Energy levels of light nuclei $A = 8, 9, 10$

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Abstract

A review of the evidence on the properties of the nuclei $A = 8, 9$ and 10, with emphasis on material leading to information about the structure of the $A = 8, 9, 10$ systems.

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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

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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>
</tr>
</thead>
<tbody>
<tr>
<td>[1937LI1A]</td>
<td>7–38</td>
<td>M.S. Livingston, H.A. Bethe, Rev. Mod. Phys. 9 (1937) 245</td>
</tr>
<tr>
<td>[1948HO1A]</td>
<td>7–20</td>
<td>W.F. Hornyak, T. Lauritsen, Rev. Mod. Phys. 20 (1948) 191</td>
</tr>
<tr>
<td>[1949LA1A]</td>
<td></td>
<td>T. Lauritsen, NRC Preliminary Report No. 5 (1949)</td>
</tr>
</tbody>
</table>

Ajzenberg-Selove evaluations:

| [1952AJ38]    | 5–23                    | F. Ajzenberg, T. Lauritsen, Rev. Mod. Phys. 24 (1952) 321 |
| [1955AJ61]    | 5–23                    | F. Ajzenberg, T. Lauritsen, Rev. Mod. Phys. 27 (1955) 77 |
| [1959AJ76]    | 5–24                    | F. Ajzenberg, T. Lauritsen, Nucl. Phys. 11 (1959) 1 |
| [1966LA04]    | 5–10                    | T. Lauritsen, F. Ajzenberg-Selove, Nucl. Phys. 78 (1966) 1 |

TUNL evaluations:


continued by Professor Ajzenberg-Selove with separate reviews for A = 5–10, A = 11–12, 13–15, 16–17, and 18–20 nuclides. It comprised a total of 23 “Energy Levels of Light Nuclei” reviews 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 reviews is given in Table 1 along with several earlier reviews and the more recent TUNL A = 5–7, 16–17, 18–19 and 20 reviews. In form, arrangement
and purpose, this present paper summarizing $A = 8–10$ is similar to the previous reviews dealing with the $A = 5–20$ nuclides.

**Arrangement of 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 from 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.

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 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 quasielastic 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. 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 for $A = 8, 9, 10$**

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

**General tables**

In previous evaluations by Fay Ajzenberg-Selove, as well as most of those by TUNL, a “general” bibliography was found at the beginning of the text material for each nucleus, consisting of a listing of mainly theoretical papers dealing with the nucleus as well as some experimental papers not otherwise classifiable. 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, the authors, beginning with the $A = 5, 6, 7$ review and continuing with the present $A = 8, 9, 10$ review have chosen to omit them in the published review and instead provide them on the TUNL Data Evaluation Projects web-
site 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.
- $E_b$: 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;
- $E_{res}$: energy corresponding to a reaction resonance;
- $\mu_N$: nuclear magneton;
- $\Gamma$: 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;
- $\Gamma_W$: The Weisskopf estimates ($\Gamma_W$ in eV, $E_\gamma$ in MeV) are: $\Gamma_W$(E1) = $6.8 \times 10^{-2} A^{2/3} E_\gamma^{3/2}$, $\Gamma_W$(E2) = $4.9 \times 10^{-8} A^{4/3} E_\gamma$, $\Gamma_W$(E3) = $2.3 \times 10^{-14} A^2 E_\gamma^7$, $\Gamma_W$(E4) = $6.8 \times 10^{-21} A^{8/3} E_\gamma^9$, $\Gamma_W$(M1) = $2.1 \times 10^{-2} E_\gamma^3$, $\Gamma_W$(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. See also [1979EN05] and Table 3 in [2002TI10];
- $\theta^2$: dimensionless reduced width, $\gamma^2 2 \mu R^2/3\hbar^2$;
- $\epsilon$-capture: electron capture;
- $S(E)$: astrophysical factor at energy $E$;
- $\sigma(E)$: reaction cross section at energy $E$;
- $\omega\gamma$: $\omega\gamma = \omega \Gamma_1 \Gamma_\gamma / \Gamma$ is derived from the resonant cross section for radiative capture to a narrow resonance approximated by a Breit–Wigner expression [1999AN35]; on resonance, $\Gamma_1$ and $\Gamma_\gamma$ are the entrance and exit channel partial widths, $\Gamma$ is the total width, and $\omega = (1 + \delta_{12}) (2J + 1)/(2I_1 + 1)(2I_2 + 1)$ is the statistical factor where $I_1$, $I_2$ and $J$ are the spins of the interacting nuclei and of the resonance;
- $^AX^*(E)$: excited state of the nucleus $^AX$, at energy $E$;
\[ B(F), \ B(GT): \ f \tau_{1/2}(B(F) + B(GT)) = 6144.4 \pm 4.0 \text{ s}, \] where [1993CH06] \( f \) is the Fermi integral, averaged over a resonance if necessary, \( \tau_{1/2} \) is the partial half-life for \( \beta \) decay, \[ B(F) = \langle \tau \rangle^2, \ B(GT) = (g_A/g_V)^2 \langle \sigma \tau \rangle^2, \] and the constant is from [2003TO29];

PWBA: plane-wave Born approximation;

DWBA: distorted-wave Born approximation;

Ma: mega-years [1 \times 10^6 \text{ years}].

The reader is reminded of the following abbreviations: 1 \( \mu \text{eV} = 10^{-6} \text{ eV} \); 1 meV = \( 10^{-3} \text{ eV} \); 1 ps = \( 10^{-12} \text{ s} \); 1 fs = \( 10^{-15} \text{ s} \); 1 W.u. = 1 Weisskopf unit.

Other review papers on light nuclei

We wish to remind the readers of the papers on \( A = 3 \) [1987TI07], \( A = 4 \) [1992TI02], and \( A = 21–44 \) [1990EN08]. Higher mass chains are discussed in Nuclear Data Sheets.

Electronic data services

Nuclear physics electronic

This review for \( A = 8–10 \) nuclides in its entirety, as well as other TUNL reviews, are available through ScienceDirect by way of the World Wide Web at www.sciencedirect.com.

TUNL nuclear data evaluation group WWW server

The TUNL Nuclear Data Evaluation Group maintains WWW pages at www.tunl.duke.edu/nucldata.

Our website is extensive and comprehensive, and provides a user-friendly environment for viewing and/or downloading information on the \( A = 5–20 \) Energy Levels of Light Nuclei series.

We have made available on our website abridged versions of our published evaluations and preliminary reports in PDF and HTML formats. We also provide PDF and HTML versions of Fay Ajzenberg-Selove’s evaluations (1959–1991). Energy level diagrams for the TUNL and Fay Ajzenberg-Selove evaluations are provided in GIF, PDF and EPS/PS formats. We also provide on our website General Tables (please see the section about the General Tables in the Introduction above), Update Lists, and Tables of Energy Levels that correspond to the evaluations of the \( A = 5–20 \) Energy Levels series. Links to the ENSDF information, and the Berkeley’s Isotopes Project’s Tables of Isotopes are provided via our website. Our website is also browser-friendly and provides a stable platform of use for both old and new browsers. Please visit our website to view all that we have to offer to the Nuclear Physics community.
Table 2
Parameters of n, p, d, t and α [2003AU03]

<table>
<thead>
<tr>
<th></th>
<th>Atomic mass excess (keV)</th>
<th>$\tau_{1/2}$</th>
<th>Decay</th>
<th>$J^G; T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1$n or n</td>
<td>8071.3171 ± 0.0005</td>
<td>613.9 ± 0.6 s</td>
<td>$\beta^-$</td>
<td>$\frac{1}{2}^+; \frac{1}{2}^-$</td>
</tr>
<tr>
<td>$^1$H or p</td>
<td>7288.9705 ± 0.0001</td>
<td>stable</td>
<td>stable</td>
<td>$\frac{1}{2}^+; \frac{1}{2}^+$</td>
</tr>
<tr>
<td>$^2$H or d</td>
<td>13135.7216 ± 0.0003</td>
<td>stable</td>
<td>stable</td>
<td>1$^+$; 0</td>
</tr>
<tr>
<td>$^3$H or t</td>
<td>14949.8060 ± 0.0023</td>
<td>12.32 ± 0.02 y</td>
<td>$\beta^-$</td>
<td>$\frac{3}{2}^+; \frac{1}{2}^+$</td>
</tr>
<tr>
<td>$^4$He or α</td>
<td>2424.9156 ± 0.0001</td>
<td>stable</td>
<td>stable</td>
<td>0$^+$; 0</td>
</tr>
</tbody>
</table>

Acknowledgments

We are extremely grateful to our many colleagues who have provided valuable suggestions and corrections to the preliminary versions of $A = 8$, 9, 10 evaluations. In particular we acknowledge with special thanks the help of Professor F.C. Barker. We especially appreciate the support and encouragement of Professor Werner Tornow, Director of Triangle Universities Nuclear Laboratories, as well as former directors Professors N.R. Roberson and E.G. Bilpuch. We are grateful to the personnel of the National Nuclear Data Center for their generous support and services as well as to the other personnel of the US Data Program and the US Department of Energy, especially Drs. R.A. Meyer and Gene Henry, and Dr. Sidney Coon. We also thank Dr. Carl Schwarz and the staff of Nuclear Physics A and the Elsevier Science Publishers for their support. Finally we wish to acknowledge in the strongest possible terms our gratitude for the cooperation, encouragement, help and valuable advice provided by Professor F. Ajzenberg-Selove beginning with the process of transferring the $A = 5$–20 evaluation project from the University of Pennsylvania to TUNL and continuing to the present time. The high quality of her reviews and their considerable value to the nuclear physics community is well known and has been widely acknowledged.

$A = 8$

General

References to articles on general properties of $A = 8$ nuclei published since the previous review [1988AJ01] are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for $A = 8$ located on our website at www.tunl.duke.edu/nucldata/General_Tables/08.shtml.

$^8$n

(not illustrated)

The nucleus $^8$n has not been observed. Reaction products from the interaction of 700 MeV and 400 GeV protons with uranium showed no evidence of an $^8$n resonance: see [1979AJ01]. See also [1988AJ01].
### Table 3
Parameters of the ground states of the light nuclei with \( A = 8, 9, 10 \)

<table>
<thead>
<tr>
<th>Element</th>
<th>Atomic Mass Excess (keV)</th>
<th>( r_{1/2} ) or ( T_{1/2} )</th>
<th>Decay</th>
<th>( J^\pi ); ( T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^8\text{He})</td>
<td>31598 ± 7</td>
<td>( r_{1/2} = 119.0 \pm 1.5 \text{ ms} )</td>
<td>( \beta^- )</td>
<td>0(^-); 2</td>
</tr>
<tr>
<td>(^8\text{Li})</td>
<td>20946.84 ± 0.09</td>
<td>( r_{1/2} = 839.9 \pm 0.9 \text{ ms} )</td>
<td>( \beta^- )</td>
<td>2(^-); 1</td>
</tr>
<tr>
<td>(^8\text{Be})</td>
<td>4941.67 ± 0.04</td>
<td>( I^\pi = 5.57 \pm 0.25 \text{ eV} )</td>
<td>( \alpha )</td>
<td>0(^-); 0</td>
</tr>
<tr>
<td>(^8\text{B})</td>
<td>22921.5 ± 1.0</td>
<td>( r_{1/2} = 770 \pm 3 \text{ ms} )</td>
<td>( \beta^+ )</td>
<td>2(^+); 1</td>
</tr>
<tr>
<td>(^8\text{C})</td>
<td>35094 ± 23</td>
<td>( I^\pi = 230 \pm 50 \text{ keV} )</td>
<td>( p, \alpha )</td>
<td>0(^+); 2</td>
</tr>
<tr>
<td>(^9\text{He})</td>
<td>39770 ± 60</td>
<td>n</td>
<td>( \frac{3}{2}^+, \frac{5}{2}^+ )</td>
<td></td>
</tr>
<tr>
<td>(^9\text{Li})</td>
<td>24954.3 ± 1.9</td>
<td>( r_{1/2} = 178.3 \pm 0.4 \text{ ms} )</td>
<td>( \beta^- )</td>
<td>( \frac{3}{2}^-, \frac{1}{2}^+ )</td>
</tr>
<tr>
<td>(^9\text{Be})</td>
<td>11347.6 ± 0.4</td>
<td>stable</td>
<td>( \frac{3}{2}^+ )</td>
<td>( \frac{1}{2}^+ )</td>
</tr>
<tr>
<td>(^9\text{B})</td>
<td>12415.7 ± 1.0</td>
<td>( I^\pi = 0.54 \pm 0.21 \text{ keV} )</td>
<td>( p, \alpha )</td>
<td>( \frac{3}{2}^-, \frac{1}{2}^- )</td>
</tr>
<tr>
<td>(^9\text{C})</td>
<td>28910.5 ± 2.1</td>
<td>( r_{1/2} = 126.5 \pm 0.9 \text{ ms} )</td>
<td>( \beta^+ )</td>
<td>( \frac{3}{2}^-, \frac{1}{2}^- )</td>
</tr>
<tr>
<td>(^9\text{N})</td>
<td>see text</td>
<td>( T = 0 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(^{10}\text{He})</td>
<td>48810 ± 70</td>
<td>( I^\pi = 0.3 \pm 0.2 \text{ MeV} )</td>
<td>n</td>
<td>0(^+); 3</td>
</tr>
<tr>
<td>(^{10}\text{Li})</td>
<td>33051 ± 15</td>
<td>see text</td>
<td>n</td>
<td>( 1^-; 2^- ); 2</td>
</tr>
<tr>
<td>(^{10}\text{Be})</td>
<td>12606.7 ± 0.4</td>
<td>( r_{1/2} = (1.51 \pm 0.04) \times 10^6 \text{ yr} )</td>
<td>( \beta^- )</td>
<td>0(^-); 1</td>
</tr>
<tr>
<td>(^{10}\text{B})</td>
<td>12050.7 ± 0.4</td>
<td>stable</td>
<td>–</td>
<td>3(^-); 0</td>
</tr>
<tr>
<td>(^{10}\text{C})</td>
<td>15698.7 ± 0.4</td>
<td>( r_{1/2} = 19.290 \pm 0.012 \text{ s} )</td>
<td>( \beta^+ )</td>
<td>0(^+); 1</td>
</tr>
<tr>
<td>(^{10}\text{N})</td>
<td>38000 ± 400</td>
<td>( I^\pi = 2.3 \pm 1.6 \text{ MeV} )</td>
<td>( \rho )</td>
<td>( T = 2 )</td>
</tr>
</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 [2003AU03]. The mass excesses of \( \pi^\pm, \eta^0 \) and \( \mu \) were taken to be 139570.18 ± 0.35, 134976.6 ± 0.6 and 105658.357 ± 0.005 keV [2000GR22].

\( b \) Values taken from [2003AU03] unless otherwise noted.

\( c \) \( J^\pi \) values in parentheses are taken from [2003AU03] or derived from systematics.

\( d \) \( \mu = +1.653560 \times (18) \mu_N \) [1989RA17], \( Q = +32.7 \pm 0.6 \text{ mb} \) [1993MI34].

\( e \) See reaction 1 in \(^8\text{Li}\).

\( f \) \( \mu = +1.0355 \times (3) \mu_N \) [1996FIZY], \( Q = 68.3 \pm 2.1 \text{ mb} \) [1992MI18,1993MI35].

\( g \) [2001CH31], and private communication from AME 2004, Audi, Wapstra and Jokinen.

\( h \) \( \mu = +3.4391 \times (6) \mu_N \) [1983CO11,2001STZZ], \( Q = -27.4 \times (10) \text{ mb} \) [1992AR07].

\( i \) \( \mu = -1.1778 \times (9) \mu_N \) [1978LEZA], \( Q = 38.6 \times (6) \text{ mb} \) [1991GL02].

\( j \) See reaction 1 in \(^{10}\text{Be}\).

\( k \) \( \mu = 1.80064475 \pm 0.00000057 \mu_N \) [1989RA17], \( Q = 84.72 \pm 0.56 \text{ mb} \) [1978LEZA,1989RA17].

\( l \) This is the only resonance observed in \(^{10}\text{N}\); however, it may not be the ground state.

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\(^8\text{He}\)

(Figs. 1 and 5)

**General**

References to articles on general properties of \(^8\text{He}\) published since the previous review [1988AJ01] are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for \(^8\text{He}\) located on our website at www.tunl.duke.edu/nucldata/General_Tables/8he.shtml.
The atomic mass excess of $^8$He adopted by us and by [2003AU03] is 31598 ± 7 keV. $^8$He is then stable with respect to decay into $^6$He + 2n by 2.140 MeV. See [1979AJ01,1984AJ01,1988AJ01].

The interaction nuclear radius of $^8$He is 2.48 ± 0.03 fm [1985TA13,1985TA18]; see also for derived nuclear matter, charge and neutron matter r.m.s. radii. See also reaction 12.

$^8$He($^7$Li,$^8$He)$^7$Li, $Q_m = 10.651$

The half-life of $^8$He is 119.0 ± 1.5 ms. The decay takes place (84 ± 1)% to $^8$Li*(0.98) [log $f_1 = 4.20$] and (16 ± 1)% via the neutron unstable states $^8$Li*(3.21, 5.4). A small decay branch (~ 0.9%) populates $^8$Li*(9.67). (32 ± 3)% of the emitted neutrons then populate $^8$Li*(0.48). The decay to $^8$Li*(3.21, 5.4) suggests $\pi = +$ for $^8$Li*(3.21) and 0+ or 1+ for $^8$Li*(5.4) [1981BJ03]. Branching ratios for intermediate states are given in [1988BA67]: see also reaction 11 in $^8$Li and Fig. 2. For discussion of $^8$He $\beta$-decay [1988BA67,1991BO31,1993BO24,1996BA66,1996GR16,1997SH19]. See also [1990ZH01,1993CH06,1994HA39].

$^1$H($^8$He,$^8$He)$^1$H, $E_b = 13.933$

Invariant mass spectroscopy was used to determine the $^8$He excitation spectra in a complete kinematics measurement of the $^1$H($^8$He,$^8$He+p) reaction at 72 MeV/A [1993KO34, 1995KO27]. The ground state and an excited state at 3.55 ± 0.15 MeV were observed. The 3.55 MeV state has $J^\pi = 2^+$, $\Gamma = 0.50 ± 0.35$ MeV and $\Gamma(\alpha + 4n)/\Gamma(\alpha + 2n) ≤ 5%$ [1995KO27]; possible evidence for a resonance at 5–6 MeV is seen.

The $^1$H($^8$He,$^8$He+p) scattering distribution at $E(\alpha)$ = 674 MeV/A was analyzed using a Glauber scattering model and yields an $^8$He matter radius $R_{m,s}$ = 2.45 ± 0.07 fm [1997AL09]. Elastic and inelastic scattering distributions from $^1$H($^8$He,$^8$He+p) at
Fig. 1. Energy levels of $^8$He. For notation see Fig. 2. a See comment c in Table 8.1.

72 MeV/A were evaluated in an eikonal approximation and indicate a matter radius $R_{\text{r.m.s.}} = 2.52 \text{ fm}$ and a deformation parameter $\beta_2 = 0.3$ for the first $2^+$ excited state [1995CH19]. A folding model analysis of the $^8$He first excited $J^\pi = 2^+$ state, using $E_x = 3.57 \text{ MeV}$, indicates $L = 2$ and a deformation parameter $\beta = 0.28$ [2002GU02].
Evaluation of the four-momentum transfer distribution yields $R_{r.m.s} = 2.45 \pm 0.07$ fm at $E(^{8}\text{He}) = 800$ MeV/A [2002EG02] and $R_{r.m.s} = 2.53 \pm 0.08$ fm at $E(^{8}\text{He}) \approx 700$ MeV/A [2002AL26]. See also ([2003LA22]; $E(^{8}\text{He}) = 15.6$ MeV/A), ([2002WO08]; $E(^{8}\text{He}) = 26$ MeV/A), ([1995KO10]; $E(^{8}\text{He}) = 33$ MeV/A), ([1997KO06]; $E(^{8}\text{He}) = 66$ MeV/A), ([1997KO12]; $E(^{8}\text{He}) = 73.5$ MeV/A), ([1995NE04]; $E(^{8}\text{He}) = 674$ MeV/A), ([2002EG02]); $E(^{8}\text{He}) \approx 700$ MeV/A), and ([1995BE26,1995CR03,1995GO32,1998AN25,2000GU19,2000KA04,2001AV02,2001SA79,2003BA65]; theor.).

3. $^{4}\text{He}(^{8}\text{He},^{8}\text{He})^{4}\text{He}, \ E_b = 8.946$

The Generator-Coordinate Method was used to calculate $^{8}\text{He}(\alpha,\alpha)$ scattering in an investigation of excited states in $^{12}\text{Be}$ [2000BB06]. A search for 4-neutron cluster contributions to the reaction was performed at $E(^{8}\text{He}) = 26$ MeV/A, no evidence was observed [2003WO13].

4. $^{8}\text{He}(p,t)^{6}\text{He}, \ \ Q_m = 6.342$

The 2-neutron transfer reaction $^{4}\text{He}(^{8}\text{He},t)$ was measured at $E(^{8}\text{He}) = 61.3$ MeV/A. The results indicate a significant contribution of $^{6}\text{He}^*(1.8)$ in the $^{8}\text{He}$ ground state [2003KO11]; spectroscopic factors yield $S(^{6}\text{He}{g.s.})/S(^{6}\text{He}^*(1.8)) = 1$.

5. (a) $^{9}\text{Be}(\pi^-,p)^{8}\text{He}, \ \ Q_m = 112.031$
(b) $^{11}\text{B}(\pi^-,p+d)^{9}\text{He}, \ \ Q_m = 96.215$

Using $E_{\pi^-} = 125$ MeV, the $^{8}\text{He}$ ground state was observed in the $^{9}\text{Be}(\pi^-,p)$ missing mass spectra; the measured $^{6}\text{He}^* + 2n$ phase space appears to favor a dineutron final state [1991SE06]. The ground state and the 4.4 MeV state were observed in [1998GO30] following the capture of stopped $\pi^- $-mesons in $^{9}\text{Be}(\pi^-,p), E_x = 4.4 \pm 0.2$ MeV, $\Gamma = 1.8 \pm 0.2$ MeV and in $^{11}\text{B}(\pi^-,p+d) E_x = 4.4 \pm 0.4$ MeV, $\Gamma = 1.2 \pm 0.2$ MeV.

6. $^{9}\text{Be}(^{7}\text{Li},^{8}\text{B})^{8}\text{He}, \ \ Q_m = -28.264$

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

7. $^{9}\text{Be}(^{9}\text{Be},^{10}\text{C})^{8}\text{He}, \ \ Q_m = -24.602$

At $E(^{9}\text{Be}) \approx 11$ MeV/A, the ground state and three excited states are populated at $E_x = 1.3 \pm 0.3$ MeV, $E_x = 2.7 \pm 0.3$ MeV, $\Gamma = 0.5 \pm 0.3$ MeV and $E_x = 4.0 \pm 0.3$ MeV, $\Gamma = 0.5 \pm 0.3$ MeV [1988BE34].
8. $^9$Be($^{13}$C,$^{14}$O)$^8$He, $Q_m = -25.133$

At $E(^{13}$C) = 380 MeV, the ground state of $^8$He was observed [1988BO20]. A measurement at $E(^{13}$C) = 337 MeV observed the ground state and the first $2^+$ excited state at 3.59 MeV, $\Gamma \approx 800$ keV [1995VO05].

9. $^{10}$Be($^{12}$C,$^{14}$O)$^8$He, $Q_m = -26.999$

At $E(^{12}$C) = 357 MeV, population of the ground state and 3.6 MeV state are reported. Excited states are also observed at $E_x = 4.54 \pm 0.15$ MeV [$\Gamma = 0.70 \pm 0.25$ MeV], 6.03 $\pm 0.10$ MeV [$\Gamma = 0.15 \pm 0.15$ MeV] and 7.16 $\pm 0.04$ MeV [$\Gamma = 0.10 \pm 0.10$ MeV] [1995ST29,1999BO26]. The narrow width of the 7.16 MeV state leads to a preliminary $J^\pi = (3^-)$ assignment [1999BO26].

10. $^{11}$B($^7$Li,$^{10}$C)$^8$He, $Q_m = -23.721$

At $E(^{11}$B) = 87 MeV the ground state of $^8$He is populated and excited states are reported at $E_x = 1.3$, 2.6 and 4.0 MeV ($\pm 0.3$ MeV). The width of the latter is 0.5 $\pm 0.3$ MeV [1987BE2B]. In [1988BE34] the ground state and a state at 2.7 $\pm 0.3$ MeV with $\Gamma = 1.0 \pm 0.5$ MeV are reported. See also [1988BEYJ].

11. nat C(µ,$^8$He)X

A measurement to determine muon induced background rates in large-volume scintillation solar neutrino detectors found $\sigma = 2.12 \pm 1.46$ µb for nat C(µ,$^8$He) or $^9$Li at $E_\mu = 100$ GeV [2000HA33].

12. (a) $^{12}$C($^8$He, $^6$He + 2n)
    (b) Al($^8$He, $^6$He + 2n)
    (c) Sn($^8$He, $^6$He + 2n)
    (d) Pb($^8$He, $^6$He + 2n)
    (e) C($^8$He, X)
    (f) Si($^8$He, X)

At $E(^8$He) = 227 MeV / A structures are seen in reaction (a) corresponding to sequential decay through the $J^\pi = \frac{3}{2}^-$ $^7$He g.s. ($E_{res} = 0.44$ MeV, $\Gamma = 0.16$ MeV), and a suggested $J^\pi = \frac{1}{2}^-$ resonance at $E_{res} = 1.2 \pm 0.2$ MeV with $\Gamma = 1.0 \pm 0.2$ MeV [2001MA05]. A reconstruction of the $^6$He + 2n reaction kinematics indicated that $^8$He$^*$($2.9 \pm 0.2$ MeV, $\Gamma = 0.3 \pm 0.3$ MeV (2$^+$) and 4.15 $\pm 0.20$ MeV, $\Gamma = 1.6 \pm 0.2$ MeV (1$^-$)) participate in the breakup. Cross sections for the one- and two-neutron knockout reactions (i.e., where one or none of the removed neutrons is observed) were determined as $\sigma_{1n} = 129 \pm 15$ mb and $\sigma_{2n} = 29 \pm 23$ mb. Contributions for various cluster configurations in $^8$He were estimated to be 45% $^6$He$^* + 2n$ ($p_3/2$, $p_1/2$), 33% $^6$He + 2n ($p_3/2$) and 22% $^6$He + 2n ($p_1/2$). See [1996NI02] for earlier work at $E(^8$He) = 240 MeV by this group, where $E_x = 3.72 \pm
0.24 MeV and $\Gamma = 0.53 \pm 0.43$ MeV, were reported for the first excited state, and where the total 2-neutron removal cross section was determined as $\sigma_{2n} = 0.27 \pm 0.03$ b.

Complete reaction kinematics were measured for reactions (b, c, d) in ($^8$He, $^6$He + 2n) on Al, Sn and Pb targets at $E(^8$He) = 24 MeV/A [2000IW05]. Observation of a peak in the $^6$He + n relative energy spectra indicates a substantial participation (40–60%) of sequential decay via $^7$He + n. A peak in the missing mass spectra corresponds to the first excited state of $^8$He, which is assumed to dominate in nuclear breakup since it cannot be excited by E1 Coulomb processes. By integrating the remaining excitation strength up to 3 MeV (assumed to be E1 Coulomb) $B$(E1) = 0.091 ± 0.026 e2 fm2 was determined.

Measurements of $^8$He breakup on C and Pb are presented in [2002ME09]; the results indicate that the $^8$He Coulomb dissociation cross section is 3 times smaller than the Coulomb dissociation cross section for $^6$He. The measurements of [2002ME09] also support $J^\pi = 1^–$ for $^8$He*(4.15). The two-neutron- and four-neutron-removal cross sections were measured for reaction (e) at 800 MeV/A [1992TA18], and for reaction (f) at $E(^8$He) = 20–60 MeV/A [1996WA27]. The large neutron removal cross sections indicate a $^8$He matter radius of 2.49 ± 0.04 fm [1992TA18]. Analysis indicates that $^8$He is well represented as four neutrons that are bound to a $^4$He core. See also ([1994ZH14,1995SU13, 2001CA50]; theor.), and a review of nuclear radii deduced from interaction cross sections in [2001OZ04].

13. $^{14}$C($^8$He, $^8$He)$^{14}$C

A double folding model was used to predict the influence of the $^8$He neutron skin on $^{14}$C($^8$He, $^8$He) elastic-scattering angular-dependent cross sections at 20, 30, 40, and 60 MeV [1988KN02].

$^8$Li

(Figs. 2 and 5)

**General**

References to articles on general properties of $^8$Li published since the previous review [1988AJ01] are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for $^8$Li located on our website at www.tunl.duke.edu/nucldata/General_Tables/8li.shtml.

**Ground state properties**

$\mu = +1.653560 \pm 0.000018 \mu_N$ see [1989RA17];

$Q = +32.7 \pm 0.6$ mb see [1993MI34].

The interaction nuclear radius of $^8$Li is 2.36 ± 0.02 fm [1985TA18] [see [1985TA18] also for derived nuclear matter, charge and neutron matter r.m.s. radii].
Table 8.2

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$J^\pi$; $T$</th>
<th>$\tau$ or $I_{cm}$ (keV)</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>$2^+; 1$</td>
<td>$\tau_{1/2} = 839.9 \pm 0.9$ ms$^a$</td>
<td>$\beta^-$</td>
<td>1, 3, 4, 8, 9, 10, 14, 15, 16, 17, 18, 21, 22</td>
</tr>
<tr>
<td>0.9808 ± 0.1</td>
<td>$1^+; 1$</td>
<td>$\tau_{m} = 12 \pm 4$ fs$^c$</td>
<td>$\gamma$</td>
<td>3, 8, 9, 11, 14, 15, 16, 21, 22, 28</td>
</tr>
<tr>
<td>2.255 ± 3</td>
<td>$3^+; 1$</td>
<td>$I^* = \approx 33 \pm 6$ keV$^c$</td>
<td>$\gamma$, n</td>
<td>3, 4, 5, 8, 14, 15, 16, 31</td>
</tr>
<tr>
<td>3.21</td>
<td>$1^+; 1$</td>
<td>$\approx 1000$</td>
<td>n</td>
<td>6, 11</td>
</tr>
<tr>
<td>5.4$^d$</td>
<td>$1^+; 1$</td>
<td>$\approx 650$</td>
<td>n</td>
<td>6, 11</td>
</tr>
<tr>
<td>6.1 ± 100</td>
<td>(3); 1</td>
<td>$\approx 1000$</td>
<td>n</td>
<td>5</td>
</tr>
<tr>
<td>6.53 ± 20</td>
<td>$4^+; 1$</td>
<td>$35 \pm 15$</td>
<td>n</td>
<td>3, 5, 8, 15, 16</td>
</tr>
<tr>
<td>7.1 ± 100</td>
<td>$\approx 400$</td>
<td></td>
<td>n</td>
<td>5</td>
</tr>
<tr>
<td>(9)</td>
<td>$\approx 6000$</td>
<td></td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>≈ 9.67$^{b,c}$</td>
<td>$1^+$</td>
<td>$\approx 1000^c$</td>
<td>t</td>
<td>11</td>
</tr>
<tr>
<td>10.8222 ± 5.5</td>
<td>$0^+; 2$</td>
<td>&lt; 12</td>
<td></td>
<td>19</td>
</tr>
</tbody>
</table>

$^a$ For additional states see reactions 5 and 16.
$^b$ From multi-level multi-channel $R$-matrix fit to $^8$He decay spectra.
$^c$ From information given in this evaluation.
$^d$ A level at $E_x = 5.4$ MeV with uncertain $J^\pi = (2^+)$ was observed in $^7$Li(n, n') [1972PR03].

$^8$Li atomic transitions

Atomic excitations in the lithium isotopes were analyzed in [2000YA05] where a theoretical framework was developed that correlates the atomic decay energies in neutral Li ions with the nuclear sizes.

1. $^8$Li($\beta^-$)$^8$Be,  $Q_m = 16.0052$

    The $\beta^-$ decay is mainly to the broad $2^+$ first-excited state of $^8$Be, which then breaks up into $2\alpha$ [see reaction 24 in $^8$Be]. The weighted average of the $^8$Li half-life is $839.9 \pm 0.9$ ms based on measured values of $838 \pm 6$ ms [1971WI05], $836 \pm 3$ ms [1979MI1E] and $840.3 \pm 0.9$ ms [1990SA16]. The log $f_I > 5.6$, using $\tau_{1/2} = 839.9$ ms, $Q = 16.0052$ MeV and branching ratio $< 100\%$; other values in the literature that account for the decay to the broad $I^* \approx 1.5$ MeV $^8$Be*(3.0) state are log $f_I = 5.37$ [1986WA01] and log $f_I = 5.72$ [1989BA31].

    The quadrupole moment of $^8$Li was deduced by measuring the asymmetry in $\beta$-NMR spectra. We adopt $Q(\beta^-)(^8$Li) = $+32.7 \pm 0.6$ mb, which results from a new method, modified $\beta$-NMR (NNQR), that is 100 times more sensitive than previous methods [1993MI34]. This value is larger than $28.7 \pm 0.7$ mb [1988AR17] and the previous adopted value $24 \pm 2$ mb [1988AJ01]. The sign of the $^8$Li quadrupole moment was measured and is positive [1994JA05].

    The tilted foil technique was used to polarize atomic $^8$Li, and the hyperfine interaction led to a nuclear polarization of $1.2 \pm 0.3\%$ which was deduced from the measured $\beta$-decay asymmetry [1987NO04]. The polarization quantum beat in the hyperfine interaction was measured by varying the foil separation distances [1993MO33,1996NO11]. See also [1987AR22] for discussion of hyperfine structure splitting in lithium isotopes.

