\) for the inverse reaction in the energy region corresponding to formation of \(^7\text{Li}*(7.46)\): see (79AJ01). See also the compilation of (85CA41). A resonating group calculation of \(\sigma(E)\) from threshold to 20 MeV is reported in (91FU02).

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

\(E_b = 2.467\)

The excitation curves for the elastic scattering show the effects of \(^7\text{Li}*(4.63, 6.68, 7.46, 9.67)\). The derived level parameters are displayed in Table 7.3. Angular distributions have been studied for \(E_\alpha = 2.13\) to 2.98 MeV and \(E_\alpha = 6.0\) to 17 MeV [see (79AJ01, 84AJ01)] and at \(E_\alpha = 56.3\) to 95.5 MeV (86YA1M; also \(A_j\)). More recently, cross section and angular distributions were measured at \(E_\alpha = 27.2\) MeV and described in an RGM method and in the phenomenological optical model. A polarization extremum \((A_j = -1)\) occurs near \(E_\alpha = 11.1\) MeV, \(\theta = 95^\circ\): see (84AJ01). For the breakup of \(^7\text{Li}\) into \(\alpha + t\) in various processes see (84AJ01) and (84SH17, 87FO08, 87PO03) as well as the General Table for \(^7\text{Li}\) located on our website at (www.tunl.duke.edu/NuclData/General_Tables/7li.shtml). For cross sections determined from shell-model and R-matrix calculations see (87KN04). Other calculations that have been reported include: phase shifts for \(E_\alpha < 300\) MeV and \(^7\text{Li}\) charge form factor (87RO24), scattering lengths (88CH47, 89CH34), phase shift and transmission coefficients with RGM (91FU02), phase shift and astrophysical \(S\)-factors in a two-cluster model (95DU09, 97DU15), RGM phase shifts (95MA37), and phase shifts versus \(E\) in a three-body cluster model (96SH02).
For muon catalysis see references cited in (88AJ01).

4. $^4\text{He}(^3\text{He}, \pi^+)^7\text{Li}$ $Q_m = -137.122$

$^7\text{Li}^*(0+0.48, 4.63)$ have been populated at $E(^3\text{He}) = 266.5$ and $280.5$ MeV: see (84AJ01). See also (84GE05, 87KA09).

5. $^4\text{He}(\alpha, p)^7\text{Li}$ $Q_m = -17.347$

Angular distributions have been reported at $E_\alpha = 39.9$ to $140$ MeV [see (79AJ01, 84AJ01)] and at 61.5 to $158.2$ MeV (82GL01) and 198.4 MeV (85WO11) for the transitions to $^7\text{Li}^*(0, 0.48)$. See (82GL01, 85WO11) for a discussion of $^7\text{Li}$ production in the Big Bang. See also $^8\text{Be}$ and (86KA26).

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

$Q_0 = 7251.02 \pm 0.09$ keV (85KO47)

The thermal capture cross section is $38.5 \pm 3.0$ mb (81MUZQ). Gamma rays are observed corresponding to transitions to $^7\text{Li}^*(0, 0.48)$ with branching ratios $62 \pm 2\%$ and $38 \pm 2\%$ (85KO47). $^7\text{Li}^*(4.63, 6.68)$ are not populated [\leq 5\%] (85KO47). See (79AJ01) for the earlier work. The decay of $^7\text{Li}^*(7.46) \rightarrow ^6\text{Li}_{g.s.} + n$ in the interaction of $35$ MeV/A $^{14}\text{N}$ ions on Ag is reported by (87BL13).

A recent study discussed in (97NO04) analyzed reaction rates of $^6\text{Li}(n, \gamma)$ and other reactions that bear on the possibility of observing primordial $^6\text{Li}$.

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

The real coherent scattering length is $2.0 \pm 0.1$ fm; the complex scattering lengths are $b_+ = (0.67 \pm 0.14) - i(0.08 \pm 0.01)$ fm, $b_- = (4.67 \pm 0.17) - i(0.62 \pm 0.02)$ fm; $\sigma_{\text{free}} = 0.70 \pm 0.01$ b (83KO17). See also (79GL12). (83AL1E) report $\sigma_\circ$ (below 10 keV) = 0.72 $\pm$ 0.02 b. See also (81MUZQ). The total cross section has been measured from $E_n = 4$ eV to 49.6 MeV [see (76GAYV, 84AJ01)], at 0.6 to 80 keV (82AL35) and at 0.08 to 3.0 MeV (83KN1D).

A pronounced resonance occurs at $E_n = 244.5 \pm 1.0$ keV [$E_x = 7459.5 \pm 1.0$ keV] with a peak cross section of $11.2 \pm 0.2$ b (82SM02): see Table 7.4. No other clearly defined resonance is observed to $E_n = 49.6$ MeV although the total cross section exhibits a broad maximum at $E_n \approx 4.5$ MeV: see (84AJ01). The analyzing power has been measured for
Table 7.4
Resonance parameters for 7.5–7.2 MeV levels in $^7$Li and $^7$Be

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

$^a$ These states are believed to have a $^4P_{3/2}$ character, consistent with their large $\theta_n^2$ and $\theta_p^2$. See Table 7.4 in (79AJ01). These parameters are from Table I of (63MC09). See also (59GA08).

$^b$ 244.5 ± 1.0 keV (82SM02).

$^c$ See also the measurements and analysis of (95SK01).

$^d$ The authors of (59GA08, 63MC09) use a definition of $\gamma_{n,p}^2$ and $\gamma_\alpha^2$ for which the units are MeV·fm.

$E_n = 1.48$ to 5 MeV [see (84AJ01)] and 5 to 17 MeV (86PF1A; prelim.). Multi-level, multi-channel $R$-matrix analyses (87KN1A, 83KN1B) for $E_n \leq 8$ MeV [using also data from other channels] include 13 normal and 14 non-normal parity states with $E_x \leq 17$ MeV. [Only ten states have been seen directly in reaction or compound nucleus cross-section work.] Two positive-parity states provide an explanation for the anisotropy of the $^6$Li(n, α) work at low energies (83KN06). For the results of an earlier $R$-matrix analysis see (84AJ01).

The excitation function for 3.56 MeV $\gamma$-rays exhibits an anomaly, also seen in the (n, p) reaction (reaction 8). The data are well fitted assuming $E_{res} = 3.50$ and 4.60 MeV [$E_x = 10.25 \pm 0.10$ and $11.19 \pm 0.05$ MeV], $T = \frac{1}{2}$ and $\frac{3}{2}$, $\Gamma_{cm} = 1.40 \pm 0.10$ and 0.27±0.05 MeV, respectively; both $J^\pi = \frac{3}{2}^-$. However, (79AJ01) notes that an $R$-matrix study of $^4$He(t, t), $^6$Li(n, n), and $^6$Li(n, α) data leads to the identification of a $\frac{3}{2}^+$ state at $E_x = 9.85$ MeV, $\Gamma = 1.2$ MeV. See (79AJ01) for a discussion of these and other unpublished data.

Differential cross sections for $n_0$ and $n_1$ were measured at $E_n = 6.8$–9.8 MeV and used with other data in an analysis to deduce $\sigma(E)$ for $E_n = 6$–14 MeV (87SC08). Elastic and
inelastic scattering cross sections $\sigma(\theta)$ were measured for $E_n = 24$ MeV (87HA1Z) and analyzed, along with existing proton scattering data to study neutron and proton transition densities. Elastic and inelastic scattering differential cross sections were measured at $E_n = 11.5, 14.1$ and $18.0$ MeV (98CH33) and used to determine a phenomenological optical model potential. A measurement of double-differential neutron emission cross sections for $E_n = 11.5$, 14.1 and 18.0 MeV was reported by (98IB02). Theoretical work includes: a calculation of coherent and incoherent thermal cross sections (90GO26), RGM calculations of $\sigma(\theta)$ at $E_n = 18$ MeV (92KA06), calculation of phase shifts and cross sections for $E_n < 18$ MeV using a potential description (93DU09), a study of antisymmetry contribution to the nucleon-nucleon potentials (95CO18), a study of the applicability of optical-model potentials for nuclear data evaluations (96CH33).

See also earlier references cited in (88AJ01).

8. (a) $^6$Li(n, 2n)$^5$Li
(b) $^6$Li(n, p)$^6$He
(c) $^6$Li(n, d)$^5$He

$Q_m = -5.39$ $E_b = 7.250$
$Q_m = -2.725$
$Q_m = -2.272$

For reaction (a) see (85CH37, 86CH1R). The excitation function for reaction (b), measured from threshold to $E_n = 8.9$ MeV, exhibits an anomaly at $E_n = 4.6$ MeV. The excitation function, at forward angles, of $p_0$ is approximately constant for $E_n = 4.4$ to 7.25 MeV; see (79AJ01). Measurements of particle spectra have been made at $E_n = 198$ MeV (87HE22), $E_n = 118$ MeV (87PO18, 88HA12, 98HA24). Studies of this reaction as a probe of Gamow-Teller strength are reported in (88JA01, 88WA24, 92SO02). Measurements at $E_n = 280$ MeV were used in a test of isospin symmetry (90MI10). Measurements at $E_n = 0.88$ GeV with polarized targets are reported in (96BB27). Theoretical studies of this reaction include: a dynamical cluster model calculation for $E_n = 280$ MeV (91DA08), a calculation of phase shifts for $E_n = 6.77$ MeV (93DU09), a calculation with hyperspherical harmonics (96DA31) and with a three-body cluster model for $E_n = 50$ MeV (97DA01). See also (97ER05, 97VA06). The excitation function, at forward angles, of deuterons (reaction (c)) increases monotonically for $E_n = 5.4$ to 6.8 MeV; see (79AJ01, 88AJ01). A multiconfiguration resonating-group method calculation of $\sigma(\theta)$ for $E_n = 12$ MeV is described in (95FU16).

9. $^6$Li(n, $\alpha$)$^3$H

$Q_m = 4.782$ $E_b = 7.250$

The thermal cross section is $940 \pm 4$ b: see (81MUZQ). See also (85SW01). A resonance occurs at $E_n = 241 \pm 3$ keV with $\sigma_{\text{max}} = 3.3$ b: see (84AJ01, 86CA28). The resonance is formed by $p$-waves, $J^\pi = \frac{1}{2}^-$, and has a large neutron width and a small $\alpha$-width: see Table 7.4. Above the resonance the cross section decreases monotonically to $E_n = 18.2$ MeV, except for a small bump near $E_n \approx 1.8$ MeV and an inflection near $E_n = 3.5$ MeV. For
a description of $R$-matrix analyses which suggest the location of higher states of $^7\text{Li}$, see reaction 7 and (84AJ01), as well as (87KN04).

Angular distributions have been measured at many energies in the range $E_n = 0.1$ to 14.1 MeV [see (79AJ01, 84AJ01)] as well as from 35 eV to 325 keV (83KN03) and 2.16 to 4.20, 7.1 and 13.7 MeV (86BA32, 86BA68). Polarization measurements have been reported for $E_n = 0.2$ to 2.4 MeV: the data suggest interference between s-waves and the p-wave resonance at 0.25 MeV. Interference between this $\frac{3}{2}^-$ state and a broad $\frac{5}{2}^-$ state 2 MeV higher also appears to contribute. At the higher energies $A_y$ is close to +0.9 near 90° and varies slowly with $E_n$: see (79AJ01). See also (83VE10, 84VE1A).

Measurements with polarized thermal neutrons for studying parity violation effects have been reported in (90VE16, 94GL07, 96VE02). Reaction rates for $E < 2$ MeV were analyzed (97NO04) in connection with the possibility of observing primordial $^6\text{Li}$. Calculations of tritium production in applications of this reaction are described in (93FA01).

For a study of coincidences in the $^6\text{Li}(n, d)n$ reaction see (86MI11). The triton production cross section at $E_n = 14.92$ MeV is $32 \pm 3$ mb (85GO18). The total $\alpha$-production cross section [which includes the (n, nd) process] at $E_n = 14.95$ MeV is $512 \pm 26$ mb (86KN06).

See also the references cited in (88AJ01).

10. $^6\text{Li}(p, \pi^+)^7\text{Li}$

At $E_p = 600$ MeV, the reaction preferentially excites $^7\text{Li}^*(4.63)$. Angular distributions have been obtained for the pions to $^7\text{Li}^*(0, 0.48, 4.63)$ at $E_p = 600$ and 800 MeV. $^7\text{Li}^*(11.24) [T = \frac{3}{2}]$ is not observed: see (84AJ01). Recently $\sigma(\theta)$ and $A_y$ measurements were reported at $E_p = 800$ MeV (87SO1C). See also (85LE19). An analysis for $E_p = 201$–800 MeV utilizing a semi-phenomenological model is discussed in (93AL05).