    The pure Gamow–Teller ($\Delta T = 1$) $\beta$-decay of $^8$Li to the $^8$Be*(3.0) level has been measured in a search for time-reversal violation [1990SR03,1992AL01,1996SR02, 2003HU06]; the present constraint for the time violating parameter is $R = (0.9 \pm 2.2) \times 10^{-3}$. See also [1992DE07,1995YI01,1998KA51]. Searches for second-class currents in
Table 8.3
Electromagnetic transitions in $^8\text{Li}$

<table>
<thead>
<tr>
<th>$E_{Q1}$ → $E_{Q2}$ (MeV)</th>
<th>$J_i^\pi$ → $J_f^\pi$</th>
<th>$\Gamma_\gamma$ (eV)</th>
<th>Mult.</th>
<th>$\Gamma_\gamma / \Gamma_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9808 → 0</td>
<td>$1^+ \rightarrow 2^+$</td>
<td>(5.5 ± 1.8) × 10^{-2}</td>
<td>M1</td>
<td>2.8 ± 0.9</td>
</tr>
<tr>
<td>2.255 → 0</td>
<td>$3^+ \rightarrow 2^+$</td>
<td>(7.0 ± 3.0) × 10^{-2}</td>
<td>M1</td>
<td>0.29 ± 0.13</td>
</tr>
</tbody>
</table>

Table 8.4
Measured $\gamma$-rays from thermal neutron capture on $^7\text{Li}$ a

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV) b</th>
<th>$\sigma_\gamma$ (mb)</th>
<th>$I_\gamma$ ($\gamma/100n$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>980.6 ± 0.2</td>
<td>4.82 ± 0.50</td>
<td>10.6 ± 1.0</td>
</tr>
<tr>
<td>1052.0 ± 0.2</td>
<td>4.80 ± 0.50</td>
<td>10.6 ± 1.0</td>
</tr>
<tr>
<td>2032.5 ± 0.3</td>
<td>40.56 ± 1.00</td>
<td>89.4 ± 1.0</td>
</tr>
</tbody>
</table>

a See Table I in [1991LY01].  
b $E_\gamma$ not corrected for recoil.

$^8\text{Li}$ $\beta$-decay have yielded negative results: see [1988HA21,1989TE04,2003SM02]. For an analysis of the anti-neutrino energy distribution shape in $^8\text{Li}$ $\beta$-decay, see [1987LY05, 2002BH03]. For a comment on the usefulness of $\beta$-decay asymmetries to reveal information on spin dynamics in nuclear reactions involving polarized projectiles see [2001DZ02]. A suggestion to use $^8\text{Li}$ $\beta$-decay for calibration of the SNO detector is described in [1998JO09,2002TA22]. $\beta$-NMR is used to measure the $^6\text{Li}$ quadrupole-coupling constants in Mg and Zn [1993OH11]. For condensed matter applications of $^8\text{Li}$ $\beta$-decay see [1993BU29,1993NO08,1994HO23,1996EB01]. See also [1993CH06, 1993MO28,2003SU04].

2. $^1\text{H}(^8\text{Li},^8\text{Li})^1\text{H}$

Small angle scattering in the $^1\text{H}(^8\text{Li},^8\text{Li})$ reaction was measured at $E(\gamma^{\text{Li}}) = 698$ MeV/A [2002EG02,2003EG03].

3. $^6\text{Li}(t,p)^8\text{Li}$, $Q_m = 0.80079$

Angular distributions have been obtained at $E_t = 23$ MeV for the proton groups to $^8\text{Li}^*(0,0.98,2.26,6.54 \pm 0.03)$; $\Gamma_{cm}$ for $^8\text{Li}^*(2.26,6.54)$ are 35 ± 10 and 35 ± 15 keV, respectively. $J$ for the latter is $\geq 4$: see [1979AJ01]. A multi-cluster model is used to calculate excitation function and $\gamma$-ray flux from $^6\text{Li}(t,p)^8\text{Li}^*(0.981)$, which is proposed as a diagnostic tool for fusion reactions [2000VO22,2001VO02].

4. $^7\text{Li}(n,\gamma)^8\text{Li}$, $Q_m = 2.03229$

At $E_n = 1.5$–1340 eV agreement was found with the expected $1/v$ (velocity) energy dependence, and a thermal cross section of $40 \pm 2$(stat.) ± 4(syst.) µb was measured [1996BL10]. [1998HE35] measured $\sigma_{\text{ave}} = 101.9$ mb for an energy bin for $E_n = 1.7$–20 meV, and $\sigma_{\text{ave}} = 36.6$ µ-barns for $E_n = 5$–150 keV. A reanalysis of the ion chamber...
Fig. 2. Caption on next page.
Fig. 2. Energy levels of $^8$Li. In these diagrams, energy values are plotted vertically in MeV, based on the ground state as zero. For the $A = 8$ diagrams all levels are represented by discrete horizontal lines. Values of total angular momentum $J^\pi$, parity, and isobaric spin $T$ which appear to be reasonably well established are indicated on the levels; less certain assignments are enclosed in parentheses. For reactions in which $^8$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 the lab reference frame, while the excitation function is scaled into the cm reference frame so that resonances are aligned with levels. 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 [2003AU03]. Further information on the levels illustrated, including a listing of the reactions in which each has been observed, is contained in Table 8.2.

Table 8.5
Resonance parameters for $^8$Li$^*(2.26)^a$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{res}}$ (keV)</td>
<td>254 ± 3</td>
</tr>
<tr>
<td>$E_x$ (MeV)$^b$</td>
<td>2.261</td>
</tr>
<tr>
<td>$\Gamma$ (keV)</td>
<td>35 ± 5</td>
</tr>
<tr>
<td>$\Gamma_n$ (keV)</td>
<td>31 ± 7$^c$</td>
</tr>
<tr>
<td>$\Gamma_Y$ (eV)$^b$</td>
<td>0.07 ± 0.03</td>
</tr>
<tr>
<td>$\gamma^2$ (keV)</td>
<td>594</td>
</tr>
<tr>
<td>$\theta^2$</td>
<td>0.091</td>
</tr>
<tr>
<td>radius (fm)</td>
<td>3.30</td>
</tr>
<tr>
<td>$\sigma_{\text{max}}$</td>
<td>12.0</td>
</tr>
<tr>
<td>$J^\pi$</td>
<td>3$^+$</td>
</tr>
<tr>
<td>$l_n$</td>
<td>1</td>
</tr>
</tbody>
</table>

$^a$ Energies in lab system except for those labeled$^b$. For references see [1974AJ01,1979AJ01].

$^b$ Energies in cm system.

$^c$ $\Gamma_n \approx \Gamma$ since $\Gamma_Y$ is small.

5. $^7$Li$(n, n)^7$Li, $E_b = 2.03229$

The thermal cross section is 0.97 ± 0.04 b [see [1981MUZQ]], $\sigma_{\text{free}} = 1.07 ± 0.03$ b [1983KO17]. The real coherent scattering length is $-2.22 ± 0.01$ fm. The complex scattering lengths are $b_+ = -4.15 ± 0.06$ fm and $b_- = 1.00 ± 0.08$ fm [1983KO17]; see also [1979GL12]. See [1984AJ01] for earlier references.
\[^8\text{Li}\]


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Total and elastic cross sections have been reported for \(E_n = 5\) eV to 49.6 MeV: see [1979AJ01,1984AJ01,1988AJ01]. Cross sections have also been reported for \(n_0\), \(n_0 + 1\) and \(n_2\) at \(E_n = 6.82, 8.90\) and 9.80 MeV. ([1987SC08]; \(n_2\) at the two higher energies).

A pronounced resonance is observed at \(E_n = 254\) keV with \(J^\pi = 3^+\), formed by p-waves: see Table 8.5. A good account of the polarization is given by the assumption of levels at \(E_n = 0.25\) and 3.4 MeV, with \(J^\pi = 3^+\) and \(2^−\), together with a broad \(J^\pi = 3^−\) level at higher energy. Broad peaks are reported at \(E_n = 4.6\) and 5.8 MeV (±0.1 MeV) \([^8\text{Li}^+(6.1, 7.1)]\) with \(I^\pi \approx 1.0\) and 0.4 MeV, respectively, and there is indication of a narrow peak at \(E_n = 5.1\) MeV \([^8\text{Li}^+(6.5)]\) with \(I^\pi \ll 80\) keV and of a weak, broad peak at \(E_n = 3.7\) MeV: see [1974AJ01,1984AJ01,1988AJ01]. A multi-level, multi-channel \(R\)-matrix calculation is reported by [1987KN04]. This analysis leads to predictions for the excitation function for \(0.48\) MeV \(\gamma\)-rays shows an abrupt rise from threshold indicating s-wave formation and emission and a broad maximum \((I^\pi \approx 1\) MeV) at \(E_n = 1.35\) MeV. A good fit is obtained with either \(J^\pi = 1^−\) or \(1^+\) (2\(^{+}\) not excluded), \(I_\text{lab} = 1.14\) MeV. A prominent peak is observed at \(E_n = 3.8\) MeV (\(I_\text{lab} = 0.75\) MeV) and there is some indication of a broad resonance \((I_\text{lab} = 1.30\) MeV) at \(E_n = 5.0\) MeV. At higher energies there is evidence for structure at \(E_n = 6.8\) and 8 MeV followed by a decrease in the cross section to 20 MeV: see [1979AJ01,1984AJ01]. The total cross section for \((n_0 + n_1)\) and \(n_2\) have been reported at \(E_n = 8.9\) MeV [1984FE1A]. For \(R\)-matrix analyses see [1987KN04] in reaction 5 and [1984AJ01].

The cross section for reaction (b) rises from threshold to \(\approx 360\) mb at \(E_n \approx 6\) MeV and then decreases slowly to \(\approx 250\) mb at \(E_n \approx 16\) MeV: see [1985SW01,1987QA01]. Cross sections for tritium production have been reported from threshold to \(E_n = 16\) MeV \([1983LI1C], 4.57\) to 14.1 MeV \([1985SW01], 7.9\) to 10.5 MeV \([1987QA01], 14.74\) MeV \([1984SMZX]\) and at 14.94 MeV \([1985GO18]: 302 \pm 18\) mb). At \(E_n = 14.95\) MeV the total \(\alpha\) production cross section \(\approx 336 \pm 16\) mb \([1986KN06]. Spectra at 14.6 MeV may indicate the involvement of states of \(^4\text{He}\) \([1986MI11]\). See also references cited in [1988AJ01].

7. \(^7\text{Li}(n, 2n)^6\text{Li}, \quad Q_m = -7.25030, \quad E_h = 2.03229\)

See [1985CH37,1986CH1R]. See also [1988AJ01].

8. \(^7\text{Li}(p, \pi^+)\)\(^6\text{Li}, \quad Q_m = -138.32024\)

Angular distributions and analyzing powers for the transitions to \(^8\text{Li}^+(0, 0.98, 2.26)\) have been studied at \(E_p = 200.4\) MeV. \(\{\text{The } (p, \pi^-)\) reaction to the analog states in \(^8\text{B}\) is
### Table 8.6

<table>
<thead>
<tr>
<th>$\sigma$ (mb)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>138 ± 20</td>
<td>[1975MC02]</td>
</tr>
<tr>
<td>144 ± 15a,b</td>
<td>[1996ST18]</td>
</tr>
<tr>
<td>146 ± 13</td>
<td>[1982EL03]</td>
</tr>
<tr>
<td>146 ± 19a,b</td>
<td>[1982FI03]</td>
</tr>
<tr>
<td>148 ± 12</td>
<td>[1982FI03]</td>
</tr>
<tr>
<td>147 ± 11</td>
<td>Recommended value$^a$</td>
</tr>
</tbody>
</table>

$^a$ [1998AD12].

$^b$ Re-evaluated.

---

**8Li**

Discussed: see reaction 4 in 8B.] The $(p, \pi^+)$ cross sections are an order of magnitude greater than the $(p, \pi^-)$ cross sections and show a much stronger angular dependence [1987CA06]. Angular distributions of cross section and $A_y$ have also been measured at $E_p = 250, 354$ and $489$ MeV to the first three states of $^8$Li. Those to $^8$Li$^+(0, 0.26)$ have differential cross sections which exhibit a maximum near the invariant mass of the $\Delta(1232)$ and $A_y$ which are similar to each other and to those of the $\bar{p}p \rightarrow d\pi^+$ reaction. $^8$Li$^+(6.53)$ is populated [1987HU12,1988HU11].

9. $^7$Li(d, p)$^8$Li, $Q_m = -0.19228$

Measurements in the vicinity of the $E_{cm} = 0.61$ MeV $^9$Be$^+(17.3)$ resonance found $\sigma[7Li(d, p)] = 143.6 \pm 8.9$ mb [1996ST18], $\sigma[7Li(d, 8Li)p, 8Li \beta^- \rightarrow 8Be \rightarrow 2\alpha] = 151 \pm 20$ mb [1996ST18], and $\sigma[7Li(d, p)] = 155 \pm 8$ mb [1998WE05]. An extensive review in [1998AD12] presented the results found in Table 8.6. However, [1998WE05] suggest that systematic errors may persist in the [1998AD12] evaluation.

Angular distributions of the $p_0$ and $p_1$ groups [$l_n = 1$] at $E_d = 12$ MeV have been analyzed using DWBA: $S_{ext} = 0.87$ and 0.48 respectively for $^8$Li$^+(0, 0.98)$. Angular distributions have also been measured at several energies in the range of $E_d = 0.49$ to 3.44 MeV ($p_0$) and 0.95 to 2.94 MeV ($p_1$). The lifetime of $^8$Li$^+(0.98)$, determined from $^2H(7Li, p)^6Li$ via the Doppler-shift attenuation method, is 10.1 ± 4.5 fs: see [1979AJ01]. See also references cited in [1988AJ01].

The $^7$Li(d, p)$^8$Li $\beta^- \rightarrow$ 8Be $\rightarrow 2\alpha$ reaction was studied in the range of 0.4–1.8 MeV to investigate a mechanism where the $^8$Li reaction products are backscattered out of the target which introduces up to a 20% systematic error in measurements of the reaction yield [1998ST20]. They determined that $^8$Li reaction products are increasingly backscattered out of the target with: (i) increasing the $Z$ of the backing material, (ii) decreasing the thickness of the deposited Li/Be target, and (iii) decreasing the incident projectile energy.

10. (a) $^7$Li($^6$Li, 3Li)$^8$Li, $Q_m = -3.632$

(b) $^7$Li($^7$Li, 6Li)$^8$Li, $Q_m = -5.21801$

See [1984KO25].
8 Li


Table 8.7
R-matrix parameters for 8 He decay to 1+ levels in 8 Li

<table>
<thead>
<tr>
<th>Decay to 8 Li+ (MeV)</th>
<th>log ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.98</td>
<td>4.20</td>
</tr>
<tr>
<td>3.08</td>
<td>4.52</td>
</tr>
<tr>
<td>5.15</td>
<td>4.53</td>
</tr>
<tr>
<td>9.67</td>
<td>2.91</td>
</tr>
</tbody>
</table>

* From [1988BA67,1996BA66].

11. 8 He(β−)8 Li, \( Q_m = 10.651 \)

See reaction 1 in 8 He.

The triton spectrum observed in 8 He β-decay was analyzed in a single-level R-matrix model that indicated the triton emission branching ratio is \( (8.0 \pm 0.5) \times 10^{-2} \) [1991BO31, 1993BO24]. The R-matrix fit indicates a level at 8 Li+ (9.3 ± 1.0 MeV, \( J^\pi = 1^+ \)) with a reduced width \( \gamma_{\text{reduced}} = 0.978 \pm 0.012 \text{ MeV}^{-1/2} \) that decays primarily by triton emission; this corresponds to \( B(\text{GT}) = 5.18 \) and \( \log ft = 2.87 \) [B(\text{GT}) = 8.29, using the definition given in the introduction]. A subsequent analysis of the [1993BO24] data used a multi-level, multi-channel R-matrix model that included low-lying 1+ states in 8 Li that participate in 8 He β-decay (see Table 8.7) and suggests \( E_x = 9.67 \text{ MeV}, B(\text{GT}) = 4.75 \) and \( \log ft = 2.91 \) [1996BA66] \( B(\text{GT}) = 7.56 \), using the definition given in the introduction]. Branching ratios for 8 Li states are given in [1988BA67]. See also Fig. 2.

12. 9 Be(γ, p)8 Li, \( Q_m = -16.8882 \)

The 9 Be(γ, p) reaction was measured in the range from \( E_\gamma = 22–25.5 \text{ MeV} \) and was evaluated in a simple cluster model [1999SH05]. The analysis indicated that mainly E1 and E2 multipolarities contribute to the breakup cross section. The photodisintegration of 9 Be was measured at \( E_\gamma = 180–240 \text{ MeV} \), and the (γ + nucleus) reaction dynamics were studied by measuring 9 Be(γ, p) at \( E_\gamma = 187–427 \text{ MeV} \) in the \( \Delta(1232) \) resonance region [1988TE04].

13. 9 Be(γ, pπ0)8 Li, \( Q_m = -151.8648 \)

The total cross section for 9 Be(γ, pπ0) was measured with bremsstrahlung γ-rays in the range of \( E_\gamma = 200–850 \text{ MeV} \) [1987AN14].

14. (a) 9 Be(e, ep)8 Li, \( Q_m = -16.8882 \)
(b) 9 Be(p, 2p)8 Li, \( Q_m = -16.8882 \)

For reaction (a) see [1984AJ01,1985KI1A], The summed proton spectrum (reaction (b)) at \( E_p = 156 \text{ MeV} \) shows peaks corresponding to 8 Li gs and 8 Li+(0.98 + 2.26) [unresolved]. In addition, s-states \( J^\pi = 1^−, 2^− \) are suggested at \( E_x = 9 \) and 16 MeV, with \( \Gamma_{\text{cm}} \approx 6 \) and 8 MeV; the latter may actually be due to continuum protons: see [1974AJ01]. At \( E_p = 1 \text{ GeV} \) the separation energy between 5 and 8 MeV broad 1p3/2 and 1s1/2 groups is reported to be 10.7 ± 0.5 MeV [1985BE30,1985DO16]. See also [1987GAZM].
Table 8.8

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$J^s$</th>
<th>$l$</th>
<th>$C^2S_{rel}$</th>
<th>$C^2S_{abs}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$2^+$</td>
<td>1</td>
<td>0.843</td>
<td>1.059</td>
</tr>
<tr>
<td>0.981</td>
<td>$1^+$</td>
<td>1</td>
<td>0.506</td>
<td>0.636</td>
</tr>
<tr>
<td>2.255</td>
<td>$3^+$</td>
<td>1</td>
<td>0.552</td>
<td>0.693</td>
</tr>
<tr>
<td>2.4–2.8</td>
<td></td>
<td></td>
<td>0.099</td>
<td></td>
</tr>
</tbody>
</table>

* See [1988LI27].

For reaction (b) angular distributions were measured at 70 MeV. The data were evaluated using the distorted wave $T$-matrix approximation (DWT A) where it was determined that the 1s and 1p shells dominate in the nucleus–nucleon single-particle-knockout reaction mechanism [2000SH01].

15. $^9$Be(d, $^3$He)$^8$Li, $Q_m = -11.3947$

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

16. $^9$Be(t, $^α$)$^8$Li, $Q_m = 2.9257$

At $E_t = 12.98$ MeV, angular distributions of the $^α$-particles to $^8$Li$^*(0, 0.98, 2.26, 6.53 \pm 0.02)$ [$Γ_{cm} < 40$ keV]) have been measured: see [1974AJ01]. Angular dependent differential cross sections for $^9$Be(t, $^α$) at $E_t = 15$ MeV were compared with DWBA and coupled-channel Born approximation calculations to extract the relative and absolute $C^2S$ factors for $^8$Li + $p$: see Table 8.8 [1988LI27]. At $E_t = 17$ MeV, $σ(\theta)$ and $A_\theta$ measurements, analyzed by CCBA, lead to $J^* = 4^+$ for $^8$Li$^*(6.53)$: see [1984AJ01]. For $^8$Li$^*(0.98)$, $τ_m = 14 \pm 5$ fs, $E_x = 980.80 \pm 0.10$ keV: see [1974AJ01].

17. $^9$Be($^7$Li, $^8$Be)$^8$Li, $Q_m = 0.3669$

At $E(^7$Li) = 52 MeV, numerous $^{12}$B states are observed with $E_x$ between 10–18 MeV; $^8$Li$^*(0, 0.98, 2.25)$ participate [2003SO22]. See also [1984KO25].

18. $^9$Be($^{11}$B, $^{12}$C)$^8$Li, $Q_m = -0.931$

See [1986BE1Q].

19. $^{10}$Be(p, $^3$He)$^8$Li, $Q_m = -15.9824$

At $E_p = 45$ MeV, $^3$He ions are observed to a state at $E_x = 10.8222 \pm 0.0055$ MeV [$Γ_{cm} < 12$ keV]: the angular distributions for the transition to this state, and to its analog ($^8$Be$^*(27.49)$), measured in the analog reaction ($^{10}$Be(p, t)$^9$Be) are very similar. They are both consistent with $L = 0$ using a DWBA (LZR) analysis: see [1979AJ01].
20. $^{11}\text{B}(\pi^+, 3p)^{8}\text{Li}$, $Q_m = 105.424$

The $^{11}\text{B}(\pi^+, 3p)$ reaction was studied at 50, 100, 140 and 180 MeV using a large solid angle detector to measure the missing energy spectra [1992RA11].

21. $^{11}\text{B}(n, \alpha)^{8}\text{Li}$, $Q_m = -6.633$

The excitation function for $^{11}\text{B}(n, \alpha)^{8}\text{Li}$ was measured at $E_n = 7.6-12.6$ MeV to determine, via detailed balance, the astrophysical rate for the $^{8}\text{Li}(\alpha, n)$ reaction in the vicinity of the $^{12}\text{B}^*(10.58)$ level [1990PA22].

Angular distributions of the $\alpha_0$ and $\alpha_1$ groups have been measured at $E_n = 14.1$ and 14.4 MeV; see [1974AJ01, 1984AJ01, 1988AJ01]. Energy dependent $^{8}\text{Li}(\alpha, \alpha)$ elastic scattering phase shifts, which are important for calculating the $^{11}\text{B}(n, \alpha)^{8}\text{Li}$ reaction rate, were calculated in the range of $E_{cm} < 4$ MeV [1996DE02].

22. $^{11}\text{B}(^{7}\text{Li}, ^{10}\text{B})^{8}\text{Li}$, $Q_m = -9.422$

At $E(^{7}\text{Li}) = 34$ MeV angular distributions have been studied involving $^{8}\text{Li}^*(0, 0.98)$ and $^{10}\text{B}^*$ g.s. [1987CO16].

23. (a) $^{12}\text{C}(\pi^-, 2d)^{8}\text{Li}$, $Q_m = 92.35190$

(b) $^{12}\text{C}(\pi^-, \alpha)^{8}\text{Li}$, $Q_m = 116.19842$

Differential and total cross sections for $^{12}\text{C}(\pi^-, 2d)$ were measured at 165 MeV [1990PA03]. See [1987GA11] for a theoretical treatment of the reaction mechanism.

24. $^{12}\text{C}(\pi^+, 4p)^{8}\text{Li}$, $Q_m = 89.46746$

The $\pi^+$ absorption reaction mechanism was studied by measuring protons produced in $^{12}\text{C} + \pi^+$ reactions at 30–135 MeV [2000GI07].

25. (a) $^{12}\text{C}(p, X)$

(b) $^{13}\text{C}(p, X)$

Nuclear effects in the spallation reaction mechanism (i.e., even–odd and odd–odd nucleon pairing) were studied via $^{12, 13}\text{C}(p, ^{6, 7, 8, 9}\text{Li})$ reactions at 1 GeV [1992BE65].

26. $^{13}\text{C}(d, ^{7}\text{Be})^{8}\text{Li}$, $Q_m = -20.45614$

See [1984NE1A].

27. $^{13}\text{C}(^{7}\text{Li}, ^{8}\text{Li})^{12}\text{C}$, $Q_m = -2.91402$

Angular distributions were measured at $E(^{7}\text{Li}) = 9$ MeV / A, and a DWBA analysis was used to determine the ratio of $p_{1/2}/p_{3/2}$ contributions, and the Asymptotic Normalization
Constant (ANC) for $^7\text{Li} + n \rightarrow ^8\text{Li}$ [2003TR04]. Then, using charge symmetry, the $^7\text{Be} + p \rightarrow ^8\text{B}$ ANC was deduced, which corresponds to $S_{17}(0) = 17.6 \pm 1.7$ eV b.

28. (a) C($^8\text{Li}$, $^8\text{Li}'$)C
(b) Ni($^8\text{Li}$, $^8\text{Li}'$)Ni
(c) Au($^8\text{Li}$, $^8\text{Li}'$)Au
(d) Pb($^8\text{Li}$, $^8\text{Li}'$)Pb

Elastic and inelastic scattering of $^8\text{Li}$ on nat C were measured at $E(^8\text{Li}) = 13.8–14$ MeV [1991SM02]. Optical model parameters were deduced for the $2^+$ ground state and the first $1^+$ excited state at $\approx 1$ MeV and $B(E2)\uparrow = 30 \pm 15$ e$^2$ fm$^4$ was deduced. In addition nat Au($^8\text{Li}$, $^8\text{Li}$) was measured for comparison with Rutherford scattering.

The $^8\text{Li}$ first $1^+$ excited state at $1.0 \pm 0.1$ MeV was observed in Coulomb excitation on nat Ni at $E(^8\text{Li}) = 14.6$ MeV [1991BR14] and $B(E2)\uparrow = 55 \pm 15$ e$^2$ fm$^4$ was determined for this excitation. See [2003BE38] for elastic and inelastic scattering on Pb at $E(^8\text{Li}) = 20–36$ MeV.

29. nat C($\mu$, $^8\text{Li}$)X

A measurement to determine muon induced background rates in large-volume scintillation solar neutrino detectors found $\sigma = 2.93 \pm 0.80$ µb and $4.02 \pm 1.46$ µb for nat C($\mu$, $^8\text{Li}$) at $E_\mu = 100$ and 190 GeV, respectively [2000HA33].

30. (a) C($^8\text{Li}$, X)
(b) Si($^8\text{Li}$, X)
(c) Pb($^8\text{Li}$, X)

Total cross sections and charge-changing cross sections for the lithium isotopes on C and Pb were measured at 80 MeV/A [1992BL10]; it was deduced that post-abrasion evaporation plays a minor role in these reactions. For reaction (b) the energy-dependent total reaction cross sections at 20–60 MeV/A were measured [1996WA27] and compared with microscopic and shell model predictions. A review of nuclear radii deduced from interaction cross sections is given in [2001OZ04].

31. (a) nat Ag($^{14}\text{N}$, $^8\text{Li}$)
(b) nat Ag($^{14}\text{N}$, $n + ^7\text{Li}$)
(c) $^{165}\text{Ho}$$^{14}\text{N}$, X

Population of the $^8\text{Li}$ ground state and 2.255 MeV neutron unbound state was reported in reactions (a) and (b) at 35 MeV/A. The reaction nuclear temperature was estimated [1987BL13]. In a similar study of 35 MeV/A $^{14}\text{N}$ on $^{165}\text{Ho}$, [1987KI05] deduced that the $^8\text{Li}^*$(2.255) state has $\Gamma = 33$ keV from the $^7\text{Li} + n$ relative energy spectrum.
$^8$Be

(Figs. 3 and 5)

General

References to articles on general properties of $^8$Be published since the previous review [1988AJ01] are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for $^8$Be located on our website at www.tunl.duke.edu/nucldata/General_Tables/8be.shtml.

1. $^8$Be $\rightarrow$ $^4$He$^4$He, $Q_m = 0.0918$

$\Gamma_{cm}$ for $^8$Be g.s. = $5.57 \pm 0.25$ eV; see reaction 4. See also reaction 29 and references cited in [1974AJ01, 1988AJ01].

2. $^4$He($\alpha$, $\gamma$) $^8$Be, $Q_m = -0.0918$

The yield of $\gamma_1$ has been measured for $E_\alpha = 32$ to 36 MeV. The yield of $\gamma_0$ for $E_\alpha = 33$ to 38 MeV is twenty times lower than for $\gamma_1$, consistent with E2 decay: see [1979AJ01]. Angular distributions were measured in the $^4$He($\alpha$, $\gamma$) reaction in the region around the 16 MeV isospin mixed doublet as a study of CVC in $A = 8$ nuclei and second class currents [1994DE30, 1995DE18]. No evidence for CVC violation was observed. Mixing ratios were reported as $\epsilon = [\Gamma_T^{E2} / \Gamma_M^{E1}]^{1/2} = +0.21 \pm 0.04$, $\delta_0 = [\Gamma_T^{E2} / \Gamma_M^{E1}]^{1/2} = +0.01 \pm 0.03$ and $\Gamma_T^{E1} = 2.80 \pm 0.18$ eV [1995DE18], and they note that earlier values [1978BO30] were troubled by a transformation error. The $E_x$ of $^8$Be$^*$ (3.0) is determined in this reaction to be 3.18 $\pm$ 0.05 MeV [1979AJ01] [see also Table 8.11].

The E2 bremsstrahlung cross section to $^8$Be g.s. has been calculated as a function of $E_x$ over the 3 MeV state: the total $\Gamma_\gamma$ for this transition is 8.3 meV, corresponding to 75 W.u. [1986LA05]. A calculation of the $\Gamma_\gamma$ from the decay of the 4$^+$ 11.4 MeV state to the 2$^+$ state yields 0.46 eV (19 W.u.). The maximum cross section for the intrastate $\gamma$-ray transition within the 2$^+$ resonance is calculated to be $\leq 2.5$ nb at $E_x \approx 3.3$ MeV [1986LA19]. See also [2001CS04] for discussion of the impact of variation in the NN force on the nucleosynthesis rates of $^8$Be and $^{12}$C.

3. (a) $^4$He($\alpha$, n)$^7$Be, $Q_m = -18.99152$, $E_0 = -0.09184$

(b) $^4$He($\alpha$, p)$^7$Li, $Q_m = -17.34695$

(c) $^4$He($\alpha$, d)$^6$Li, $Q_m = -22.372683$

The cross sections for formation of $^7$Li$^*$ (0, 0.48) [$E_\alpha = 39$ to 49.5 MeV] and $^7$Be$^*$ (0, 0.43) [39.4 to 47.4 MeV] both show structures at $E_\alpha \approx 40.0$ and $\approx 44.5$ MeV; they are due predominantly to the 2$^+$ states $^8$Be$^*$ (20.1, 22.2): see [1979AJ01]. The excitation functions for p$_0$, p$_2$, d$_0$, d$_1$ for $E_\alpha = 54.96$ to 55.54 MeV have been measured in order to study the decay of the first $T = 2$ state in $^8$Be: see Table 8.5 in [1984AJ01]. Cross sections for
Table 8.9
Energy levels of $^8$Be

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$J^\pi$</th>
<th>$T_{\text{cm}}$ (keV)</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>$0^+; 0$</td>
<td>5.57 ± 0.25 eV$^i$</td>
<td>$\alpha$</td>
<td>1, 2, 4, 5, 10, 11, 12, 13, 14, 19, 20, 21, 22, 23, 25, 28, 29, 30, 31, 33, 36, 39, 40, 41, 42, 43, 44, 45, 46, 47, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62</td>
</tr>
<tr>
<td>3.03 ± 10$^i$</td>
<td>$2^+; 0$</td>
<td>1513 ± 15$^i$</td>
<td>$\alpha$</td>
<td>2, 4, 5, 10, 11, 12, 13, 14, 19, 20, 21, 22, 24, 27, 28, 29, 30, 31, 33, 36, 40, 41, 42, 43, 44, 45, 46, 47, 50, 51, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62</td>
</tr>
<tr>
<td>11.35 ± 150$^b$</td>
<td>$4^+; 0$</td>
<td>$\approx 3500$</td>
<td>$\alpha$</td>
<td>4, 12, 13, 19, 21, 29, 30, 31, 41, 51, 53</td>
</tr>
<tr>
<td>16.626 ± 3</td>
<td>$2^+; 0 + 1$</td>
<td>108.1 ± 0.5</td>
<td>$\gamma, \alpha$</td>
<td>2, 4, 10, 11, 13, 14, 19, 20, 21, 27, 29, 30, 31, 40, 41, 44, 51, 53</td>
</tr>
<tr>
<td>16.922 ± 3</td>
<td>$2^+; 0 + 1$</td>
<td>74.0 ± 0.4</td>
<td>$\gamma, \alpha$</td>
<td>2, 4, 10, 11, 13, 14, 19, 20, 21, 29, 30, 31, 40, 41, 44, 51, 53</td>
</tr>
<tr>
<td>17.640 ± 1.0$^b$</td>
<td>$1^+; 1$</td>
<td>10.7 ± 0.5</td>
<td>$\gamma, p$</td>
<td>5, 11, 14, 16, 19, 20, 29, 30, 31, 41, 53</td>
</tr>
<tr>
<td>18.150 ± 4</td>
<td>$1^+; 0$</td>
<td>138 ± 6</td>
<td>$\gamma, p$</td>
<td>11, 14, 16, 19, 20, 29, 30, 41, 44</td>
</tr>
<tr>
<td>18.91</td>
<td>$2^−; 0 (+ -1)$</td>
<td>122$^e$</td>
<td>$\gamma, n, p$</td>
<td>11, 14, 15, 16, 19, 23</td>
</tr>
<tr>
<td>19.07 ± 30</td>
<td>$3^+; (1)$</td>
<td>270 ± 20</td>
<td>$\gamma, p$</td>
<td>11, 14, 16, 19, 20, 30</td>
</tr>
<tr>
<td>19.235 ± 10$^b$</td>
<td>$3^+; (0)$</td>
<td>227 ± 16$^i$</td>
<td>$n, p$</td>
<td>15, 16, 19, 29, 30, 31, 41, 64</td>
</tr>
<tr>
<td>19.40</td>
<td>$1^−$</td>
<td>$\approx 645$</td>
<td>$n, p$</td>
<td>11, 15, 16, 29</td>
</tr>
<tr>
<td>19.86 ± 50$^b$</td>
<td>$4^+; 0$</td>
<td>700 ± 100</td>
<td>$p, \alpha$</td>
<td>4, 11, 18, 21, 22, 30, 31, 41</td>
</tr>
<tr>
<td>20.1$^b$</td>
<td>$2^+; 0$</td>
<td>880 ± 20$^b$</td>
<td>$n, p, \alpha$</td>
<td>4, 15, 16, 18, 19, 22, 41</td>
</tr>
<tr>
<td>20.2</td>
<td>$0^+; 0$</td>
<td>720 ± 20$^o$</td>
<td>$\alpha$</td>
<td>4, 19, 41</td>
</tr>
<tr>
<td>20.9</td>
<td>$4^−$</td>
<td>1600 ± 200</td>
<td>$p$</td>
<td>16</td>
</tr>
<tr>
<td>21.5</td>
<td>$3^(+)$</td>
<td>1000</td>
<td>$\gamma, n, p$</td>
<td>14, 15, 41</td>
</tr>
<tr>
<td>22.0$^c$</td>
<td>$1^−; 1$</td>
<td>$\approx 4000$</td>
<td>$\gamma, p$</td>
<td>14</td>
</tr>
<tr>
<td>22.05 ± 100</td>
<td>$2^+$</td>
<td>270 ± 70</td>
<td>$n, p, d, \alpha$</td>
<td>4, 9, 13, 15, 16, 18, 41</td>
</tr>
<tr>
<td>22.2</td>
<td>$2^+; 0$</td>
<td>$\approx 800$</td>
<td>$n, p, d, \alpha$</td>
<td>31</td>
</tr>
<tr>
<td>22.63 ± 100</td>
<td></td>
<td>100 ± 50</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>22.98 ± 100</td>
<td></td>
<td>230 ± 50</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>24.0$^e$</td>
<td>$(1, 2)^−; 1$</td>
<td>$\approx 7000$</td>
<td>$\gamma, p, \alpha$</td>
<td>14, 18, 41</td>
</tr>
<tr>
<td>25.2</td>
<td>$2^+; 0$</td>
<td></td>
<td>$p, d, \alpha$</td>
<td>4, 9, 18, 41</td>
</tr>
<tr>
<td>25.5</td>
<td>$4^+; 0$</td>
<td></td>
<td>$d, \alpha$</td>
<td>9</td>
</tr>
<tr>
<td>27.494 ± 1.8$^d$</td>
<td>$0^+; 2$</td>
<td>5.5 ± 2.0</td>
<td>$\gamma, n, p, d, t, ^3\text{He}, \alpha$</td>
<td>5, 7, 9, 35</td>
</tr>
<tr>
<td>(28.6)</td>
<td>$0^+$</td>
<td>1 MeV$^i$</td>
<td>$\gamma, p$</td>
<td>14</td>
</tr>
<tr>
<td>$^{(\approx 41)^i}$</td>
<td></td>
<td></td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

(continued on next page)
Table 8.9 (continued)

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$J^\pi$, $T$</th>
<th>$\Gamma_{em}$ (keV)</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>($\approx 43$)</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>($\approx 50$)</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a See also Table 8.10 and reaction 4.
b See, however, reaction 29.
c Giant resonance: see reaction 14.
d For the parameters of this state please see Table 8.5 in [1984AJ01].
e From $R$-matrix fit: see reaction 23.
f $\Gamma_\gamma/\Gamma_{(\gamma_0+\gamma_1)} = 0.72 \pm 0.07$ [1995ZA03].
g $\Gamma_\gamma/\Gamma_p = 4.5 \pm 0.6$ [1992PU06].
h From data reviewed in this evaluation.
i Intruder state at $\approx 9$ MeV, deduced from $R$-matrix analysis of $\beta$-delayed $2\alpha$ breakup spectra [2000BA89]. The placement of this level is dependent on the channel radius used in the $R$-matrix fit [1986WA01,2000BA89]. However, [1986WA01] finds no need to introduce intruder states below $E_x = 26$ MeV.

The production of $^6$Li, $^7$Li and $^7$Be [and $^6$He] has been studied at $E_\alpha = 61.5$ to 158.2 MeV by [1982GL01], at 198.4 MeV by [1985WO11], and at $E_\alpha = 160, 280$ and 320 MeV by [2001ME13]. The production of $^7$Li (via reactions (a) and (b)) and of $^6$Li is discussed. At energies beyond $E_\alpha \approx 250$ MeV the $\alpha + \alpha$ reaction does not contribute to the natural abundance of lithium, reinforcing theories which produce $^6$Li in cosmic-ray processes and the "missing" $^7$Li in the Big Bang: thus the universe is open [1982GL01, 1985WO11]. The measurements of [2001ME13] have observed smaller cross sections for $^6$Li production than previous extrapolations, and reduce uncertainty in extrapolation to higher energies.

The inclusive cross section for production of $^3$He has been measured at $E_\alpha = 218$ MeV [1984AL03]. For a fragmentation study at 125 GeV see [1985BE1E]. See also references cited in [1988AJ01].

4. $^4$He($\alpha$, $\alpha$)$^4$He, $E_b = -0.091839$

The $^8$Be$_{g.s.}$ parameters are determined from $\alpha-\alpha$ scattering across the resonance region. Evaluation of the parameters requires an analysis of the influence of various possible charge states in the low-energy $^4$He($\alpha$, $\alpha$) scattering process [1992WU09]. A measurement that detected $\alpha-\alpha$ coincidences at $\theta(\alpha_1, \alpha_2) = (45^\circ, 45^\circ)$ and $(30^\circ, 60^\circ)$ was performed using a gas jet target, which permitted an energy resolution of 26 eV; the resulting parameters for $^8$Be$_{g.s.}$ are $E_b = -92.04 \pm 0.05$ keV and $\Gamma = 5.57 \pm 0.25$ eV [1992WA09]. Previous values that had been obtained in a configuration that yielded 95 eV energy resolution were $E_b = -92.12 \pm 0.05$ keV and $\Gamma = 6.8 \pm 1.7$ eV [1968BE02]. For $E_\alpha = 30$ to 70 MeV the $l = 0$ phase shift shows resonant behavior at $E_\alpha = 40.7$ MeV, corresponding to a $0^+$ state at $E_x = 20.2$ MeV, $\Gamma < 1$ MeV, $\Gamma_\alpha/\Gamma < 0.5$. No evidence for other $0^+$ states is seen above $E_\alpha = 43$ MeV.
The d-wave phase shift becomes appreciable for $E_\alpha > 2.5$ MeV and passes through a resonance at $E_\alpha = 6$ MeV ($E_x = 3.18$ MeV, $I = 1.5$ MeV, $J^\pi = 2^+$): see Table 8.11. Five $2^+$ levels are observed from $l = 2$ phase shifts measured from $E_\alpha = 30$ to 70 MeV: $^8\text{Be}^*$$(16.6,16.9)$ with $I_\alpha = I$ [see Table 8.11], and states with $E_x = 20.1, 22.2$ and 25.2 MeV. The latter has a small $I_\alpha$. The $l = 2 \alpha$-$\alpha$ phase shifts have been analyzed by [1986WA01] up to $E_\alpha = 34$ MeV; intruder states below $E_x = 26$ MeV need not be introduced. However, see discussion in reactions 24 and 27, and see [1988BA75,1989BA31,2000BA89] which introduces an intruder state at $\approx 9$ MeV.
The $l = 4$ phase shift rises from $E_{\alpha} \approx 11$ MeV and indicates a broad 4\textsuperscript{+} level at $E_\chi \approx 11.5 \pm 0.3$ MeV [$\Gamma = 4.0 \pm 0.4$ MeV]. A rapid rise of $\delta_4$ at $E_{\alpha} = 40$ MeV corresponds to a 4\textsuperscript{+} state at 19.9 MeV with $\Gamma_\alpha / \Gamma \approx 0.96$; $\Gamma \ll 1$ MeV and therefore $\Gamma_\alpha < 1$ MeV, which is $< 5\%$ of the Wigner limit. A broad 4\textsuperscript{+} state is also observed near $E_{\alpha} = 51.3$ MeV ($E_\chi = 25.5$ MeV). Over the range $E_{\alpha} = 30$ to 70 MeV a gradual increase in $\delta_4$ is observed. Some indications of a 6\textsuperscript{+} state at $E_\chi \approx 28$ MeV and of an 8\textsuperscript{+} state at $\approx 57$ MeV have been reported; $\Gamma_{\text{cm}} \approx 20$ and $\approx 73$ MeV, respectively. A resonance is not observed at the first $T = 2$ state, $^{8}\text{Be}^* (27.49)$. See [1979AJ01] for references.

The elastic scattering has also been studied at $E_{\alpha} = 56.3$ to 95.5 MeV [1987NE1C], 158.2, 650 and 850 MeV, and at 4.32 and 5.07 GeV/c [see [1979AJ01,1984AJ01]], as well as at 198.4 MeV [1985WO11]. For $\alpha - \alpha$ correlations involving $^{8}\text{Be}^* (0,3)\text{MeV}$ see [1987CH33,1987PO03]. Resonances in $\alpha - \alpha$ scattering and the role of $\alpha$ clustering in $^{8}\text{Be}$ have been investigated in theoretical studies of $^4\text{He}(\alpha, \alpha)$ [1987PR01,1987VI05, 1987WA07,1995LI07,1996KU08,1996VO15,2000MO07,2002BH03]. For inclusive cross sections see [1984AJ01] and (1984AL03; 218 MeV). For studies at very high energies see reaction 3 and references cited in [1988AJ01].
5. $^6$Li(d, $\gamma$)$^8$Be, \( Q_m = 22.2809 \)

The yield of $\gamma$-rays to $^8$Be*(17.64) [1+; \( T = 1 \)] has been measured for $E_d = 6.85$ to 7.10 MeV. A resonance is observed at $E_d = 6965$ keV \( |E_x| = 27495.8 \pm 2.4 \) keV, $\Gamma_{cm} = 5.5 \pm 2.0$ keV; $\Gamma_\gamma = 23 \pm 4$ eV \( [1.14 \pm 0.20 \) W.u.] for this M1 transition from the first 0+; \( T = 2 \) state in $^8$Be, in good agreement with the intermediate coupling model: see Table 8.5 in [1984AJ01].1 Angular distributions of cross sections and polarization observables \( A_{\alpha}^{\nu(9)} \), \( A_{\alpha}^{\nu(9)} \), \( T_{20}^{(6)} \) were measured at $E_d = 9$ MeV [1991WI19] and $E_d = 2$ and 9 MeV [1994WI08]. In addition, [1994WI08] measured the excitation function from $E_d = 7$–14 MeV; capture to the $^8$Be ground state and 3.0 MeV state were observed. A transition matrix element analysis for $^6$Li(d, $p_0$) at 9 MeV indicates a 13–21% E1 contribution in addition to the expected dominant E2 strength. This suggests \( \approx 1.5\% \) D-state admixture in the $^8$Be ground state. See also [1979AJ01].

6. $^6$Li(d, n)$^7$Be, \( Q_m = 3.38117 \), \( E_b = 22.28085 \)

Yield curves and cross sections have been measured for $E_d = 48$ keV to 17 MeV: see [1979AJ01,1984AJ01]. At $E_{cm} = 96.6$ keV \( \sigma = 3.17 \) mb \( \pm 3\% \) (stat.) \( \pm 7.5\% \) (syst.) [2001HO23]. Polarization measurements are reported at $E_d = 0.27$ to 3.7 MeV. Angular distributions were measured for $^6$Li(d, n) at $E_d = 0.7$–2.3 and 5.6–12.1 MeV and excitation functions for neutrons corresponding to $^7$Be*\((0, 0.43, 4.57, 7.21)\) are reported [1996BO27]. Comparisons of the populations of $^7$Be*\((0, 0.43)\) and of $^7$Li*\((0, 0.48)\) have been made at energies up to $E_d = 7.2$ MeV. The \((d, n)/(d, p)\) ratios are closely equal for analog states, as expected from charge symmetry: see [1979AJ01]. However, the \( n_1/p_1 \) yield ratio decreases from 1.05 at $E_d = 160$ keV to 0.94 at 60 keV; it is suggested that this is due to charge polarization of the deuteron [1985CE12]. See reaction 7 for additional comments about the \((d, p)/(d, n)\) ratio. See also $^7$Be in [2002TI10,1988AJ01].

7. $^6$Li(d, p)$^7$Li, \( Q_m = 5.02573 \), \( E_b = 22.28085 \)

Excitation functions have been measured for $E_d = 30$ keV to 5.4 MeV: see [1979AJ01,1984AJ01]. The thick target yield of 0.48 MeV $\gamma$-rays is reported from \( \approx 50 \) to 170 keV [1985CE12]. An anomaly is observed in the \( p_1/p_0 \) intensity ratio at $E_d = 6.945$ MeV [see [1979AJ01]], corresponding to the first 0+; \( T = 2 \) state, \( \Gamma = 10 \pm 3 \) keV, \( \Gamma_0 \approx \Gamma_{p_0} \), \( \Gamma_{p_0} < \Gamma_{d_0} \). The \((d, p_0)/(d, n_0)\) ratio is measured in the astrophysical range from 65 keV < $E_d$ < 200 keV [1993CZ01,1997CZ04]. In this region the subthreshold isospin mixed 2+ level at $^8$Be*\((22.2; \Gamma \approx 800 \) keV) could influence the \((d, p_0)/(d, n_0)\) ratio, which is important in inhomogeneous Big Bang nucleosynthesis models. The observed ratio is \( \Gamma_{n_0}/\Gamma_{p_0} \approx 0.95 \pm 0.03 \) which is consistent with the presently accepted isospin mixing parameter \( \epsilon = 0.20 \). The $^6$Li(d, p) and $^6$Li(d, $\alpha$) reactions were measured at $E_d = 20$–135 keV [1993CE02], and a nearly constant \( \sigma (d, p_0 + p_1)/\sigma (d, \alpha) \) ratio of 0.55 was observed indicating that there is no anomalous behavior in the low energy $^6$Li(d, p) cross section.

1 However, please note that there is an error in Table 8.5 from [1984AJ01]. For the 27.5 MeV level, the parameter given as $\Gamma_{p_0}$ should be listed as $\Gamma_\gamma(27.5$ to 17.6).
Polarization measurements have been reported at $E_d = 0.6$ to 10.9 MeV; see [1979AJ01]. See also $^7$Li in [2002TI10] and ([1984KU15]; theor.).

8. (a) $^6$Li(d, d)$^6$Li, $E_b = 22.280845$
(b) $^6$Li(d, t)$^5$Li, $Q_m = 0.593$

The yield of elastically scattered deuterons has been measured for $E_d = 2$ to 7.14 MeV. No resonances are observed; see [1974AJ01]. See also ([1983HA1D,1985LI1C]; theor.).

The cross section for tritium production rises rapidly to 190 mb at 1 MeV, then more slowly to 290 mb near 4 MeV; see [1974AJ01]. For VAP and TAP measurements at $E_d = 191$ and 395 MeV see [1986GA18].

9. (a) $^6$Li(d, $^a$He), $Q_m = 22.372683$, $E_b = 22.280845$
(b) $^6$Li(d, $^a$p)$^3$H, $Q_m = 2.558823$

Cross sections and angular distributions (reaction (a)) have been measured at $E_d = 10$ keV to 31 MeV; see [1979AJ01,1984AJ01,1992EN01,1992EN04] for $E_d = 10$–1450 keV, and [1997CZ01] for $E_d = 50$–180 keV. A DWBA analysis by [1997CZ01] of data up to 1 MeV evaluated the impact of the subthreshold resonance $^8$Be$^*$ (22.2) on the measured cross sections. In the DWBA analysis, data was limited to energies above $E_d = 60$ keV in order to minimize the effect of screening; the analysis indicated an energy $E_{res} = (-50 \pm 20)$ keV for the subthreshold resonance. The $^6$Li(6Li, 2$^a$p) reaction was measured at $E_{(6Li)} = 6$ MeV and was evaluated in the “Trojan Horse” method to extract the $^6$Li(d, $^a$He) reaction cross sections and $S$-factors in the astrophysically relevant range from $E_{cm} = 13$ to 750 keV [2001SP04]; a detailed analysis of these data, that accounted for the electron screening process, deduced $S(0) = 16.9 \pm 0.5$ MeV b [2001MU30]. See also [1992EN01,1992EN04] for detailed discussion of electron screening in direct measurements of $^6$Li(d, $^a$He) and $^3$H($^6$Li, $^a$He) in the energy range of $E_{cm} < 1500$ keV. See also [2002BA77]. Polarization measurements are reported in the range 0.4 to 11 MeV; see [1979AJ01,1984AJ01] and see below. See also reaction 7 for comments about the astrophysical (d, p)/(d, $^a$He) ratio. See [1984AJ01] for a critical analysis of thermonuclear reaction rate parameters.

Pronounced variations are observed in the cross sections and in the analyzing powers. Maxima are seen at $E_d = 0.8$ MeV, $T_{lab} \approx 0.8$ MeV and $E_d = 3.75$ MeV, $T_{lab} \approx 1.4$ MeV. The 4 MeV peak is also observed in the tensor component coefficients with $L = 0$, 4 and 8 and in the vector component coefficients: two overlapping resonances are suggested. At higher energies all coefficients show a fairly smooth behavior which suggests that only broad resonances can exist. The results are in agreement with those from reaction 4, that is with two $^2$ states at $E_x = 22.2$ and 25.2 MeV and a $^4$ state at 25.5 MeV. A strong resonance is seen in the $^a$ channel [to $^4$He(20.1), $J^g = 0^+$] presumably due to $^8$Be$^*$ (25.2, 25.5). In addition the ratio of the $^a$/$^a$ differential cross sections at 30$^\circ$ shows a broad peak centered at $E_x \approx 26.5$ MeV (which may be due to interference effects) and suggests a resonance-like anomaly at $E_x \approx 28$ MeV. $A_{yy} = 1$ points are reported at $E_d = 5.55 \pm 0.12$ ($\theta_{cm} = 29.7 \pm 1.0^\circ$) and $8.80 \pm 0.25$ MeV ($\theta_{cm} = 90.0 \pm 1.0^\circ$) [corresponding to $E_x = 26.44$ and 28.87 MeV]. For references see [1974AJ01,1979AJ01].
Table 8.11
Some $^8$Be states with $3.0 < E_x < 23.0$ MeV

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$\Gamma_{cm}$ (keV)</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.18 ± 50</td>
<td>1750 ± 300</td>
<td>$^4\text{He}(\alpha, \gamma)$</td>
</tr>
<tr>
<td>2.83 ± 200</td>
<td>1200 ± 300</td>
<td>$^6\text{Li}(^3\text{He}, \alpha)^{10}\text{B}(d, \alpha)$</td>
</tr>
<tr>
<td>3.1 ± 100</td>
<td>1750 ± 100</td>
<td>$^7\text{Li}(d, \alpha)$</td>
</tr>
<tr>
<td>3.10 ± 90</td>
<td>1740 ± 80</td>
<td>$^7\text{Li}(d, n)$</td>
</tr>
<tr>
<td>2.90 ± 60</td>
<td>1530 ± 40</td>
<td>$^7\text{Be}(d, p)^9\text{Be}(p, d)$</td>
</tr>
<tr>
<td>3.038 ± 25</td>
<td>1500 ± 20</td>
<td>$^9\text{Be}(p, d)^{11}\text{B}(p, \alpha)$</td>
</tr>
<tr>
<td>3.03 ± 10</td>
<td>1430 ± 60</td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td>2.90 ± 40</td>
<td>1350 ± 150</td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td>3.03 ± 0.01</td>
<td>1513 ± 15</td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td>11.5 ± 300</td>
<td>4000 ± 400</td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td>11.3 ± 400</td>
<td>2800 ± 300</td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td>11.3 ± 200</td>
<td>5200 ± 100</td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td><strong>11.35 ± 150</strong></td>
<td><strong>≈ 3500</strong></td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td>16.627 ± 5</td>
<td>113 ± 3</td>
<td>$^7\text{Li}(^3\text{He}, d)^{10}\text{B}(d, \alpha)$</td>
</tr>
<tr>
<td>16.623 ± 3</td>
<td>107.7 ± 0.5</td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td>16.630 ± 3</td>
<td>108.5 ± 0.5</td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td><strong>16.626 ± 3</strong></td>
<td><strong>108.1 ± 0.5</strong></td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td>16.901 ± 5</td>
<td>77 ± 3</td>
<td>$^7\text{Li}(^3\text{He}, d)^{10}\text{B}(d, \alpha)$</td>
</tr>
<tr>
<td>16.925 ± 3</td>
<td>74.4 ± 0.4</td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td>16.918 ± 3</td>
<td>73.6 ± 0.4</td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td><strong>16.922 ± 3</strong></td>
<td><strong>74.0 ± 0.4</strong></td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td><strong>17.640 ± 1.0</strong></td>
<td><strong>10.7 ± 0.5</strong></td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td>18.155 ± 5</td>
<td>147</td>
<td>$^7\text{Li}(p, \gamma)^{10}\text{B}(d, \alpha)$</td>
</tr>
<tr>
<td>18.150 ± 5</td>
<td>138 ± 6</td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td>18.144 ± 5</td>
<td>90 ± 5</td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td><strong>18.150 ± 4</strong></td>
<td><strong>138 ± 6</strong></td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td>19.06 ± 20</td>
<td>270 ± 20</td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td>19.071 ± 10</td>
<td>270 ± 30</td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td><strong>19.07 ± 30</strong></td>
<td><strong>270 ± 20</strong></td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td>19.21</td>
<td>208 ± 30</td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td>19.22 ± 30</td>
<td>265 ± 30</td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td>19.23 ± 12</td>
<td>210 ± 35</td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td>19.26 ± 30</td>
<td>220 ± 30</td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td><strong>19.235 ± 10</strong></td>
<td><strong>227 ± 10</strong></td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td>19.86 ± 50</td>
<td>700 ± 100</td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td>22.05 ± 100</td>
<td>270 ± 70</td>
<td>“mean” value$^d$</td>
</tr>
<tr>
<td><strong>22.05 ± 100</strong></td>
<td><strong>270 ± 70</strong></td>
<td>“mean” value$^d$</td>
</tr>
</tbody>
</table>

(continued on next page)
Table 8.11 (continued)

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$\Gamma_{cm}$ (keV)</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.63 ± 100</td>
<td>100 ± 50</td>
<td>$^8\text{Be}(^3\text{He},\alpha)$</td>
</tr>
<tr>
<td>22.98 ± 100</td>
<td>230 ± 50</td>
<td>$^9\text{Be}(^3\text{He},\alpha)$</td>
</tr>
</tbody>
</table>

a See Table 8.5 in [1979AJ01] for references. See also Tables 8.11 and 8.12 here.
b From $R$-matrix analysis.
c Complex eigenvalue theory.
d These parameters represent the weighted average of values given in Table 8.4 of [1974AJ01]: the value $E_x = 3.18 ± 0.05$ MeV from $^4\text{He}(\alpha,\gamma)$, the values $E_x = 3.038 ± 0.025$ MeV, $\Gamma = 1500 ± 20$ keV from $^9\text{Be}(p,d)$ that were adopted in [1984AJ01]; and $E_x = 3.03 ± 0.01$ MeV, $\Gamma = 1430 ± 60$ keV from $^9\text{Be}(d,t)$. The average of the most recent values from $^9\text{Be}(p,d)$ and $^9\text{Be}(d,t)$ yields $E_x = 3.03 ± 0.01$ MeV and $\Gamma = 1490 ± 20$ keV. See also [2002BH03].

At $E_d = 6.945$ MeV, the $\alpha_0$ yield shows an anomaly corresponding to $^8\text{Be}^*(27.49)$, the $0^+$; $T = 2$ analog of $^8\text{He}^*$.

A measurement of angular distributions and the excitation function for $^6\text{Li}(d,\alpha)$ for $E_d = 18.2–44.5$ MeV [1994AR24] found evidence for possible states at $\approx 41$ MeV, $\approx 43$ MeV and $\approx 50$ MeV.

A kinematically complete study of reaction (b) has been reported at $E_d = 1.2$ to 8.0 MeV: the transition matrix element squared plotted as a function of $E_{\alpha\alpha^*}$ (the relative energy in the channel $^4\text{He}^*(20.1) \otimes 0^+$) shows a broad maximum at $E_x \approx 25$ MeV. Analysis of these results, and of a study of $^7\text{Li}(p,\alpha)\alpha^*$ [see reaction 18] which shows a peak of different shape at $E_x \approx 24$ MeV, indicate the formation and decay of overlapping states of high spatial symmetry, if the observed structures are interpreted in terms of $^8\text{Be}$ resonances: see [1984AJ01]. For other work see [1984AJ01]. See also $^6\text{Li}$ in [2002TI10] and references cited in [1988AJ01].

10. $^6\text{Li}(t,n)^8\text{Be}$, $Q_m = 16.0236$

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

11. (a) $^6\text{Li}(^3\text{He},p)^8\text{Be}$, $Q_m = 16.7874$
(b) $^6\text{Li}(^3\text{He},p)^4\text{He}^3\text{He}$, $Q_m = 16.879206$

Angular distributions have been studied in the range $E(^3\text{He}) = 0.46$ to 17 MeV and at $E(^6\text{Li}) = 21$ MeV: $^8\text{Be}^*(0, 3.0, 16.63, 16.92, 17.64, 18.15, 19.0, 19.4, 19.9)$ are populated in this reaction: see [1974AJ01,1979AJ01,1984AJ01]. Angular distributions of cross sections and $A_y(\theta)$ were measured for $^6\text{Li}(^3\text{He},p_0$ and $p_1$) at $E_{^3\text{He}} = 4.6$ MeV [1995BA24]. A DWBA analysis indicates that a direct reaction mechanism dominated for both states, in contradiction with previous results that suggested a dominant compound nucleus contribution. See also [2003VO02,2003VO08] for an evaluation of the reaction rates below $E(^3\text{He}) = 1$ MeV. For reaction (b) see [1974AJ01,1987ZA07]. See also $^9\text{B}$. 
12. (a) $^6\text{Li}(\alpha, d)^8\text{Be}$, \( Q_m = -1.5657 \)
(b) $^6\text{Li}(\alpha, 2\alpha)^3\text{H}$, \( Q_m = -1.473844 \)

Deuteron groups have been observed to $^8\text{Be}^*(0, 3.0, 11.3 \pm 0.4)$. Angular distributions have been measured at $E_a = 15.8$ to 48 MeV; see [1974AJ01, 1979AJ01]. A study of reaction (b) shows that the peak due to $^8\text{Be}^*(3.0)$ is best fitted by using $\Gamma = 1.2 \pm 0.3$ MeV. At $E_a = 42$ MeV the $\alpha-\alpha$ FSI is dominated by $^8\text{Be}^*(0, 3.0)$. See also Table 8.11 and ([1983BE1H]; theor.).

13. (a) $^6\text{Li}(^6\text{Li}, \alpha)^8\text{Be}$, \( Q_m = 20.8070 \)
(b) $^6\text{Li}(^6\text{Li}, \alpha)^4\text{He}^2\text{He}$, \( Q_m = 20.898839 \)
(c) $^6\text{Li}(^6\text{Li}, 2\alpha)^4\text{He}^2\text{He}$, \( Q_m = -2.947688 \)

At $E_{\text{max}}(^6\text{Li}) = 13$ MeV reaction (a) proceeds via $^8\text{Be}^*(0, 3.0, 16.6, 16.9, 22.5)$. The involvement of a state at $E_x = 19.9$ MeV ($\Gamma = 1.3$ MeV) is suggested. Good agreement with the shapes of the peaks corresponding to $^8\text{Be}^*(16.6, 16.9)$ is obtained by using a simple two-level formula with interference, corrected for the effect of final-state Coulomb interaction, assuming $\Gamma(16.6) = 90$ keV and $\Gamma(16.9) = 30$ keV; see also Table 8.11. The ratio of the intensities of the groups corresponding to $^8\text{Be}^*(16.6, 16.9)$ remains constant for $E(^6\text{Li}) = 4.3$ to 5.5 MeV: $I(16.6)/I(16.9) = 1.22 \pm 0.08$. Partial angular distributions for the $a_0$ group have been measured at fourteen energies for $E(^6\text{Li}) = 4$ to 24 MeV. See [1979AJ01] for the references. The reaction mechanism for $^6\text{Li}(^6\text{Li}, X)$ was studied by measuring charged particle angular distributions for $E(^6\text{Li}) = 2$ to 16 MeV [1990LE05]. Analysis in a statistical model indicated that the $^6\text{Li}(^6\text{Li}, \alpha$) reaction proceeds dominantly via direct, cluster transfer rather than an intermediate compound nucleus.

At $E(^6\text{Li}) = 36$ to 46 MeV sequential decay (reaction (b)) via $^8\text{Be}$ states at $E_x = 3.0, 11.4, 16.9$ and 19.65 MeV is reported; see [1984AJ01]. [1987LA25] report the possible involvement of the $2^+$ state $^8\text{Be}^*(22.2)$. At $E(^6\text{Li}) = 6$ MeV the “Trojan Horse” method was used to evaluate $^6\text{Li}(^6\text{Li}, 2\alpha)$ data to extract the $^6\text{Li}(d, \alpha)$ reaction cross sections and $S$-factors [2001SP04, 2001MU30]; see reaction 9.

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

14. (a) $^7\text{Li}(p, e^+ e^-)^8\text{Be}$, \( Q_m = 16.2331 \)
(b) $^7\text{Li}(p, \gamma)^8\text{Be}$, \( Q_m = 17.2551 \)

For reaction (a) electron/positron pair decay from $^8\text{Be}^*(17.6, 18.15)$ $J^\pi = 1^+$ levels was measured in a search for M1 de-excitation via pair production that would indicate the involvement of a short-lived isoscalar axion 4–15 MeV/$c^2$ in mass. While an anomaly is seen in the pair production, the overall results are not consistent with the involvement of a neutral boson [1996DE51, 1997DE46, 2001DE11]. Limits of $< 10^{-3}$ [1990DE02] and $4.1 \times 10^{-4}$ [2001DE11] were obtained for the axion to $\gamma$-ray ratio.

For reaction (b) cross sections and angular distributions have been reported from $E_p = 30$ keV to 18 MeV. Gamma rays are observed to the ground ($\gamma_0$) and to the broad, $2^+$, excited state at 3.0 MeV ($\gamma_1$) and to $^8\text{Be}^*(16.6, 16.9)$ ($\gamma_3, \gamma_4$). An $R$-matrix
Table 8.12

<table>
<thead>
<tr>
<th>$E_{\text{ex}}$ (keV)</th>
<th>$I_{\text{lab}}$ (keV)</th>
<th>$^{8}\text{Be}^{*}$ (MeV)</th>
<th>$l_{p}$</th>
<th>$J^{\pi}$</th>
<th>Res.(^{b})</th>
</tr>
</thead>
<tbody>
<tr>
<td>441.4 ± 0.5(^{c})</td>
<td>12.2 ± 0.5</td>
<td>17.640</td>
<td>1</td>
<td>$1^{+}$</td>
<td>$\gamma_{0}, \gamma_{1}, \gamma_{2}$</td>
</tr>
<tr>
<td>1030 ± 5</td>
<td>168</td>
<td>18.155</td>
<td>1</td>
<td>$1^{+}$</td>
<td>$\gamma_{0}, \gamma_{1}, \gamma_{2}$</td>
</tr>
<tr>
<td>1890</td>
<td>150 ± 50</td>
<td>18.91</td>
<td>(2(^{-}))</td>
<td>$\gamma_{3}, \gamma_{4}$</td>
<td></td>
</tr>
<tr>
<td>2060 ± 20</td>
<td>310 ± 20</td>
<td>19.06</td>
<td>$J = 1, 2, 3$</td>
<td>$\pi = (-)^{d}$</td>
<td>$\gamma_{1}$</td>
</tr>
<tr>
<td>(3100)</td>
<td>(20.0)</td>
<td></td>
<td></td>
<td></td>
<td>$\gamma_{1}$</td>
</tr>
<tr>
<td>4900</td>
<td></td>
<td>21.5</td>
<td></td>
<td></td>
<td>$\gamma_{1}$</td>
</tr>
<tr>
<td>5000</td>
<td>≈ 4500</td>
<td>21.6</td>
<td>0</td>
<td>$1^{-}; T = 1$</td>
<td>$\gamma_{0}$</td>
</tr>
<tr>
<td>6000</td>
<td></td>
<td>22.5</td>
<td></td>
<td></td>
<td>$\gamma_{1}$</td>
</tr>
<tr>
<td>7500</td>
<td>≈ 8000</td>
<td>23.8</td>
<td>(0)</td>
<td>(1(^{-}), 2(^{-})); $T = 1$</td>
<td>$\gamma_{1}$</td>
</tr>
<tr>
<td>(11100)</td>
<td>(27.0)</td>
<td></td>
<td></td>
<td></td>
<td>$\gamma_{1}$</td>
</tr>
<tr>
<td>13000</td>
<td></td>
<td>28.6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^{a}\) See Tables 8.6 in [1974AJ01,1979AJ01] for the references.

\(^{b}\) $\gamma_{0}, \gamma_{1}, \gamma_{2}, \gamma_{3}$ represent transitions to $^{8}\text{Be}^{*}(0, 3.0, 16.6, 16.9)$, respectively.

\(^{c}\) See [1959AJ76]. See also [1983FI13,1984JE1B].

\(^{d}\) See, however, reaction 16.

fit to the $\gamma$-ray spectrum obtained at $E_{p} = 7.5$ and 8 MeV yielded $E_{x} = 2.91$ MeV and $\Gamma = 1.23$ MeV for the $^{8}\text{Be}$ first excited state [1990RI06]. See also [1994DE09] for comments on model dependences for deduced widths. Resonances for both $\gamma_{0}$ and $\gamma_{1}$ occur at $E_{p} = 0.44$ and 1.03 MeV, and for $\gamma_{1}$ alone at $E_{p} = 2, 4.9, 6.0, 7.3$, and possibly at 3.1 and 11.1 MeV. The excitation function was measured for $\gamma_{0}$ and $\gamma_{1}$ across the resonance at $E_{p} = 441$ keV; the peak cross section was $\sigma(\gamma_{0} + \gamma_{1}) = 5.00 ± 0.50$ mb (yielding an average of 5.9 ± 0.5 mb when weighted with previous measurements). The branching ratio was $\sigma(\gamma_{0})/\sigma(\gamma_{0} + \gamma_{1}) = 0.52 ± 0.07$ [1995ZA03]. Broad resonances are reported at $E_{p} ∝ 5$ MeV ($\gamma_{0}$), $\Gamma ∝ 4–5$ MeV, and at $E_{p} ∝ 7.3$ MeV ($\gamma_{1}$), $\Gamma ∝ 8$ MeV; see Table 8.12. The $E_{p} ∝ 5$ MeV resonance ($E_{x} ∝ 22$ MeV) represents the giant dipole resonance based on $^{8}\text{Be}_{g.s.}$, while the $\gamma_{1}$ resonance, $\sim 2.2$ MeV higher, is based on $^{8}\text{Be}^{*}(3.0)$. The $\gamma_{0}$ and $\gamma_{1}$ giant resonance peaks each contain about 10% of the dipole sum strength. The main trend between $E_{p} = 8$ and 17.5 MeV is a decreasing cross section.