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

Angular distributions of proton groups have been studied for $E_d = 0.12$ to 15 MeV and at 698 MeV: see (66LA04, 74AJ01, 79AJ01, 84AJ01). $J^\pi$ of $^7\text{Li}^*(0.48)$ is $\frac{1}{2}^-$. The two higher states have $E_x = 4630 \pm 9$ and 7464 $\pm 10$ keV, $\Gamma_{cm} = 93 \pm 8$ and 91 $\pm 8$ keV. The breakup reactions involve $^7\text{Li}^*(4.63, 7.46)$ and possibly $^7\text{Li}^*(9.6) [\Gamma = 0.5 \pm 0.1$ MeV]: see (79AJ01). See also $^8\text{Be}$ and (88KO1C).

The $(d,p)/(d,n)$ yield ratio for low deuteron energies ($E_d < 1$ MeV) has been studied. Calculations in (90KO26) concluded that Coulomb-induced predissociation of the deuteron should influence the ratio by < 10%. Measurements in (93CE02) found no evidence of an enhanced ratio for $E_{cm} = 20$–135 keV. The yield ratio was studied in experiments of (93CZ01, 97CZ04). This work explained the charge-symmetry violation in terms of a subthreshold $2^+$ state in $^8\text{Be}$. See also the instrumentation-related measurements of (94YE09) and the
thick-target gamma yield measurements of (00EL08). Calculations involving conservation of channel spin are described in (96MA36). This reaction was also discussed by (97NO04) in connection with deduction of a primordial $^6$Li component. Calculations for energy balance in controlled fusion are described in (00HA50). See also the compilation of charged-particle-induced thermonuclear reaction rates in (99AN35).

12. $^6$Li($^6$Li, $^5$Li)$^7$Li 

$Q_m = 1.86$

See (87MI34) and $^5$Li.

13. $^6$Li($^7$Li, $^7$Be)$^6$He 

$Q_m = -4.37$

The reaction was studied by (99NA36) for $E(^7$Li) = 65 MeV/A to compare the GT transition strengths to those deduced from $\beta$ decay.

14. (a) $^7$Li(γ, n)$^6$Li 

$Q_m = -7.2499$

(b) $^7$Li(γ, 2n)$^5$Li 

$Q_m = -12.64$

(c) $^7$Li(γ, p)$^6$He 

$Q_m = -9.975$

(d) $^7$Li(γ, pn)$^5$He 

$Q_m = -11.747$

(e) $^7$Li(γ, d)$^5$He 

$Q_m = -9.52$

(f) $^7$Li(γ, t)$^4$He 

$Q_m = -2.467$

The total photoneutron cross section rises sharply from 10 MeV to reach a broad plateau at about 15 mb from 14 to 20 MeV, decreases more slowly to about 0.5 mb at 25 MeV and then decreases further to about 0.3 mb at $E_\gamma = 30$ MeV (monoenergetic photons): there are indications of weak structure through the entire region: see (79AJ01), (88DI02) and (88AJ01). A study by (86SI18) reported evidence for the excitation of $^7$Li*(7.46), as well as of states at $E_x = 13.75 \pm 0.03$ and $14.65 \pm 0.03$ MeV with $\Gamma \approx 500$ and 700 keV [and integrated cross sections of $\approx 0.14$ and 0.17 MeV mb], in addition to a major broad structure at 17 MeV. The integrated cross section to 23 MeV is $39 \pm 4$ MeV mb for the $n_0$ transition and $17 \pm 4$ MeV mb for the $n_1$ transition: together these account for 0.4 of the exchange augmented dipole sum of $^7$Li: see (79AJ01). The integrated cross section for formation of $^6$Li*(3.56) is $4 \pm 1$ MeV mb to 30 MeV and $11 \pm 3$ MeV mb to 55 MeV: see (84AJ01).

The total absorption cross section for natural Li in the range 10 to 340 MeV shows a broad peak at $\approx 30$ MeV ($\sigma_{max} \approx 3$ mb), a minimum centered at $\approx 150$ MeV at $\approx 0.3$ mb and a fairly smooth increase in cross section to $\approx 3$ mb at $\approx 320$ MeV: see (84AJ01).
The cross section for the \((\gamma, p)\) reaction (reaction (c)) shows a maximum at \(\approx 15.6\) MeV with a width of \(\approx 4\) MeV. It then decreases fairly smoothly to 27 MeV. The integrated cross section for \(11 \to 28\) MeV is \(13.2 \pm 2.0\) MeV mb; see (74AJ01, 79AJ01, 84AJ01). Differential cross sections for the \((\gamma, n_0 + n_2)\) and \((\gamma, p_0)\) processes are reported by (83SE07, 85SE17). \(E_\gamma = 48 \text{ to } 141\) MeV. Photodisintegration cross sections in the giant resonant range were analyzed by (87VA05). Analyses of photodisintegration data for reactions (a, b, c, d) at \(E_\gamma < 50\) MeV (90VA16). Analyses of photodisintegration data for reactions (a, b, c, d) were used to deduce the role of cluster configuration. Reaction (e) has been studied in the giant resonance region with bremsstrahlung photons, \(E_{\text{brem.}} \leq 30\) MeV. Deuteron groups to \(^5\text{He}_{g.s.}\) and possibly to the first excited state are reported. States of \(^7\text{Li}\) with \(E_x = 25\)–30 MeV may be involved when \(E_{\text{brem.}} = 37\) to 50 MeV is used: see (79AJ01). At \(E_\gamma = 0.9\) GeV, (85RE1A) have studied \(\pi^-\) emission with the population of \(^6\text{Li}^*(2.19)\).

The cross section for reaction (f) at 90° displays a broad resonance at \(E \approx 7.7\) MeV (\(\Gamma = 7.2\) MeV) with an integrated cross section of 6.2 MeV mb, a plateau for 12 \(\to\) 22 MeV (at \(\approx 0.6\) the cross section at 7.7 MeV) and a gradual decrease to 48 MeV. The \((\gamma, t)\) cross section integrated from threshold to 50 MeV is 8.1 MeV mb: see (84AJ01), and (86VO20). More recently, measurements of differential cross sections with linearly polarized photons \((E_\gamma < 90\) MeV) were reported (95BU08). Angular distribution at \(E_\gamma = 6.4, 6.7, 8.5, 9.0\) MeV have been measured by (99LI02). Theoretical studies on this reaction include: a microscopic analysis for \(E < 70\) MeV (87BU04), an analysis in the giant resonance range (87VA05), a cluster structure study \((E < 50\) MeV) (90ZH19), and a calculation of photodisintegration observables for \(E < 90\) MeV (98KO17). For earlier work, see references cited in (88AJ01).

15. \(^7\text{Li}(\gamma, \gamma)^7\text{Li}\)

See Table 7.4 in (66LA04) [summary of early measurements] for \(\tau_m\) of \(^7\text{Li}^*(0.48) = 107\pm5\) fsec. See also (84AJ01), (87BE1K) and (86DU03).

16. (a) \(^7\text{Li}(e, e)^7\text{Li}\)
    (b) \(^7\text{Li}(e, e^+\pi^-)X\)
    (c) \(^7\text{Li}(e, ep)^6\text{He}\)
        \(Q_m = -9.975\)
    (d) \(^7\text{Li}(e, en)^6\text{Li}\)
        \(Q_m = -7.2499\)

The electric form factor measurements for \(E_e = 100\) to 600 MeV are well accounted for by a simple harmonic-oscillator shell model with a quadrupole contribution described by an undeformed p-shell: \(r_{\text{r.m.s.}} = 2.39 \pm 0.03\) fm, \(|Q| = 42 \pm 2.5\) mb. From results obtained for \(E_e = 24.14\) to 97.19 MeV, \(r_{\text{r.m.s.}} = 2.35 \pm 0.10\) fm (model independent), 2.29 \pm 0.04 fm (shell model). A study of the ratio of the electric charge scattering from \(^6\text{Li}\) and from \(^7\text{Li}\) as a
Table 7.5
Levels of $^7\text{Li}$ from $^7\text{Li}(e, e')$ $^a$

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$J^\pi; T$</th>
<th>$\Gamma_\gamma$ (eV)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.48</td>
<td>$\frac{1}{2}^-; \frac{3}{2}^-$</td>
<td>$(2.8 \pm 1.6) \times 10^{-7}$</td>
<td>C2</td>
</tr>
<tr>
<td>4.63 ± 0.05</td>
<td>$\frac{7}{2}^-; \frac{5}{2}^-$</td>
<td>$(6.30 \pm 0.31) \times 10^{-3}$</td>
<td>M1</td>
</tr>
<tr>
<td>6.6 ± 0.1</td>
<td>$\frac{5}{2}^-; \frac{3}{2}^-$</td>
<td>0.6 ± 0.3</td>
<td>C2</td>
</tr>
<tr>
<td>7.5 ± 0.08</td>
<td>$\frac{5}{2}^-; \frac{3}{2}^-$</td>
<td>0.9 ± 0.4</td>
<td>C2</td>
</tr>
</tbody>
</table>

$^a$ For a summary of $B(E2)$ measurements, see Table 7.6 in (66LA04) and $^7\text{Li}$, GENERAL. For references see (79AJ01, 84AJ01).

$^b$ $B(E2) \left[ \frac{3}{2}^- \rightarrow \frac{7}{2}^- \right] = 17.5 e^2 \cdot fm^4$.

$^c$ Purely longitudinal.

$^d$ $\Gamma_{\text{c.m.}} = 875^{+200}_{-100}$ keV.

$^e$ From $^7\text{Li}(\gamma, \text{n})$. See also fit by (80BA34).

function of (momentum transfer)$^2$ yields $\langle r^2 \rangle^{1/2}_{6}/\langle r^2 \rangle^{1/2}_{7} = 1.001 \pm 0.008$. The r.m.s. radius of the ground state magnetization density distribution, $\langle r^2 \rangle^{1/2}_M = 2.98 \pm 0.05$ fm. See (79AJ01) for references. More recent theoretical studies include: a study by (91BE40) which obtained vertex constants from an analysis of form factors, a shell-model calculation of large-basis space and mesonic effects (92BO30), a calculation of form factors including meson exchange contributions (92WA37), a study of shell-model structures of low lying states (97KA24).

Inelastic scattering studies show peaks corresponding to $^7\text{Li}^*(0.48, 4.63, 6.68, 7.46)$: see (74AJ01) and Table 7.5. Form factors for $^7\text{Li}^*(0, 0.48)$ have recently been studied at $E_e = 80$ to 680 MeV (89LI09, 90LI21). Theoretical work includes: a calculation by (89TA31) of cross section and reduced transition matrix elements for oriented nuclei, a calculation for polarized electron and polarized targets (90LE14), shell model calculation in a $(0+2)h\omega$ space (90WO10), a study of spin modes (91AR22), a microscopic cluster calculation (91UN01), calculation of form factors including meson exchange contribution (92BO30, 92WA37), and a shell-model study of low lying states (97KA24). For reaction (b) energy and angular distributions were measured at $E_e = 203$ MeV (99SH25) to study spin-isospin flip giant resonances.

For reaction (c) and (d) a measurement of the momentum distribution and study of clustering effects was reported in (89LA22). Calculations discussed in (00LA17) were used to study correlations in the $^7\text{Li}$ ground-state wave function. See also the PWIA calculation for polarized electrons and targets of (93CA11), and see also (88BO05). For earlier work see the references cited in (88AJ01).
17. $^7\text{Li}(\pi, \pi)^7\text{Li}$

$^7\text{Li}^*(0, 0.48, 4.63, 6.68, 7.46, 9.67)$ have been populated in this reaction. Angular distributions have been measured at $E_{\pi^+} = 49.7$ MeV and $E_{\pi^\mp} = 143$ and 164.4 MeV: see (84AJ01). Total and partial cross sections have been obtained for $E_{\pi^\pm}$ in the range 85–315 MeV [see (84AJ01)] and at $E_{\pi^+} = 50$ MeV (83NA18). A measurement of inclusive analyzing power at $E_{\pi} = 134, 164, 194$ MeV was reported by (94ME01). A cluster-model calculation of quadrupole effects is described in (94NO06). The $^7\text{Li}(\pi^-, \pi^-p)$ reaction was studied at 0.7 GeV/c by (00AB25). For $^7\text{Li}(\pi^+, \pi^-p)$, see (98PA31). For the $(\pi^+, 2p)$ reaction see $^5\text{He}$ (86RI01). For studies of $(\pi^+, \text{pd})$ and $(\pi^\pm, \text{pn})$ see (86WH01) and (86YO06), respectively. For $\pi^+$ induced fission of $^7\text{Li}$ see (83BA26). See also references in the General Table for $^7\text{Li}$ located on our website at (www.tunl.duke.edu/NuclData/General Tables/7li.shtml).