At the $E_{p} = 0.44$ MeV resonance ($E_{x} = 17.64$ MeV) the radiation is nearly isotropic and has been interpreted as arising from p-wave formation, $J^{\pi} = 1^{+}$, with channel spin ratio $\sigma(J_{c} = 2)/\sigma(J_{c} = 1) = 3.2 ± 0.5$. Radiative widths for the $\gamma_{0}$ and $\gamma_{1}$ decay are displayed in Table 8.10. A careful study of the $\alpha$-breakup of $^{8}\text{Be}^{*}(16.63, 16.92)$ [both $J^{\pi} = 2^{+}$] for $E_{p} = 0.44$ to 2.45 MeV shows that the non-resonant part of the cross section for production of $^{8}\text{Be}^{*}(16.63)$ is accounted for by an extranuclear direct-capture process. The $\gamma$-ray transitions to $^{8}\text{Be}^{*}(16.63, 16.92)$ are observed at $E_{p} = 0.44, 1.03$ and 1.89 MeV [$^{8}\text{Be}^{*}(17.64, 18.15, 18.9)$]. The results are consistent with the hypothesis of nearly maximal isospin mixing for $^{8}\text{Be}^{*}(16.63, 16.92)$; decay to these states is not observed from the $3^{+}$ states at $E_{x} = 19$ MeV, but rather from the $2^{-}$ state at $E_{x} = 18.9$ MeV. Squared $T = 1$ components calculated for $^{8}\text{Be}^{*}(16.6, 16.9)$ are 40 and 60%, and for $^{8}\text{Be}^{*}(17.6, 18.2)$ they are 95 and 5%, respectively. At $E_{p} = 25$ MeV, the capture cross section to the 16 MeV $2^{+}$ doublet was measured ($\sigma(\gamma_{2}) < 0.04$ Mb/sr) via a triple coincidence $\gamma + 2\alpha$ method [1991BR11]. The cross section for $(\gamma_{3} + \gamma_{4})$ has also been measured for $E_{p} = 11.5$ to
$^{8}$Be


30 MeV ($\theta = 90^\circ$) by detecting the $\gamma$-rays and for $E_p = 4$ to 13 MeV (at five energies) by detecting the two $\alpha$-particles from the decay of $^8$Be$^*$ (16.6, 16.9); a broad bump is observed at $E_p = 8 \pm 2$ MeV [1981MA33]. The angle and energy integrated yield only exhausts 8.6% of the classical dipole sum for $E_p = 4$ to 30 MeV, suggesting that this structure does not represent the GDR built on $^8$Be$^*$ (16.6, 16.9). A weak, very broad [$\Gamma \geq 20$ MeV] peak may also be present at $E_x = 20$–30 MeV. A direct capture calculation adequately describes the observed cross section [1981MA33]. For the earlier references see [1979AJ01]. See also references cited in [1988AJ01].

Low energy $^7$Li(p, $\gamma$) angular distributions and cross sections, mainly for $\gamma_0$ and $\gamma_1$ capture, were measured at $E_p = 40$–180 keV [1992CE02], $E_p = 80$ keV [1994CH23, 1996GO01, 1997GO13], $E_p = 100$–1500 keV [1995ZA03], $E_p = 80$, 402 and 450 keV [1996HA06], and $E_p = 40$–100 keV [2000SP01]. The angular dependent cross-section and analyzing power data indicate significant near-threshold contributions from p-wave capture. Estimates of the p-wave strength have been deduced from Transition Matrix Element (TME) fits to the polarization data [1994CH23, 1996GO01, 1997GO13], $R$-matrix fits to the data [1995BB21, 1996BB26, 2000BA89], and other direct-plus-resonances capture calculations [1992CE02, 1994RO16, 1995WE11, 1996CS05, 1997BA04, 1997GO13, 2000SP01, 2001SA30]. The estimates range from $< 10\%$ up to $\approx 95\%$. It was suggested that the origin of p-wave strength was the result of interference in the extended tails of the two 1$^+$ resonances at $E_p = 441$ keV and 1030 keV, while a more recent measurement [2000SP01] that observed a negative slope in the astrophysical $S$-factor, as the energy approaches zero, indicates that the sub-threshold $^8$Be state at $E_x = 16.92$ MeV is involved in the capture.

There appears to be some agreement on the issue that there is a need for new model calculations for low-energy capture that include the subthreshold state and the two resonances at $E_p = 441$ and 1030 keV. Polarized proton capture to the $^8$Be$^*$ (16.6) state was measured at $E_p = 80$ keV [1996GO01]. See [1988BO37] for thermonuclear reaction rates and [1994CH70] for applications. Thick target proton induced $\gamma$-ray yields, useful for elemental analysis, were measured at $E_p = 2.2$–3.8 MeV [1988BO37] and $E_p = 7$–9 MeV [1987RA23].

15. $^7$Li(p, n)$^7$Be. \[ Q_m = -1.64456, \quad E_b = 17.25512 \]

Measurements of cross sections have been reported for $E_p = 1.9$ to 199.1 MeV [see 1974AJ01, 1979AJ01, 1984AJ01] and in the range 60.1 to 480.0 MeV ([1984DA22]; activation $\sigma$). Polarization measurements have been reported at $E_p = 2.05$ to 5.5 MeV, 30 and 50 MeV [see 1974AJ01] and at $E_p = 52.8$ MeV [1988HE08] [$K_z' = 0.07 \pm 0.02$]. See also below.

The yield of ground state neutrons (n0) rises steeply from threshold and shows pronounced resonances at $E_p = 2.25$ and 4.9 MeV. The yield of n1 also rises steeply from threshold and exhibits a broad maximum near $E_p = 3.2$ MeV and a broad dip at $E_p \approx 5.5$ MeV, also observed in the p1 yield. Multi-channel scattering length approximation analysis of the 2$^-$ partial wave near the n0 threshold indicates that the 2$^-$ state at $E_x = 18.9$ MeV has a width $\Gamma = 50 \pm 20$ keV. See, however, reaction 23 here. The ratio of the cross section for $^7$Li(p, $\gamma$)$^8$Be$^*$ (18.9) $\rightarrow$ $^8$Be$^*$ (16.6 + 16.9) + $\gamma$ to the thermal neutron
capture cross section $^7$Be(n, $\gamma$)$^8$Be$^*(18.9) \rightarrow ^8$Be$^*(16.6 + 16.9) + \gamma$, provides a rough estimate of the isospin impurity of $^8$Be$^*(18.9)$: $\sigma_{p,\gamma}/\sigma_{n,\gamma} \approx 1.5 \times 10^{-5}$. The $T = 1$ isospin impurity is $\lesssim 10\%$ in intensity. See also reaction 23 here and [1979AJ01,1984AJ01].

The structure at $E_p = 2.25$ MeV is ascribed to a $J^\pi = 3^+$, $T = (1), l = 1$ resonance with $\Gamma_n \approx \Gamma_p$ and $\gamma_n^2/\gamma_p^2 = 3$ to 10: see [1966LA04]. At higher energies the broad peak in the $n_0$ yield at $E_p = 4.9$ MeV can be fitted by $J^\pi = 3^+$ with $\Gamma = 1.1$ MeV, $\gamma_n^2 \approx \gamma_p^2$. The behavior of the $n_1$ cross section can be fitted by assuming a $1^-$ state at $E_x = 19.5$ MeV and a $J = 0, 1, 2$, positive-parity state at 19.9 MeV [presumably the 20.1–20.2 MeV states reported in reaction 4]. In addition the broad dip at $E_p \approx 5.5$ MeV may be accounted for by the interference of two $2^+$ states. See Table 8.8 in [1979AJ01]. The $0^+$ differential cross section increases rapidly to $\approx 35$ mb/sr at 30 MeV and then remains constant to 100 MeV: see references cited in [1988AJ01]. The total reaction cross section [$^7$Be$^*(0, 0.43)$] decreases inversely with $E_p$ in the range 60.1 to 480.0 MeV [1984DA22] [note: the values of $\sigma_l$ supersede those reported earlier in [1979AJ01]]. The transverse polarization transfer, $\rho_N(0^0)$, for the ground-state transition has been measured at $E_p = 160$ MeV [1984TA07]. See also ([1986MC09]; $E_p = 800$ MeV) and references cited in [1988AJ01].

16. (a) $^7$Li(p, p)$^7$Li, \quad $E_b = 17.25512$
\quad \quad \quad \quad \quad (b) $^7$Li(p, p)$^7$Li$^*$

Absolute differential cross sections for elastic scattering have been reported for $E_p = 0.4$ to 12 MeV and at 14.5, 20.0 and 31.5 MeV. The yields of inelastically scattered protons (to $^7$Li$^*(0.48)$) and of 0.48 MeV $\gamma$-rays have been measured for $E_p = 0.8$ to 12 MeV: see [1974AJ01]. Polarization measurements have been reported at a number of energies in the range $E_p = 0.67$ MeV to 2.1 GeV/c [see [1974AJ01,1979AJ01,1984AJ01]], at $E_p = 1.89$ to 2.59 MeV ([1986SA1P]; $p_0$) and at 65 MeV ([1987TO06]; continuum). See also [1983GLZZ].

Anomalies in the elastic scattering appear at $E_p = 0.44$, 1.03, 1.88, 2.1, 2.5, 4.2 and 5.6 MeV. Resonances at $E_p = 1.03, 3$ and 5.5 MeV and an anomaly at $E_p = 1.88$ MeV appear in the inelastic channel. A phase-shift analysis and a review of the cross-section data show that the 0.44 and 1.03 MeV resonances are due to $1^-$ states which are a mixture of $^3$P$_1$ and $^3$P$_3$, with a mixing parameter of +25%; that the $2^-$ state at the neutron threshold ($E_p = 1.88$ MeV) has a width of about 50 keV [see also reaction 14]; and that the $E_p = 2.05$ MeV resonance corresponds to a $3^+$ state. The anomalous behavior of the $^3$P$_3$ phase around $E_p = 2.2$ MeV appears to result from the coupling of the two $3^+$ states [resonances at $E_p = 2.05$ and 2.25 MeV]. The $^3$S$_1$ phase begins to turn positive after 2.2 MeV suggesting a $1^-$ state at $E_p = 2.5$ MeV: see Table 8.13. The polarization data show structures at $E_p = 1.9$ and 2.3 MeV. A phase-shift analysis of the (p, p) data finds no indication of a possible $1^-$ state with $17.4 < E_x < 18.5$ MeV [see, however, reaction 15 in [1979AJ01]].

An attempt has been made to observe the $T = 2$ state [$^8$Be$^*(27.47)$] in the $p_0$, $p_1$ and $p_2$ yields. None of these shows the effect of the $T = 2$ state. Table 8.5 in [1984AJ01] displays the upper limit for $\Gamma_{p_0}/\Gamma$.

The proton total reaction cross section has been reported for $E_p = 25.1$ to 48.1 MeV by [1985CA36]. [1987CH33,1987PO03] have studied p-$^7$Li correlations involving $^8$Be$^*$
Table 8.13
$^8$Be levels from $^7$Li(p, p0)$^7$Li and $^7$Li(p, p1)$^7$Li

<table>
<thead>
<tr>
<th>$E_p$ (MeV)</th>
<th>$I_{lab}$ (keV)</th>
<th>$^8$Be (MeV)</th>
<th>$J^*$</th>
<th>$I_{p'}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.441</td>
<td>12.2bh</td>
<td>17.640f</td>
<td>1$^+$</td>
<td></td>
</tr>
<tr>
<td>1.030 ± 0.005</td>
<td>168</td>
<td>18.155</td>
<td>1$^+$</td>
<td>$\approx$ 6</td>
</tr>
<tr>
<td>1.895d,1</td>
<td>55 ± 20</td>
<td>18.912i</td>
<td>2$^-$</td>
<td></td>
</tr>
<tr>
<td>2.058i</td>
<td>$\approx$ 294i</td>
<td>19.055i</td>
<td>3$^+$</td>
<td>small</td>
</tr>
<tr>
<td>2.245i</td>
<td>$\approx$ 203i</td>
<td>19.218i</td>
<td>3$^+$</td>
<td>small</td>
</tr>
<tr>
<td>2.451i</td>
<td>$\approx$ 640e,i</td>
<td>19.399i</td>
<td>1$^-$</td>
<td>$&gt; 0$</td>
</tr>
<tr>
<td>4.2 ± 0.2</td>
<td>1800 ± 200f</td>
<td>20.9</td>
<td>4$^-$</td>
<td>($&gt; 0$)</td>
</tr>
<tr>
<td>5.6</td>
<td>broad</td>
<td>22.2</td>
<td>b</td>
<td>$&gt; 0$</td>
</tr>
</tbody>
</table>

a See references in Table 8.9 in [1979AJ01] and [1988GU10].
b $\theta_{2p} = 0.064$.
c See also ([1981BA36]; theor.).
d (p, n) threshold: see reaction 15.
e See also Table 8.8 in [1979AJ01], $\gamma_{n1}$ and $\gamma_{p1} \approx 1%$ of Wigner limit.
f A $2^+$ state at $E_x \approx 20$ MeV appears to be necessary to account for the cross sections: see Table 8.9 and reaction 4.
g Reduced width is 70% of the Wigner limit.
h May be due to two $2^+$ states. See also reaction 15.
i [1988GU10].

(17.64, 18.15, 18.9 + 19.1 + 19.2). Elastic proton scattering on $^7$Li was measured near the (p, n) threshold, $E_{cm} = 1.2–2.4$ MeV [1988GU10]. Parameters for observed near-threshold resonances are in Table 8.13. See also [1994DE09] for comments on model dependences for deduced widths. See also $^7$Li in [2002TI10] and references cited in [1988AJ01].

17. $^7$Li(p, d)$^6$Li, $Q_m = -5.02573$, $E_b = 17.25512$

Angular distributions were measured for $^7$Li(p, d) at $E_p = 18.6$ MeV [1987GO27]; neutron spectroscopic factors were deduced, via DWBA analysis, for deuterons corresponding to the $^6$Li ground state and first excited state. The excitation function for d0 measured for $E_p = 11.64$ to 11.76 MeV does not show any effect from the $T = 2$ state $[^8$Be$^*(27.47)]$: see [1979AJ01]. See also [1984BA1T].

18. $^7$Li(p, a)$^4$He, $Q_m = 17.34695$, $E_b = 17.25512$

The cross section increases from $(4.3 \pm 0.9) \times 10^{-5}$ mb at $E_p = 28.1$ keV to 6.33 mb at 998 keV. Astrophysical $S$-factors have been calculated over that range: $S(0) = 52 \pm 8$ keV b [1986RO13], $S(0) = 0.59$ keV b [1992EN01,1992EN04]. An analysis of the $^7$Li($^7$Li, $\alpha$) reaction (see reaction 19) in the Trojan Horse Method (THM), which assumes that the deuteron acts as a participant proton plus a spectator neutron and is not sensitive to electron screening effects, indicates $S(0) = 55 \pm 3$ keV b [2001LA35,2003PI13,2003SP02]. Earlier work on the THM by the same group published the value $S(0) = 36 \pm 7$ keV b [1997CA36,1999SP09,2000AL04]. For comments on the $S$ factor see [1990RA28,1991SC12,1991SC25,1991SC32,1992SC22,1992SO25,1993SO13,1994CH02].
Excitation functions and angular distributions have been measured at $E_p = 10$ keV–62.5 MeV; see [1979AJ01,1984AJ01]. $E_p = 20–250$ keV [1989HA14], and $E_{cm} = 10–1450$ keV [1992EN01,1992EN04]. Polarization measurements have been carried out for $E_p = 0.8$ to 22 MeV; see [1974AJ01,1979AJ01]. $E_p = 9–22$ MeV [1992TA21]. In the range $E_p = 23$ keV to 62.5 MeV; see [1979AJ01,1984AJ01]. Polarization measurements have been carried out for $E_p = 0.8$ to 10.6 MeV [see [1974AJ01]]; in the range $E_p = 3$ to 10 MeV the asymmetry has one broad peak in the angular distribution at all energies except near 5 MeV; the peak value is $0.98 \pm 0.04$ at 6 MeV and is essentially 1.0 for $E_p = 8.5$ to 10 MeV. Above 10 MeV the asymmetry begins to decrease slowly.

Broad resonances are reported to occur at $E_p = 3.0$ MeV [$\Gamma \approx 1$ MeV] and at $\approx 5.7$ MeV [$\Gamma \approx 1$ MeV]. Structures are also reported at $E_p = 6.8$ MeV and at $E_p = 9.0$ MeV; see [1979AJ01]. The 9.0 MeV resonance is also reflected in the behavior of the $A_2$ coefficient. The experimental data on yields and on polarizations appear to require including two 0$^+$ states [at $E_x \approx 19.7$ and 21.8 MeV] with very small $\alpha$-particle widths, and four 2$^+$ states [at $E_x \approx 15.9$, 20.1, 22.2 and 25 MeV]. See, however, reaction 4. A 4$^+$ state near 20 MeV was also introduced in the calculation but its contribution was negligible. The observed discrepancies are said to be probably due to the assumption of pure $T = 0$ for these states. At $E_p = 11.64$ to 11.76 MeV the excitation function does not show any effect due to the $T = 2$ state at $E_x = 27.47$ MeV. See [1979AJ01] for references.

A study of the $^7\text{Li}(p,\alpha)^4\text{He}\,^*\to^4\text{He}\,^*\to^8\text{Be}\,^*$ reaction to $^4\text{He}^\ast(20.1)\,[0^+\,\Gamma]$ at $E_p = 4.5$ to 12.0 MeV shows a broad maximum at $E_x \approx 24$ MeV; see reaction 9 and [1984AJ01]. See also references cited in [1988AJ01].

19. (a) $^7\text{Li}(d,n)^8\text{Be}, \quad Q_m = 15.0306$
    (b) $^7\text{Li}(d,n)^4\text{He}^\ast\,^4\text{He}, \quad Q_m = 15.12239$

The population of $^8\text{Be}^\ast(0,\,3.0,\,16.6,\,16.9,\,17.6,\,18.2,\,18.9,\,19.1,\,19.2)$ has been reported in reaction (a). For the parameters of $^8\text{Be}^\ast(3.0)$ see Table 8.4 in [1974AJ01]. Angular distributions were measured for $^7\text{Li}(d,n)$ at $E_d = 0.7–2.3$ and 5.6–12.1 MeV and excitation functions were reported for neutrons corresponding to $^8\text{Be}^\ast(0+\,3.0,\,16.6+\,16.9,\,17.6,\,18.15)$ [1996BO27]. The $^8\text{Be}^\ast(11.4)$ level is not observed. Angular distributions of $n_0$ and $n_1$ have been reported at $E_d = 0.7$ to 3.0 MeV and at $E_d = 15.25$ MeV [see [1974AJ01,1979AJ01]], at 0.19 MeV [1983DA32,1987DA25] and at 0.40 and 0.46 MeV ([1984GA07]; $n_0$ only). The angular distributions of the neutrons to $^8\text{Be}^\ast(16.6,\,17.6,\,18.2)$ are fit by $I_p = 1$: see [1974AJ01]. At $E_{cm} = 50$, 83 and 199 keV, the measured cross sections are $\sigma = 0.125, 2.11$ and 4.01 mb, respectively ($\pm \approx 5\%$ (stat.), $\pm 7.5\%$ (syst.)) [2001HO23].

Reaction (b) at $E_d = 2.85$ to 14.97 MeV proceeds almost entirely through the excitation and sequential decay of $^8\text{Be}^\ast(16.6,\,16.9)$ [1987WA21]. See also [1988AJ01]. At $E_d = 19.7$ MeV, $^8\text{Be}^\ast(11.4)$ was observed at $E_x = 11.3 \pm 0.2$ MeV with $\Gamma = 3.7 \pm 0.2$ MeV [1995AR25]. At $E_d = 7$ MeV, population of the two $T = 0$ levels at 20.1, 2$^+$ and 20.2,
$^8\text{Be}$

0$^+$ is reported with widths $\Gamma_{20,1} = 0.85 \pm 0.25$ MeV and $\Gamma_{20,2} = 0.75 \pm 0.25$ MeV [1991AR18], and $\Gamma_{20,1} = 0.90 \pm 0.20$ MeV and $\Gamma_{20,2} = 0.70 \pm 0.20$ MeV [1992DA22]. A complete kinematics measurement of $d^3\sigma/(d\Omega_d d\Psi dE_{12})$ at $E_d = 3–6$ MeV reported population of the 2$^+$ doublet at 16.6 MeV and 16.9 MeV; intense forward neutrons were observed corresponding to the 16.6 MeV state indicating the $^7\text{Li} + p$ configuration of that state [1999GO15]. See [2001LA35,2003PI13,2003SP02], and reaction 18 for measurements at $E_p = 19–21$ MeV that are evaluated in the “Trojan Horse” method to obtain information on the astrophysical $^7\text{Li}(p,\alpha)$ rate. See also [2000HA50] for fusion applications. See also $^9\text{Be}$.

20. (a) $^7\text{Li}(^3\text{He},d)^8\text{Be}$, $Q_m = 11.7616$
(b) $^7\text{Li}(^3\text{He},a)^4\text{He}$, $Q_m = 11.85348$

Deuteron groups are observed to $^8\text{Be}^*(0,3.0,16.6,16.9,17.6,18.2)$. For the $J^\pi = 2^+$ isospin mixed states see Table 8.11. Angular distributions have been measured for $E(^3\text{He}) = 390–1130$ keV [2003FR22], for $E(^3\text{He}) = 0.9$ to 24.3 MeV and at $E(^3\text{He}) = 33.3$ MeV: see [1974AJ01,1979AJ01,1984AJ01]. Reaction (b) has been studied at $E(^3\text{He}) = 5.0$ MeV [1985DA29] and at 9, 11 and 12 MeV [1986ZA09]. $^8\text{Be}^*(0,3.0)$ are reported to be involved [1985DA29]. Implications of this reaction for destroying $^7\text{Li}$ and $^7\text{Be}$ in astrophysical environments is discussed in [2003FR22]. See also $^{10}\text{B}$.

21. (a) $^7\text{Li}(\alpha,t)^8\text{Be}$, $Q_m = -2.5588$
(b) $^7\text{Li}(\alpha,\alpha^1)^4\text{He}$, $Q_m = -2.46691$

Angular distributions have been measured to $E_\alpha = 50$ MeV: see [1974AJ01,1979AJ01,1988AJ01]. The ground state of $^8\text{Be}$ decays isotropically in the cm system: $J^\pi = 0^+$. Sequential decay (reaction (b)) is reported at $E_\alpha = 50$ MeV via $^8\text{Be}^*(0,3.0,11.4,16.6,16.9,19.9)$: see [1974AJ01]. See also [1992KO26].

22. (a) $^7\text{Li}(^7\text{Li},^6\text{He})^8\text{Be}$, $Q_m = 7.2789$
(b) $^7\text{Li}(^7\text{Li},\alpha + ^4\text{He})^4\text{He}$, $Q_m = 7.3707$

$^8\text{Be}^*(0,3.0)$ have been populated. For reaction (a) see ([1987BO1M]; $E(^7\text{Li}) = 22$ MeV), and for reaction (b) see ([1996SO17]; $E(^7\text{Li}) = 8$ MeV).

23. (a) $^7\text{Be}(n,p)^7\text{Li}$, $Q_m = 1.64456$, $E_b = 18.89968$
(b) $^7\text{Be}(n,\alpha)^4\text{He}$, $Q_m = 18.99152$
(c) $^7\text{Be}(n,\gamma\alpha)^4\text{He}$, $Q_m = 18.99152$

The total (n,p) cross section has been measured from $25 \times 10^{-3}$ eV to 13.5 MeV. For thermal neutrons the cross sections to $^7\text{Li}^*(0,0.48)$ are $38400 \pm 800$ and $420 \pm 120$ b, respectively. A departure from a 1/$v$ shape in $\sigma_t$ is observed for $E_n > 100$ eV. The astrophysical reaction rate is $\approx \frac{1}{4}$ lower than that previously used, which could lead to an increase in the calculated rate of production of $^7\text{Li}$ in the Big Bang by as much as 20% [1988AJ01]: see also [1998FI02]. Results from a $R$-matrix analysis of reaction (a) over
Table 8.14

$^8\text{Be}$ levels observed in $^7\text{Be}(n, p)$ [2003AD05]

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$E_{res}$ (MeV)</th>
<th>$\Gamma_n$ (MeV)</th>
<th>$\Gamma_p$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.90</td>
<td>0.0027</td>
<td>0.225</td>
<td>1.409</td>
</tr>
<tr>
<td>19.23</td>
<td>0.33</td>
<td>0.077</td>
<td>0.088</td>
</tr>
<tr>
<td>21.56</td>
<td>2.66</td>
<td>0.490</td>
<td>0.610</td>
</tr>
</tbody>
</table>

The range from $E_{cm} = 10^{-8} – 9.0$ MeV [2003AD05] are summarized in Table 8.14. In their analysis, $^8\text{Be}^*$ (19.07) and $^8\text{Be}^*$ (19.24) are treated as a single resonance. A different $R$-matrix analysis [1988KO03] found a $T = 1$ impurity of $\approx 24\%$ and $\Gamma = 122$ keV for the $2^- \ ^8\text{Be}^*$ (18.9) state. At thermal energies the $(n, \alpha)$ cross section is $\leq 0.1$ mb and the $(n, \gamma \alpha)$ cross section is 155 mb: see [1974AJ01]. See also references cited in [1988AJ01].

24. $^8\text{Li}(\beta^-) ^8\text{Be}, \ Q_m = 16.0052$

$^8\text{Li}$ decays mainly to the broad 3.0 MeV, 2$^+$ level of $^8\text{Be}$, which decays into two $\alpha$-particles. Both the $\beta$-spectrum and the resulting $\alpha$-spectrum have been extensively studied: see [1955AJ61,1966LA04]. See also $^8\text{B}(\beta^+)$. Studies of the distribution of recoil momenta and neutrino recoil correlations indicate that the decay is overwhelmingly GT, axial vector [see reaction 1 in $^8\text{Li}$] and that the ground state of $^8\text{Li}$ has $J^\pi = 2^+$: see [1980MC07]. Detailed calculations are necessary to obtain the log $ft$ values for decay to $^8\text{Be}^*$ (3.0); values in the literature are: log $ft = 5.37$ [1986WA01], log $ft = 5.72$ [1989BA31].

The data of [1971WI05] for $^8\text{Li}$ and $^8\text{B}$ $\beta$-decay have been analyzed extensively [1986WA01,1989BA31,2002BH03]. In [1986WA01] a many-level one-channel approximation $R$-matrix analysis of the $\beta$-delayed $\alpha$ particle spectra in the decay of both $^8\text{Li}$ and $^8\text{B}$ [as well as of the $L = 2 \alpha-\alpha$ phase shifts] found that there was no need to introduce “intruder” states below $E_x \approx 26$ MeV of $^8\text{Be}$ in order to explain the data [see, e.g., [1969BA43,1974AJ01,1976BA67,1979AJ01]]. Warburton extracted the GT matrix elements, for the decay to $^8\text{Be}^*$ (3.0) and the doublet near 16 MeV, and pointed out the difficulties in extracting meaningful $E_x, \Gamma$ and log $ft$ values from $\beta^\pm$ decay to the broad $^8\text{Be}^*$ (3.0) state. On the other hand, the $R$-matrix analysis of Barker [1989BA31] requires a broad 2$^+$ intruder state at $\approx 9$ MeV. See [1998FA05,2000BA89,2001CA50] for further comments on intruder states in $^8\text{Be}$.

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

25. $^8$Li(p, n)$^8$Be. \[Q_m = 15.2228\]

Angular distributions of $^8$Be from $^1$H($^8$Li, $^8$Be) were measured at $E_{cm} = 1.5$ MeV \[1993CA04\]. The $^8$Be$_{g.s.}$ was reconstructed by detecting the coincident $\alpha$ particles and the data were transformed to represent the inverse kinematics $^8$Li(p, n) reaction. The observed cross section, $\sigma_{tot} = 21 \pm 2$(stat.) $\pm 4.2$(norm.) mb, was 2 times smaller than estimates based on a Hauser–Feshbach calculation and indicates that $^8$Li(p, n) does not contribute significantly to $^8$Li burning in nucleosynthesis. See also \[2003IS12\].

26. $^8$Be($\gamma$, p)$^7$Li, \[Q_m = -17.2551\]

A dynamic semi-microscopic model study of $^8$Be($\gamma$, p) considered dipole–dipole and quadrupole–quadrupole forces on the properties of Giant Dipole Resonances built on the ground state and first excited state of $^8$Be \[1995GO21\]. See also reaction 14 here.

27. $^8$B($\beta^+$)$^8$Be, \[Q_m = 17.9798\]

The decay [see reaction 1 in $^8$B] proceeds mainly to $^8$Be$^*$($3.0$). Detailed study of the high-energy portion of the $\alpha$-spectrum reveals a maximum near $E_\alpha = 8.3$ MeV, corresponding to transitions to $^8$Be$^*$($16.63$), for which parameters $E_x = 16.67$ MeV, $\Gamma = 150$ to $190$ keV or $E_x = 16.62$ MeV, $\Gamma = 95$ keV are derived: see \[1974AJ01\]. Analyses \[1986WA01,1989BA31\] of the $\beta^\pm$ delayed $\alpha$-spectra following $^8$B and $^8$Li decay are described in reaction 24. The analysis of \[1989BA31\] requires a $2^+$ intruder state in $^8$Be at $E_x \approx 9$ MeV, while the analysis of \[1986WA01\] excludes intruder states below $E_x = 26$ MeV. See also \[1988WA1E\] and \[1988BA75,1998FA05,2000BA89,2001CA50\].

The determination of log $ft$ values requires detailed calculations; values in the literature are: for decay to $^8$Be$^*$($3.0$) log $ft = 5.6$ \[1974AJ01\], log $ft = 5.77$ \[1989BA31\]; for decay to $^8$Be$^*$($16.63$) log $ft = 3.3$ \[1969BA43,1979AJ01\].

The $\beta^+$ spectrum has been measured by \[1987NA08\] and by \[2000OR04\]; see reaction 1 in $^8$B. See \[1988AJ01\] for additional references and discussion. See also \[2000GR03,2000GR07\] for theoretical discussion of the cluster structure of 16.6 and 16.9 MeV resonances and their role in $^7$B $\beta$-decay. See also \[1994DE30\].

28. (a) $^9$Be($\gamma$, n)$^4$He$^4$He, \[Q_m = -1.5736\]
(b) $^9$Be($\gamma$, n)$^8$Be, \[Q_m = -1.6654\]
(c) $^9$Be(n, 2n)$^8$Be, \[Q_m = -1.6654\]
(d) $^9$Be(t, n + t)$^8$Be, \[Q_m = -1.6654\]
(e) $^9$Be($\alpha$, $\alpha$n)$^8$Be, \[Q_m = -1.6654\]

Neutron groups to $^8$Be$^*$($0, 3.0$) have been studied for $E_\gamma = 18$ to 26 MeV: see \[1974AJ01,1979AJ01\]. For reactions (a) and (b) bremsstrahlung $\gamma$ rays from 4–8 MeV electrons were used to measure the $\theta_{lab} = 90^\circ$ photo-neutron emission excitation function
A measurement from neutron threshold to $E_γ \approx 20$ MeV indicated that $^8\text{Be}$ excited states are strongly populated following neutron emission [1992GO27].

The $\alpha(\text{en}, \gamma)$ reaction competes with the $3\alpha$ reaction to bridge the $A = 5$ and $A = 8$ mass gaps. $\gamma$-rays with $E_γ > 1$ to 6 MeV were used to study the $\alpha(\text{en}, \gamma)$ reaction rate in inverse kinematics [2001UT03], and the resulting cross sections favor the compilation by NACRE [1999AN35] rather than the evaluation by [1988CA28]. A theoretical study of photodisintegration in the threshold region around the $^9\text{Be}$ $^*(1.684)$ $J^π = \frac{3}{2}^+$ resonance is presented in [2001ME11]. A multicluster-model study of $^9\text{Be}$ photodisintegration [1999EF05] and an R-matrix analysis of the situation [2000BA21] address discrepancies in the low-energy cross section measurements. See also [(1994KA25); theor.] for $^9\text{Be}$ Coulomb dissociation. Neutrons from $^9\text{Be}(\gamma, n)$ were used to estimate the number of hard X-rays (with $E_γ > 1.67$ MeV) that are produced in the plasma that results from impinging a $5 \times 10^8$ W/cm² laser on a Ta foil [2001SC12]. See [1974AJ01,1979AJ01] and $^9\text{Be}$.

Reaction (c) appears to proceed largely via excited states of $^9\text{Be}$ with subsequent decay mainly to $^8\text{Be}^*(3.0)$: see [1966LA04,1974AJ01], and $^9\text{Be}$ and $^{10}\text{Be}$ here. Neutrons from $^9\text{Be}(n, 2n)$ for $E_n < 10$ MeV were analyzed to determine the neutron–neutron scattering length $a_{nn} = -16.5 \pm 1.0$ fm [1990BO43]. Measurements of $^9\text{Be}(n, 2n)$ for $E_n < 12$ MeV were made to assess the possibility of using $^9\text{Be}$ as a neutron multiplier in fusion reactors [1994ME08]. See also [1988BE04] for a theoretical evaluation in the range from 5.9–14.1 MeV.

For reactions (d) and (e) see [1974AJ01] and $^9\text{Be}$. For reaction (e) see [1979AJ01].