18. (a) $^7\text{Li}(n, n)^7\text{Li}$  
(b) $^7\text{Li}(n, nt)^4\text{He}$  

\[ Q_m = -2.4673 \]

Angular distributions have been measured at $E_n = 0.5–3$ MeV (91AL04), $E_n = 1.5$ to 18 MeV [see (79AJ01, 84AJ01)], $E_n = 5.4, 6.0, 14.2$ MeV (85CH37; $n_{0^+, 1}$, $n_2$), $E_n = 6.82–9.80$ MeV (87SC08; $n_{0^+ + 1}$), 7 to 14 MeV (83DA22; $n_0$), $E_n = 11, 13$ MeV (88CH09), 8.0 and 24.0 MeV (88HA25; $n_0$ and $n_2$ at 24 MeV), $E_n = 9, 9.5, 10$ MeV (95HU17; $n_1$) and at 14.7 MeV (84SH01; $n_{0^+ + 1}$). Double differential cross sections were measured at $E_n = 11.5$ and 18.0 MeV (98IB02). Theoretical work includes: calculations of coherent and incoherent scattering for $E_n = 0.0728$ eV (87VE02, 90GO26), DWBA calculations of $\sigma(\theta)$ for inelastic excitation of $^7\text{Li}^*(0, 478$ MeV) (92HU05), multi-configuration RGM calculations, $E_n = 9.58–12.2$ MeV (95FU16), and studies of optical model potentials for nuclear data evaluation, $E_n < 200$ MeV (96CH33). Reaction (b) at $E_n = 14.4$ MeV proceeds primarily via $^7\text{Li}^*(4.63)$ although some involvement of $^7\text{Li}^*(6.68)$ may also occur: see (79AJ01). Cross sections have been measured by activation methods at $E_n = 14.7$ MeV (87ME18) and 7.9–10.5 MeV (87QA01). See also the evaluation of tritium production cross section for $E < 17$ MeV (90YU02). See also $^8\text{Li}$, (86LI1H, 87DE14, 87SC08) and (85CO18; applications).

19. (a) $^7\text{Li}(p, p)^7\text{Li}$  
(b) $^7\text{Li}(p, 2p)^6\text{He}$  
(c) $^7\text{Li}(p, pd)^5\text{He}$  
(d) $^7\text{Li}(p, pn)^6\text{Li}$  
(e) $^7\text{Li}(p, pt)^4\text{He}$  
(f) $^7\text{Li}(p, p\alpha)^3\text{H}$  
(g) $^7\text{Li}(p, \alpha)^4\text{He}$  

\[ Q_m = -9.975 \]
\[ Q_m = -9.522 \]
\[ Q_m = -7.2499 \]
\[ Q_m = -2.467 \]
\[ Q_m = -2.467 \]
\[ Q_m = 17.347 \]
Angular distributions of protons have been measured for $E_p = 1.0$ to 185 MeV [see (74AJ01, 84AJ01)] and at $E_p = 1.89$ to 2.59 MeV (86SA1P; $p_0$). Inelastic proton groups have been observed to $^7$Li*(0.48, 4.63, 6.68, 7.46, 9.6): see (52AJ38, 74AJ01). Double differential cross sections for the continuum are reported at $E_p = 65$ MeV and 85 MeV (87TO06, 89TO04). Measurements of differential cross sections and analyzing powers for $p_0$, $p_1$ and $p_2$ for $E_p = 200$ MeV were used to deduce radial transition density differences (91GL01). Cross sections for inelastic scattering to the $^7$Li $E_x = 0.478$ MeV level have been measured in application-related experiments for $E_p = 2.2$–3.8 MeV (88BO37), 3.2–3.6 MeV (90BO15), 2.5–3.5 MeV (94MI21), 1.03 MeV (94WI15), 0.7–3.2 MeV (95RI14). See also (99SA16).

For reaction (b) see (84PA1B, 85PA1B; 50–100 MeV) and (85BE30, 85DO16; 1 GeV). See also $^6$He and (84AJ01). Cross section measurements at $E_p = 70$ MeV were used to distinguish contributions of 1p and 1s shell nucleons by (88PA26, 98SH33). Proton spectra and polarization measurements at $E_p = 1$ GeV are reported by (00MI17). For reaction (c) see (86WA11). For reaction (d) see (85BE30) and $^6$Li. Reaction (d) has been studied at $E_p = 200$ MeV (86WA11): the deuteron spectroscopic factor is close to unity and the results indicate that the deuteron cluster momentum distribution is characterized, at small momentum, by a FWHM of 140 MeV/c. For measurements at $E_p = 70$ MeV, see (98SH33). Cross sections for the (p, pt) reaction (reaction (e)) are very small but are consistent with a spectroscopic factor of unity for t+$^4$He in $^7$Li (86WA11). For reaction (f) recent measurement of cross section and analyzing power measured for $E_p = 296$ MeV were used to deduce alpha spectroscopic factor for $^7$Li (98YO09). See also (83GO06, 85PA1C, 85PA04). See also $^5$He and (84AJ01).

See also $^8$Be, and references to earlier work cited in (88AJ01). For early theoretical work on these reactions see references cited in (88AJ01). More recent calculations include: threshold effects in elastic scattering for $E_p = 1.35$–3 MeV (90GU22); differential cross section calculated at high energies with a geometric model (90HU09); a potential description of $^7$Li(p, p) with $E_p < 7$ MeV (92DU07); calculation with a microscopic effective interaction (93KO44); a folding model description for $E_p = 25$–50 MeV (93PE13); a microscopic three-cluster model calculation for $E_{cm} = 0.5$–25 MeV, $\sigma(E)$, $S$ factors (94DE09); a fully microscopic analysis for $E_p = 200$ MeV (97DO01); an analysis of $E_p = 200$ MeV data studying shell model structures of low lying $^7$Li levels (97KA24); and a microscopic analysis of elastic scattering at $E_p = 65$ MeV (98DO16), and at 60–70 MeV (98FUZP). Reaction rate uncertainties for reaction (g) were analyzed by (98FI02).

20. $^7$Li(d, d)$^7$Li

Angular distributions have been reported for $E_d = 1.0$ to 28 MeV [see (74AJ01, 79AJ01)] and at 50 MeV (88KO1C). See also $^9$Be and (87GOZF) for a breakup study.
21. (a) $^7\text{Li}(^3\text{He}, ^3\text{He})^7\text{Li}$
(b) $^7\text{Li}(^3\text{He}, \text{pd})^7\text{Li}$  \[ Q_m = -5.494 \]

Angular distributions have been reported at $E(^3\text{He}) = 11 \text{ MeV}$ to $44.0 \text{ MeV}$ and at $E(^3\text{He}) = 33.3 \text{ MeV}$: see (74AJ01, 84AJ01). See also the compilation and analysis of differential cross sections for $E(^3\text{He}) = 24 \text{ MeV}$ (95MI16). The missing mass spectrum in reaction (b) at $E(^3\text{He}) = 120 \text{ MeV}$ indicates, in addition to the unresolved group to $^7\text{Li}^*(0, 0.48)$, a small peak at $E_x = 17.8 \pm 0.5 \text{ MeV}$, possibly some structure between 30 and 40 MeV, a peak at $40.5 \pm 0.5 \text{ MeV}$ ($\Gamma \approx 2$–$3 \text{ MeV}$) and possibly some structure at higher energies (85FR01). Measurements of cross sections for yields of protons, deuterons, $^4\text{He}$, $^3\text{H}$ and $^3\text{He}$ from $93$ MeV $^3\text{He}$ on $^7\text{Li}$ are reported by (94DO32). For pion production see (84BR22).

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

Angular distributions (reaction (a)) have been reported for $E_\alpha = 3.6$ to $29.4 \text{ MeV}$ [see (74AJ01, 84AJ01)] and at $E_\alpha = 35.3 \text{ MeV}$ (85DI08; $\alpha$ to $^7\text{Li}^*(0, 0.48, 4.63, 6.68, 7.46, 9.67$; collective coupled channel analysis). See also (87BU27). More recently, differential cross sections were measured at $E_\alpha = 50.5 \text{ MeV}$ for inelastic scattering to $^7\text{Li}^*(0, 0.478, 4.63 \text{ MeV})$ by (96BU06). The $\alpha$, $t$ cluster spectroscopic factor extracted for the $^7\text{Li}$ ground state is $S_{at} = 1.03 \pm 0.1$. Measurements of target polarization in $^7\text{Li}(\alpha, \alpha')$ to $E_\alpha = 4.63 \text{ MeV}$ for $E_\alpha = 27.2 \text{ MeV}$ were reported by (91KO41). See also coupled-channels calculations for these data (97DM02). Gamma emission yields for $E_\alpha = 0.7$–$3.2 \text{ MeV}$ were measured for nuclear microprobe applications by (95RI14).

Reaction (b) has been studied at $E_\alpha = 18$ to $64.3 \text{ MeV}$ [see (74AJ01, 84AJ01)] and at $27.2 \text{ MeV}$ (85KO29). $^7\text{Li}^*(4.63)$ is strongly involved in the sequential decay, as are possibly $^7\text{Li}^*(6.68, 7.46)$. Cross sections measured for $E_\alpha = 77$–$119 \text{ MeV}$ were used to deduce triton momentum distributions for $\alpha + t$ states in $^7\text{Li}$ by (92WA09). An analysis is reported in (96JA01). See also (87DM1C, 87VA29, 88DM1A), (88BO46) and (86ZE01, 87KO1L).

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

Elastic and inelastic ($^7\text{Li}$, $E_x = 0.476 \text{ MeV}$) differential cross sections for reaction (a) have been reported for $E_\alpha = 9$–$40 \text{ MeV}$ (98PO03). See also $^6\text{Li}$. The elastic angular distribution (reaction (b)) has been studied for $E(^7\text{Li}) = 4.0$ to $6.5 \text{ MeV}$ [see (74AJ01)] and 2.0 to $5.5 \text{ MeV}$ (83NO08). Elastic and inelastic ($^7\text{Li}$, $E_x = 0.476 \text{ MeV}$) cross sections for $E_\alpha = 8$–$17$
MeV were measured and analyzed with an optical model (93BA43, 97PO03). For reaction (c) cross sections for \( E(^{11}\text{Li}) = 300 \) MeV were calculated in connection with a study of nuclear matter compressibility (98GR21).

24. \(^7\text{Li}(^9\text{Be}, ^9\text{Be})^7\text{Li}\)

Elastic angular distributions have been measured at \( E(^7\text{Li}) = 34 \) MeV [see (79AJ01)] and at 78 MeV (86GL1C, 86GL1D; also to \(^7\text{Li}^*(4.63)\)). For the interaction cross section at 790 MeV/\( A \) see (85TA18).

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

For reaction (a) see \(^{10}\text{B}\). Angular distributions have been studied for reaction (b) to \(^7\text{Li}^*(0, 0.48)\) at \( E(^7\text{Li}) = 34 \) MeV (87CO1D, 87CO02). See also (87HN1A).

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

Angular distributions (reaction (a)) involving \(^7\text{Li}^*(0, 0.48)\) have been studied at \( E(^7\text{Li}) = 4.5 \) to 89 MeV [see (75AJ02, 79AJ01, 84AJ01)] and at \( E(^7\text{Li}) = 53.8 \) MeV and \( E(^{12}\text{C}) = 92.3 \) MeV (84VI02, 86CO02; also to \(^7\text{Li}^*(4.63)\)) and at \( E(^7\text{Li}) = 131.8 \) MeV (88KA09; \(^7\text{Li}^*(0+0.48)\); and various states in \(^{12}\text{C}\)) as well as at \( E(^7\text{Li}) = 21.1 \) MeV (84MO06; \(^7\text{Li}^*(4.63)\)). See also (86GL1D) and \(^{12}\text{C}\) in (85AJ01, 90AJ01). Breakup studies involving \(^7\text{Li}^*(4.63)\) are reported at \( E(^7\text{Li}) = 70 \) MeV (86DA1C, 86YO1C) and 132 MeV (86SH1Q). See also the measurement at \( E(^{12}\text{C}) = 58.4 \) MeV reported by (87PA12). The interaction cross section on carbon at 790 MeV/\( A \) has been measured by (85TA18).

The elastic scattering in reaction (b) has been studied for \( E(^7\text{Li}) = 4.5 \) to 34 MeV [see \(^{13}\text{C}\) in (85AJ01)] and by (87CO02, 87CO16; 34 MeV; also to \(^7\text{Li}^*(0.48)\)). For earlier work, see references cited in (88AJ01).