For reaction (a) angular distributions of deuteron groups have been reported at $E_p = 0.11$ to 185 MeV [see [1974AJ01,1979AJ01,1984AJ01]] and at 18.6 MeV [(1986GO23, 1987GO27); $d_0$ and $d_1$] and 50 and 72 MeV [(1984ZA07); to $^8\text{Be}^*(0, 3.0, 16.9, 19.2)$]. Angular distributions of cross sections and analyzing powers were measured for deuterons from $^9\text{Be}(p, d)$ at $E_p = 60$ MeV. Analyzing powers for deuterons corresponding to $^8\text{Be}^*(3.04, 11.4, 16.92, 19.24)$ were presented while peaks corresponding to $^8\text{Be}$ states at (0, 11.04, 17.64, 18.25, 19.4, 22.05) were observed; evidence for very broad states at higher energies was also reported [1987KA25]. The angular distributions to $^8\text{Be}^*(0, 3.0, 16.9, 17.6, 18.2, 19.1)$ are consistent with $l_n = 1$: see [1974AJ01]. Neutron spectroscopic factors for $n + ^8\text{Be}_{g.s.}$ and $n + ^8\text{Be}^*(3.04)$ were extracted from a DWBA analysis of $^9\text{Be}(p, d)$ at $E_p = 18.6$ MeV [1987GO27], and spectroscopic factors for $n + ^8\text{Be}^*(0, 3.04, 16.626, 16.922, 17.640, 18.15, 19.07)$ were extracted from $^9\text{Be}(p, d)$ at 33.6 MeV [1991AB04]; see $^9\text{Be}$. For other spectroscopic factor measurements see [1979AJ01,1984ZA07].
An anomalous group is reported in the deuteron spectra between the $d_0$ and the $d_1$ groups. At $E_p = 26.2$ MeV, $E_x = 0.6 \pm 0.1$ MeV (constant with $\theta$). Analyses of the spectral shape and transfer cross sections are consistent with this “ghost” feature being part of the Breit–Wigner tail of the $J^2 = 0^+$ $^8$Be$^*$ state: it contains $< 10\%$ of the ground-state transfer strength. An analysis of reported $\Gamma_{cm}$ widths for $^8$Be$^*(3.0)$ in this reaction shows that there is no $E_p$ dependence. The average $\Gamma_{cm}$ at $E_p = 14.3$ and 26.2 MeV is $1.47 \pm 0.04$ MeV. $\Gamma_{cm} = 5.5 \pm 1.3$ eV for $^8$Be$^*$ and $5.2 \pm 0.1$ MeV for $^8$Be$^*(11.4)$. Spectroscopic factors for $^8$Be$^*$ (including the “ghost” anomaly) and $^8$Be$^*(3.0)$ are 1.23 and 0.22 respectively at $E_p = 14.3$ MeV, and 1.53 and 1.02 respectively at $E_p = 26.2$ MeV. The width of $^8$Be$^*(3.0)$ is not appreciably ($< 10\%$) reaction dependent but the nearness of the decay threshold indicates that care must be taken in comparing decay widths from reaction and from scattering data: $E_{\text{res}} = 3130 \pm 25$ keV (resonance energy in the $\alpha + \alpha$ cm system) [$E_x = 3038 \pm 25$ keV] and $\Gamma_{cm} = 1.50 \pm 0.02$ MeV for $^8$Be$^*(3.0)$: the corresponding observed and formal reaction widths and channel radii are $\gamma_{\text{res}}^2 = 580 \pm 50$ keV, $\gamma_x^2 = 680 \pm 100$ keV and $r_c = 4.8$ fm. A study of the continuum part of the inclusive deuteron spectra is reported at $E_p = 60$ MeV [1987KA25]. See [1979AJ01,1984AJ01] for the earlier work.

The effects of electron screening were studied at around $E_p = 16–390$ keV. A direct-plus resonance model fit to the data result in the values of $E_{\text{res}} = 336 \pm 3$ keV and $\Gamma_{lab} = 205 \pm 6$ keV for $^{10}$B$^*(6.87)$ and $\Gamma_x = 68 \pm 2$ keV and $\Gamma_d = 90 \pm 4$ keV [1997ZA06]. See also [2002BA77]. At $E_p = 77–321$ keV, angular distributions and analyzing powers of deuterons were measured; an $R$-matrix evaluation of the data indicated that a direct-reaction model can adequately account for the observations [1998BR10] indicating that the sub-threshold state in $^{10}$B at $E_x = 6.57$ MeV does not contribute. An $R$-matrix analysis of $^{10}$B levels populated for $E_p < 700$ keV is reported in [2001BA47].

Reaction (b) has been studied at $E_p = 45$ and 47 MeV: the reaction primarily populates $^8$Be$^*(0, 3.0)$. At $E_p = 70$ MeV data were evaluated using a DWT A ($T$-matrix) approach to decompose the $1s$ and $1p$ shell contributions in the quasielastic knockout of neutrons [2000SH01]. See [1979AJ01], and $^{9}$Be, $^{9}$B here. For work at $E_p = 1$ GeV see [1985BE30], [1985DO16]. For reaction (c) [FSI through $^8$Be$^*(0, 3.0)$] see [1974AJ01,1984AJ01]. See also ([1992KO26]; theor.) and $^{10}$B.

30. (a) $^9$Be(d,t) $^8$Be, \( Q_m = 4.5919 \)
(b) $^9$Be(d,t) $^4$He$^*$He, \( Q_m = 4.6834 \)

At astrophysically-relevant energies, $E_{cm} = 57–139$ keV, $^9$Be(d,t) angular distributions and total cross sections were measured and are compared with DWBA calculations [1997YA02]. At $E_d = 8–50$ MeV, angular distributions of $t_0$ and $t_1$ are evaluated in a DWBA analysis and vertex constants, \(|G|^2\), and neutron spectroscopic factors are deduced [1995GU22]. Angular distributions of $t_0$ were measured at $E_d = 7$ MeV and were evaluated in a DWBA analysis that indicated transfer mechanisms dominated at forward angles while compound nucleus mechanisms were most important at backward angles [1989SZ02]. Levels of $^{11}$B were observed in measurements of the excitation function and angular distribution for tritons from $^9$Be(d,t) at $E_d = 0.9–11.2$ MeV [1994AB25] and $E_d = 3–11$ MeV [1995AB41,2000GE16]. A review of the $^9$Be(d,t) excitation function...
for $E_d = 237$ keV to 11 MeV is given in [2000GE16]. Angular distributions have been measured at $E_d = 0.3$ to 28 MeV [see [1979AJ01]], at $E_d = 18$ MeV ([1988GO02]; $t_0$, $t_1$) and at $E_d = 2.0$ to 2.8 MeV ([1984AN16]; $t_0$). At $E_d = 28$ MeV angular distributions of triton groups to $^8$Be$^*$($16.6, 16.9, 17.6, 18.2, 19.1, 19.2, 19.8$) have been analyzed using DWUCK: absolute $C^2S$ are 0.074, 1.56, 0.22, 0.17, 0.41, 0.48, 0.40, respectively. See also Table 8.11. An isospin amplitude impurity of 0.21 ± 0.03 is found for $^8$Be$^*$($17.6, 18.2$): see [1979AJ01].

At $E_d = 7$ MeV a complete kinematics measurement of $^9$Be(d, t + $^8$Be) observed states participating in the sequential decay of $^8$Be [1991SZ06]. The relative energy spectrum was reconstructed and yielded peaks corresponding to the ground state, $E_x \approx 0.6$ MeV and 3.00 ± 0.01 MeV; the observed width for the 3 MeV state was $\Gamma = 1.23 \pm 0.02$ MeV. Analysis in a single-level $R$-matrix formalism, best fit with $r_c = 4.5 \pm 0.1$ fm, indicates that the “ghost anomaly” structure at $\approx 0.6$ MeV is the result of deformation in the high-energy tail of the $^8$Be ground state. While the cross section corresponding to the first excited state peaks at 3.00 MeV, the $R$-matrix fit indicates that the resonance energy is $3.12 \pm 0.01$ MeV ($E_x = 3.03 \pm 0.01$ MeV) with $\Gamma_m = 1.43 \pm 0.06$ MeV [1991SZ06].

A kinematically complete study of reaction (b) at $E_d = 26.3$ MeV indicates the involvement of $^8$Be$^*$($0, 3.0, 11.4, 16.9, 19.9 + 20.1$): see [1974AJ01].

 Angular distributions have been measured in the range $E(^3\text{He}) = 3.0$ to 26.7 MeV and at $E(^3\text{He}) = 33.3$ MeV (to $^8$Be$^*$($16.9, 17.6, 19.2$)) [$S = 1.74, 0.72, 1.17$, assuming mixed isospin for $^8$Be$^*$($16.9$)]. The possibility of a broad state at $E_x \approx 25$ MeV is also suggested: see [1979AJ01]. See also [1987VA11].

Reaction (b) has been studied at $E(^3\text{He}) = 1.0$ to 10 MeV [see [1979AJ01,1984AJ01]], at $E(^3\text{He}) = 3$ to 12 MeV [1986LA26] and at 11.9 to 24.0 MeV [1987WA25]. The reaction is reported to proceed via $^8$Be$^*$($0, 3.0, 11.4, 16.6, 16.9, 19.9, 22.5$): see [1979AJ01] and [1986LA26,1987WA25]. For a discussion of the width of $^8$Be$^*$($11.4$) see [1987WA25]. Angular distributions for $^9$Be($^3\text{He}, \alpha$) were evaluated to determine the contributions from neutron pickup vs. heavy particle stripping; $^9$Be spectroscopic factors for $S_0$ and $S_0$ were calculated [1997ZH40]. See also ([1992KO26]; theor.). See also $^9$Be here and $^{12}$C in [1980AJ01,1988AJ01].

32. $^9$Be($\alpha, \alpha'n$)$^9$Be, \hspace{1cm} $Q_m = -1.6654$

A summary of the ($\alpha, \alpha'n$) cross sections used in the SOURCES code is given in [2003SH22]. The SOURCES code [2002WI1K] is used, for example, to calculate neutron energies and doses from $^9$Be-actinide radioactive sources.
Angular distributions have been studied at $E(\text{6 Li}) = 32$ MeV involving $^8\text{Be}^*(0, 3.0)$ and $^7\text{Li}^*(0, 0.48)$ [1985CO09]. For reaction (b) see [1984KO25]. For reaction (c) measurements at $E(^9\text{Be}) = 48$ MeV were evaluated with a CCBA model; $^8\text{Be}^*(3.0, 11.3)$ played an important role in the reaction [2003AS04]. Also see $^{10}\text{Be}$ and [1985JA09]. For the earlier work see [1979AJ01].

Optical model parameters for $^8\text{Be}^* + ^{13}\text{C}$ were deduced from $^9\text{Be}(^{12}\text{C}, ^{13}\text{C})^8\text{Be}$ for $E(^{12}\text{C}) = 65$ MeV. For $^9\text{Be} + ^{12}\text{C}$ and $^8\text{Be} + ^{13}\text{C}$, energy-dependent optical model parameters are given for $E_{cm} = 5$–50 MeV [1999RU10].

Angular distributions were measured for $^{10}\text{Be}(K^+, K^+ + d)^8\text{Be}$ at $E_{K^+} = 130$–268 MeV. A DWIA analysis indicated that direct knock-out and 2-step mechanisms are important [1991BE42].

Bremsstrahlung photons were used to measure the $^{10}\text{B}(\gamma, pn)^8\text{Be}$ reaction at $E_\gamma = 66$–103 MeV in a study of two-body photon absorption and final state interactions [1988SU14].

The breakup of $^{10}\text{B}$ by 14.4 MeV neutrons involves, among others, $^8\text{Be}_{g.s.}$ [1984TU02]. The cross section of $^{10}\text{B}(n, t)^4\text{He}$ for thermal neutrons is reported as $\sigma_{\text{thermal}} = 7 \pm 2$ mb [1987KA32]. See also [1979AJ01] and $^{11}\text{B}$ in [1990AJ01].
Angular distributions of the \( ^3\text{He} \) ions to \( ^8\text{Be}^* \)\((0, 3.0, 16.6, 16.9)\) have been studied at \( E_p = 39.4 \text{ MeV} \) [see [1974AJ01] and at \( E_p = 51.9 \text{ MeV} \) ([1983YA05]; see for a discussion of isospin mixing of the 16.8 MeV states).

41. (a) \( ^{10}\text{B}(d, \alpha)^8\text{Be} \), \( Q_m = 17.8198 \)
(b) \( ^{10}\text{B}(d, \alpha)^4\text{He}^4\text{He} \), \( Q_m = 17.9117 \)

Angular distributions have been reported at \( E_d \) = 0.5 to 7.5 MeV: see [1974AJ01, 1979AJ01]. At \( E_d = 67–141 \text{ keV} \), angular distributions of \( \alpha_0 \) and \( \alpha_1 \) were measured and the \( ^{10}\text{B}(d, \alpha_0) \) and \( ^{10}\text{B}(d, \alpha_1) \) astrophysical \( S \)-factors were deduced [1997YA02]. The angular-dependent cross sections for \( \alpha \) reactions were measured for \( E_d = 120–340 \text{ keV} \) and in each case the \( S \)-factor was observed to increase with decreasing energy [2001HO22]. Yield ratios for \( ^{10}\text{B}(d, p)/^{10}\text{B}(d, \alpha) \) were measured at \( E_d = 58–142 \text{ keV} \) [1993CE02]. At \( E_d = 7.5 \text{ MeV} \) the population of \( ^8\text{Be}^*(16.6, 16.9) \) is closely the same, consistent with their mixed isospin character while \( ^8\text{Be}^*(17.64) \) is relatively weak consistent with its nearly pure \( T = 1 \) character. \( ^8\text{Be}^*(16.6, 16.9, 17.64, 18.15) \) have been studied for \( E_d = 4.0 \) to 12.0 MeV. Interference between the \( 2^+ \) states \( ^8\text{Be}^*(16.6, 16.92) \) varies as a function of energy. The cross-section ratios for formation of \( ^8\text{Be}^*(17.64, 18.15) \) vary in a way consistent with a change in the population of the \( T = 1 \) part of the wave function over the energy range: at the higher energies, there is very little isospin violation. At higher \( E_x \) the \( 3^+ \) state at \( E_x = 19.2 \text{ MeV} \) is observed, the neighboring \( 3^+ \) state at \( E_x = 19.07 \text{ MeV} \) is not seen. \( \Gamma_{16.6} = 90 \pm 5 \text{ keV} \), \( \Gamma_{16.9} = 70 \pm 5 \text{ keV} \), \( \Delta Q = 290 \pm 7 \text{ keV} \); see Table 8.11 and [1979AJ01]. Relative widths of \( ^8\text{Be}^* \) levels at 19.86 and 20.1 MeV, \( \Gamma_{\alpha}/\Gamma_p = 2.3 \pm 0.5 \) and \( \Gamma_{\alpha}/\Gamma_p = 4.5 \pm 0.6 \), respectively, were determined by a complete kinematics measurement of \( ^{10}\text{B}(d, 2\alpha) \) and \( ^{10}\text{B}(d, ^7\text{Li}+p) \) at \( E_d = 13.6 \text{ MeV} \) [1992PU06]. At \( E_d = 48 \text{ MeV} \) evidence was observed for an \( ^8\text{Be}^* \) state at \( E_x = 32 \text{ MeV} \) with \( \Gamma = 1 \text{ MeV} \) [1993PA31]; levels were also seen at \( ^8\text{Be}^*(0, 3.0, 11.4, 16.6[^u], 16.9[^u], 17.6, \approx 19, \approx 20, 21.5, 22.2, 24, 25.2) \).

At \( E_d = 4.2 \) to 6.6 MeV measurements were carried out by detecting \( \alpha \) coincidences in a kinematical star configuration [1992BO1H]. \( ^{12}\text{C} \) was excited into the excitation energy region near 30 MeV, which was then followed by \( 3\alpha \) decay. The analysis, which indicated sequential decay through the \( ^8\text{Be}^*(11.4) \) state, was intended to stimulate activity in 3-body interactions by invoking an alternative approach.

Reaction (b) \( [E_d < 5 \text{ MeV}] \) takes place mainly by a sequential process involving \( ^8\text{Be}^*(0, 2.9, 11.4, 16.6, 16.9) \); see [1979AJ01]. See also [1983DA11] [The work quoted in [1984AJ01] has not been published.] At \( E_d = 13.6 \text{ MeV} \) in addition to \( ^8\text{Be}^*(16.6, 16.9) \), states with \( E_x \approx 19.9–20.2 \text{ MeV} \) with \( \Gamma \approx 0.7–1.1 \text{ MeV} \) are involved [1988KA1K]. See also [1992KO26].

42. \( ^{10}\text{B}(\alpha, ^6\text{Li})^8\text{Be} \), \( Q_m = -4.5529 \)

Angular distributions for the \( ^8\text{Be}^*(0, 3.0) \) are reported in a measurement of \( ^{10}\text{B}(\alpha, ^6\text{Li}) \) at \( E_\alpha = 27.2 \text{ MeV} \) [1995FA21]; it was deduced that direct processes are dominant in the reactions. See reaction 40 in [1984AJ01] and \( ^6\text{Li} \) in [2002T110].
Angular distributions have been measured at $E_p = 0.04$ to 45 MeV [see [1974AJ01, 1979AJ01, 1984AJ01]]. The $\alpha_0$ and $\alpha_1$ excitation functions and astrophysical reaction rates have been determined by measuring angular dependent differential cross sections and total cross sections at $E_{cm} = 0.12$–1.10 MeV [1987BE17], at $E_p = 4.5$ to 7.5 MeV [1983BO19], at $E_p = 40$–180 keV [1992CE02], at $E_{cm} = 17$–134 keV [1993AN06], at 1.7–2.7 MeV [1998MA54], and at $E_p = 0.4$–1.6 MeV [2002LI29]. A DWBA evaluation of data at 398, 498 and 780 keV indicated that direct mechanisms dominated over exchange processes at astrophysical energies [1995YA07]. A calculation of the expected influence of electron screening, due to using atomic nuclei, indicates that the astrophysical S($0$)-factor deduced from lab measurements may be 2.5 times greater than the rate when bare ions participate in the reaction [1993AN06]. See also [2002BA77, 2002HA51]. The effects of higher order processes including vacuum polarization, relativity, bremsstrahlung, atomic screening and atomic polarization are reviewed in [1997BA95]. See also [1996RA14] for DWBA analysis of data from 10–1000 keV.

Angular distributions of $\alpha_0$ and $\alpha_1$ particles were measured around the $^{12}$C($^{16}$) resonance at $E_p = 163$ keV, $E_{cm} = 148.3 \pm 0.1$ keV and $\Gamma = 5.3 \pm 0.2$ keV were deduced [1987BE17]. The $^{12}$C($^{16}$) resonance was evaluated in (p, $\alpha$) data and resonance parameters of $E_{res} = 596 \pm 30$ keV and $\Gamma = 383 \pm 40$ keV were deduced [1993AN06].

Reaction (b) has been studied for $E_p = 0.15$ to 20 MeV: see [1974AJ01, 1984AJ01]. The reaction proceeds predominantly by sequential two-body decay via $^8$Be($0$, $3.0$). See also $^{12}$C in [1990AJ01], and [1992KO26].

Reaction (c) was measured at $E_p = 2$–5.5 MeV by [1995BO35]. A reconstruction of the $2\alpha$ relative energy spectrum was analyzed to evaluate parameters for $^8$Be($3.0$).

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

The work reported in [1984AJ01] has not been published. See also $^7\text{Li}$ in [2002TI10] and references cited in [1988AJ01].

See [1984DA17] and $^{12}$B in [1990AJ01].
47. $^{12}\text{C}(\gamma, p + t)^8\text{Be}$, $Q_m = -27.1804$

The $^8\text{Be}$ ground state and excited $0^+$ and $2^+$ states are reported to participate in the $^{12}\text{C}$ photodisintegration reaction $^{12}\text{C}(\gamma, pt)$ at energies up to $E_\gamma = 150$ MeV; see [1989VO04, 1990DO03].

48. $^{12}\text{C}(\gamma', p + t)^8\text{Be}$, $Q_m = -27.1804$

A DWIA calculation of $^{12}\text{C}(\gamma', p + t)^8\text{Be}$ at 500–650 MeV qualitatively evaluated the restructuring of excited clusters following knockout reactions [1999SA27].

49. $^{12}\text{C}(\pi^+, 3p + n)^8\text{Be}$, $Q_m = 104.6903$

The energy and mass dependence of pion ($\pi^+$) absorption leading to multiple protons in the final state was measured at $E_{\pi^+} = 30–135$ MeV [2000GI07].

50. (a) $^{12}\text{C}(n, n\alpha)^8\text{Be}$, $Q_m = -7.3666$

(b) $^{12}\text{C}(p, p\alpha)^8\text{Be}$, $Q_m = -7.3666$

(c) $^{12}\text{C}(p, d + ^3\text{He})^8\text{Be}$, $Q_m = -25.7196$

The first two of these reactions involve $^8\text{Be}^*(0, 3.0)$; see [1974AJ01, 1979AJ01, 1984AJ01] and [1985AJ01]. For reaction (a), see [1986AN1M]. For reaction (b) $\alpha$-spectroscopic factors in $^{12}\text{C}$ for $\alpha + ^8\text{Be}^*(0, 3.0)$ are deduced in [1995NE11, 1997SA04, 1998YO09]. The $\alpha$-cluster knockout reaction mechanism is evaluated in [1987ZH10, 1994NE05, 1995GA39, 1995NE11, 1997SA01, 1997SA04, 1998YO09, 1999HA27]. For reaction (c) see ([1983LI18]; theor.).

51. (a) $^{12}\text{C}(d, ^6\text{Li})^8\text{Be}$, $Q_m = -5.8927$

(b) $^{12}\text{C}(d, d\alpha)^8\text{Be}$, $Q_m = -7.3666$

Measurements of angular distributions and polarization observables [$T_1(\theta)$, $T_2(\theta)$, $T_2(\theta)$ and $T_2(\theta)$] are reported for $^{12}\text{C}(d, ^6\text{Li})^8\text{Be}_{g.s.}$ at 18 and 22 MeV [1987TA07]. DWBA analysis is used to evaluate $\alpha$-spectroscopic factors from $^{12}\text{C}(d, ^6\text{Li})$ at $E_d = 41$ MeV [1988RA20] and at $E_d = 15–55$ MeV [1988RA27]. Angular distributions have been studied at $E_d = 12.7$ to 54.3 MeV [see [1974AJ01, 1979AJ01, 1984AJ01]] and at $E_d = 18$ and 22 MeV ([1986YA12]; to $^8\text{Be}_{g.s.}$) and 51.7 MeV ([1986YA12]; to $^8\text{Be}^*(0, 3.0, 11.4)$ as well as at $E_d = 50$ MeV [1987GO1S], 54.2 MeV ([1984UM04]; FRD-WBA) [$S_p = 0.48, 0.51$ and 0.82 for $^8\text{Be}^*(0, 3.0, 11.4)$] and 78.0 MeV ([1986JA14]; to $^8\text{Be}^*(0, 3.0, 16.6, 16.9)$). See also ([1985GO1G]; $E_d = 50$ MeV). For reaction (b) see ([1984AJ01]). See also [1984NE1A] and references cited in [1988AJ01].

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

(b) $^{12}\text{C}(t, ^8\text{Li})^8\text{Be}$, $Q_m = -7.8137$

Angular distributions from $^{12}\text{C}(t, ^7\text{Li})$ and $^{13}\text{C}(t, ^8\text{Li})$ were evaluated in a DWBA analysis to deduce spectroscopic factors in $^{12}\text{C}$ for $\alpha + ^8\text{Be}_{g.s.}$ [1989SI02]. See also $^7\text{Li}$ in [2002TI10].
53. $^{12}\text{C}(^{3}\text{He}, ^{7}\text{Be})^{8}\text{Be}$, $Q_m = -5.7805$

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

54. (a) $^{12}\text{C}(\alpha, 2\alpha)^{8}\text{Be}$, $Q_m = -7.3666$
(b) $^{12}\text{C}(^{8}\text{Be}, 2\alpha)^{8}\text{Be}$, $Q_m = -7.4584$

These reactions have been studied at $E_{\alpha}$ to 104 MeV [see [1979AJ01,1984AJ01] and $^{12}\text{C}$ in [1985AJ01]] and at 31.2 MeV ([1986XI1A]; reaction (a)): $^{8}\text{Be}^*$(0, 3.0, 11.4) are populated. See also references cited in [1988AJ01]. Alpha spectroscopic factors $^{8}\text{Be}^*$(0, 3.0) were measured by $\alpha$ knockout at 200 MeV [1999ST06] and 580 MeV [1999NA05]. $\alpha$-particle angular correlations were measured from the $^{12}\text{C}^* \rightarrow \alpha + ^{8}\text{Be}$ decay to determine the polarization characteristics of the $^{12}\text{C}^*$(9.64, 3$^-$) state, which was excited by $^{12}\text{C}(\alpha, \alpha')^{12}\text{C}^*$(9.64) → $\alpha + ^{8}\text{Be}$ [1989KO55].

55. (a) $^{12}\text{C}(^{9}\text{Be}, ^{13}\text{C})^{8}\text{Be}$, $Q_m = 3.2809$
(b) $^{12}\text{C}(^{11}\text{B}, ^{15}\text{N})^{8}\text{Be}$, $Q_m = 3.6248$

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

56. (a) $^{12}\text{C}(^{12}\text{C}, ^{16}\text{O})^{8}\text{Be}$, $Q_m = -0.2047$
(b) $^{12}\text{C}(^{16}\text{O}, ^{20}\text{Ne})^{8}\text{Be}$, $Q_m = -2.6367$
(c) $^{12}\text{C}(^{20}\text{Ne}, ^{24}\text{Mg})^{8}\text{Be}$, $Q_m = 1.9500$
(d) $^{12}\text{C}(^{20}\text{Ne}, \alpha + ^{20}\text{Ne})^{8}\text{Be}$, $Q_m = -7.3666$
(e) $^{12}\text{C}(^{24}\text{Mg}, ^{16}\text{O} + ^{12}\text{C})^{8}\text{Be}$, $Q_m = -14.1382$

For reaction (a) $^{12}\text{C}(^{12}\text{C}, ^{16}\text{O})$ was measured in a study of $^{24}\text{Mg}$ excited states near 33 MeV at $E(^{12}\text{C}) = 27–36$ MeV [1995AL25,1996AL03,1997SZ01]. See also $^{16}\text{O}$ in [1993TI06] and references cited in [1988AJ01]. For reaction (b) see reaction 18 in $^{20}\text{Ne}$ in [1987AJ02,1985MU14] and ([1988AL07]; location of a 10$^+$ state in $^{20}\text{Ne}$ at $E_x \approx 27.5$ MeV). Evidence for 11 states in $^{24}\text{Mg}$ with excitation energy between 22 and 30 MeV is seen in reaction (c) at $E(^{20}\text{Ne}) = 110$ and 160 MeV [2001FR03]. For reaction (d) see [1987SI06]. States in $^{28}\text{Si}$ at $E_x = 28.0$ MeV [J$^\pi = 13^-$], 29.8 MeV ([11]), 33.4 MeV [8$^+$ (10$^+$)] and 34.5 MeV ([12, 14]+) are observed in reaction (e) at $E(^{24}\text{Mg}) = 170$ MeV [2001SH08].

57. $^{13}\text{C}(d, ^{7}\text{Li})^{8}\text{Be}$, $Q_m = -3.5888$

See $^{7}\text{Li}$ in [2002TI10].
58. \(^{13}\text{C}(\alpha,^{9}\text{Be})^{8}\text{Be})\), \(Q_m = -10.7393\)

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

59. \(^{13}\text{C}^{9}\text{Be},^{14}\text{C})^{8}\text{Be}\), \(Q_m = 6.5110\)

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

60. \(^{14}\text{N}(n,^{7}\text{Li})^{8}\text{Be}\), \(Q_m = -8.9148\)

See \(^{7}\text{Li}\) in [2002TI10].

61. \(^{16}\text{O}(\gamma,4\alpha)^{8}\text{Be}\), \(Q_m = -14.4367\)

The \(^{16}\text{O}(\gamma,4\alpha)\) reaction was studied with bremsstrahlung \(\gamma\) rays up to \(E_{\gamma} = 300\ \text{MeV}\) [1995GO10]. Evidence in the energy reconstruction spectra indicates that participation of the \(^{8}\text{Be}^*(0,3.0)\) states increases with increasing \(\gamma\)-ray energy.

62. \(^{16}\text{O}(p,p + 2\alpha)^{8}\text{Be}\), \(Q_m = -14.5285\)

See ([1986VD04]; \(E_p = 50\ \text{MeV}\)).

63. \(^{16}\text{O}^{16}\text{O},^{24}\text{Mg})^{8}\text{Be}\), \(Q_m = -0.4821\)

See [1987CZ02].

64. \(^{\text{nat}}\text{Ag}(^{14}\text{N},^{8}\text{Be})X\)

Sequential-decay neutron spectroscopy of \(^{7}\text{Be} + \text{n}\) products from \(^{\text{nat}}\text{Ag} + ^{14}\text{N}\) at 35 MeV/A indicates the participation of \(^{8}\text{Be}^*(19.24)\) with 19.234 ± 0.012 MeV and \(\Gamma = 210 \pm 35\ \text{keV}\) [1989HE24].
The $\beta^+$ decay leads mainly to $^8\text{Be}^*(3.0)$. The half-life is $770 \pm 3$ ms; $\log t = 5.6$ [1974AJ01]. There is also a branch to $^8\text{Be}^*(16.63)$, and evidence for population of an $^8\text{Be}$ intruder state at $E_x \approx 9$ MeV. See reactions 24 and 27 in $^8\text{Be}$. See also references cited in [1988AJ01].

A new $\beta$-NMR technique (NNQR) was used to measure the quadrupole moment of $^8\text{B}$, $|Q(8\text{B}, 2^+)| = 68.3 \pm 2.1$ mb [1992MI18,1993MI35]. The large quadrupole moment was reported as the first evidence of a proton halo in $^8\text{B}$.

The tilted foil technique was used to polarize atomic $^8\text{B}$ nuclei. The polarization was transferred to the nucleus via the hyperfine interaction and the resulting $\beta$-decay asymmetry indicated that the polarization was saturated at $3.71 \pm 0.28\%$ [1993MO34].

The $\beta$-decay of $^8\text{B}$ provides the high-energy neutrinos that are measured by large volume neutrino detectors that are attempting to resolve the “solar neutrino problem”. The neutrino energy spectrum from $^8\text{B} \beta$-decay, which is essential to interpret the data from these detectors, has been measured and evaluated in [1987NA08,1996BA28,1999DE33,2000OR04,2003RE26,2003WI16]. The $^8\text{B}$ neutrino absorption cross sections $(\pm 3\sigma)$ for Cl and Ga are $\sigma_{\text{Cl}} = 1.14 \pm 0.11 \times 10^{-42}$ cm$^2$ and $\sigma_{\text{Ga}} = 2.46^{+2.1}_{-1.1} \times 10^{-42}$ cm$^2$ [1996BA28]. However, the results of [2000OR04] suggest a harder neutrino spectrum than that used by [1996BA28].

For comments about the weak neutral current interaction in $^8\text{B} \beta$-decay see [1989TE04,1992DE07,2003SM02]. For theoretical discussion of $^8\text{Be}$ levels that are involved in the decay see [1989BA31,1993CH06,2000GR07,2002BH03] and reaction 27 in $^8\text{Be}$.

Angular distributions and analyzing powers have been measured for the transitions to $^8\text{Be}^*(0, 2.32)$ at $E_p = 199.2$ MeV [1987CA06] and at 280, 345 and 489 MeV [1988HU11]; the $A_y$ to $^8\text{B}^*(2.32)$ is characteristic of that to a stretched high-spin, two-particle one-hole final state [$J^\pi$ of $^8\text{B}^*(2.32)$ is $3^+$] [1987CA06].

Angular distributions and analyzing powers have been measured for the transitions to $^8\text{B}^*(0, 2.32)$ at $E_p = 199.2$ MeV [1987CA06] and at 280, 345 and 489 MeV [1988HU11]; the $A_y$ to $^8\text{B}^*(2.32)$ is characteristic of that to a stretched high-spin, two-particle one-hole final state [$J^\pi$ of $^8\text{B}^*(2.32)$ is $3^+$] [1987CA06].
Table 8.15
Energy levels of $^8$B

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$J^\pi; T$</th>
<th>$\tau_{1/2}$ or $I^\text{cm}$ (keV)</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s. 2.1</td>
<td>2$^+$; 1</td>
<td>$\tau_{1/2} = 770 ± 3$ ms</td>
<td>$\beta^+$</td>
<td>1, 2, 3, 4, 5, 6, 8, 9, 10, 12</td>
</tr>
<tr>
<td>0.7695 ± 2.5$^{b,c}$</td>
<td>1$^+$; 1$^{c,d}$</td>
<td>$I' = 35.6 ± 0.6^{b,c}$</td>
<td>$\gamma, p$</td>
<td>2, 3, 4, 6, 7, 9, 10, 12</td>
</tr>
<tr>
<td>2.32 ± 20$^d$</td>
<td>3$^-$; 1 350 ± 30$^e$</td>
<td>&lt; 60</td>
<td>$\gamma$</td>
<td>4, 6, 7, 9, 10, 12</td>
</tr>
<tr>
<td>3.5 ± 500$^f$</td>
<td>2$^-$</td>
<td>8 ± 4 MeV$^e$</td>
<td></td>
<td>6, 7</td>
</tr>
<tr>
<td>10.619 ± 9</td>
<td>0$^+$; 2</td>
<td>&lt; 60</td>
<td></td>
<td>12</td>
</tr>
</tbody>
</table>

$^a$ See reactions 6 and 7 for evidence of additional states.

$^b$ Average of values from reactions 3, 6 and 7.

$^c$ From data reviewed in this evaluation.

$^d$ See [2004TA17].

Table 8.16
Electromagnetic transition strengths in $^8$B

<table>
<thead>
<tr>
<th>$E_i → E_f$ (MeV)</th>
<th>$I^\text{cm}$ (keV)</th>
<th>$I^\text{cm}$ (keV)</th>
<th>$\Gamma^\gamma$ (eV)</th>
<th>Mult.</th>
<th>$\Gamma^\gamma / I^W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7695 → 0</td>
<td>(1$^+$; 1) → 2$^+$; 1</td>
<td>(2.52 ± 0.11) $\times 10^{-2}$</td>
<td>M1</td>
<td>2.63 ± 0.12</td>
<td></td>
</tr>
<tr>
<td>2.32 → 0</td>
<td>3$^+$; 1 → 2$^+$; 1</td>
<td>0.10 ± 0.05$^b$</td>
<td>M1</td>
<td>0.38 ± 0.19</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ $\Gamma^\gamma$ is an average of 24.8 ± 2.9 meV [2003BA51] and 25.3 ± 1.2 meV [2003JU04].

$^b$ From a reanalysis of the data in [2003JU04] [K.A. Snover, private communication].