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

Elastic angular distributions (reaction (a)) are reported at \( E(^7\text{Li}) = 36 \) MeV [see (81AJ01)] and \( E(^{14}\text{N}) = 150 \) MeV (86GO1H) while those for reaction (b) have been studied at \( E(^7\text{Li}) = 28.8 \) MeV [see \(^{15}\text{N}\) in (86AJ01)].
28. $^7\text{Li}(^{16}\text{O}, ^{16}\text{O})^7\text{Li}$

The elastic scattering has been studied from $E(^7\text{Li}) = 9.0$ to 20 and at 68 MeV [see $^{16}\text{O}$ in (86AJ04)] as well as at $E(^7\text{Li}) = 50$ MeV (84CO20). For fusion cross section and breakup studies see (84MA28, 86MA19, 86SC28, 88MA07). See also (82GU21, 88PR02).

29. $^7\text{Li}(^{20}\text{Ne}, ^{20}\text{Ne})^7\text{Li}$

Angular distributions have been studied at $E(^7\text{Li}) = 36, 68$ and 89 MeV: see $^{20}\text{Ne}$ in (83AJ01).

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

The elastic scattering has been studied at $E(^7\text{Li}) = 89$ MeV and at 27 MeV (reaction (b)): see (84AJ01). A study of the breakup on $^{27}\text{Al}$ is reported by (86NA1D) and the interaction cross section at 790 MeV/A has been measured by (85TA18). See also (88OT01, 88SA10).

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

Angular distributions involving $^7\text{Li}^*(0, 0.48)$ and various states of $^{28}\text{Si}$ and $^{40}\text{Ca}$ have been studied at $E(^7\text{Li}) = 45$ MeV. The elastic scattering on $^{40}\text{Ca}$ and $^{48}\text{Ca}$ has been studied at $E(^7\text{Li}) = 28, 34$ and 89 MeV [the latter also to $^7\text{Li}^*(0.48)$]: see (84AJ01). Angular distributions (reaction (b)) involving $^7\text{Li}^*(0, 0.48)$ have also been reported at $E(^7\text{Li}) = 34$ MeV (85SA25). See also (85GO11, 86SA1D, 87SA1C).

32. $^7\text{Be}(\epsilon)^7\text{Li}$

\[ Q_m = 0.862 \]
The decay proceeds to the ground and 0.48 MeV states. The branching ratio to \(^7\text{Li}^*(0.48)\) is 10.44 ± 0.04\%, and the adopted half-life is 53.22 ± 0.06 d, see Table 7.6. Both transitions are superallowed: \(\log fm = 3.32\) and 3.55 for the decays to \(^7\text{Li}^*(0, 0.48)\). See also (79AJ01). The first-excited state has \(E_x = 477.612 ± 0.002\) keV: see (84AJ01). A recent investigation of the decay utilized a high efficiency BeO calorimeter developed for use in a \(^7\text{Li}\) solar neutrino experiment (98GA08). A large change in the decay rate for \(^7\text{Be}\) implanted in Au and Al\(_2\)O\(_3\) was observed by (98RA12). Significant effects of the chemical environment on the measured half-life have also been measured by (49SE20, 53KR16, 56BO36, 70JO21, 73HE27, 99HU20, 99RA12). A systematic discussion of these effects is included in the evaluation of R. Helmer (see Table 7.6).

In related threshold investigations, the polarization of the internal bremsstrahlung has been calculated (88ME06) as well as the effect of daughter atom ionization (94RE18) and the fractional electron probabilities (98SC28). For earlier work, see references cited in (88AJ01).

33. \(^7\text{Be}(n, p)^7\text{Li}\) \(Q_m = 1.644\)

Total cross sections have been measured at \(E_n = 0.025–13.5\) keV (88KO03). The cross sections obtained for the \(^7\text{Li}\) ground and first excited states \((E_x = 0.477\) MeV\) were 38400 ± 800 b and 420 ± 120 b respectively. The astrophysical reaction rate \(N_A < \sigma \nu >\) was calculated. Uncertainties in elemental abundances from primordial nucleosynthesis were deduced in (98FI02).

34. \(^8\text{Li}(\alpha, \alpha n)^7\text{Li}\) \(Q_m = -2.033\)

Cross sections \(\sigma(E)\) for \(E_\alpha = 2–7\) MeV were measured by (98MIZY). See (99ZHZN) for a compilation and evaluation of cross section data.

35. \(^9\text{Be}(\gamma, d)^7\text{Li}\) \(Q_m = -16.696\)

Differential cross sections for \(E_\gamma = 21–39\) MeV were measured by (99SH05). See (99ZHZN) for a compilation and evaluation of cross section data.

36. \(^9\text{Be}(\pi^{-}, 2n)^7\text{Li}\) \(Q_m = 119.867\)

The capture of stopped pions has been studied in a kinematically complete experiment: \(^7\text{Li}^*(0, 0.48)\) are weakly populated. Two large peaks are attributed to the excitation of \(^7\text{Li}^*(7.46, 10.25)\). The recoil momentum distributions corresponding to these peaks are rather similar and both indicate a strong \(L = 0\) component: see (79AJ01).
Table 7.6
$^7$Be($\epsilon$)$^7$Li decay $^a$

<table>
<thead>
<tr>
<th>Branching ratio (%)</th>
<th>References</th>
<th>$^7$Be Half-life</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{+20}_{-7}$</td>
<td>(38RU01)</td>
<td>$53 \pm 2$</td>
<td>(40HI01)</td>
</tr>
<tr>
<td>$10.7 \pm 2.0$</td>
<td>(49WI13)</td>
<td>$52.93 \pm 0.22$</td>
<td>(49SE20)</td>
</tr>
<tr>
<td>$11.8 \pm 1.2$</td>
<td>(491U06)</td>
<td>$53.61 \pm 0.17$</td>
<td>(53KR16)</td>
</tr>
<tr>
<td>$12.3 \pm 0.6$</td>
<td>(51DI12)</td>
<td>$53.0 \pm 0.4$</td>
<td>(56BO36)</td>
</tr>
<tr>
<td>$10.35 \pm 0.08$</td>
<td>(69TAZX)</td>
<td>$53.5 \pm 0.2$</td>
<td>(57WR37)</td>
</tr>
<tr>
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<td>(70MUZU)</td>
<td>$53.1 \pm 0.3$</td>
<td>(65EN01)</td>
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<tr>
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<td>(73PO10)</td>
<td>$53.52 \pm 0.10$</td>
<td>(70JO21)</td>
</tr>
<tr>
<td>$10.35 \pm 0.08$</td>
<td>(74GO26)</td>
<td>$53.0 \pm 0.3$</td>
<td>(74CR05)</td>
</tr>
<tr>
<td>$10.10 \pm 0.45$</td>
<td>(83BA15)</td>
<td>$53.17 \pm 0.02$</td>
<td>(75LA16)</td>
</tr>
<tr>
<td>$10.61 \pm 0.23$</td>
<td>(83DA14)</td>
<td>$53.16 \pm 0.01$</td>
<td>(82CHZF)</td>
</tr>
<tr>
<td>$10.6 \pm 0.5$</td>
<td>(83DO07)</td>
<td>$53.284 \pm 0.004$</td>
<td>(82RUZV)</td>
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<tr>
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<td>$53.12 \pm 0.07$</td>
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</tr>
<tr>
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<td>(83MA34)</td>
<td></td>
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<td>(83NO03)</td>
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<tr>
<td>$11.4 \pm 0.7$</td>
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<tr>
<td>$10.61 \pm 0.17$</td>
<td>(84FI10)</td>
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<tr>
<td>$10.49 \pm 0.07$</td>
<td>(84SK01)</td>
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<tr>
<td>$10.44 \pm 0.04$</td>
<td>weighted average</td>
<td>$53.22 \pm 0.06$</td>
<td>adopted</td>
</tr>
</tbody>
</table>

$^a$ Evaluated by R. Helmer in conjunction with the Decay Evaluation Project (99BEZQ, 99BEZS). We are grateful to Dr. Helmer for providing this information to us.

$^b$ Adopted by the evaluator from Limitation of Relative Statistical Weight (LRSW) (85ZIZY, 92RA09) analysis.
37. \(^9\text{Be}(n, t)^7\text{Li}\) \(Q_m = -10.4387\)

An angular distribution is reported at \(E_n = 14.6\) MeV (87ZA01; \(t_{0+1}\)). See also (79AJ01) and \(^{10}\text{Be}\).

Cross section measurements have also been reported for \(E_n = 12.9–19.6\) MeV (88LI05) and for \(E_n = 16–19.6\) MeV with Hauser-Feshbach calculations (90WO07).

38. (a) \(^9\text{Be}(p, \alpha)^7\text{He}\) \(Q_m = -11.2021\)
(b) \(^9\text{Be}(p, \alpha)^7\text{Li}\) \(Q_m = -16.6961\)

At \(E_p = 43.7\) MeV, angular distributions have been obtained for the \(^3\text{He}\) particles corresponding to \(^7\text{Li}^*(0, 0.48, 4.63, 7.46)\). The 7.46 MeV state is strongly excited while the analog state in \(^7\text{Be}\) is not appreciably populated in the \(^9\text{Be}(p, t)^7\text{Be}\) reaction (see reaction 21 in \(^7\text{Be}\)). The angular distribution indicates that the transition to \(^7\text{Li}^*(7.46)\) involves both \(L = 0\) and 2, with a somewhat dominant \(L = 0\) character. The \(J^* = \frac{3}{2}^-, T = \frac{3}{2}\) state is located at \(E_x = 11.28 \pm 0.04\) MeV, \(\Gamma = 260 \pm 50\) keV: see (79AJ01). Reaction (b) at \(E_p = 58\) MeV involved \(^7\text{Li}^*(0, 0.48, 7.47)\) (85DE17). See also (87KA25).

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

Angular distributions have been measured for \(E_d = 0.4\) to 27.5 MeV [see (66LA04, 74AJ01, 79AJ01)] and at \(E_d = 2.0\) to 2.8 MeV (84AN1D; \(\alpha_0, \alpha_1\)). A study at 11 MeV finds \(\Gamma_{\text{cm}} = 93 \pm 25\) and 80 \pm 20 keV, respectively for \(^7\text{Li}^*(4.63, 7.46)\). No evidence is found for the \(T = \frac{3}{2}\) state \(^7\text{Li}^*(11.25)\). Differential cross sections measured at \(E_d = 67–75\) MeV for excitation of \(^7\text{Li}^*(0, 0.48, 4.63, 7.46)\) were used to deduce spectroscopic amplitudes (89SZ02). Measurements of vector analyzing powers for \(^7\text{Li}^*(0, 0.48)\) were reported by (94LY02) for \(E_d = 1.3–3.1\) MeV. Measurements at \(E_{\text{cm}} = 57–139\) keV (97YA02) and \(E_{\text{cm}} = 30–130\) keV (97YA08) were used to deduce astrophysical \(S\)-factors. See also (99OCZZ). The previous review (88AJ01) notes that in a kinematically complete study of reaction (b) at \(E_d = 26.3\) MeV, \(^7\text{Li}^*(4.6, 6.5 + 7.5, 9.4)\) are strongly excited. No sharp \(\alpha\)-decaying states of \(^7\text{Li}\) are observed with \(10 < E_x < 25\) MeV. Parameters for \(^7\text{Li}^*(9.7)\) are \(E_x = 9.36 \pm 0.05\) MeV, \(\Gamma = 0.8 \pm 0.2\) MeV; see (79AJ01). [\(E_x = 6.75 \pm 0.20\) MeV, \(\Gamma = 0.87 \pm 0.20\) MeV (86PA1E)]. A study of inclusive \(\alpha\)-spectra at \(E_d = 50\) MeV has been reported by (87KA17) who suggest the involvement of a \(^7\text{Li}\) state at \(E_x = 18 \pm 1\) MeV, \(\Gamma = 5 \pm 1\) MeV. For reaction (b) see also (87VA29). See also \(^{11}\text{Be}\) in (85AJ01) and (88NE1A).

In more recent studies of reaction (b), differential cross sections have been measured at \(E_d = 18\) MeV (88GO02, 88GU1M) and \(E_d = 7\) MeV (88SZ02). See also the measurements of \(\sigma(E)\) for \(E_d = 0.9–11.2\) MeV.
(94AB25), $A_y(\theta)$ for $E_d = 1.3$–3.1 MeV (94LY02), $\sigma(\theta)$ at $E_d = 3$–11 MeV (95AB41) and $E_d = 8$–50 MeV (95GU22). Astrophysical $S$ factors were determined in measurements at $E_{cm} = 57$–139 keV (97YA02, 97YA08).