Table 8.17
Resonances observed in $^7$Be($p$, $\gamma$)$^8$B

<table>
<thead>
<tr>
<th>$E_{cm}$ (MeV)</th>
<th>$I^\text{p}$ (keV)</th>
<th>$\sigma$ (ab)</th>
<th>$I^\text{p}$ (meV)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>632 ± 10</td>
<td>37 ± 5</td>
<td>1180 ± 120</td>
<td>24.7 ± 4.2</td>
<td>[1983FI13]</td>
</tr>
<tr>
<td>633</td>
<td>35 ± 3</td>
<td>1250 ± 100</td>
<td>24.8 ± 2.9</td>
<td>[2003BA51]</td>
</tr>
<tr>
<td>630 ± 3</td>
<td>35.7 ± 0.6</td>
<td>25.3 ± 1.2</td>
<td>25.3 ± 1.2</td>
<td>[2003JU04]</td>
</tr>
<tr>
<td>630 ± 3</td>
<td>35.7 ± 0.6</td>
<td>1221 ± 77</td>
<td>25.2 ± 1.1</td>
<td>&quot;mean&quot; value$^a$</td>
</tr>
</tbody>
</table>

$^{2183}$350 $^{100 ± 50}$ $^{b}[2003JU04]$

$^a$ Excludes $\sigma_R = 2200 ± 220$ nb, $I^\gamma = 50 ± 25$ meV from [1966PA16], which had been cited in [1988AJ01].

$^b$ Private communication from K.A. Snover; revised from $I^\gamma = 150 ± 30$ meV [2003JU04].

6. $^7$Be($p$, $\gamma$)$^8$B, $Q_{cm} = 0.1375$

Absolute cross sections have been measured for $E_p = 112$ keV to 10.0 MeV. See also [1984AJ01] and references cited in [1988AJ01]. Resonances are observed at $E_p = 720$ and 2497 keV; see Table 8.17. An $R$-matrix evaluation of ($p$, $\gamma$) and ($p$, $p'$) [reaction 7] data supports the existence of a 2$^-$ level at $E_x = 3–4$ MeV [2000BA46], and a 1$^+$ resonance is predicted at $E_x ≈ 1.4$ MeV [2000CS01]. See however [2001RO32] and reaction 9.

Direct measurements of $^7$Be($p$, $\gamma$) at low energies are typically carried out by measuring $\beta$-delayed alpha particles from decay of the residual $^8$B nucleus. However, systematic errors associated with $^8$B backscattering losses from the target prior to counting have become a concern, based on new measurements and Monte Carlo calculations (see [1998ST20] and reaction 9 in $^7$Li).
A review of astrophysical reaction rates [1998AD12] favored the measurements of 1982FI03 and deduced a value of \( S(0) = 19^{+4}_{-2} \) eV b, however, several measurements [see Table 8.18] have been reported since this review. See other overviews of direct and indirect measurements in [2001MO32,2001MU20,2002MO11,2003DA30,2003MO23,2003MO28]; for cluster model calculations see [1988DE38,1988KO29,1993DE30,1993RO04,1994DE03,1995CS01,1997CS07,1998CS03,1998MO13,2000CS03]; for di-
The nature of the shape of the $S$-factor as the proton capture energy approaches zero is discussed in [1998JE10, 19998JE11, 2000BA09, 2000BB09, 2000JE10, 2002MU16]. The authors of [1998JE10], [2000VE01] suggest that $S(20 \text{ keV})$ is more relevant than $S(0)$ since the Gamow energy is $\approx 20 \text{ keV}$, and they suggest that the extrapolation of the reaction rate to $20 \text{ keV}$ has less uncertainty than the extrapolation to zero energy proton capture.

The time reversed reaction $^8\text{B} + \gamma \rightarrow ^7\text{Be} + p$ has been measured by exciting $^8\text{B}$ nuclei in the Coulomb field of high-Z target nuclei and detecting the $^7\text{Be}$ and proton products [1994MO33, 1998KI19, 1999WI03, 2001DA03, 2001DA11, 2002DA15, 2002DA26, 2003HA30, 2003SC14]. The $^7\text{Be}(p, \gamma)^8\text{B}$ cross sections are related to the photodisintegration cross sections by the Detailed Balance Theorem. Resulting values of $S(0)$ are $18.9 \pm 1.8 \text{ eV b}$ ([1998KI19]; RIKEN), $18.6 \pm 1.2 \text{ (expt.) } \pm 1.0 \text{ (theor.) eV b}$ ([1999WI03, 2003HA30, 2003SC14]; GSI), and $17.8^{+1.5}_{-1.2} \text{ eV b}$ ([2001DA03, 2001DA11, 2002DA15, 2002DA26]; MSU). The field of virtual photons that induce breakup can excite the $^8\text{B}$ mainly via E1 and E2 multiplicities; however, the proton capture reaction is dominated by E1 strength. Since the numbers of E1 and E2 virtual photons cre-
ated in the Coulomb field of the target are calculable, depending on projectile energy and impact parameter, the ratio of $\sigma(E2)/\sigma(E1)$ in the Coulomb dissociation experiments was deduced from asymmetries in, for example, the measured angular distributions. Values for the ratio, which depends on the relative $p + ^7\text{Be}$ energy and theory that is used to determine the E2 strength, range from $(0.5\text{ to } 5) \times 10^{-4}$ at $E_{\text{cm}} = 0.6\text{ MeV}$ [1997KI01, 1999IW03, 2001DA03, 2001DA11, 2002DA15, 2003SC14]. See also [1996KE16, 1996VO09]. Calculated estimates of the $\sigma(E2)/\sigma(E1)$ ratio in Coulomb dissociation are given in [1994LA08, 1995GA25, 1995LA17, 1996BE83, 1996ES02, 1996SH08, 1997TY01, 1999BB07, 1999DE23, 2002BE76, 2003FO07]. Interference between nuclear and Coulomb mechanisms is discussed in [1997TY01, 1998DA15, 1998NU01, 2003MA88]. See also [1993TI01, 1994TY03, 1996RE16, 1997CS02].

Calculations showing the relationship between the low-energy astrophysical $S$-factor for $^7\text{Be}(p, \gamma)$ and the asymptotic normalization coefficient (ANC) for $^7\text{Be}, ^8\text{B}$ reactions are presented in [1990MU13, 1994XU08, 1995MU10, 1997TI03, 1998GR07, 2000JE10, 2003TI13]. See also reactions 8 and 11.

7. $^7\text{Be}(p, p)^7\text{Be}$, \ $E_b = 0.1375$

The $^7\text{Be}(p, p)^7\text{Be}$ scattering was measured at $E_{\text{cm}} = 0.3\text{–}0.75\text{ MeV}$ using a $^7\text{Be}$ beam [2003AN29]. The data were analyzed in an $R$-matrix analysis and indicate $E_{\text{res}} = 634 \pm 5\text{ keV}$ and $\Gamma_{\text{res}} = 31 \pm 4\text{ keV}$ for the $1^+$ first excited state. Scattering length of $a_{01} = 25 \pm 9\text{ fm}$ (channel spin $I = 1$) and $a_{02} = -7 \pm 3\text{ fm}$ (channel spin $I = 2$) were also deduced from the data.

At $E(^7\text{Be}) = 32\text{ MeV}$ [1998GO16], two resonances were prominent in the inverse kinematics scattering excitation function, $E_x = 2.32 \pm 0.02\text{ MeV}$, $\Gamma = 350 \pm 30\text{ keV}$, $J^\pi = 3^+$ and $E_x = 2.83 \pm 0.15\text{ MeV}$, $\Gamma = 780 \pm 200\text{ keV}$, $J^\pi = 1^+$, though poor statistics in the measurement prevent a firm acceptance of the $2.83\text{ MeV}$ level. At $E(^7\text{Be}) = 25.5\text{ MeV}$ the $E_x = 2.32\text{ MeV}$ $J^\pi = 3^+$ level was observed with an additional level at $E_x = 3.5 \pm 0.5\text{ MeV}$, $\Gamma = 8 \pm 4\text{ MeV}$ [2001RO32]. An $R$-matrix analysis of the interference between the $2.32$ and $3.5\text{ MeV}$ levels indicates $J^\pi = 2^-$ for the higher state. In the later work, the $1^+$ state at $E_x = 2.8\text{ MeV}$, suggested by [1998GO16], was not necessary to obtain a good fit to the data. In addition there was no evidence for a level at $E_x = 1.4\text{ MeV}$ that had been suggested by [2000CS01]: see reaction 6.

8. $^7\text{Be}(d, n)^8\text{B}$, \ $Q_m = -2.0871$

The total $^2\text{He}^7\text{Be}, n$ cross section was measured at $E(^7\text{Be}) = 26\text{ MeV}$ ($\sigma_{\text{tot}} = 58 \pm 8\text{ mb}$) and was evaluated to determine the $^8\text{B} \rightarrow ^7\text{Be} + p$ asymptotic normalization coefficient (ANC) $C_{p,0}^2 = 0.711 \pm 0.092\text{ fm}^{-1}$. This can be related to the $^7\text{Be}(p, \gamma)$ astrophysical capture rate and indicates $S_{17}(0) = 27.4 \pm 4.4\text{ eV b}$ [1996LI12, 1997LI05]. Reanalysis of the data using better optical model parameters indicates a smaller ANC and a reduced value of $S_{17}(0) = 23.5 \pm 3.7\text{ eV b}$ [1998GA02, 1999FE04]. To remove the dependence on the optical model parameters, [2003OG02] performed a continuum-discretized coupled channels calculation using the spectroscopic factors $S = 0.849$ [1987KI01], from this they deduce $S_{17}(0) = 20.96\text{ eV b}$. 


Angular dependent differential cross sections were measured for $^9\text{Be}(^7\text{Li},^8\text{He})^8\text{B}$ from $0^\circ$ to $\approx 12^\circ$ at $E(^7\text{Li}) = 350 \text{ MeV}$. States in $^8\text{B}$ were observed at 0, 0.770 and 2.32 MeV [2001CA37].

At $E_p = 49.5 \text{ MeV}$ [see [1974AJ01]] and 51.9 MeV [1983YA05] angular distributions have been measured for $^{10}\text{B}(p, t)^8\text{B}$, $Q_m = -18.5316$.

In reaction (a) the asymptotic normalization coefficient (ANC), $C_{3/2}^2$, for $^8\text{B} \rightarrow ^7\text{Be} + p$ was determined by measuring differential cross sections for $^{10}\text{B}(^7\text{Be},^8\text{B})$ from $0^\circ$ to $\approx 35^\circ$ at $E(^7\text{Be}) = 84 \text{ MeV}$. The value of $C_{3/2}^2 = 0.398 \pm 0.062 \text{ fm}^{-1}$ was deduced which, together with $C_{1/2}^1/C_{3/2}^1 = 0.157$, corresponds to $S_{17}(0) = 17.8 \pm 2.8 \text{ eV b}$ [1999AZ02]. For reaction (b) $C_{3/2}^2 = 0.371 \pm 0.043 \text{ fm}^{-1}$ was measured in $^{14}\text{N}(^7\text{Be},^8\text{B})^1\text{N}$ at $E(^7\text{Be}) = 85 \text{ MeV}$, and $S_{17}(0) = 16.6 \pm 1.9 \text{ eV b}$ was deduced [1999AZ04].

A re-evaluation of the data from (a) and (b) using improved model parameters leads to revised values and a weighted average of $C_{3/2}^2 = 0.388 \pm 0.039 \text{ fm}^{-1}$ which corresponds to $S(0) = 17.3 \pm 1.8 \text{ eV b}$ [2001AZ01,2001GA19,2002GA11]. In addition, the $C_{3/2}^2$ gives $R_{r.m.s.} = 4.20 \pm 0.22 \text{ fm}$ for the valence proton [2001CA21]. See also $^{13}\text{C}(^7\text{Li},^8\text{Li})^{12}\text{C}$ [reaction 27 in $^8\text{Li}$] for a determination of the ANC from charge symmetry.

The pion absorption mechanism, which has a characteristic of high energy transfer and small momentum transfer, was studied at $E(\pi^+) = 100$ and 165 MeV [2002HU06]. The role of 2-step processes, such as pion scattering prior to absorption and nucleon pickup after absorption, is discussed, and simple models for neutron-pickup final state interactions are presented and shown to reasonably represent the data.
**8**\(^{8}\)B

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Table 8.19

Inclusive measurements of \(^{8}\)B breakup

<table>
<thead>
<tr>
<th>(^{8})B energy (MeV/A)</th>
<th>Target</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>10–40</td>
<td>nat(^{5})Si</td>
<td>[1996NE06,1997SK03]</td>
</tr>
<tr>
<td>20–60</td>
<td>nat(^{5})Si</td>
<td>[1995WA19]</td>
</tr>
<tr>
<td>40</td>
<td>(^{12})C</td>
<td>[1995WA19]</td>
</tr>
<tr>
<td>40, 60</td>
<td>(^{9})Be, (^{12})C, (^{27})Al</td>
<td>[1995PE09]</td>
</tr>
<tr>
<td>41</td>
<td>(^{9})Be, (^{197})Au</td>
<td>[1996KE16]</td>
</tr>
<tr>
<td>44, 81</td>
<td>(^{208})Pb</td>
<td>[1998DA14]</td>
</tr>
<tr>
<td>76</td>
<td>(^{12})C</td>
<td>[2003EN05]</td>
</tr>
<tr>
<td>142, 285</td>
<td>nat(^{27})Al, (^{208})Pb</td>
<td>[1997BL08]</td>
</tr>
<tr>
<td>790</td>
<td>(^{9})Be, (^{12})C, (^{27})Al</td>
<td>[1998TA10]</td>
</tr>
<tr>
<td>936</td>
<td>nat(^{12})C, (^{208})Pb</td>
<td>[2002CO04]</td>
</tr>
<tr>
<td>1440</td>
<td>(^{12})C</td>
<td>[1999SK04]</td>
</tr>
<tr>
<td>1440</td>
<td>(^{12})C, (^{208})Pb</td>
<td>[2001CO06]</td>
</tr>
<tr>
<td>1470</td>
<td>(^{12})C, (^{27})Al, (^{208})Pb</td>
<td>[1995SS10]</td>
</tr>
</tbody>
</table>

14. \(^{12}\)C\(^{8}\)B, \(^{8}\)B\(^{12}\)C

Angular distributions from quasielastic scattering of \(^{8}\)B on \(^{12}\)C were measured at 40 MeV/A [1995PE09]. Analysis of the data appears consistent with a proton halo [1995FA17,1996KN05,1997PE03].

15. \(^{14}\)C\(^{8}\)B, \(^{8}\)B\(^{14}\)C

Elastic scattering of \(^{8}\)B on \(^{14}\)C was calculated in a folding potential model. Results suggest that scattering of exotic nuclei from non-(\(N = Z\)) nuclei could reveal new information about the nuclear potentials, particularly in cases where rainbow effects are observed [1998KN02].

16. nat\(^{\mu}\)C\(^{8}\)B\(^{8}\)B

A measurement to determine muon induced background rates in large-volume scintillation solar neutrino detectors found \(\sigma = 4.16 \pm 0.81 \mu\)b and 7.13 \pm 1.46 \mu\)b for nat\(^{\mu}\)C\(^{8}\)B at \(E_{\mu} = 100\) and 190 GeV, respectively [2000HA33].

17. \(^{58}\)Ni\(^{8}\)B, \(^{7}\)Be\(^{59}\)Cu, \(Q_m = 3.2810\)

Angular distributions of \(^{7}\)Be following the breakup of \(^{8}\)B on a \(^{58}\)Ni target were measured at \(E\)(\(^{8}\)B) = 25–75 MeV to evaluate the importance of Coulomb-nuclear interference effects [2000GU05].

18. \(^{9}\)Be to \(^{208}\)Pb\(^{8}\)B, \(^{8}\)B

Inclusive measurements of \(^{8}\)B breakup have been reported: see Table 8.19.

The measured total reaction cross sections for nuclear processes are related to the \(^{8}\)B r.m.s. radius and valence proton r.m.s. radius in simple Glauber-type models. The cross sec-
cross sections range from $\sigma_{\text{tot}} \approx 800 \text{ mb}$ and $\sigma(\text{proton removal}) \approx 95 \text{ mb}$ at $E(\text{8B}) = 1471 \text{ MeV}/A$ on a $^{12}\text{C}$ target to $\sigma_{\text{tot}} \approx 1.95 \text{ b}$ at $E(\text{8B}) \approx 15 \text{ MeV}/A$ on Si [1995WA19, 1996NE06]. These cross sections correspond to $^8\text{B}$ r.m.s. radii around $2.43 \pm 0.01 \text{ fm}$ [1996OB01]; the valence proton r.m.s. radius deduced from the proton removal cross-section measurements is model dependent and values in the range of $3.97 \pm 0.12 \text{ fm}$ [1996NE06] to $6.83 \text{ fm}$ [1995SC10] are deduced. See also [1997KN07, 1998SH09, 1999KN04]. A review of nuclear sizes deduced from interaction cross sections is in [2001OZ04].

Measurements of the parallel momentum distribution of $^7\text{Be}$ fragments following the breakup of $^8\text{B}$ projectiles are reported in [1995SC10, 1996KE16, 1996NE06, 1997SC03, 1998DA14, 1999SM04, 2000CO31] and are interpreted in Serber-type models as reflecting detailed information about the $^8\text{B}$ valence proton wave function. At $E(\text{8B}) = 1.47 \text{ GeV}/A$ the momentum distribution widths from breakup on C, Al and Pb are $\Gamma_{\text{FWMH}} \approx 81 \pm 6 \text{ MeV}/c$ [1995SC10]. This width is much narrower than that expected from the breakup of nuclei with “normal” densities and was interpreted as an indication of a proton halo in $^8\text{B}$. However, at energies near $40 \text{ MeV}/A$ the momentum distribution of $^7\text{Be}$ fragments from $^8\text{B}$ breakup range from $\Gamma = 62 \pm 3 \text{ MeV}/c$ on an Au target (mainly Coulomb breakup processes) [1996KE16] to $\Gamma = 95 \pm 7 \text{ MeV}/c$ on a Si target (mainly nuclear breakup processes) [1996NE06]; this is an indication that at this energy, simple Serber-type models are not adequate to explain the observed momentum distributions since the breakup mechanisms play a role in determining the observed distributions.

By evaluating fragment momentum distributions in more complex models, it was suggested that the asymmetric $^7\text{Be}$ fragment momentum distribution from $^8\text{B}$ breakup on Au at $41 \text{ MeV}/A$ reflects the interference of E1 and E2 contributions in Coulomb Dissociation and gives information about the relative E2/E1 strength [1996ES02], [1996KE16]. A high-resolution measurement of the asymmetric distribution from breakup on Pb at $E(\text{8B}) = 44$ and $81 \text{ MeV}/A$ deduced that $\sigma(\text{E2})/\sigma(\text{E1}) \approx 6.7 \times 10^{-4}$ at $E_{\text{rel}}(p + ^7\text{Be}) = 0.6 \text{ MeV}$ [1998DA14]. A more precise value of $\sigma(\text{E2})/\sigma(\text{E1}) \approx 4.9 \times 10^{-4}$ at $E_{\text{rel}} = 0.6 \text{ MeV}$ was deduced by including measurements at $E(\text{8B}) = 83 \text{ MeV}/A$ [2002DA15].

Breakup cross sections and $^7\text{Be}$ core-like fragment momentum distributions are analyzed in a modified Glauber model to obtain asymptotic normalization coefficients (ANC) for the $^8\text{B} \rightarrow ^7\text{Be} + p$ reaction [2004TR06]. In this analysis of breakup data, the value $S_{17}(0) = 18.7 \pm 1.9 \text{ eV b}$ is deduced.

At $E(\text{8B}) = 936 \text{ MeV}/A$, the ratio of $(^7\text{Be}^*(0.429) + \gamma)/^7\text{Be}$ production was measured on C and Pb targets [2002CO04, 2003CO06, 2003ME16]. The measurements indicate a $13.3 \pm 2.2\%$ component of $^7\text{Be}^*(0.429)$ in the ground state of $^8\text{B}$ [2003ME16]. Spectroscopic factors for $^7\text{Be}^*(0, 0.43)$ were deduced from measurements of $^{12}\text{C}(^8\text{B}, ^7\text{Be})$ at $E(\text{8B}) = 76 \text{ MeV}/A$; $C^2S = 1.036$ and 0.220, respectively [2003EN05].

$^8\text{B}, ^8\text{C}$

Mass of $^8\text{C}$ The atomic mass excess of $^8\text{C}$ is $35094 \pm 23 \text{ keV}$ [2003AU03]; $\Gamma_{\text{cm}} = 230 \pm 50 \text{ keV}$ [$J^\pi = 0^+; T = 2$]; see [1979AJ01]. $^8\text{C}$ is stable with respect to $^7\text{B} + p$. 

(Fig. 5)
Fig. 5. Isobar diagram, \( A = 8 \). The diagrams for individual isobars have been shifted vertically to eliminate the neutron–proton mass difference and the Coulomb energy, taken as \( E_C = 0.60 \frac{Z(Z - 1)}{A^{1/3}} \). Energies in square brackets represent the (approximate) nuclear energy, \( E_N = M(Z, A) - ZM(H) - NM(n) - E_C \), minus the corresponding quantity for \( ^8\text{Be} \): here \( M \) represents the atomic mass excess in MeV. Levels which are presumed to be isospin multiplets are connected by dashed lines.
Table 8.20
Isospin triplet states \((T = 1)\) in \(A = 8\) nuclei

<table>
<thead>
<tr>
<th>(A = 8) Li</th>
<th>(A = 8) Be</th>
<th>(A = 8) B</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>2(^+)</td>
<td>16.626 ± 16.922(^d)</td>
</tr>
<tr>
<td>2.255</td>
<td>3(^+)</td>
<td>19.07(^f)</td>
</tr>
</tbody>
</table>

\(^a\) As taken from Tables 8.2, 8.9 and 8.15. The analogs of the broad 1\(^+\) levels near 3.2 and 5.4 MeV and the narrow 4\(^+\) level at 6.53 MeV in \(A = 8\) Li (see Table 8.2) are unknown in \(A = 8\) Be and \(A = 8\) B.

\(^b\) Defined as \(E_x(8\text{Be}) - E_x(8\text{Li}) - 16.802\).

\(^c\) Defined as \(E_x(8\text{B}) - E_x(8\text{Li})\).

\(^d\) The \(T = 1\) centroid of the 16.626 and 16.922 MeV levels is 16.802 MeV in \(A = 8\) Be, assuming an isospin-mixed doublet with \(T = 0\) intensities proportional to the observed \(\alpha\) widths in Table 8.9.

\(^e\) Predominantly \(T = 1\). A small amount of isospin mixing improves the \(\gamma\)-ray branching ratios for the decay of the 17.64 and 18.15 MeV levels, and also the channel spin ratio for the formation of the 17.64 MeV level in the \(7\text{Li}(p,\gamma)\) reaction.

\(^f\) Predominantly \(T = 1\). Isospin mixing at the few \% level is needed to reproduce the widths of the 19.07 and 19.24 MeV levels.

\((Q = -0.07\) MeV) and unstable with respect to \(6\text{Be} + 2\text{p}\) \((Q = 2.14)\), \(5\text{Li} + 3\text{p}\) \((Q = 1.55)\) and \(4\text{He} + 4\text{p}\) \((Q = 3.51)\). At \(E(T = 3\text{He}) = 76\) MeV the differential cross section for formation of \(8\text{C}_{8.5}\) in the \(14\text{N}(3\text{He},8\text{Li})\) reaction is \(\approx 5\) nb/sr at \(\theta_{lab} = 10^\circ\). The \(12\text{C}(\alpha,8\text{He})\) reaction has been studied at \(E_{\alpha} = 156\) MeV: \(d\sigma/d\Omega \approx 20\) nb/sr at \(\theta_{lab} = 20^\circ\); see [1979AJ01]. See also [1985AN28,1987BL18,1987SA15,1988CO15,1996GR21,1996KA14,1996SU24,1997BA54,1997PO12,1998WI10,1999HA61,2000WI09,2001CO21,2003BA99].

### A = 9

**General**

References to articles on general properties of \(A = 9\) nuclei published since the previous review [1988AJ01] are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for \(A = 9\) located on our website at www.tunl.duke.edu/nucldata/General_Tables/9.shtml.

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Mass of $^9$He

Although the value adopted in the 2003 Atomic Mass Evaluation [2003AU02] for the $^9$He ground state is 40.939 ± 0.029 MeV based on the results of [1999BO26], an experiment [2000CH31] suggests that the ground-state of $^9$He has $J^\pi = \frac{1}{2}^+$ and lies within 0.2 MeV of the $^8$He + n threshold. In light of this result, the Atomic Mass Evaluation center [private communication from Audi, Wapstra, and Jokinen] has adopted an atomic mass excess of 39.770 ± 0.060 MeV for $^9$He. See the discussion below.

The experimental data on states of $^9$He, all from double-charge exchange reactions on $^9$Be, was reviewed in [1999KA67] and compared with results from shell-model calculations. From the $^9$Be($\pi^-$, $\pi^+$)$^9$He reaction at $E_{\pi^-} = 180$ and 194 MeV [1987SE05] an atomic mass excess of 40.80 ± 0.10 MeV was obtained, implying that $^9$He is unstable with respect to decay into $^8$He + n by 1.13 MeV. [1987SE05] also reported the population of excited states of $^9$He at 1.2, 3.8 and 7.0 MeV. In the $^9$Be($^{14}$C, $^{14}$O)$^9$He reaction at $E_{\text{lab}} = 337$ MeV, [1999BO26] find a state of $^9$He at 1.27 ± 0.10 MeV above the $^8$He + n threshold with $\Gamma = 0.10 ± 0.06$ MeV. Assuming this to be the ground-state of $^9$He, the measurements of [1999BO26] indicate $^9$He excited states at $E_x = 1.15 ± 0.10$ MeV ($\Gamma = 0.7 ± 0.2$ MeV), 3.03 ± 0.10 MeV, and 3.98 ± 0.12 MeV. See also [2001PE27]. Analogues of the lowest three states have been observed in $^9$Li via $^8$He + p elastic scattering [2003RO07].

Evidence has been obtained from neutron-fragment velocity difference measurements in the two-proton knockout reaction $^9$Be($^{11}$Be, $^9$He + n)X that the ground-state of $^9$He is a virtual s-wave state within 0.2 MeV of the $^8$He + n threshold [2001CH31]. Most structure calculations predict that the two lowest states of $^9$He have $J^\pi = \frac{1}{2}^+$ or $J^\pi = \frac{3}{2}^-$ [1999KA67], [2001CH31] obtain the $J^\pi = \frac{1}{2}^+$ state lowest but both states are underbound by several MeV with respect to the experimental candidates. Quantum Monte Carlo calculations have a similar problem for the $J^\pi = \frac{3}{2}^-$ state [2002PI19], if it is identified with the state at $S_n = -1.27$ MeV. Both [2001CH31] and [2002PI19] suggest that the promotion of neutrons to the sd shell could play an important role. The narrow width from [1999BO26] also argues against the simple p-shell structure because the single-particle width for a p-wave resonance at the observed energy is $\approx 2$ MeV and a typical p-shell spectroscopic factor is 0.74 ± 0.10. Similar conclusions were reached in [2003RO07].

Attempts have also been made to assign spins to excited states by comparing calculated two-step transfer angular distributions with those measured for the $^9$Be($^{13}$C, $^{13}$O)$^9$He and $^9$Be($^{14}$C, $^{14}$O)$^9$He reactions [1999BO26,1999KA67].

$^9$Li

(Figs. 6 and 10)

General

References to articles on general properties of $^9$Li published since the previous review [1988AJ01] are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for $^9$Li located on our website at www.tunl.duke.edu/nucldata/General_Tables/9li.shtml.
Table 9.1 Energy levels of $^9$Li$^a$

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$J^\pi$; $T$</th>
<th>$\Gamma_{1/2}$ or $\Gamma_{c.m.}$ (keV)</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>$\frac{1}{2}^-$; $\frac{3}{2}^-$</td>
<td>$t_{1/2} = 178.3 \pm 0.4$ ms</td>
<td>$\beta^-$</td>
<td>1, 3, 4, 5, 6, 7, 8, 9, 10</td>
</tr>
<tr>
<td>2.691 ± 5</td>
<td>$\frac{1}{2}^-$</td>
<td>($\gamma$)</td>
<td>4, 6, 7, 10</td>
<td></td>
</tr>
<tr>
<td>4.296 ± 15</td>
<td>($\frac{5}{2}^-$)</td>
<td>$\Gamma = 100 \pm 30^b$</td>
<td>4, 10, 11</td>
<td></td>
</tr>
<tr>
<td>5.38 ± 60</td>
<td>600 ± 100</td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>6.43 ± 15</td>
<td>40 ± 20</td>
<td></td>
<td>4, 10</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ The first evidence for $T = \frac{5}{2}$ states of $^9$Li has been obtained from $^8$He + p elastic scattering (see reaction 2).

$^b$ From reaction 4. See also reaction 11.

Ground state properties

$\mu = 3.4391 \pm 0.0006 \mu_N$ [1983CO11]. See also [1987AR22,2001STZZ];

$Q = -27.4 \pm 1.0$ mb [1992AR07,2001STZZ]. See also [1988AR17], and see [1992LI24,1993NE08].

The isospin quartets which contain the ground and first-excited states of $^9$Li are well established [1974BE66,1974KA15]. The energies, widths, and relative cross sections in the $^7$Li(t,p)$^9$Li reaction for the states listed in Table 9.1 are consistent with the expected properties of the first five p-shell states (see the discussion of reaction 4). The lowest positive-parity states are expected between 4 and 5 MeV in excitation energy but could be very broad on account of s-wave parentage to $^8$Li. The lowest $2\hbar\omega$ state is predicted just above 5 MeV [B.A. Brown, private communication].

1. $^9$Li($\beta^-$)$^9$Be, $Q_m = 13.6067$

The half-life of $^8$Li is 178.3 ± 0.4 ms: see [1979AJ01]. See also [1986CU01,1988SA04,1991RE02]. $^8$Li decays to a number of states in $^9$Be: see reaction 12 in $^9$Be and Table 9.8. The nature of the decay to $^9$Be*(0, 2.43) with $J^\pi = \frac{1}{2}^-$, $\frac{3}{2}^-$ is evidence for $J^\pi = \frac{3}{2}^-$ for $^9$Li g.s. The probability for delayed neutron decay, $P_n$, is $(50.8 \pm 0.9)$%, obtained by averaging $(50.0 \pm 1.8)$% from [1991RE02] and $(51.0 \pm 1.0)$% from [1992TE03]. A recent study has concentrated on the decays to the highest accessible states in $^9$Be [2003PR11]. See also [1990NY01,1993CH06] and references cited in [1984AJ01,1988AJ01].

2. $^1$H($^8$He,$^8$He)$^1$H, $E_b = 13.933$

From an analysis of the excitation function for $^8$He + p elastic scattering obtained by the thick target inverse kinematics method, three $T = \frac{1}{2}$ states of $^9$Li were identified at $E_x = 16.0 \pm 0.1$, 17.1 ± 0.2, and 18.9 ± 0.1 MeV. The corresponding widths are < 100, 800 ± 300, and 240 ± 100 keV, respectively. The properties of the three levels are compared with the apparent analog states in $^9$He [2003RO07].
$^9\text{Li}$


3. $^1\text{H}(^9\text{Li},^9\text{Li})^1\text{H}$

The elastic scattering angular distribution was measured at $E(^9\text{Li}) = 703$ MeV/A and analyzed using Glauber multiple-scattering theory to obtain an r.m.s. matter radius for $^9\text{Li}$ of $2.43 \pm 0.07$ fm [2002EG02].

4. $^7\text{Li}(t,p)^9\text{Li}$, $Q_m = -2.3857$

Protons are observed to excited states at $E_x = 2.691 \pm 0.005, 4.31 \pm 0.02, 5.38 \pm 0.06$ and $6.430 \pm 0.015$ MeV. The widths of the three states above the neutron threshold are $100 \pm 30, 600 \pm 100$ and $40 \pm 20$ keV, respectively. Angular distributions have been studied at $E_t = 11.3$ (1964MI04); p0, 15 (1971YO04); p0, p2, p4) and 23 MeV (1978AJ02); p0, p1, p2, p4). It is plausible that the observed levels can be identified with the first five predicted p-shell levels with $J^T = \frac{3}{2}^-, \frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$. The largest two-neutron spectroscopic factors are for the ground state ($L = 0$) and the $\frac{3}{2}^-$ state ($L = 2$), consistent with the observed angular distributions and the fact that the 4.3 MeV level has the largest cross section. The excited $\frac{3}{2}^-$ state is predicted to decay via n0, n1 and the $\frac{5}{2}^-$ state mainly via n2. See also $^{10}\text{Be}$ [1987AB15,1990GU36].

5. $^9\text{Be}(\gamma,\pi^+)^9\text{Li}$, $Q_m = -153.1769$

The angular distribution of the $\pi^+$ to $^9\text{Li}_{g.s.}$ has been measured at $E_e = 200$ MeV [1983SH19]. For the earlier work see [1984AJ01].

6. $^9\text{Be}(\pi^-,\gamma)^9\text{Li}$, $Q_m = 125.9635$

Capture branching ratios to $^9\text{Li}^*(0, 2.69)$ are reported by [1986PE05].

7. $^9\text{Be}(n,p)^9\text{Li}$, $Q_m = -12.8244$

Double differential cross sections were measured at $E_n = 96$ MeV [2000DA22]. Cross sections for reactions to the $^9\text{Li}$ ground state and to the first excited state ($E_x = 2.69$ MeV) were analyzed and compared with DWBA calculations. A Gamow–Teller unit cross section was determined for the (weak) ground state transition. At $E_n = 198$ MeV, the ground and first excited states are clearly seen, as is a strong spin-dipole peak centered near an excitation energy of 7 MeV [1988JA1K].

8. $^9\text{Be}(t,^3\text{He})^9\text{Li}$, $Q_m = -13.5881$

The $0^+$ cross section for $E_t = 381$ MeV shows a weak ground-state transition and a strong spin-dipole peak at $E_t \approx 6.5$ MeV [1998DA05].