40. (a) $^{9}\text{Be}(^{6}\text{Li}, ^{8}\text{Be})^{7}\text{Li}$ $Q_m = 5.584$
(b) $^{9}\text{Be}(^{9}\text{Be}, ^{11}\text{B})^{7}\text{Li}$ $Q_m = -0.8805$

Angular distributions involving $^{7}\text{Li}^*(0, 0.48)$ have been reported at $E(^{6}\text{Li}) = 32$ MeV (85CO09) and $E(^{9}\text{Be}) = 14$ MeV (85JA09).

41. $^{10}\text{B}(n, \alpha)^{7}\text{Li}$ $Q_m = 2.7891$

Angular distributions of $\alpha_0$, $\alpha_1$ and of $\alpha_2$ at the higher energies have been measured from $E_n = 2$ keV to 14.4 MeV: see (79AJ01, 84AJ01). $\tau_m(0.48) = 102 \pm 5$ fsec (85KO47). More recently measurements of the ground to excited-state transition ratio $\sigma(n, \alpha_0)/\sigma(n, \alpha\gamma)$ for $E_n = 0.2$–1.0 MeV were reported by (91WE11). A relative measurement of the $^{10}\text{B}(n, \alpha\gamma)^{7}\text{Li}$ cross section has been made (93SC20) for $E_n = 0.2$–4.0 MeV. A study of P-odd effects (in the mixing of opposite-parity levels) in this reaction determined forward-backward asymmetries for the $\alpha_0$ and $\alpha_1$ groups ($3.4 \pm 6.7 \times 10^{-7}$ and $(-2.5 \pm 1.6) \times 10^{-7}$ respectively (96VE02). Earlier work was reported in (86ER05, 94GL07). Measurement and analysis of the Doppler-broadened gamma line shapes produced in the $(n, \alpha, \gamma)$ reaction for the purpose of boron concentration determination are described in (94SA72, 98MA61). See also (97SA70). For early polarization studies (involving both n and $^{10}\text{B}$) see (86KO19) and $^{11}\text{B}$ in (90AJ01). See also (86CO1M; applications). See also the more recent measurements and calculations of (99VE03) and the measurement at thermal energies of (00GO03). A calculation of $\alpha - \gamma$ correlation parameters and study of time-reversal invariance related features are described in (00GA43).

42. $^{10}\text{B}(d, ^{5}\text{Li})^{7}\text{Li}$ $Q_m = -1.12$

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

43. $^{10}\text{B}(\alpha, ^{7}\text{Be})^{7}\text{Li}$ $Q_m = -16.202$

Angular distributions involving $^{7}\text{Li}_{g.s.}$ and $^{7}\text{Be}_{g.s.}$ and $^{7}\text{Li}^*(0.48) + ^{7}\text{Be}^*(0.43)$ have been studied at $E_\alpha = 91.8$ MeV (85JA12, 86JA03). See also (88SH1E theor.).
44. $^{11}\text{Be}(\beta^-)^{11}\text{B}^* \rightarrow ^7\text{Li} + \alpha$ \hspace{1cm} $Q_m = 1.211$

Delayed $\alpha$-particles have been observed in the $\beta^-$ decay of $^{11}\text{Be}$: they are due to the decay of $^{11}\text{B}^*(9.88) \ [J^\pi = \frac{3}{2}^+]$. This state decays by $\alpha$-emission $87.4 \pm 1.2\%$ to the ground state of $^7\text{Li}$ and $12.6 \pm 1.2\%$ to $^7\text{Li}^*(0.48)$ (81AL03). See also $^{11}\text{Be}$, $^{11}\text{B}$ in (85AJ01).

45. $^{11}\text{B}(^3\text{He}, ^7\text{Be})^7\text{Li}$ \hspace{1cm} $Q_m = -7.079$

Angular distributions involving $^7\text{Li}_{g.s.}$ and $^7\text{Be}_{g.s.}$ and $^7\text{Li}^*(0.48) + ^7\text{Be}^*(0.43)$ have been studied at $E(^3\text{He}) = 71.8$ MeV (86JA02, 86JA03). See also (87KW01, 87KW03).

46. $^{11}\text{B}(\alpha, ^8\text{Be})^7\text{Li}$ \hspace{1cm} $Q_m = -8.7567$

Angular distributions have been measured at $E_\alpha = 27.2$ to 29.0 MeV and at 65 MeV. At $E_\alpha = 65$ and 72.5 MeV, $^7\text{Li}^*(0, 4.63)$ are very strongly populated while $^7\text{Li}^*(0.48, 6.68, 7.46)$ are weakly excited: see (79AJ01, 84AJ01).

47. $^{12}\text{C}(\gamma, p\alpha)^7\text{Li}$ \hspace{1cm} $Q_m = -24.622$

Cross sections were measured at $E_\gamma = 27–47$ MeV with bremsstrahlung photons by (98KO77).

48. $^{12}\text{C}(d, ^7\text{Be})^7\text{Li}$ \hspace{1cm} $Q_m = -17.542$

Angular distributions involving $^7\text{Li}_{g.s.}$ and $^7\text{Be}_{g.s.}$ and $^7\text{Li}^*(0.48) + ^7\text{Be}^*(0.43)$ have been studied at $E_d = 39.8$ MeV [see (79AJ01)] and at 78.0 MeV (86JA03, 86JA15). See also (84NE1A) and (87KW01, 87KW03).

More recently differential cross sections at $E_d = 78$ MeV were measured in a study of five-nucleon transfer (96JA12).

49. $^{12}\text{C}(t, ^8\text{Be})^7\text{Li}$ \hspace{1cm} $Q_m = -4.8997$

Angular distributions have been studied at $E_t = 38$ MeV to $^8\text{Be}_{g.s.}$ and $^7\text{Li}^*(0, 0.48)$ (86SI1B).
50. $^{12}$C($\alpha$, $^9$B)$^7$Li

Angular distributions are reported at $E_\alpha = 49.0$ and 80.1 MeV (84GO03). See also (84AJ01). Differential cross sections were measured at $E_\alpha = 90$ MeV by (91GL03).

51. $^{12}$C($^6$Li, $^{11}$C)$^7$Li

Angular distributions have been obtained at $E(^6$Li) = 36 MeV for the transitions to $^7$Li*($0$, 0.48): see (79AJ01). See also (86GL1E). More recently differential cross sections and polarization observables were measured at $E(^6$Li) = 50 MeV in a study of mirror states in $^7$Li, $^7$Be (97KE04).

52. $^{12}$C($^7$Li, $^7$Be)$^{12}$B

The reaction was studied (99NA36) at $E(^7$Li) = 65 MeV/A, and GT transition strengths were compared to those deduced from $\beta$ decay.

53. $^{13}$C(d, $^8$Be)$^7$Li

At $E_d = 14.6$ MeV angular distributions are reported for the transitions to $^7$Li*($0$, 0.48) and $^8$Be$^*_\text{g.s.}$: see (79AJ01). See also (84NE1A, 84SH1D).

54. $^{14}$N(n, 2$\alpha$)$^7$Li

At $E_n = 14.1$ MeV, $^7$Li*($0$, 0.48) are approximately equally populated: see (79AJ01). Differential cross sections have been measured at $E_n = 14.4$ and 18.2 MeV involving $^8$Be$^*_\text{g.s.}$ and $^7$Li*($0 + 0.48$, 4.63) (86TU02).

55. (a) $^{17}$O(d, $^{12}$C)$^7$Li
(b) $^{18}$O(d, $^{13}$C)$^7$Li
(c) $^{19}$F(d, $^{14}$N)$^7$Li

At $E_d = 14.6$ to 15.0 MeV, angular distributions have been measured for the transitions to $^{12}$C($0^+$)$^7$Li*($0$, 0.48) [reaction (a)], $^{13}$C($0^+$)$^7$Li*($0$, 0.48) [reaction (b)] and $^{14}$N($0^+$)$^7$Li*($0$, 0.48) [reaction (c)]: see (79AJ01). See also (84AJ01).
56. $^{208}$Pb($^7$Li, $^7$Li)

Elastic and inelastic cross sections and analyzing powers were measured at $E(^7$Li) = 27 MeV to study the effect of electric dipole polarizability of $^7$Li (98MA65).
GENERAL: References to articles on general properties of $^7\text{Be}$ published since the previous review (88AJ01) are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for $^7\text{Be}$ located on our website at (www.tunl.duke.edu/NuclData/General_Tables/7be.shtml).

The interaction nuclear radius of $^7\text{Be}$ is $2.22 \pm 0.02$ fm (85TA18). [See also for derived nuclear matter, charge and neutron matter r.m.s. radii]. A measurement of the magnetic moment by (98KAZN) gave a preliminary result $\mu = -1.398 \pm 0.015 \mu_N$.

1. $^7\text{Be}(\epsilon)^7\text{Li}$

   The $\epsilon$-capture decay is complex: see $^7\text{Li}$, reaction 32.

2. $^4\text{He}(^3\text{He}, \gamma)^7\text{Be}$

   The capture cross sections have been measured for $E_\alpha = 0.250$ to 5.80 MeV and at $E(\alpha)^3\text{He} = 19$ to 26 MeV [see (74AJ01, 84AJ01)], at $E_{\text{cm}} = 195$ to 686 keV (88HI06), and at $E_\alpha = 385$ to 2728 keV (84OS03) and 1225 keV (84AL24). One of the main reasons for doing these measurements is to determine the astrophysical $S(0)$ factor. The values of $S(0)$ appear, on the average, to be higher if the experiment involves measurement of the 0.48 MeV $\gamma$ following $\epsilon$-capture rather than if it involves a direct measurement of the capture $\gamma$-rays. It is not entirely clear why this should be so. Contaminant production of $^7\text{Be}$ may be involved: see (88HI06) and e.g. (84AL24, 85FI1D, 86LA22). Earlier measurements, sometimes recalculated, are discussed by (86LA22, 87KA1R, 88HI06). The latter adopt best values of $S(0) = 0.51 \pm 0.02$ keV b [prompt $\gamma$-rays] and $0.58 \pm 0.02$ keV b [$^7\text{Be}$ activity] (88HI06). See also (84AL24, 85FI1D, 87KA1R, 88BA1H). More recently, (93MO11) measured differential cross sections for $^3\text{He} - \alpha$ scattering for $E_{\text{Lab}}(^3\text{He}) < 3$ MeV and obtained optical potentials which were used to calculate $S(0)$ for the capture reaction. They obtained $S(0) = 0.516$ keV b in agreement with (88HI06). They also calculated the branching ratio for transition to the first excited state and ground state to be $R = 0.43$. Theoretical calculations are in general agreement with the experimental values. See (88AJ01) for examples from some of the early work. Calculations of astrophysical $S$ factors for the capture reaction are included in (88BU17, 88KA07, 89CH37, 89CH48, 89KA18, 95DU09, 95LI07, 97DU15). The reaction rate at $T = 300$ K was calculated in (89SC25). See also the related work of (90SC16, 90SC26). The reaction rate and the effects of electron screening on the solar neutrino flux has been calculated by (00LI13). The reaction rate and a correction to the
Table 7.7
Energy levels of \(^7\)Be

<table>
<thead>
<tr>
<th>(E_x) (MeV ± keV)</th>
<th>(J^\pi; T)</th>
<th>(\tau) or (\Gamma_{\text{c.m.}})</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>(\frac{3}{2}^- ; \frac{3}{2})</td>
<td>(\tau_{1/2} = 53.22 \pm 0.06) d</td>
<td>(\epsilon)-capture</td>
<td>1, 2, 4, 5, 9, 10, 11, 13, 14, 15, 16, 17, 21, 22, 24, 25, 26, 27, 28, 29, 32, 33</td>
</tr>
<tr>
<td>0.42908 ± 0.10</td>
<td>(\frac{1}{2}^- ; \frac{1}{2})</td>
<td>(\tau_m = 192 \pm 25) fsec</td>
<td>(\gamma)</td>
<td>2, 4, 5, 9, 10, 14, 16, 17, 21, 22, 23, 24, 25, 26, 27, 28, 29, 32, 33</td>
</tr>
<tr>
<td>4.57 ± 50</td>
<td>(\frac{2}{2}^- ; \frac{3}{2})</td>
<td>(\Gamma = 175 \pm 7) keV</td>
<td>(^3)He, (\alpha)</td>
<td>3, 5, 10, 14, 16, 17, 21, 22</td>
</tr>
<tr>
<td>6.73 ± 100</td>
<td>(\frac{5}{2}^- ; \frac{5}{2})</td>
<td>1.2 MeV</td>
<td>(^3)He, (\alpha)</td>
<td>3, 8, 9, 14, 21</td>
</tr>
<tr>
<td>7.21 ± 60</td>
<td>(\frac{1}{2}^- ; \frac{1}{2})</td>
<td>0.40 (\pm 0.05)</td>
<td>(\text{p}, ^3)He, (\alpha)</td>
<td>3, 6, 8, 9, 14, 17</td>
</tr>
<tr>
<td>9.27 ± 100</td>
<td>(\frac{1}{2}^- ; \frac{1}{2})</td>
<td>(\approx 1.8) MeV</td>
<td>(\text{p}, ^3)He, (\alpha)</td>
<td>3</td>
</tr>
<tr>
<td>9.9</td>
<td>(\frac{3}{2}^- ; \frac{3}{2})</td>
<td>(\approx 1.8) MeV</td>
<td>(\text{p}, ^3)He, (\alpha)</td>
<td>3, 6</td>
</tr>
<tr>
<td>11.01 ± 30</td>
<td>(\frac{5}{2}^- ; \frac{5}{2})</td>
<td>320 (\pm 30)</td>
<td>(\text{p}, ^3)He, (\alpha)</td>
<td>3, 6, 14, 21</td>
</tr>
<tr>
<td>17 (^a)</td>
<td>(\frac{1}{2}^- ; \frac{1}{2})</td>
<td>(\approx 6.5) MeV</td>
<td>(^3)He</td>
<td>3</td>
</tr>
</tbody>
</table>

\(^a\) For possible states at higher \(E_x\) see reactions 3 and 6.

Gamow penetration factor were calculated by (94KA02). See also the calculations described in (98FI02, 99BU10, 99SH13, 00BA09). As noted in (88AJ01), the solar model calculations of (82BA1F) used \(S_{34}[S(0)] = 0.52 \pm 0.02\) keV b. It appears clear that the uncertainty in \(S_{34}\) is not of severe consequence to the solar neutrino problem [see, e.g. (85FI11)]. For other early astrophysical-related work see (84AJ01, 88AJ01). See also (86LI04).

3. (a) \(^4\)He\(^3\)He, \(^3\)He\(^4\)He  \(E_b = 1.586\)

(b) \(^4\)He\(^3\)He, \(p\)\(^6\)Li  \(Q_m = -4.0193\)

Elastic-scattering studies have been reported for \(E = 0.25\) to 198.4 MeV [see (74AJ01, 79AJ01, 84AJ01)] and at \(E_\alpha = 56.3\) to 95.5 MeV (85NE08, 86YA14). Analyzing power measurements have been carried out at \(E = 4.3\) to 98 MeV [see (79AJ01)] and at \(E(^3\)He\) = 55 to 95 MeV (86YA14).

For \(l \leq 4\), only f-wave phase shifts show resonance structure for \(E(^3\)He\) < 18 MeV, corresponding to \(^7\)Be\(^*(4.57, 6.73, 9.27)\): see Table 7.8. No structure corresponding to \(^7\)Be\(^*(7.21\)
(\(J^\pi = \frac{5}{2}^-\)) is seen in the elastic data. The s-wave phase shift is somewhat greater than hard-sphere. The decay of \(^7\text{Be}^*(9.27)\) (\(J^\pi = \frac{7}{2}^-\)) to \(^6\text{Li}(0)\) requires f-shell configuration admixture. An estimate of the yield of ground-state protons relative to those corresponding to \(^6\text{Li}^*(2.19)\) yields \(\gamma^2(p_0)/\gamma^2(p_1) = (16\pm5\%)\) (67SP10). A phase-shift analysis (single-level \(R\)-matrix) has been carried out for \(E(^3\text{He}) = 18\) to 32 MeV: the p-wave phase shifts indicate a \(\frac{1}{2}^-\) state at \(E_x \approx 16.7\) MeV \((E_x = 26.4\) MeV\), with \(\Gamma = 6.5\) MeV (78LU05). An \(R\)-matrix and \(S\)-matrix analysis (92ZU03) of elastic scattering at \(E_o = 11 - 41\) MeV on a polarized \(^3\text{He}\) target gave evidence of broad \(\frac{3}{2}^+\) and \(\frac{11}{2}^-\) resonances. The \(R\)-matrix center-of-mass resonance energies and widths for the \(\frac{3}{2}^+\) and \(\frac{11}{2}^-\) resonances are \(E_{\text{res}} = 29.5 \pm 1.0\) MeV, \(\Gamma = 8.5 \pm 2.5\) MeV and \(E_{\text{res}} = 32.5 \pm 1.5\) MeV, \(\Gamma = 10.5 \pm 3.0\) MeV, respectively (see Table 7.9). See also the earlier analysis reported in (89OS06). Differential cross sections were measured for \(E(^3\text{He}) = 1 - 3\) MeV by (93MO11). The data together with other available data were analyzed, and the optical potentials obtained were used to calculate astrophysical \(S\) factors for the radiative capture reaction (see reaction 1).

The differential cross section for reaction (b) has been determined for \(E(^3\text{He}) = 8\) to 28 MeV [see (79AJ01)] and at \(E_o = 22.2\) to 26.5 MeV. Resonances are observed corresponding to \(^7\text{Be}^*(7.21, 9.27)\) in the \(p_0\) yield, to \(^7\text{Be}^*(9.27)\) in the \(p_1\) yield and to states at \(E_x \approx 10\) MeV \((T = \frac{1}{2})\) and 11.0 MeV \((T = \frac{3}{2})\) in the yield of 3.56 MeV \(\gamma\)-rays. The evidence for the latter derives mainly from interference arguments. There is also some evidence for an extremely broad \(J^\pi = \frac{5}{2}^-\) structure at \(E_x \geq 10\) MeV [see also \(^6\text{Li}(p, p)\): see Table 7.8 and (74AJ01, 84AJ01). For \(\alpha + ^3\text{He}\) correlations see (87PO03). See also the General Table for \(^7\text{Be}\) located

<table>
<thead>
<tr>
<th>(E_x ) (MeV ± keV)</th>
<th>(J^\pi)</th>
<th>(l_o)</th>
<th>(LS) term</th>
<th>(\theta^2) (a)</th>
<th>(\theta^2) (p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.57 ± 50</td>
<td>(\frac{5}{2}^-)</td>
<td>3</td>
<td>(2F_{7/2})</td>
<td>0.70 ± 0.04</td>
<td>0.000 ± 0.002</td>
</tr>
<tr>
<td>6.73 ± 100</td>
<td>(\frac{7}{2}^-)</td>
<td>3</td>
<td>(2F_{5/2})</td>
<td>1.36 ± 0.13</td>
<td>0.26 ± 0.02</td>
</tr>
<tr>
<td>7.21 ± 100</td>
<td>(\frac{5}{2}^-)</td>
<td>3</td>
<td>(4P_{5/2})</td>
<td>0.010 ± 0.001</td>
<td>0.29±0.09</td>
</tr>
<tr>
<td>9.27 ± 100</td>
<td>(\frac{7}{2}^-)</td>
<td>3</td>
<td>(4D_{5/2})</td>
<td>0.70 ± 0.26</td>
<td>0.29±0.18</td>
</tr>
<tr>
<td>10.0 (d)</td>
<td>(\frac{1}{2}^-)</td>
<td>1</td>
<td>(4P_{3/2})</td>
<td>0.13 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>(\approx 10.0) (e)</td>
<td>(\frac{1}{2}^-)</td>
<td>1</td>
<td>(4P_{1/2})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.00 ± 50 (f)</td>
<td>(\frac{3}{2}^-)</td>
<td>1</td>
<td>(2P_{3/2}, 2D_{3/2})</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(a\) See also Table 7.10 (66LA04). For references see Table 7.7 in (79AJ01).

\(b\) \(\gamma^2\rho R^2/3\hbar^2\). \(R = 4.0\) fm.

\(c\) \(\delta_{p1}^d = 1.8 \pm 0.5\).

\(d\) \(\Gamma = 1.8\) MeV.

\(e\) Broad.

\(f\) \(\Gamma = 0.4 \pm 0.05\) MeV; \(T = \frac{3}{2}\).

\(g\) \(\delta_{p2}^d\).
Table 7.9

$^7$Be levels from $^3$He($\alpha$, $\alpha$) $^a$ for $l \geq 4$

<table>
<thead>
<tr>
<th>$E_{\text{res}}$ (MeV) $^b$</th>
<th>$\Gamma$ (MeV)</th>
<th>$E_x$</th>
<th>$J^\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.5 ± 1.0</td>
<td>8.5 ± 2.5</td>
<td>31.1 ± 1.0</td>
<td>$\frac{9}{2}^+$</td>
</tr>
<tr>
<td>32.5 ± 1.5</td>
<td>10.5 ± 3.0</td>
<td>34.1 ± 1.5</td>
<td>$\frac{11}{2}^-$</td>
</tr>
</tbody>
</table>

$^a$ From $R$-matrix analysis (92ZU03). See also the analysis of (89OS06).

$^b$ Center of mass energies.

on our website at (www.tunl.duke.edu/NuclData/General_Tables/7be.shtml). For elastic and inelastic inclusive scattering cross sections at $p_\alpha = 7.0$ GeV/c see (84SA1C, 87BA13). See also (84IW01, astrophysics).

References to early theoretical work on $^3$He + $^4$He reactions are given in (88AJ01). More recent theoretical studies include: an RGM study of the d + $^5$He cluster configuration (91FU02); a potential description of cluster channels (93DU02); inversion of phase shifts and $^7$Be bound-state energies to obtain potentials (94CO08); a calculation of $^7$Be charge form factors (87RO24); microscopic cluster theory (87TA06); Glauber amplitude expansion calculation of $\sigma(\theta)$ (88CH16, 90LI11); a calculation of scattering lengths and astrophysical $S$ factors (88CH47, 89CH34); a study of potentials deduced from phase shifts (95MA37); and a multiconfiguration RGM calculation of reaction cross sections (95FU16).

4. $^4$He($\alpha$, n)$^7$Be

$Q_m = -18.991$

Angular distributions have been reported at $E_\alpha = 61.5$ to 158.2 MeV (82GL01) and 198.4 MeV (85WO11) for the transitions to $^7$Be*(0 + 0.43). See also $^8$Be. Thermoneutral reaction rates for this reaction calculated from evaluated data are presented in the compilation (99AN35).

5. $^6$Li(p, $\gamma$)$^7$Be

$Q_m = 5.605$

At low energies ($E_p = 0.2$ to 1.2 MeV) gamma transitions to the ground ($\gamma_0$) and to the 0.43 MeV ($\gamma_1$) states have been observed. The yield shows no resonance and the branching ratio remains approximately constant at 61 ± 5% to the ground state and 39 ± 2% to $^7$Be*(0.43); see (74AJ01, 84AJ01). Angular distributions of $\gamma_0$ and $\gamma_1$ have been studied at $E_p = 0.50, 0.80$ and 1.00 MeV (87TI05). At $E_p = 44.4$ MeV, $^7$Li*(4.57) is strongly populated (85HA05). See also (83OS04), (83HA1B, 84BO1C, 85CA41; astrophysics) and (85BL1B).
Figure 10: Energy levels of $^7$Be. For notation see Fig. 5.
In more recent work, $\gamma$ angular distributions and $\gamma$-to-charged-particle ratios were measured for $E_p = 40$–180 keV and used to deduce astrophysical $S$ factors (92CE02). Measurements of thick-target yields and analyzing power versus $\theta$ were made with 80 keV polarized beams and used to deduce relative s-p wave contributions and astrophysical $S$ factors (96LA10). A compilation and review of Coulomb dissociation experiments of astrophysical significance is presented in (96RE16). Reaction rates for $E_p < 2$ MeV were analyzed by (97NO04). The primordial $^6$Li component was deduced. A compilation of charged-particle induced thermonuclear reaction rates is presented in (99AN35). Cross section measurements at $E_p = 0.8$ MeV are reported by (00SK02).