9. $^9\text{Be}(^7\text{Li},^7\text{Be})^9\text{Li}$, $Q_m = -14.4689$

See [1984GL06]: $E(^7\text{Li} = 78$ MeV).
Fig. 6. Energy levels of $^9$Li. For notation see Fig. 2.
9Li, 9Be

10. 11B(6Li, 8B)9Li, \( Q_m = -25.121 \)

At \( E(6Li) = 80 \text{ MeV} \) the angular distribution to \( ^9\text{Li}_{g.s.} \) has been measured. States at \( E_x = 2.59 \pm 0.10, 4.36 \pm 0.10 \) and \( 6.38 \pm 0.12 \text{ MeV} \) are also populated: see [1977WE03].

11. natAg(14N, 8Li + n)X

Neutron unbound states in light fragments from \(^{14}\text{N}–\text{Ag} \) reactions at 35 MeV/A were studied by [1989HE24]. They report a measurement of a \(^9\text{Li} \) level at \( E_x = 4.296 \pm 0.015 \text{ MeV}, I = 60 \pm 45 \text{ keV} \).

12. natPb(9Li, 8Li + n)X

Coulomb dissociation of 28.53 MeV/A \(^9\text{Li} \) on targets of Pb and U was studied by [1998ZE01] to determine an upper limit for the \(^8\text{Li}(n, \gamma) \) reaction at astrophysical energies. Cross sections calculated in a potential model by [1999BE46] were compared with the data of [1998ZE01]. See also the reaction cross section measurements at 80 MeV/A discussed in [1991BL10,1992BL10], and see the shell model calculation for \(^8\text{Li}(n, \gamma) \) in [1991MA04].

13. natU(9Li, 8Li + n)X

See reaction 12.

9Be

(Figs. 6, 7 and 10)

General

References to articles on general properties of \(^9\text{Be} \) published since the previous review [1988AJ01] are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for \(^9\text{Be} \) located on our website at www.tunl.duke.edu/nucldata/General_Tables/9be.shtml.

\[
\mu = -1.1778 \pm 0.0009 \mu_N \quad \text{see [1978LEZA]}; \\
Q = 52.88 \pm 0.38 \text{ mb} \quad \text{see [1967BL09,1991SU05,2001STZZ]}. 
\]

Interaction cross sections of \(^9\text{Be} \) with Be, C, and Al targets have been measured at \( E = 790 \text{ MeV/A} \) yielding an interaction nuclear radius of \(^9\text{Be} \) is \( 2.45 \pm 0.01 \text{ fm} \) [1985TA18] [see also for derived nuclear matter, charge and neutron matter r.m.s. radii]. See [2001OZ04] for references to derivations of radii for \(^9\text{Be} \).

The decay \(^9\text{Li} \rightarrow \pi^- + ^{9}\text{Be}^* \rightarrow \pi^- + p + ^8\text{Li} \) appears to take place via a \( T = \frac{3}{2} \) state of \(^9\text{Be} \) at \( E_x = 18.6 \pm 0.1 \text{ MeV} (I \leq 300 \text{ keV}) \) that appears to be an analog of the 4.3 MeV level of \(^9\text{Li} \) [1985PN01].
Table 9.2
Energy levels of $^9\text{Be}$

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$J^\pi; T$</th>
<th>$I_{\gamma\text{em}}$ (keV)</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>$\frac{1}{2}^-$; $\frac{1}{2}^+$</td>
<td>stable</td>
<td>2, 3, 4, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 41, 42, 44, 45, 47, 48, 50, 51, 52, 54</td>
<td></td>
</tr>
<tr>
<td>1.684 ± 7</td>
<td>$\frac{1}{2}^+$</td>
<td>217 ± 10</td>
<td>$\gamma, n$</td>
<td>4, 9, 10, 13, 16, 18, 19, 21, 23, 24, 33, 39, 42, 44</td>
</tr>
<tr>
<td>2.294 ± 1.3</td>
<td>$\frac{3}{2}^-$</td>
<td>0.78 ± 0.13</td>
<td>$\gamma, n, \alpha$</td>
<td>4, 9, 10, 11, 12, 16, 17, 18, 19, 21, 22, 23, 24, 26, 27, 33, 34, 35, 36, 38, 39, 41, 42, 44, 50</td>
</tr>
<tr>
<td>2.78 ± 120</td>
<td>$\frac{3}{2}^-$</td>
<td>1080 ± 110</td>
<td>n</td>
<td>4, 9, 12, 19, 42, 50</td>
</tr>
<tr>
<td>3.049 ± 9</td>
<td>$\frac{5}{2}^+$</td>
<td>282 ± 11</td>
<td>$\gamma, n$</td>
<td>4, 9, 16, 18, 19, 21, 23, 24, 33, 39, 42, 44</td>
</tr>
<tr>
<td>4.704 ± 25</td>
<td>$\frac{7}{2}^+$</td>
<td>743 ± 55</td>
<td>$\gamma, n$</td>
<td>4, 9, 16, 19, 21, 23, 24, 42, 50</td>
</tr>
<tr>
<td>5.59 ± 100</td>
<td>$\frac{7}{2}^-$</td>
<td>1330 ± 360</td>
<td>$\gamma, n$</td>
<td>19, 35</td>
</tr>
<tr>
<td>6.38 ± 60</td>
<td>$\frac{5}{2}^-$</td>
<td>1210 ± 230</td>
<td>$\gamma, n$</td>
<td>9, 11, 16, 17, 18, 19, 21, 23, 24, 26, 34, 35, 38, 44</td>
</tr>
<tr>
<td>6.76 ± 60</td>
<td>$\frac{9}{2}^+$</td>
<td>1330 ± 90</td>
<td>$\gamma, n$</td>
<td>16, 19</td>
</tr>
<tr>
<td>7.94 ± 80</td>
<td>$\frac{3}{2}^+$</td>
<td>$\approx$ 1000</td>
<td></td>
<td>12, 19, 35</td>
</tr>
<tr>
<td>11.28 ± 24</td>
<td>$\frac{7}{2}^+$</td>
<td>575 ± 50</td>
<td>n</td>
<td>9, 12, 16, 19, 24, 34, 35, 38, 39</td>
</tr>
<tr>
<td>11.81 ± 20</td>
<td>$\frac{9}{2}^-$</td>
<td>400 ± 30</td>
<td>$\gamma, n$</td>
<td>9, 12, 13, 41, 50</td>
</tr>
<tr>
<td>13.79 ± 39</td>
<td>$\frac{11}{2}^- = -\frac{1}{2}^+$</td>
<td>590 ± 60</td>
<td>$\gamma, n$</td>
<td>9, 16, 19, 41</td>
</tr>
<tr>
<td>14.3922 ± 1.8d</td>
<td>$\frac{3}{2}^-$; $\frac{1}{2}^+$</td>
<td>0.381 ± 0.033</td>
<td>$\gamma, n, \alpha$</td>
<td>9, 16, 19, 23, 39, 41</td>
</tr>
<tr>
<td>14.48 ± 90</td>
<td>$\frac{5}{2}^-; \frac{3}{2}^+$</td>
<td>$\approx$ 800</td>
<td></td>
<td>19, 34, 35, 39</td>
</tr>
<tr>
<td>15.10 ± 50</td>
<td></td>
<td>350 ± 180</td>
<td>$\gamma$</td>
<td>16, 19, 41</td>
</tr>
<tr>
<td>15.97 ± 30</td>
<td>$T = \frac{1}{2}$</td>
<td>$\approx$ 300</td>
<td>$\gamma$</td>
<td>16, 19, 41</td>
</tr>
<tr>
<td>16.67 ± 8</td>
<td>$\frac{9}{2}^+$; $\frac{3}{2}^+$</td>
<td>41 ± 4</td>
<td>$\gamma$</td>
<td>9, 16, 19, 39</td>
</tr>
<tr>
<td>16.9752 ± 0.86d</td>
<td>$\frac{3}{2}^-$; $\frac{1}{2}^+$</td>
<td>0.389 ± 0.010</td>
<td>$\gamma, n, p, d$</td>
<td>4, 5, 6, 15, 16, 19</td>
</tr>
<tr>
<td>17.29 ± 7</td>
<td>$\frac{7}{2}^+$</td>
<td>200</td>
<td>$\gamma, n, p, d, \alpha$</td>
<td>5, 6, 7, 13, 16, 19</td>
</tr>
<tr>
<td>17.49 ± 7</td>
<td>$\frac{3}{2}^+$; $\frac{1}{2}^+$</td>
<td>47</td>
<td>$\gamma, n, p, d, \alpha$</td>
<td>5, 6, 7, 16, 19</td>
</tr>
<tr>
<td>18.02 ± 50</td>
<td></td>
<td>$\gamma$</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>18.58 ± 40</td>
<td></td>
<td>$\gamma, n, p, d, \alpha$</td>
<td>6, 16</td>
<td></td>
</tr>
<tr>
<td>18.650 ± 50</td>
<td>$\frac{3}{2}^-; \frac{3}{2}^+$</td>
<td>300 ± 100</td>
<td>p</td>
<td>19</td>
</tr>
<tr>
<td>19.20 ± 50</td>
<td></td>
<td>310 ± 80</td>
<td>$n, p, d, t$</td>
<td>6, 19</td>
</tr>
<tr>
<td>19.420 ± 50</td>
<td></td>
<td>600 ± 300</td>
<td>$\gamma$</td>
<td>13, 16, 19</td>
</tr>
<tr>
<td>19.92 ± 200</td>
<td></td>
<td>$\gamma, n$</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>20.51 ± 30</td>
<td></td>
<td>600 ± 100</td>
<td>$\gamma, p, d$</td>
<td>13, 19</td>
</tr>
<tr>
<td>20.75 ± 30</td>
<td></td>
<td>680 ± 90</td>
<td>$\gamma, n, p, t$</td>
<td>13, 16, 19</td>
</tr>
<tr>
<td>21.4 ± 200</td>
<td></td>
<td>$\gamma, n$</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>22.4 ± 200</td>
<td></td>
<td>broad</td>
<td>$\gamma, n$</td>
<td>13, 19</td>
</tr>
<tr>
<td>23.8 ± 200</td>
<td></td>
<td></td>
<td>$\gamma, n$</td>
<td>13</td>
</tr>
</tbody>
</table>

(continued on next page)
Table 9.2 (continued)

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$J^\pi; T$</th>
<th>$\Gamma_{cm}$ (keV)</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>(27.0 ± 500)</td>
<td>broad</td>
<td>$\gamma$, n</td>
<td></td>
<td>13</td>
</tr>
</tbody>
</table>

- See reaction 19 and Table 9.11.
- [1991DI03]. See reaction 19; see also [1991GL02]. See, however, reaction 35 and Table 9.12.
- See reactions 12 and 35.
- See Table 9.4.
- See Table 9.5.
- Spin assignment from [1985PN01].

1. (a) $^6\text{Li}(t, n)^9\text{Be}$, $Q_m = 16.0236$, $E_b = 17.6890$
(b) $^6\text{Li}(t, p)^7\text{Li}$, $Q_m = 0.80079$
(c) $^6\text{Li}(t, n)^4\text{He}^4\text{He}$, $Q_m = 16.115451$

The 0$^+$ differential cross section for reaction (a) increases monotonically between $E_t = 0.10$ and 2.4 MeV. A resonance has been reported at $E_t = 1.875$ MeV ($^9\text{Be}^*(18.94)$). The excitation function for $^6\text{Li}$ (reaction (b)) increases monotonically for $E_t = 0.275$ to 1.000 MeV. See [1974AJ01] for references. In the range $E_t = 2$ to 10 MeV the total cross section for reaction (b) shows a broad structure [$\Gamma_{cm} = 1.5$ MeV] at $E_t = 4.2$ MeV ($^9\text{Be}^*(20.5)$) [1986AB04]. Yields and angular distributions for reaction (c) have been measured at $E_t = 2$ to 4.5 MeV [1984LIZY]. See also [1984AJ01] for other channels and [1984KR1B].

2. $^6\text{Li}(^3\text{He}, \pi^+)^9\text{Be}$, $Q_m = -121.8998$

The energy dependence of the cross section for population of $^9\text{Be}_{g.s.}$ has been measured at $E(^3\text{He}) = 235$ to 283 MeV [1984WI06].

3. $^6\text{Li}(\alpha, p)^9\text{Be}$, $Q_m = -2.1249$

Angular distributions of $p_0$ have been measured at $E_\alpha = 10.2$ to 14.7 MeV and at 30 MeV; see [1974AJ01]. Differential cross sections were measured at $E_\alpha = 26.7$ MeV [1990L137] in a study of exchange processes. See also [1987BI1C,1983BE51].

4. $^7\text{Li}(d, \gamma)^9\text{Be}$, $Q_m = 16.6959$

For $E_d = 0.1$ to 1.1 MeV, a resonance in the yield of capture $\gamma$-rays is observed at $E_d = 360.8 \pm 0.3$ keV [1987ZI01], 360.7 ± 1.8 keV [1986BE33], corresponding to the excitation of $^9\text{Be}^*(16.97)$, the second $T = \frac{1}{2}$ state [$J^\pi = \frac{1}{2}^-$]; see Table 9.5. Another measurement of the total width of this state determined $\Gamma = 389 \pm 10$ eV; see [1992KI05]. The reduced width for the isospin “forbidden” deuteron breakup is $3.9 \times 10^{-4}$ relative
to the Wigner limit [1992KI05]. See also [1984AJ01]. The differential cross section and vector analyzing power were measured by [1993SC19] at $E_d = 6$ MeV.
Table 9.3
Electromagnetic transitions in $^9$Be

<table>
<thead>
<tr>
<th>$E_{\text{ij}}$ → $E_{\text{ij}}$ (MeV)</th>
<th>$J_i^T$ → $J_i^T$</th>
<th>$\Gamma_\gamma$ (eV)</th>
<th>Mult.</th>
<th>$\Gamma_\gamma / \Gamma_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.68 → 0</td>
<td>$\frac{1}{2}^+$ → $\frac{1}{2}^+$</td>
<td>0.30 ± 0.12</td>
<td>E1</td>
<td>0.22 ± 0.09</td>
</tr>
<tr>
<td>2.43 → 0</td>
<td>$\frac{3}{2}^+$ → $\frac{1}{2}^+$</td>
<td>(8.9 ± 1.0) × 10^{-2}</td>
<td>M1</td>
<td>0.30 ± 0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1.89 ± 0.14) × 10^{-3}</td>
<td>E2</td>
<td>24.4 ± 1.8</td>
</tr>
<tr>
<td>3.05 → 0</td>
<td>$\frac{3}{2}^+$ → $\frac{1}{2}^-$</td>
<td>0.30 ± 0.25</td>
<td>E1</td>
<td>(3.6 ± 3.0) × 10^{-2}</td>
</tr>
<tr>
<td>6.38 → 0</td>
<td>$\frac{3}{2}^-$ → $\frac{1}{2}^-$</td>
<td>(8.2 ± 3.5) × 10^{-2}</td>
<td>E2</td>
<td>8.5 ± 3.7</td>
</tr>
<tr>
<td>14.39 → 0</td>
<td>$\frac{3}{2}^-$ : $\frac{1}{2}^-$</td>
<td>6.60 ± 0.40</td>
<td>M1</td>
<td>0.106 ± 0.007</td>
</tr>
<tr>
<td></td>
<td>$\frac{3}{2}^- : \frac{1}{2}^-$</td>
<td>7.46 ± 0.56</td>
<td>M1</td>
<td>0.208 ± 0.016</td>
</tr>
<tr>
<td></td>
<td>$\frac{3}{2}^- : \frac{1}{2}^-$</td>
<td>1.20 ± 0.28</td>
<td>E1</td>
<td>(2.8 ± 0.7) × 10^{-3}</td>
</tr>
<tr>
<td></td>
<td>$\frac{3}{2}^- : \frac{1}{2}^-$</td>
<td>0.84 ± 0.20</td>
<td>E1</td>
<td>(3.2 ± 0.8) × 10^{-3}</td>
</tr>
<tr>
<td>16.98 → 0</td>
<td>$\frac{3}{2}^- : \frac{1}{2}^-$</td>
<td>16.9 ± 1.0</td>
<td>M1</td>
<td>0.165 ± 0.010</td>
</tr>
<tr>
<td></td>
<td>$\frac{3}{2}^- : \frac{1}{2}^-$</td>
<td>1.99 ± 0.15</td>
<td>E1</td>
<td>(1.90 ± 0.15) × 10^{-3}</td>
</tr>
<tr>
<td></td>
<td>$\frac{3}{2}^- : \frac{1}{2}^-$</td>
<td>0.56 ± 0.12</td>
<td>E2</td>
<td>0.94 ± 0.20</td>
</tr>
<tr>
<td></td>
<td>$\frac{3}{2}^- : \frac{1}{2}^-$</td>
<td>2.2 ± 0.7</td>
<td>M1</td>
<td>(3.7 ± 1.2) × 10^{-2}</td>
</tr>
<tr>
<td></td>
<td>$\frac{3}{2}^- : \frac{1}{2}^-$</td>
<td>2.2 ± 0.3</td>
<td>E1</td>
<td>(4.1 ± 0.6) × 10^{-3}</td>
</tr>
</tbody>
</table>

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

$^b$ See Table 9.8 of [1988AJ01].

$^c$ See Table 9.4.

$^d$ See Table 9.5.

5. (a) $^7$Li(d, n)$^8$Be, $Q_m = 15.0306$, $E_b = 16.6959$

(b) $^7$Li(d, $\alpha$)$^4$He, $Q_m = 14.229$

(c) $^7$Li(d, n)$^3$He$^4$He, $Q_m = 15.12239$

The yield of neutrons has been measured for $E_d = 0.2$ to 23 MeV [see [1979AJ01]] and at $E_d = 0.19$ to 0.55 MeV [1987DA25]. See also [1983SZZY]. Polarization measurements have been carried out at $E_d = 0.64$ MeV and 2.5 to 3.7 MeV [see [1974AJ01]] and at 0.40 and 0.46 MeV ([1984GA07]; $n_0$). Resonances are reported at 0.36, 0.68 and 0.98 MeV: see Table 9.3 in [1974AJ01]. See also ([1985CA41]; astrophys.) and the measurements at $E_d = 195–550$ keV of [1987DA25]. Neutron yields for 40 MeV deuterons on $^7$Li thick targets were measured by [1987SC11]. See also the measurements at $E_{cm} = 0.7–2.3$ MeV [1996BO27] and the fusion calculations of [2000HA50].

The yields of $\alpha$-particles have been measured for $E_d = 0.25$ to 3.0 MeV: see [1974AJ01], [1979AJ01]. Resonances are reported at $E_d = 0.75, 1.00$ and 2.5 MeV; the latter is broad: see Table 9.3 in [1979AJ01]. See also [1983SZZY], ([1986D11B,1987LE1F]; applied) and [1984KR1B]. In recent work, measurements of astrophysical S factors at $E_{cm} = 57–141$ keV have been reported by [1997YA08]. See also the calculations described in [2000HA50].
The values of $6.7$ Be correspond to $9$ Be.

The $7$ Be($p$, $\gamma$) $8$ Li, $20$ mb $[1985HA40]$. Deuteron energies (in MeV) and widths [$\Gamma_{lab}$ in brackets in keV] of resonances reported are: $E_d = 0.360 \pm 0.003$ [<0.5], $0.776 \pm 0.007$ [250], $1.027 \pm 0.007$ [60], $2.0$ [broad], $2.375 \pm 0.050$, $3.220 \pm 0.050$ [400 ± 100] and $\approx 4.8$ MeV corresponding to $^{9}$Be($\gamma$,16.975) [see also Table 9.5], 17.298, 17.493 (18.5), 18.54, 19.20, 20.4): for references see Tables 9.3 in [1979AJ01,1984AJ01]. The total cross section at the $E_d = 0.78$ MeV resonance is important because it serves as a normalization for the $^7$Be(p, $\gamma$)$^8$B reaction: the “best” value suggested by [1983FI13] is $157 \pm 10$ mb. See also [1986BA38] and [1974AJ01,1984AJ01] for the earlier values. At $E (^7$Li) = $12.2 \pm 1.3$ MeV [corresponding to $E_d = 3.5$ MeV] the cross section is reported to be $155 \pm 20$ mb $[1985HA40]$.

<table>
<thead>
<tr>
<th>$E_d$ (keV)</th>
<th>$14.822 \pm 1.8$</th>
<th>$14.655 \pm 2.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_0$ (eV)</td>
<td>$6.60 \pm 0.40^b$</td>
<td>$(6.97 \pm 0.42)^c$</td>
</tr>
<tr>
<td>$\Gamma$ (eV)</td>
<td>$365 \pm 29$</td>
<td>$377 \pm 38$</td>
</tr>
<tr>
<td>$\Gamma_{10}$ (to $\frac{1}{2}^+$)/$\Gamma$ (%)</td>
<td>$1.81 \pm 0.09$</td>
<td>$1.85 \pm 0.15$</td>
</tr>
<tr>
<td>$\Gamma_{11}$ (to $\frac{3}{2}^+$)/$\Gamma$ (%)</td>
<td>$&lt;0.07$</td>
<td>$&lt;0.08$</td>
</tr>
<tr>
<td>$\Gamma_{12}$ (to $\frac{5}{2}^-$)/$\Gamma$ (%)</td>
<td>$2.05 \pm 0.11$</td>
<td>$1.93 \pm 0.22$</td>
</tr>
<tr>
<td>$\Gamma_{13}$ (to $\frac{7}{2}^+$)/$\Gamma$ (%)</td>
<td>$&lt;0.2$</td>
<td>$0.31 \pm 0.18$</td>
</tr>
<tr>
<td>$\Gamma_{14}$ (to $\frac{9}{2}^+$)/$\Gamma$ (%)</td>
<td>$0.33 \pm 0.07$</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{15}$ (to $\frac{11}{2}^+$)/$\Gamma$ (%)</td>
<td>$0.23 \pm 0.05$</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{12}/\Gamma_0$</td>
<td>$1.13 \pm 0.05$</td>
<td>$1.03 \pm 0.11$</td>
</tr>
<tr>
<td>$\Gamma_{10}/\Gamma$</td>
<td>$0.028 \pm 0.021$</td>
<td>$\Gamma_{10}/\Gamma$</td>
</tr>
<tr>
<td>$\Gamma_{11}/\Gamma$</td>
<td>$0.50 \pm 0.11$</td>
<td>$\Gamma_{11}/\Gamma$</td>
</tr>
<tr>
<td>$\Gamma_{12}/\Gamma_0$</td>
<td>$18 \pm 14$</td>
<td>$\Gamma_{12}/\Gamma_0$</td>
</tr>
<tr>
<td>$\Gamma_{13}/\Gamma_0$</td>
<td>$16.1 \pm 1.4$</td>
<td>$\Gamma_{13}/\Gamma_0$</td>
</tr>
<tr>
<td>$\Gamma_{14}/\Gamma_0$</td>
<td>$10 \pm 9$</td>
<td>$\Gamma_{14}/\Gamma_0$</td>
</tr>
<tr>
<td>$\Gamma_{15}/\Gamma_0$</td>
<td>$182 \pm 43$</td>
<td>$\Gamma_{15}/\Gamma_0$</td>
</tr>
<tr>
<td>$\Gamma_{16}/\Gamma_0$</td>
<td>$156 \pm 43^d$</td>
<td>$196 \pm 43^c$</td>
</tr>
</tbody>
</table>

$^a$ $\gamma$-ray branching ratios from [1978DI08]. Branching ratios for nucleon decays from [1976MC10]. See Table 9.6 in [1979AJ01] for additional references. See Table 9.3 for radiative widths and transitions strengths.

$^b$ Average of $8.1 \pm 0.8$ eV [1968CL08], $6.2 \pm 0.6$ eV [1973BE19], $5.9 \pm 0.8$ eV [1992Kl05]. Unpublished values of $6.7 \pm 1.4$ eV and $7.2 \pm 0.3$ eV are quoted in [1973BE19,1992KI05].

$^c$ Assuming the same reduced transition strength as for $^9$Be.

$^d$ By subtraction.

$^e$ $\Gamma_{10}/\Gamma_0 = 31.2 \pm 9.8$ [1972AD04] gives $\Gamma_{10} = 206 \pm 65$ eV.

$^f$ $\Gamma_{10}/\Gamma_0 \approx 1.4$ [2001BE51] gives $\Gamma_{10} \approx 174$ eV.

6. $^7$Li(d, p)$^8$Li, $Q_m = -0.19228$, $E_b = 16.69594$
Table 9.5
Parameters \( a \) of the second \( T = \frac{3}{2} \) state in \( ^9 \text{Be} \), \( J^\pi = \frac{1}{2}^- \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_x ) (keV)</td>
<td>16975.2 ± 0.8</td>
</tr>
<tr>
<td>( \Gamma_{\text{c.m.}} ) (eV)</td>
<td>389 ± 10</td>
</tr>
<tr>
<td>( \Gamma_\gamma ) (eV)</td>
<td>23.8 ± 1.6</td>
</tr>
<tr>
<td>( \Gamma_{\gamma 0} ) (eV)</td>
<td>16.9 ± 1.0^f</td>
</tr>
<tr>
<td>( \Gamma_{\gamma 2} ) (eV)</td>
<td>1.59 ± 0.15</td>
</tr>
<tr>
<td>( \Gamma_{\gamma 4} ) (eV)</td>
<td>0.56 ± 0.12</td>
</tr>
<tr>
<td>( \Gamma_{\gamma 5} ) (eV)</td>
<td>2.2 ± 0.7</td>
</tr>
<tr>
<td>( \Gamma_{\gamma 3} ) (eV)^b</td>
<td>&lt; 0.8</td>
</tr>
<tr>
<td>( \Gamma_{\gamma 5} ) (eV)^b</td>
<td>2.2 ± 0.3</td>
</tr>
<tr>
<td>( \Gamma_{\alpha} ) (eV)</td>
<td>&lt; 290^d</td>
</tr>
<tr>
<td>( \Gamma_{\text{tot}} ) (eV)</td>
<td>36 ± 36</td>
</tr>
<tr>
<td>( \Gamma_{\text{p}} ) (eV)</td>
<td>12 ± 12</td>
</tr>
<tr>
<td>( \Gamma_{\text{d}} ) (eV)</td>
<td>62 ± 10</td>
</tr>
<tr>
<td>( \Gamma_{\text{tot}} ) (eV)</td>
<td>&lt; 290</td>
</tr>
</tbody>
</table>

a \cite{1992KI05}. These are revised values of the partial widths given in Table 9.4 of \cite{1988AJ01}. They are based on the resonant absorption measurements of \cite{1992KI05}.

b See Table 9.4 of \cite{1988AJ01}.
c See also Table 9.8 of \cite{1988AJ01}.
d \( \Gamma_{\alpha} + \Gamma_{\text{tot}} = 290 ± 20 \) eV.

At the peak of the \( E_d = 0.78 \) MeV resonance, \( \sigma = 143.6 ± 8.9 \) mb from the proton yield and \( \sigma = 151 ± 20 \) mb from the \( \beta \)-delayed \( \alpha \) activity of the residual \( ^8 \text{Li} \) nucleus \cite{1996ST18}. In \cite{1998WE05}, a value \( \sigma = 155 ± 8 \) mb was obtained, backscattering effects were examined, and the consequences for the \( ^7 \text{Be}(p, \gamma) \) cross sections were discussed. The \( ^7 \text{Li}(d, p) \) yield for \( E_d = 0.4–1.8 \) MeV was measured by \cite{1998ST20} to deduce corrections due to recoil loss. See also the compilation and analysis of astrophysical \( S \)-factor data and calculations in \cite{1998AD12}.

7. \( ^7 \text{Li}(d, d)^7 \text{Li}, \ E_h = 16.69594 \)

The elastic scattering \( [E_d = 0.4 \text{ to } 1.8 \text{ MeV}] \) shows a marked increase in cross section for \( E_d = 0.8 \) to 1.0 \text{ MeV} (perhaps related to \( ^9 \text{Be}^*(17.30) \)) and a conspicuous anomaly at \( E_d = 1.0 \) MeV, due to p-wave deuterons \([^9 \text{Be}^*(17.50)]\). The elastic scattering has also been studied for \( E_d = 1.0 \) to 2.6 MeV and 10.0 to 12.0 MeV: see \cite{1979AJ01}, and at \( E_d = 9.05 \) MeV \cite{1980YE02}.

8. \( ^7 \text{Li}(d, t)^6 \text{Li}, \ Q_m = -0.99306, \ E_h = 16.69594 \)

The cross section rises steeply from threshold to 95 mb at \( E_d = 2.4 \) MeV and then more slowly to \( \approx 165 \) mb at \( E_d = 4.1 \) MeV. The \( t_0 \) yield curve \( (\theta_{\text{lab}} = 155^\circ) \) decreases monotonically for \( E_d = 10.0 \) to 12.0 MeV: see \cite{1974AJ01}. Differential cross sections measured at \( E_d = 30.7 \) MeV were reported in \cite{1987BO39}. An analysis of data from this reaction at \( E_d = 8–50 \) MeV is discussed in \cite{1995GU22}.
9. \( ^7\text{Li}(^{3}\text{He}, p)^9\text{Be} \), \( Q_m = 11.2025 \)

Observed proton groups are displayed in Table 9.6. The parameters for the particle and \( \gamma \)-decay of observed states are displayed in Tables 9.4 and 9.7. Angular distributions have been reported in the range \( E(^3\text{He}) = 0.9 \) to 14 MeV [see [1974AJ01,1979AJ01]] and at \( E(^3\text{He}) = 14 \) and 33 MeV ([1983LE17,1983RO22]; \( p_0 \)). See also \( ^{10}\text{B} \), [1984ME11] and ([1986SC35]; applications).

In more recent work cross sections \( \sigma(E_p, \theta) \) were measured at \( E_{cm} = 0.5–2 \) MeV, and the astrophysical \( S \)-factor was deduced [1990RA16]. Polarization observables were measured at \( E(^3\text{He}) = 4.6 \) MeV and analyzed by DWBA [1995BA24]. See [1993YA01] for \( S \)-factor calculations and discussions of astrophysical implications. See also the earlier theoretical work of [1988KH11] on time-reversal violating amplitude features.

10. \( ^7\text{Li}(\alpha, d)^9\text{Be} \), \( Q_m = -7.1506 \)

Angular distributions of \( d_0 \), \( d_1 \) and \( d_2 \) have been reported at \( E_\alpha = 30 \) MeV: see [1974AJ01]. See also [1983BE51].

11. \( ^7\text{Li}(^{6}\text{Li}, \alpha)^9\text{Be} \), \( Q_m = 15.2221 \)

Angular distributions of the \( \alpha \)-groups to \( ^9\text{Be}^* \) (0.243, 6.76) have been measured at \( E(^7\text{Li}) = 78 \) MeV [1989GL03]. For the excitation of \( ^8\text{He}^* \) see ([1987GLZX,1987GLZY]; \( E(^6\text{Li}) = 93 \) MeV). For the earlier work see [1974AJ01].

12. \( ^9\text{Li}(\beta^-)^9\text{Be} \), \( Q_m = 13.6067 \)

\( ^9\text{Li} \) decays by \( \beta^- \) emission with \( r_{1/2} = 178.3 \pm 0.4 \) ms and \( P_n = 50.8 \pm 0.9% \) to several \( ^9\text{Be} \) states: see reaction 1 in \( ^9\text{Li} \) and Table 9.8. A series of studies at ISOLDE [1981LA11,1990NY01,2003PR11] have measured \( \beta^-\alpha \) coincidences and established the
Table 9.7
Neutron decay of $^9\text{Be}$ states

<table>
<thead>
<tr>
<th>$^9\text{Be}$ state (MeV)</th>
<th>$\Gamma_m$ (keV)</th>
<th>$l_n$</th>
<th>Decay (in %) to $^8\text{Be}$</th>
<th>$^9\text{Be}^*$ (3.0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.43</td>
<td>0.77</td>
<td>3</td>
<td>7.0 ± 1.0</td>
<td>0.047</td>
</tr>
<tr>
<td>2.78</td>
<td>1080</td>
<td>1</td>
<td>mainly</td>
<td>0.67</td>
</tr>
<tr>
<td>3.05</td>
<td>282</td>
<td>2</td>
<td>87 ± 13</td>
<td>1.24</td>
</tr>
<tr>
<td>4.70</td>
<td>743</td>
<td>2</td>
<td>13 ± 4</td>
<td>0.080</td>
</tr>
<tr>
<td>6.67$^a$</td>
<td>1210</td>
<td>3</td>
<td>$\ll 2$</td>
<td>$&lt; 0.044$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>55 ± 14</td>
<td>0.47</td>
</tr>
<tr>
<td>11.28</td>
<td>575</td>
<td>3</td>
<td>$\ll 2$</td>
<td>$&lt; 0.003$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>14 ± 4</td>
<td>0.014</td>
</tr>
<tr>
<td>11.81</td>
<td>400</td>
<td>3</td>
<td>$\ll 3$</td>
<td>$&lt; 0.003$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>12 ± 4</td>
<td>0.008</td>
</tr>
</tbody>
</table>

$^a$ For references to the experimental decay branches see Table 9.5 in [1979AJ01]. For the two lowest $T = \frac{3}{2}$ states see Tables 9.4 and 9.5.

$^b$ See Table 9.2.

$^c$ The $l_n$ values for the 11.28 and 11.81 MeV levels reflect the probable assignments of $^2_2^-$ and $^5_2^-$, respectively.

$^d$ For decays to $^8\text{Be}$, the spectroscopic factor is computed using the single-particle width for a Woods–Saxon well with $r_0 = 1.25$ fm and $a = 0.65$ fm. For decays to $^8\text{Be}^*(3.0)$, an integration is performed over an $R$-matrix profile function for the broad $^8\text{Be}^*(3.0)$ level. In addition, for large decay energies an $R$-matrix single-particle width is matched to the Woods–Saxon width at an energy below the centrifugal barrier.

$^e$ Excitation energy taken to be that from the proton knockout reaction on $^{10}\text{B}$; see reaction 35.

The information in Table 9.8 is based largely on the results of [1990NY01] and an analysis by [1993CH06]. The most recent study [2003PR11] finds that the low-energy decays are mostly to $^9\text{Be}^*(11.28)$ with a $B(GT)$ value of $8.5 ± 1.5$, that a spin assignment of $^2_2^-$ is favored, and note that the $B(GT)$ value is a factor of $4.4 ± 1.0$ larger than that of the mirror transition in $^9\text{C}$ (see reaction 10 in $^9\text{B}$). Such a large asymmetry for a strong transition and the magnitude of the $B(GT)$ value for $^9\text{Li}$ decay are difficult to understand theoretically. The latter difficulty is highlighted by the fact that, in the limit of good supermultiplet symmetry only $\frac{1}{2}$ of the GT sum-rule strength $9(g_A/g_V)^2_{\text{eff}}$ [see footnote $^c$ in Table 9.8] goes to $^5_2^-$ states.