6. (a) $^6$Li(p, p)$^6$Li
   \[ Q_m = -4.497 \]  
   $E_b = 5.605$

   (b) $^6$Li(p, 2p)$^5$He
   \[ Q_m = -1.4747 \]

   (c) $^6$Li(p, pa)$^2$H

The previous review (88AJ01) notes that measurements of elastic angular distributions have been reported for $E_p = 0.5$ to 600 MeV; see (66LA04, 74AJ01) and $^4$Li. Two resonances are reported at $E_p = 1.84$ and 5 MeV in the elastic yield [$^7$Be$^*$(7.21, 9.9)]. The parameters of the lower resonance are shown in Table 7.4. The 5 MeV resonance has $\Gamma \approx 1.8$ MeV and appears to also be formed by p-waves: $\gamma^2_p$ is then $3 \pm 2$ MeV fm. A weak rise near $E_p = 8$ to 9 MeV may indicate a further level, $^7$Be$^* \approx 13$ MeV. A broad resonance at $E_p = 14$ MeV has also been suggested. Polarization measurements have been carried out for $E_p = 1.2$ to 800 MeV [see (74AJ01, 79AJ01, 84AJ01)] and at $E_p = 4$ to 10 MeV (86BE1H; $p_0$ and 25 and 35 MeV (82ROZT, 83PO1B, 83POZX; $p_0$, $p_1$). A phase-shift analysis for $E_p = 0.5$ to 5.6 MeV shows that only $^2$S, $^4$S and $^4$P are involved. The $^4$P$_{5/2}$ amplitude resonates at $E_p = 1.8$ MeV, and the broad resonance at 5 MeV can be reproduced equally well by either $^4$P$_{3/2}$ or $^4$P$_{1/2}$. Tensor polarization measurements are necessary to distinguish between the two; see (74AJ01).

In more recent work, cross sections and analyzing powers were measured at $E_p = 1.6$–10 MeV (89HA17), at $E_p = 200$ MeV (90GL04) and at $E_p = 0.4$–2.2 MeV (95SK01). Parameters for the $E_p$(lab) = 1.8 MeV resonance were measured by (95SK01) (see Table 7.10). The depolarization parameter was measured at $E_p = 72$ MeV (94HE11).

The reaction cross section for formation of $^6$Li$^*(2.19)$ has been measured for $E_p = 3.6$ to 9.40 MeV; a broad resonance indicates the presence of a state with $E_x \approx 10$ MeV, $\Gamma = 1.8$ MeV, $J^\pi = (\frac{3}{2}^-, \frac{5}{2}^-)$, $T = \frac{1}{2}$. The cross-section and angular distributions of $p_2$ ($^6$Li$^*(3.56)$) for $E_p = 4.26$ to 9.40 MeV are analyzed in terms of two $J^\pi = \frac{5}{2}^-$ states at $E_x \approx 10$ and 11 MeV: see reaction 3. The total cross section for formation of $^6$Li$^*(3.56)$ decreases slowly with energy for $E_p = 24.3$ to 46.4 MeV. The total reaction cross section has been measured for $E_p = 25.0$ to 48 MeV (85CA36). $K^2$ spectra at $E_p = 50$, 65 and 80 MeV, $\theta = 3^\circ$–20$, are reported by (87SA46). For the inclusive cross section at $E_p = 200$ MeV [back angles] see (84AV07). See also the measurement of cross sections and
Table 7.10

$^7$Be level parameters from $^6$Li + p phase shift analysis $^a$.$^b$

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

$^a$ From Table 1 of (95SK01).
$^b$ From Table 2 of (89HA18).
$^c$ Center of mass energies.

Analyzing powers for excitation of $^6$Li* (2.18, 3.56) at $E_p = 200$ MeV (90GL04). Theoretical work on this reaction published since the previous review (88AJ01) includes: a folding-model calculation to deduce halo effects (92GA27); self-consistent calculation with matter-cluster dynamic model (92KA06); a potential description study with a supermultiplet symmetry approximation (93DU09); a description with a microscopic effective interaction (93KO44); a consistent folding-model description (93PE13); a calculation for (p, p) and (p, p') with Glauber-Sitenko diffraction theory (94ZH28, 94ZH34); an analysis with phenomenological microscopic optical potentials (95GA24); a consistent analysis of the analyzing power puzzle (95KA03); a continuum-continuum coupling analysis (95KA07); a fully-microscopic analysis at $E_p = 200$ MeV (97DO01); an RGM study of a $\frac{3}{2}^-$ resonance (97IG04); a study of shell-model structures observed in proton and electron scattering (97KA24); and a microscopic-model analysis for $E_p = 65$ MeV (98DO16).

For reaction (b) see $^5$He and $^6$Li. For reaction (c) see $^6$Li, and references cited in (88AJ01).

7. $^6$Li(p, n)$^6$Be

The yield of neutrons increases approximately monotonically from threshold to $E_p = 14.3$ MeV: see (74AJ01). The transverse polarization transfer, $D_{NN}$ (0°), for the g.s. transition has been measured for $E_p = 30$ to 160 MeV: see (84TA07, 86TA1E) and $^6$Be. Analyzing-power measurements are reported at $E_p = 50$ and 80 MeV (87SA46) and at 52.8 MeV (88HE08) [$K_y^0(0°) = -0.33 ± 0.04$; also $K_y^0$]. See also (86MC09; $E_p = 800$ MeV) and (84BA1U, 86RA21, 86SA1Q). For more recent work see the discussion on this reaction under $^6$Be.

8. $^6$Li(p, α)$^3$He

The yield of nuclei increases approximately monotonically from threshold to $E_p = 14.3$ MeV: see (74AJ01). The transverse polarization transfer, $D_{NN}$ (0°), for the g.s. transition has been measured for $E_p = 30$ to 160 MeV: see (84TA07, 86TA1E) and $^6$Be. Analyzing-power measurements are reported at $E_p = 50$ and 80 MeV (87SA46) and at 52.8 MeV (88HE08) [$K_y^0(0°) = -0.33 ± 0.04$; also $K_y^0$]. See also (86MC09; $E_p = 800$ MeV) and (84BA1U, 86RA21, 86SA1Q). For more recent work see the discussion on this reaction under $^6$Be.
Thermonuclear reaction rates and the astrophysical S-factor have been derived from the low-energy \((E_p < 0.7 \text{ MeV})\) cross section measurements: \(S(0) \approx 3.1 \text{ MeV b}\): see \((74AJ01, 79AJ01, 84AJ01)\). At higher energies the cross section exhibits a broad, low maximum near \(E_p = 1 \text{ MeV}\) and a pronounced resonance at \(E_p = 1.85 \text{ MeV}\) \((\Gamma < 0.5 \text{ MeV})\). No other structure is reported up to \(E_p = 5.6 \text{ MeV}\). Measurements between \(E_p = 0.4\) and \(3.4 \text{ MeV}\) show that the polarizations are generally large and positive: see \((74AJ01)\).

Angular distributions have been reported for \(E_p = 0.15\) to \(45 \text{ MeV}\) \([\text{see } (74AJ01, 79AJ01, 84AJ01)]\) and at \(47.8, 53.5, 58.5\) and \(62.5 \text{ MeV}\) \((84NE05)\). For other early work see references cited in \((88AJ01)\). More recently, measurements of analyzing power versus \(E_p\) for \(E_p = 180–280 \text{ keV}\) were reported by \((91BU14)\). Tests of isotopic dependence of electron-screening effects on the astrophysical \(S\)-factor were reported for \(E_{\text{cm}} = 10–1004 \text{ keV}\) \((92EN01, 92EN04)\). See also an analysis of \(S\) factor data for \(E_{\text{cm}} = 10–100 \text{ keV}\) \((92SO25)\), a study of atomic screening and other small effects in reaction rates \((97BA95)\), a study of screening effects for solid targets \((97BO12)\), an optical-model formulation and \(S\) factor calculation for \(E = 10–100 \text{ keV}\) \((97KI02)\), a study of reaction rates and the primordial \(^6\text{Li}\) component \((97NO04)\), and a study of \(R\)-matrix parameterization for \(E_{\text{cm}} < 1 \text{ MeV}\) \((98AN18)\). Thermonuclear reaction rates for this reaction calculated from evaluated data are presented in the compilation \((99AN35)\).

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

\(Q_m = 3.381\)

Angular distributions of the \(n_0\) and \(n_1\) groups have been measured at \(E_d = 0.20\) to \(15.25 \text{ MeV}\): see \((74AJ01, 79AJ01)\). The \(n_1 - \gamma\) correlations are isotropic, indicating \(J^\pi = \frac{1}{2}^-\) for \(^7\text{Be}^*(0.43)\). Broad maxima are observed in the ratio of low-energy to high-energy neutrons at \(E_d = 4.2\) and \(5.1 \text{ MeV}\) \([^7\text{Be}^*(6.5, 7.2), \Gamma_{\text{cm}} = 1.2\) and \(0.5 \text{ MeV},\) respectively\]: see \((66LA04)\). See also \(^8\text{Be}\) and \((88KO1C)\).

Measurements at \(E < 1 \text{ MeV}\) and determination of the astrophysical \(S\)-factor as well as studies of the \((d,n)/(d,p)\) ratio are described in \((93CZ01, 97CZ04)\). A calculation of the \((d,n)/(d,p)\) branching ratio and discussions of the rate of Coulomb-induced predissociation is presented in \((90KO26)\). See also \((96BO27, 97NO04)\).

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

\(Q_m = 0.111\)

Angular distributions of the \(d_0\) and \(d_1\) groups to \(^7\text{Be}^*(0, 0.43)\) have been measured at \(E(^3\text{He}) = 8, 10, 14\) and \(18 \text{ MeV}\) and at \(E(^3\text{He}) = 33.3 \text{ MeV}\) \([^7\text{Be}^*(4.57)\) is also populated]: see \((74AJ01, 84AJ01)\).

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

\(Q_m = 1.109\)

130
See (87MI34) and $^5$He.

12. $^6$Li($^7$Li, $^7$Be)$^6$He $Q_m = -4.37$

The reaction was used by (98NA1F) to separate $\Delta S = 0$ and $\Delta S = 1$ transitions through coincidence measurements of $\gamma$-rays from the $^7$Be 0.43 MeV state.

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

Forward-angle differential cross sections have been measured at $E_{\pi^+} = 20$ MeV (87IR01; also at 155° and 166°), at 33.5, 41.1, 48.7 and 58.8 MeV (85IR01, 85IR02), 70 to 180 MeV [see (84AJ01)] and from 300 to 550 MeV (88RO03).

A Glauber-model analysis of $\sigma(\theta)$ for $E = 250$–650 MeV is described in (90OS01). Model calculations of cross sections and polarization observables are presented in (99NO02).

14. $^7$Li(p, n)$^7$Be $Q_m = -1.644$

$E_{\text{thresh.}} = 1880.443 \pm 0.020$ keV (85WH1A)

The excitation energy of $^7$Be*(0.43) is 429.20±0.10 keV, $\tau_m = 192\pm25$ fsec; see (79AJ01). Angular distributions of $n_0$ and $n_1$ have been reported at $E_p = 1.9$ to 119.8 MeV [see (74AJ01, 79AJ01, 84AJ01)] and at 200, 300 and 400 MeV (87WAZT prelim.; $n_{0+1}$). $^7$Be*(4.55, 6.51, 7.19, 10.79) have also been populated: see (74AJ01, 79AJ01). The ratios of $\sigma_1/\sigma_0$ ($^7$Be*(0.43)/$^7$Be$_{g.s.}$) have been measured at 24.8, 35 and 45 MeV and yield the ratio of spin-flip to non spin-flip strength $|V_\sigma/V_\tau|^2$ (80AU02).

Cross section measurements related to neutron production targets and detector efficiency calibration include (87TE04, 88HE08, 89AM03, 89BY02, 89GU13, 90BR2G, 90DR1A, 90TA11, 92AM03, 92DA20, 97TA03, 98KA20, 98MA49, 99BA73, 99NA02, 99NA15). Measurements or analyses of Gamow-Teller transition strength are reported in (87TA13, 89RA09, 90RA08, 94SA43). See also (87HE22, 87OR02). A compilation of analyzing-power data is presented in (87TA22). For studies of quadrupole excitation see (94RA23, 94WA22) and (95YA12). Application-related measurements are described in (87RA23, 88BO33, 89CR05, 95RI14, 96BB13, 96SH29, 96TA23, 97DE54, 97WU01, 97ZH35, 99LE16, 99NA02, 99SA16, 99SH16). See also the astrophysical-related analysis in (89BU10). See also the analysis (98IO03) of 647 and 800 MeV data, and the study of the isovector part of optical potentials for 35 MeV (p, n) data (98JOZW, 00JO17). For earlier work see (88AJ01).
15. (a) $^7\text{Li}(d, 2n)^7\text{Be}$ \hspace{1cm} $Q_m = -3.868$
(b) $^7\text{Li}(t, 3n)^7\text{Be}$ \hspace{1cm} $Q_m = -10.125$

See (87AL10; $E(^7\text{Li}) = 65$ MeV).

16. $^7\text{Li}(^3\text{He}, t)^7\text{Be}$ \hspace{1cm} $Q_m = -0.881$

Angular distributions of $t_0$ and $t_1$ have been measured at $E(^3\text{He}) = 3.0$ to 4.0 MeV and at $E(^3\text{He}) = 33.3$ MeV: see (74AJ01, 84AJ01). The width of $^7\text{Be}^*(4.57)$, $\Gamma_{cm} = 175 \pm 7$ keV: see (74AJ01). See also $^{10}\text{B}$.

17. $^7\text{Li}(^6\text{Li}, ^6\text{He})^7\text{Be}$ \hspace{1cm} $Q_m = -4.370$

This reaction has been studied at $E(^6\text{Li}) = 14$, 25 and 35 MeV/$A$. $^7\text{Be}^*(0, 0.43)$ are strongly populated and $^7\text{Be}^*(4.57, 7.21)$ are also evident. At the highest energy the reaction mechanism is predominantly one-step (86AN29, 87WI09). See also $^6\text{He}$, (84BA53, 86AU1C, 87AU04, 87WI09, 88AL1G, 88AN06, 88BU1Q, 88BUZH). See also reaction 12.

18. $^7\text{Li}(^7\text{Li}, ^7\text{Be})^7\text{He}$ \hspace{1cm} $Q_m = -12.064$

See (98NA1F).

19. $^8\text{Be}(\gamma, n)^7\text{Be}$ \hspace{1cm} $Q_m = -18.899$

Neutron yields have been measured with backscattered laser photons (99TOZZ).

20. $^9\text{Be}(n, 3n)^7\text{Be}$ \hspace{1cm} $Q_m = -20.564$

Cross sections were measured at $E_n = 28$–68 MeV (98DU06).

21. $^9\text{Be}(p, t)^7\text{Be}$ \hspace{1cm} $Q_m = -12.083$
Angular distributions of tritons have been measured at $E_p = 43.7$ and 46 MeV [see (79AJ01)] and at 50 and 72 MeV (84ZA07; $t_{0+1}$, $t_2$). The 11 MeV state has $E_x = 11.01 \pm 0.04$ MeV, $\Gamma = 298 \pm 25$ keV, $J^\pi = \frac{3}{2}^-$, $T = \frac{1}{2}$ [the $J^\pi$; $T$ assignments are based on the similarity of the angular distribution to that in the $(p, \, ^3\text{He})$ reaction to $^7\text{Li}^*(11.13)$]: see (79AJ01).

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

$Q_m = 1.145$

Angular distributions have been studied for $E_p = 2.8$ to 7.0 MeV [see (74AJ01)] and for 18 to 45 MeV (86HA27, $\alpha_0$, $\alpha_1$, $\alpha_2$; see for spectroscopic factors). $E_x$ of $^7\text{Be}^*(0.43) = 428.89 \pm 0.13$ keV (79RI12). See also $^{11}\text{C}$ in (85AJ01), (83DO07) and (88KOZL; applied).

More recently several studies at astrophysical energies have been reported. They include measurements of $\sigma(\theta)$ and $\sigma(E)$ at $E_p = 120 - 480$ keV (91YO04), measurements of electron screening corrections at $E_{cm} = 17$–134 keV and determination of $S(E)$ (93AN06), direct-model calculations of astrophysical reaction rates (96RA14), and a calculation of small-effect corrections in fusion reactions (97BA95). A calculation of $^7\text{Be}$ level population intensities at $E_p = 45$ MeV is described in (92KW01). For application-related measurements see (90BO15, 95RI14, 95SJ01, 99SA16).

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

$Q_m = -1.877$

See $^5\text{He}$.

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

$Q_m = -16.202$

See $^7\text{Li}$.

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

$Q_m = -7.079$

Spectroscopic amplitudes calculated with an intermediate-coupling model are reported in (87KW03). See also the discussion under $^7\text{Li}$.

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

$Q_m = -22.567$

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A calculation of spectroscopic amplitudes in an intermediate coupling model is reported in (87KW03). See also the discussion under $^6$Li.

27. $^{12}$C(d, $^7$Li)$^7$Be $Q_m = -17.542$

Differential cross sections were measured at $E_d = 78$ MeV in a study of 5-nucleon simultaneous transfer (96JA12). Spectroscopic amplitudes were calculated in an intermediate coupling model by (87KW03). See (95CH69) for a measurement of $^{12}$C(d, $^7$Be)$^7$Li, and see $^7$Li in the present review.

28. $^{12}$C($^3$He, $^8$Be)$^7$Be $Q_m = -5.781$

Angular distributions involving $^7$Be*(0, 0.43) have been reported at $E(^3$He) = 25.5 to 70 MeV [see (79AJ01, 84AJ01)] and at $E(^3$He) = 33.4 MeV (86CL1B; also $A_y$; prelim.). See also (86RA15) and see discussions of $^{12}$C($^3$He, $^7$Be)$^8$Be under $^8$Be.

29. $^{12}$C($\alpha$, $^9$Be)$^7$Be $Q_m = -24.693$

At $E_\alpha = 42$ MeV, angular distributions have been measured involving $^7$Be*(0, 0.43) and $^9$Be$_{g.s.}$: see (74AJ01). Angular distributions have also been measured at $E_\alpha = 49.0$ and 80.1 MeV (84GO03). An angular distribution and DWBA analysis for $^{12}$C($\alpha$, $^7$Be)$^9$Be is reported in (91GL03).

30. $^{12}$C($^7$Li, $^{12}$B)$^7$Be $Q_m = -14.231$

See (84BA53, 98NA1F, 98NA16).

31. $^{16}$O(\gamma, X)$^7$Be

$^7$Be yields were measured with 250–1050 MeV bremsstrahlung photons on O, Al, Cr, Cl, CO targets (98SH18).

32. $^{16}$O($^3$He, $^{12}$C)$^7$Be $Q_m = -5.5760$
Angular distributions have been reported at $E(^3\text{He}) = 25.5$ to 70 MeV to $^7\text{Be}^* (0, 0.43)$ and to various states of $^{12}\text{C}$; see $^{12}\text{C}$ in (85AJ01). See also (86BA1F). A measurement of $\sigma(\theta)$ for $^{16}\text{O}(^3\text{He}, ~^7\text{Be})^{12}\text{C}$ at $E(^3\text{He}) = 41$ MeV is reported in (87RA37). See also the calculation for $E(^3\text{He}) = 60$ MeV in (95MA57).

33. $^{16}\text{O}(^7\text{Li}, ~^{16}\text{N})^7\text{Be}$

$$Q_m = -11.282$$

Angular distributions have been studied at $E(^7\text{Li}) = 50$ MeV involving $^7\text{Be}^* (0, 0.43)$ and various states of $^{16}\text{N}$ (84CO20, 86CL03). See also $^{16}\text{N}$ in (86AJ04) and (84BA53). A compilation and analysis of data for $E(^7\text{Li}) = 78$ MeV is presented in (89GA26).

34. $^{27}\text{Al}(\gamma, ~\text{X})^7\text{Be}$

See (98SH18).

35. $^{24}\text{Mg}(^3\text{He}, ~^{20}\text{Ne})^7\text{Be}$

$$Q_m = -7.730$$

See the calculations reported in (86RA15). Measurements of $\sigma(\theta)$ for $^{24}\text{Mg}(^3\text{He}, ~^7\text{Be})$ at $E(^3\text{He}) = 41$ MeV are reported in (87RA37). Spectroscopic factors were deduced (88RA20).

36. $^{58}\text{Ni}(^8\text{B}, p)^7\text{Be})\text{X}$

Cross sections have been calculated for $E(^8\text{B}) = 25.8$, 415 MeV (99SH20).

37. $^{208}\text{Pb}(^8\text{B}, p^7\text{Be})\text{X}$

Dissociation of $^8\text{B}$ in the Coulomb field of $^{208}\text{Pb}$ was measured at $E(^8\text{B}) = 51.9$ MeV/A. Cross sections for $^7\text{Be}(p, \gamma)^8\text{B}$ were extracted (98KI19).

38. $^{232}\text{Th}(\gamma, ~^7\text{Be})\text{X}$

Yields of $^7\text{Be}$ from photon-induced $^{232}\text{Th}$ fission were measured by (98KAZL).

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The mass excess of $^7\text{B}$ adopted by (97AU04) is $27.870 \pm 0.070 \text{ MeV}$. It was obtained by averaging the values of $27.94 \pm 0.10 \text{ MeV}$ from the $^{10}\text{B}(^3\text{He}, ^6\text{He})^7\text{B}$ reaction (67MC14, 88AJ01) and the value $27.800 \pm 0.10 \text{ MeV}$ obtained in the $^7\text{Li}(\pi^+, \pi^-)^7\text{B}$ reaction (81SE1B). The width of the ground state is $\Gamma = 1.4 \pm 0.2 \text{ MeV}$: see (67MC14, 88AJ01). $^7\text{B}$ is unbound with respect to $^6\text{Be} + \text{p}$, $^5\text{Li} + 2\text{p}$ and $^4\text{He} + 3\text{p}$ by 2.21, 1.61 and 3.38 MeV, respectively.

The predicted mass excess for $^7\text{B}$ based on the isobaric multiplet mass equation using the $T = \frac{3}{2}$ level energies in $^7\text{He}$, $^7\text{Li}$ and $^7\text{Be}$ is $27.76 \pm 0.17 \text{ MeV}$ (67MC14). See also the early references cited in (88AJ01, 84AJ01, 79AJ01, 74AJ01). Recent cross section measurements for $^7\text{Li}(\pi^+, \pi^-)^7\text{B}$ (98PA40) were used to deduce information on $^7\text{B}$ proton halo features. Theoretical studies relevant to $^7\text{B}$ include work on the spherical properties of nuclei (95JA06, 97AB27), Skyrme Hartree-Fock model calculations (97BA54), Coulomb-energy studies (97PO12), large-basis shell-model calculations of level energies and other properties (98NA17).
Table 7.11
Mirror states in $A = 7$ nuclei $^a$

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<thead>
<tr>
<th></th>
<th>$^7$Li</th>
<th></th>
<th>$^7$Be</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_x$ (MeV)</td>
<td>$J^\pi$</td>
<td>$E_x$ (MeV)</td>
<td>$J^\pi$</td>
<td>$\Delta E_x$ (MeV) $^b$</td>
</tr>
<tr>
<td>0</td>
<td>$\frac{1}{2}^+$</td>
<td>0</td>
<td>$\frac{3}{2}^+$</td>
<td>—</td>
</tr>
<tr>
<td>0.478</td>
<td>$\frac{1}{2}^-$</td>
<td>0.429</td>
<td>$\frac{1}{2}^-$</td>
<td>-0.049</td>
</tr>
<tr>
<td>4.63</td>
<td>$\frac{3}{2}^-$</td>
<td>4.57</td>
<td>$\frac{3}{2}^-$</td>
<td>-0.06</td>
</tr>
<tr>
<td>6.68</td>
<td>$\frac{3}{2}^-$</td>
<td>6.73</td>
<td>$\frac{3}{2}^+$</td>
<td>+0.05</td>
</tr>
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<td>7.46</td>
<td>$\frac{3}{2}^-$</td>
<td>7.21</td>
<td>$\frac{3}{2}^-$</td>
<td>-0.25</td>
</tr>
<tr>
<td>9.67</td>
<td>$\frac{3}{2}^-$</td>
<td>9.27</td>
<td>$\frac{3}{2}^-$</td>
<td>-0.4</td>
</tr>
<tr>
<td>9.85</td>
<td>$\frac{3}{2}^-$</td>
<td>9.9</td>
<td>$\frac{3}{2}^-$</td>
<td>+0.05</td>
</tr>
</tbody>
</table>

$^a$ As taken from Tables 7.2 and 7.7.

$^b$ Defined as $E_x(^7$Be$) - E_x(^7$Li$)$.

Table 7.12
Isospin quadruplet components ($T = \frac{3}{2}$) in $A = 7$ $^a$

<table>
<thead>
<tr>
<th></th>
<th>$^7$He</th>
<th></th>
<th>$^7$Li</th>
<th></th>
<th>$^7$Be</th>
<th></th>
<th>$^7$B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_x$ (MeV)</td>
<td>$J^\pi$</td>
<td>$E_x$ (MeV)</td>
<td>$J^\pi$; $T$</td>
<td>$E_x$ (MeV)</td>
<td>$J^\pi$; $T$</td>
<td>$E_x$ (MeV)</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>$(\frac{3}{2}^-)$</td>
<td>11.24</td>
<td>$\frac{3}{2}^-; \frac{1}{2}^-$</td>
<td>11.01</td>
<td>$\frac{3}{2}^-; \frac{3}{2}^-$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.9</td>
<td>$(\frac{5}{2}^-)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ As taken from Tables 7.1, 7.2 and 7.7.

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

Abstracts to contributed papers presented at various conferences, meetings, etc are referred to by the following (The list is alphabetical by name; some names may be repeated for different publication years):


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(Closed 29 August 2000)

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