13. (a) $^9\text{Be}(\gamma,n)^9\text{Be}$, $Q_m = -1.6654$
(b) $^9\text{Be}(\gamma,\alpha)^7\text{He}$, $Q_m = -2.467$
(c) $^9\text{Be}(\gamma,n)^9\text{He}^4\text{He}$, $Q_m = -1.5736$

As noted in the previous review [1988AJ01], “the photoneutron cross section has been measured from threshold to 320 MeV: see Table 9.6 in [1966LA04,1979AJ01,1988DI02]. A pronounced peak occurs $\approx 29$ keV above threshold with $\sigma_{\text{max}} = 1.33 ± 0.24$ mb. The shape of the resonance has been measured very accurately for $E_{\gamma} = 1675$ to 2168 keV. The FWHM of the peak is estimated to be 100 keV [1982FU11]. See also [1983BA52, 1987KU05]. The cross section then decreases slowly to 1.2 mb at 40 keV above threshold.
Energies from threshold to 20 MeV was extracted. Resonances were observed corresponding to photoneutron spectra from bremsstrahlung photons. The reaction cross section for energies from threshold to 20 MeV was extracted. Resonances were observed corresponding to \( \gamma \) to \( n \) cross section resonance parameters for the \( ^9 \text{Be} \) states.

From bremsstrahlung studies, peaks in the \((\gamma, n)\) cross section are observed corresponding to \( E_X = 1.80 \) and 3.03 MeV.

Subsequently [1992GO27] measured the photoneutron yield and mean energies of photoneutron spectra from bremsstrahlung photons. The reaction cross section for energies from threshold to 20 MeV was extracted. Resonances were observed corresponding to \( E_X = 1.68 \) MeV (\( \frac{3}{2}^{-} \)), 2.43 MeV (\( \frac{5}{2}^{-} \)), and 3.05 MeV (\( \frac{5}{2}^{+} \)) in \( ^9 \text{Be} \). See Table 1 in [1992GO27] for resonance parameters. In other work [2001UT01,2002SU19], laser-induced Compton backscattering photons with \( E_\gamma = 1.78-6.11 \) MeV were used to measure the photoneutron cross section resonance parameters for the \( ^9 \text{Be} \) states; see Table 9.9. The radiative widths in Table 9.9 are not in good agreement with those

### Table 9.9

Resonance parameters for \(^9\text{Be} \beta^-(\gamma,n)\)

<table>
<thead>
<tr>
<th>( J^\pi )</th>
<th>Mult.</th>
<th>( E_R ) (MeV)</th>
<th>( \Gamma_\gamma ) (eV)</th>
<th>( \Gamma \approx \Gamma_\gamma ) (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{3}{2}^- )</td>
<td>E1</td>
<td>1.735 ± 0.003</td>
<td>0.568 ± 0.011</td>
<td>225 ± 12</td>
</tr>
<tr>
<td>( \frac{5}{2}^- )</td>
<td>E1</td>
<td>3.077 ± 0.009</td>
<td>1.24 ± 0.02</td>
<td>549 ± 12</td>
</tr>
</tbody>
</table>

---

\(^a\) From Table 1 of [2002SU19]; see also Table I of [2001UT01], and reaction 13 here.
from low-energy electron scattering listed in Table 9.3. Also, the width given for the $\frac{1}{2}^+$ state is roughly twice the accepted width of $282 \pm 11$ keV in Table 9.2; using the accepted width while maintaining a fit to the peak ($\gamma, n$) cross section would reduce $\Gamma_{\gamma}$ by almost a factor of two and into the range of the values from (e, e') listed in Table 9.3. Shell-model calculations give a stable $B(M1)\downarrow \approx 1$ W.u. ($\Gamma_{\gamma} \approx 0.45$ eV) for the broad $\frac{1}{2}^-$ state at 2.78 MeV implying significant ($\gamma, n$) cross section underlying the energy region of interest. A one-level $R$-matrix analysis of the $E_{\gamma} = 1.6$–2.2 MeV cross section is described in [2000BA21]. The energy at which the cross section due to the $\frac{1}{2}^+$ state peaks and the FWHM of the peak vary somewhat for different fits to a number of data sets but are relatively stable. However, the extracted $B(E1)\downarrow$ values vary considerably and generally correspond to larger $\Gamma_{\gamma}$’s than those listed in Table 9.3 and Table 9.9. For theoretical calculations of the low-energy ($\gamma, n$) cross section see [1998EF05,1999EF01,2002IT07]. See also the calculation of $^9$Be Coulomb dissociation [1994KA25] and polarized neutron production by magnetic Bremsstrahlung gamma rays [1997ER03].

[1988AJ01] notes that “at higher energies, using monoenergetic photons, the ($\gamma, n$) cross section is found to be relatively smooth from $E_{\gamma} = 17$ to 37 MeV with weak structures which correspond to $E_x = 17.1, 18.8, 19.9, 21.4, 22.4, 23.8 [\pm 0.2]$ MeV and $27 \pm 0.5$ MeV (broad). In the range $E_{\gamma} = 18$ to 26 MeV the integrated ($\gamma, n_1$) cross section is $< 0.1$ MeV mb, that for ($\gamma, n_2$) is $2.4 \pm 0.4$ MeV mb and the combined integrated cross section for ($\gamma, n$) to $^8$Be’(16.6) and ($\gamma, a_0$) to $^5$He" is $13.1 \pm 2$ MeV mb”.

“"The total absorption cross section has been measured for $E_{\gamma} = 10$ to 210 MeV: it rises to $\approx 5$ mb at $\approx 21$ MeV, decreases to about 0 at 160 MeV and then increases to $\approx 1.5$ mb at 210 MeV. An integrated cross section of 156 $\pm 15$ MeV mb is reported for $E_{\gamma} = 10$ to 29 MeV as is resonant structure at $E_{\gamma} = 11.8, (13.5), 14.8, (17.3), (19.5), 21.0, (23.0),$ and (25.0) MeV. Fine structure is also reported at $E_{\gamma} = 20.47 \pm 0.04$ and 20.73 $\pm 0.04$ MeV. See [1979AJ01] for references. At $E_{\gamma} = 1.58$ MeV, the cross section for reaction (c) is $0.40 \pm 0.18 \mu$ [1983FU13]. For the electroproduction and photoproduction of helium nuclei for $E_e = 100$ to 225 MeV see [1986LI22]. For hadron production at high energies see [1983AR24].” See also the earlier work cited in [1988AJ01].

14. (a) $^9$Be($\gamma, p)^{6}$Li, $Q_m = -16.8882$
(b) $^9$Be($\gamma, n + p)^{7}$Li, $Q_m = -18.9205$
(c) $^9$Be($\gamma, d)^{3}$Li, $Q_m = -16.6959$
(d) $^9$Be($\gamma, t)^{6}$Li, $Q_m = -17.6890$

The yield shows structure in the energy region corresponding to the $^9$Be levels at 17–19 MeV followed by the giant resonance at $E_{\gamma} \approx 23$ MeV ($\sigma = 2.64 \pm 0.30$ mb). Structure attributed to eleven states of $^9$Be with $18.2 < E_x < 32.2$ MeV has also been reported. Integrated cross sections have been obtained for each of these resonances, and over different energy intervals for protons leading to $^8$Li$^*(0 + 0.98, 2.26 + 3.21, 9.0, 17.0)$. Angular and energy distributions of photoprotons in various energy intervals have been studied by many groups: see [1974AJ01] for early references. For momentum spectra of protons using tagged photons with $E_\gamma = 360$–600 MeV, see [1984BA09]. See also [1984AJ01] and [1984HO24], and see the analysis for $E_\gamma = 200$–420 MeV by [1988TE04].
The integrated cross sections are reported to be $1.0 \pm 0.5$ MeV mb ($E_\gamma = 21-33$ MeV) for reaction (c) to $^7\text{Li}^{(0 + 0.4)}$, and $0.6 \pm 0.3$ MeV mb ($E_\gamma = 25-33$ MeV) for reaction (d) to $^6\text{Li}^{g.s.}$. The total integrated cross section for $[ (\gamma, p) + (\gamma, \text{pn}) + (\gamma, d) + (\gamma, t) ]$ is $33 \pm 3$ MeV mb. Calculations for reaction (b) at $E_\gamma = 247$ MeV are presented in [1993BO35].

Resonances in the $(\gamma, d)$ and $(\gamma, t)$ cross sections corresponding to $^9\text{Be}^*(26.0 \pm 0.2)$ and $^9\text{Be}^*(32.2 \pm 0.3)$, respectively, have been reported: see [1974AJ01]. A recent measurement and cluster-model analyses for reactions (a), (c), (d) for $E_\gamma = 21-39$ MeV are described in [1999SH05].

Resonances in the $(\gamma, d)$ and $(\gamma, t)$ cross sections corresponding to $^9\text{Be}^*(26.0 \pm 0.2)$ and $^9\text{Be}^*(32.2 \pm 0.3)$, respectively, have been reported: see [1974AJ01]. A recent measurement and cluster-model analyses for reactions (a), (c), (d) for $E_\gamma = 21-39$ MeV are described in [1999SH05]. For momentum spectra of deuterons and tritons at $E_\gamma = 360-600$ MeV see [1986BA07]. Cross sections have been measured in the region of the $\Delta(1232)$ resonance by [1984HO09] $(\gamma, n)$, $(\gamma, 2p)$, [1987KA13] $(\gamma, p)$, $(\gamma, \text{pn})$, $(\gamma, 2p)$ and [1986AR06] $(\gamma, \pi^0)$. For a high energy study of hadron production see [1983AR24]. See also [1986MC1G, 1985HO27, 1985MA1G] and the calculations of [1983TR04, 1986HO11, 1987LU1B, 1988DU04].

15. $^9\text{Be}(\gamma, \gamma)^9\text{Be}$

The integrated cross sections are reported to be $1.0 \pm 0.5$ MeV mb ($E_\gamma = 21-33$ MeV) for reaction (c) to $^7\text{Li}^{(0 + 0.4)}$, and $0.6 \pm 0.3$ MeV mb ($E_\gamma = 25-33$ MeV) for reaction (d) to $^6\text{Li}^{g.s.}$. The total integrated cross section for $[ (\gamma, p) + (\gamma, \text{pn}) + (\gamma, d) + (\gamma, t) ]$ is $33 \pm 3$ MeV mb. Calculations for reaction (b) at $E_\gamma = 247$ MeV are presented in [1993BO35].

Resonances in the $(\gamma, d)$ and $(\gamma, t)$ cross sections corresponding to $^9\text{Be}^*(26.0 \pm 0.2)$ and $^9\text{Be}^*(32.2 \pm 0.3)$, respectively, have been reported: see [1974AJ01]. A recent measurement and cluster-model analyses for reactions (a), (c), (d) for $E_\gamma = 21-39$ MeV are described in [1999SH05]. For momentum spectra of deuterons and tritons at $E_\gamma = 360-600$ MeV see [1986BA07]. Cross sections have been measured in the region of the $\Delta(1232)$ resonance by [1984HO09] $(\gamma, n)$, $(\gamma, 2p)$, [1987KA13] $(\gamma, p)$, $(\gamma, \text{pn})$, $(\gamma, 2p)$ and [1986AR06] $(\gamma, \pi^0)$. For a high energy study of hadron production see [1983AR24]. See also [1986MC1G, 1985HO27, 1985MA1G] and the calculations of [1983TR04, 1986HO11, 1987LU1B, 1988DU04].

16. (a) $^9\text{Be}(e, e)^9\text{Be}$

(b) $^9\text{Be}(e, e'p)^8\text{Be}, \quad Q_m = -1.6654$

(c) $^9\text{Be}(e, ep)^8\text{Li}, \quad Q_m = -16.8882$

(d) $^9\text{Be}(e, e'\alpha)^5\text{Li}, \quad Q_m = -2.757$

\[
\langle r^2 \rangle^{1/2} = 2.519 \pm 0.012 \text{ fm} \quad [1973BE19, 1979AJ01];
\]

\[
Q = 5.86 \pm 0.06 \text{ fm}^2 \quad [1991GL02];
\]

\[
b = 1.5^{+0.3}_{-0.2} \text{ fm} \quad [1973BE19, 1979AJ01] \quad [b = \text{oscillator parameter}];
\]

\[
\langle r^2 \rangle_B^{1/2} = 3.2 \pm 0.3 \text{ fm}, \quad \Omega = 6 \pm 2 \mu_N \text{ fm}^2 \quad [\text{this value of the magnetic octupole moment implies a deformation of the average nuclear potential}];
\]

\[
[1975LA23, 1979AJ01].
\]

The previous review [1988AJ01] observed that: “The elastic scattering of electrons has been studied for $E_e$ up to 700 MeV. Magnetic elastic scattering gives indications of both M1 and M3 contributions. Inelastic scattering populates a number of levels; see Table 9.8 in [1988AJ01]. At $E_e = 45$ and 49 MeV $^9\text{Be}^*(1.68)$ has a strongly asymmetric line shape, as expected from its closeness to the $^8\text{Be} + n$ threshold. The form factor is dominated by a $0p_3/2 \rightarrow 1s_1/2$ particle–hole transition. $^9\text{Be}^*(2.43)$ is strongly excited [1987KU05]. Form factors have also been measured for $^9\text{Be}^*(0, 14.39, 16.67, 16.98, 17.49)$ by ([1983LO11]; $E_e = 100.0$ to 270.2 MeV). See also [1985HY1A, 1986MA48, 1987HY01], [1984WO09].
suggests that the $T = \frac{1}{2}$ states $[^{9}\text{Be}^*](16.67, 17.49)$ have $J^\pi = \frac{5}{2}^+$ and $\frac{7}{2}^+$, respectively, and that they have large parentage amplitudes with $[^{8}\text{Be}^*](16.6 + 16.9) [J^\pi = 2^+]$, rather than with $[^{9}\text{Be}]_{\text{g.s.}}$. See [1974AJ01, 1979AJ01, 1984AJ01].”

In a more recent study [1991GL02], electrons at energies between 110 and 360 MeV were used along with detailed line-shape analysis to extract cross sections for states at $E_x = 0, 1.68, 2.43, 3.05, 4.70, 6.38, 6.76, 11.28$, and $13.79$ MeV, and for momentum transfers between 1.0 and 2.5 fm$^{-1}$. See Table 9.10.

A previously unknown state at 6.38 MeV was isolated from the known 6.76 MeV state in both the (e, e$'$) data of [1991GL02] and the (p, p$'$) data [1991DI03] using the dependence of the peak position upon momentum transfer. On the basis of the form factor the 6.38 MeV state replaces the 6.76 MeV state as the $\frac{7}{2}^-$ member of the ground state rotational band, and the 6.76 MeV state is identified with the lowest $\frac{5}{2}^+$ state predicted by the shell model. Results of these measurements are tabulated and compared with the shell model prediction in Table V in [1991GL02] and in Table 9.10 here.

An analysis of form factors to deduce vertex constants is described in [1991BE40]. Harmonic scattering calculations are presented in [1992DE42].

For early work in the quasifree and $\Delta$-resonance regions see references cited in [1988AJ01].

17. $[^{9}\text{Be}(\pi^\pm, \pi^\pm)]^{9}\text{Be}$

The elastic scattering, and inelastic scattering to $[^{9}\text{Be}^*](2.43, 6.76)$ have been studied at $E_{\pi^\pm} = 162$ and 291 MeV. Quadrupole contributions appear to be quite important for the elastic scattering at 162 MeV, but are much less so at the higher energy; see [1984AJ01] and see the General Table for $[^9\text{Be}$ located on our website at www.tunl.duke.edu/nudata/General_Tables/9be.shtml. Calculations of threshold pion–nucleus amplitude by current algebra are discussed in [1989GE10]. See also the diffraction theory calculations of the scattering process by [2000ZH50].

18. (a) $[^{9}\text{Be}(n, n)]^{9}\text{Be}$

(b) $[^{9}\text{Be}(n, 2n)]^{9}\text{Be}$, $Q_m = -1.6654$

The population of $[^{9}\text{Be}^*](0, 1.7, 2.4, 3.1, (6.8))$ has been reported in this reaction: see [1974AJ01]. For the neutron decay of these states see Table 9.7. Angular distributions have been measured at $E_n = 3.5$ to 14.93 MeV [see [1974AJ01, 1979AJ01, 1984AJ01]], at $E_n = 7$ to 15 MeV ([1983DA22]; $n_0$), 11 to 17 MeV ([1985TE01]; $n_0$, $n_2$), 14.6 MeV ([1985HA02, 1986HA02]; $n_0$) and 14.7 MeV ([1984SH01]; $n_0$, $n_2$) as well as at $E_n = 9$ to 17 MeV ([1984BY03]; $n_0$, $n_2$; see also for transition to $[^{9}\text{Be}^*](6.76)$). See also $^{10}\text{Be}$ and other early work cited in [1988AJ01].

Spin-dependent scattering lengths were measured at low energies [1987GL06] by a pseudomagnetic precession method, and cross sections were measured at $E_n = 1–10$ MeV [1989SU13] and $E_n = 21.6$ MeV [1990OL01]. Calculations and analysis for $[^{9}\text{Be}(n, n)$ are reported in [1988FE06, 1991IO01, 1996CH33, 2001BO10].

For reaction (b) the n–n scattering length was measured at $E_n = 10.3$ MeV [1990BO43]. A thick target neutron spectrum was used in a measurement of the reaction cross section by
Table 9.10
Electromagnetic matrix elements for $^9$Be(e, $e'$)$^\alpha$

<table>
<thead>
<tr>
<th>$E_{\text{expt.}}$ (MeV)</th>
<th>$E_{\text{theor.}}$ (MeV)</th>
<th>$J^\pi$</th>
<th>Matrix element$^e$</th>
<th>($e,e'$)$^f$</th>
<th>Other</th>
<th>Theory$^g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>$^3_2^-$</td>
<td>$Q$ (fm$^2$)</td>
<td>5.86 ± 0.06</td>
<td>5.3 ± 0.3$^f$</td>
<td>4.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\mu$ (µN)</td>
<td>−1.16 ± 0.02</td>
<td>−1.1778 ± 0.0009$^f$</td>
<td>−1.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B$(M3)</td>
<td>4.4 ± 0.3</td>
<td>9.72</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B$(C2)</td>
<td>17.1 ± 0.3</td>
<td>9.43</td>
<td></td>
</tr>
<tr>
<td>1.68</td>
<td>1.68</td>
<td>$^3_2^+$</td>
<td>$B$(C1)</td>
<td>0.034 ± 0.003</td>
<td>0.027 ± 0.002$^f$</td>
<td>0.0045</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B$(M2)</td>
<td>0.023 ± 0.008</td>
<td>0.097 ± 0.017$^f$</td>
<td>0.022</td>
</tr>
<tr>
<td>2.43</td>
<td>2.64</td>
<td>$^5_2^-$</td>
<td>$B$(C2)</td>
<td>46.0 ± 0.5</td>
<td>41.6 ± 2.9$^h$</td>
<td>32.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B$(M1)</td>
<td>0.0090 ± 0.0003</td>
<td>0.0089 ± 0.0010$^b$</td>
<td>0.0068</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B$(M3)</td>
<td>0.5 ± 0.3</td>
<td>2.22</td>
<td></td>
</tr>
<tr>
<td>3.05</td>
<td>2.87</td>
<td>$^5_2^+$</td>
<td>$B$(C1)</td>
<td>0.029 ± 0.005</td>
<td>0.015 ± 0.013$^b$</td>
<td>0.0039</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B$(M2)</td>
<td>0.16 ± 0.02</td>
<td>0.018</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B$(C3)</td>
<td>0.9 ± 0.6</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B$(M4)</td>
<td>58 ± 3</td>
<td>127.6</td>
<td></td>
</tr>
<tr>
<td>6.38</td>
<td>6.19</td>
<td>$^3_2^-$</td>
<td>$B$(C2)</td>
<td>33 ± 1</td>
<td>25.6 ± 1.4$^i$</td>
<td>12.7</td>
</tr>
<tr>
<td>6.76</td>
<td>6.39</td>
<td>$^5_2^+$</td>
<td>$B$(C3)</td>
<td>216 ± 5</td>
<td>17.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B$(M4)</td>
<td>174 ± 16</td>
<td>223.8</td>
<td></td>
</tr>
<tr>
<td>7.52</td>
<td></td>
<td>$^5_2^+$</td>
<td>$B$(C3)</td>
<td>25.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.17</td>
<td></td>
<td>$^5_2^+$</td>
<td>$B$(C3)</td>
<td>19.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.28</td>
<td>8.46</td>
<td>$^5_2^+$</td>
<td>$B$(C3)</td>
<td>57 ± 6</td>
<td>26.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B$(M4)</td>
<td>35.9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^\alpha$ Adapted from Table V of [1991GL02].
$^\beta$ Normalized to the ground-state for negative-parity levels and to the $^1_2^+$ state for positive-parity levels.
$^\gamma$ The units of $B$(CJ) and $B$(MJ) are both $e^2$ fm$^2$.J.
$^\delta$ Polynomial-Gaussian expansion (PGE) fits [1991GL02]. The error is from the statistical error on the leading polynomial coefficient and is dependent on the number of terms in the polynomial.
$^\epsilon$ Harmonic oscillator (HO) wave functions with $b = 1.765$ fm, $c_p + \delta c_p + \delta c_n = 1.0c_p$, $c_p + \delta c_p - \delta c_n = 0.7c_p$, and bare nucleon g factors [1991GL02].
$^f$ From [1988AJ01].
$^g$ Low $q$ (e, $e'$) from [1987KI05].
$^h$ Low $q$ (e, $e'$) from [1968CL08]. Data from [1968CL08] is included in the fits of [1991GL02].
$^i$ Low $q$ (e, $e'$) from [1963NG1A].

[1994ME08]. See also the analysis and model calculations for $^9$Be(n, 2n) at $E_n = 5.9$ MeV [1988BE04].

19. (a) $^9$Be(p, p)$^9$Be
(b) $^9$Be(p, p)$^\prime$Be$^\ast$

The previous review [1988AJ01] summarized the information available from the reaction as follows: "Elastic and inelastic angular distributions have been studied at many energies in the range $E_p = 2.3$ to 1000 MeV [see [1974AJ01,1979AJ01,1984AJ01]], at $E_p = 2.31$ to 2.73 MeV ([1983AL10]; p0), 11 to 17 MeV ([1988AJ01]; p0) and..."
and Table 9.8 in [1988AJ01] for its parameters. At 1 GeV ([1985AL16]; p_0) a well sat a 9 Be parameters are taken from [1988AJ01].

A quadrupole-deformed optical-model potential is necessary to obtain a good fit to the p_0 ([1985RO15]; p_0, p_2). The elastic distributions show pronounced diffraction maxima. A 0f o r the p_2 group, which is expected in view of the collective nature of the transition ≈ 0.

The structure corresponding to ⁹Be* (1.7) is asymmetric, as expected: see reaction 16 and Table 9.8 in [1988AJ01] for its parameters. [At E_p = 13 MeV the spectra are dominated by ⁹Be* (2.43) [1987KU05].] The weighted mean of the values of E_x for ⁹Be* (2.4) listed in [1974AJ01] is 2432 ± 3 keV. ⁹Be* (3.1) has E_x = 3.03 ± 0.03 MeV,

### Table 9.11
Energy levels (E_x) and widths (Γ) for ⁹Be states observed in ⁹Be(p, p')

<table>
<thead>
<tr>
<th>E_x (MeV)</th>
<th>Γ (MeV)</th>
<th>J^π; T</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.217 ± 0.010</td>
<td>¹/₂⁺; ¹/₂</td>
<td></td>
</tr>
<tr>
<td>1.680 ± 0.015</td>
<td>0.217 ± 0.010</td>
<td>¹/₂⁺; ¹/₂</td>
<td></td>
</tr>
<tr>
<td>2.4294 ± 0.0013</td>
<td></td>
<td>¹/₂⁻; ¹/₂</td>
<td></td>
</tr>
<tr>
<td>2.78 ± 0.12</td>
<td>1.08 ± 0.11</td>
<td>¹/₂⁻; ¹/₂</td>
<td></td>
</tr>
<tr>
<td>3.049 ± 0.009</td>
<td>0.282 ± 0.011</td>
<td>¹/₂⁻; ¹/₂</td>
<td></td>
</tr>
<tr>
<td>4.704 ± 0.025</td>
<td>0.743 ± 0.055</td>
<td>¹/₂⁻; ¹/₂</td>
<td></td>
</tr>
<tr>
<td>5.59 ± 0.10*</td>
<td>1.33 ± 0.36*</td>
<td>(¹/₂⁻; ¹/₂)</td>
<td>clearly member of K = ³/₂⁻ band</td>
</tr>
<tr>
<td>6.38 ± 0.06*</td>
<td>1.21 ± 0.23*</td>
<td>(¹/₂⁻; ¹/₂)</td>
<td>assignment based on C3 angular distribution</td>
</tr>
<tr>
<td>6.76 ± 0.06</td>
<td>1.33 ± 0.09*</td>
<td>(¹/₂⁻; ¹/₂)</td>
<td>weak assignment based on C3 shape</td>
</tr>
<tr>
<td>11.28 ± 0.05*</td>
<td>1.10 ± 0.23*</td>
<td>(¹/₂⁻; ¹/₂)</td>
<td>also consistent with J^π; T = ³/₂⁻; ¹/₂</td>
</tr>
<tr>
<td>13.79 ± 0.03</td>
<td>0.59 ± 0.06</td>
<td>(¹/₂⁻; ¹/₂)</td>
<td></td>
</tr>
<tr>
<td>14.3926 ± 0.0018</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.4 ± 0.3</td>
<td>0.35 ± 0.18*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.10 ± 0.05</td>
<td>0.310</td>
<td>(¹/₂⁻; ¹/₂)</td>
<td>also consistent with J^π; T = ³/₂⁻; ¹/₂</td>
</tr>
<tr>
<td>15.97 ± 0.05</td>
<td>0.411 ± 0.004</td>
<td>¹/₂⁻; ¹/₂</td>
<td></td>
</tr>
<tr>
<td>16.761 ± 0.009</td>
<td>0.411 ± 0.004</td>
<td>¹/₂⁻; ¹/₂</td>
<td></td>
</tr>
<tr>
<td>16.976 ± 0.002</td>
<td></td>
<td>¹/₂⁻; ¹/₂</td>
<td></td>
</tr>
<tr>
<td>17.297 ± 0.010</td>
<td>0.2</td>
<td>(¹/₂⁻; ¹/₂)</td>
<td></td>
</tr>
<tr>
<td>17.490 ± 0.009</td>
<td>0.047</td>
<td>¹/₂⁻; ¹/₂</td>
<td></td>
</tr>
<tr>
<td>18.65 ± 0.05*</td>
<td>0.3 ± 0.1*</td>
<td>¹/₂⁻; ¹/₂</td>
<td>assignment based on M2 shape</td>
</tr>
<tr>
<td>19.20 ± 0.05</td>
<td>0.31 ± 0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19.42 ± 0.05*</td>
<td>0.6 ± 0.3*</td>
<td>(¹/₂⁻; ¹/₂)</td>
<td>assignment based on M4 shape</td>
</tr>
<tr>
<td>20.53 ± 0.03*</td>
<td>0.6 ± 0.1*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.8 ± 0.1*</td>
<td>0.68 ± 0.09*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* As presented in Table I of [1991DI03]. New values for positions or widths are marked with asterisks (*). Widths smaller than 40 keV were neglected. Proposed assignments are given within parentheses. Unmarked parameters are taken from [1988AJ01].
In an experimental and theoretical study of $^{9}$Be structure [1991DI03], cross section and analyzing power measurements made with 180 MeV protons provided data for 24 states below $E_x = 21$ MeV. Detailed line shape analysis was used to isolate several broad states. In particular the strong resonance at 6.76 MeV [1988AJ01] was separated into two levels identified as the $\frac{7}{2}^-$ member of the ground state rotational band at 6.38 MeV and the $\frac{9}{2}^+$ weak-coupling state at 6.76 MeV. Level energies, suggested assignments and widths are summarized in Table 9.11. Transition densities were fitted to $(p, p')$ data and compared with results from $(e, e')$ data [1991GL02]. Shell model calculations in $0^+$ and $1^+$ model space were performed and used in making suggested assignments [1991DI03].

In other experimental work, measurements have been reported for cross sections and polarization observables at $E_p = 135$ MeV [1988KE04,1989KE03], and at $E_p = 54.7$ and 74.7 MeV [1994DE23]. The data from these experiments were analyzed with other data for $30 < E_p < 220$ MeV in terms of a variety of optical model and coupled-channel analyses to calculate final-state interaction effects for proton knockout reactions on $^{10}$B [1994DE23]. Microscopic coupled-channel calculations for the ground-state rotational band of $^{9}$Be and $100 < E_p < 500$ MeV have been made using the folding model and density-dependent interactions [1992KE05]. Elastic scattering cross sections have been reported at $E_p \leq 2.66$ MeV [1994WR01], and application-related scattering cross sections at $E_p = 2.3–2.7$ keV [1988LA07] and $E_p = 2.4–2.7$ MeV [1994LE18].

Other theoretical work published since the previous review [1988AJ01] includes geometric model calculations [1990HU09]; construction of interaction potentials from phase shifts [1996KU14]; Glauber–Stenken theory calculations for $E_p = 0.22$, 1 GeV [1996ZH31]; microscopic-model analysis for $E_p = 200$ MeV [1997DO01]; Glauber-model calculations for $E_p = 0.22$, 1.0 GeV [1997ZH39]; calculations of polarization features for $E_p = 0.22$, 1.0 GeV [1998ZH02]; and diffraction theory calculations for $E_p = 0.16–1.04$ GeV [2000ZH50].

20. (a) $^{9}$Be($p$, 2$p$)$^8$Li, $Q_m = -16.8882$
(b) $^{9}$Be($p$, d)$^7$Li, $Q_m = -16.6959$
(c) $^{9}$Be($p$, $p$ + $n$)$^8$Be, $Q_m = -1.6654$
(d) $^{9}$Be($p$, $p$ + $t$)$^6$Li, $Q_m = -17.6890$
(e) $^{9}$Be($p$, $p$ + $^3$He)$^6$He, $Q_m = -21.1787$
(f) $^{9}$Be($p$, $p\alpha$)$^5$He, $Q_m = -2.467$

The reactions $(p, 2p)X$ and $(p, pd)X$ have been studied at $E_p = 300$ MeV [1983GR21, 1984HE03]. For reactions (a) and (c) see also $^8$Li, $^8$Be ([1985BE30,1985DO16]; 1 GeV) and [1984AJ01]. Reaction (c) at $E_p = 10–24$ MeV involves $^9$Be$(^3, 4.7)$: see
\[ ^{9}\text{Be} \]


[1984AJ01]. See also [1984WA21]. For reactions (b) and (d) at \( E_p = 58 \text{ MeV} \) see \(^7\text{Li}\) and \(^6\text{Li}\) in [2002TI10], and [1984DE1F,1985DE17]. For reactions (e) and (f) see ([1985PA1C]; \( E_p = 70 \text{ MeV} \)). The (p,\( p\alpha \)) process (reaction (f)) has been studied at \( E_p = 150.5 \text{ MeV} \) [1985WA13], at 200 MeV [1989NA10], and at 296 MeV [1998YO09]. Alpha cluster knockout spectroscopic factors were deduced. For inclusive proton spectra yields see [1985SE15]. Inclusive differential cross sections for \(^4\text{He},^6\text{Li}\) formation by 1 GeV protons on \(^9\text{Be}\) were measured by [1994AM09]. Cross section and proton and neutron spectra for reactions (a) and (c) at \( E_p = 70 \text{ MeV} \) were studied by [2000SH01]. See also the earlier work cited in [1988AJ01].

21. \(^{9}\text{Be}(d,d)^{9}\text{Be}\)

Angular distributions have been measured in the range 1.0 to 410 MeV [see [1974AJ01, 1979AJ01,1984AJ01]] and at \( E_d = 2.0 \) to 2.8 MeV [1983DE50,1984AN16]. See also \(^{11}\text{B}\) in [1990AJ01].

Inelastic groups have been reported to \(^9\text{Be}^*\)(1.7, 4.7, 6.8) and to states with \( E_x = 2431.9 \pm 7.0 \text{ keV} \) and \( 3040 \pm 15 \text{ keV} \) \((I^* = 294 \pm 20 \text{ keV})\); see [1974AJ01]. Measurements at \( E_d = 6.7–7.5 \text{ MeV} \) of differential cross sections for inelastic groups to \(^9\text{Be}^*\)(2.43) and DWBA analysis were reported by [1989SZ02]. An analysis by [1989VA17] of \(^9\text{Be}^*\)(2.43) at \( E_d = 4–11 \text{ MeV} \) found evidence for kinematic focusing of the products of 3-particle decay of \(^9\text{Be}^*(2.43)\). An optical-model description for \( E_d = 4–11 \text{ MeV} \) is discussed in [1993AB10].

22. (a) \(^{9}\text{Be}(t,t)^{9}\text{Be}\)

\( \begin{align*}
(\text{b) } ^{9}\text{Be}(t,n+t)^{8}\text{Be}, \quad Q_m = -1.6654
\end{align*} \)

Angular distributions of elastically scattered tritons have been measured at \( E_t = 2.10 \text{ MeV} \) and at \( E_t = 15 \) and 17 MeV; see [1974AJ01,1984AJ01]. A more recent analysis by a strong absorption model of cross sections measured at \( E_t = 17 \text{ MeV} \) is reported in [1994SO26]. Reaction (b) at 4.2 and 4.6 MeV proceeds via \(^9\text{Be}^*\)(2.43); see [1974AJ01].

23. (a) \(^{9}\text{Be}(^{3}\text{He},^{3}\text{He})^{9}\text{Be}\)

(\text{b) } ^{9}\text{Be}(^{3}\text{He},2\alpha)^{4}\text{He}, \quad Q_m = 19.0041
\)

Angular distributions have been studied for \( E(^{3}\text{He}) = 1.6 \) to 46.1 MeV and at 217 MeV [see [1974AJ01,1979AJ01,1984AJ01]]. At \( E(^{3}\text{He}) = 39.8 \text{ MeV} \), \(^9\text{Be}^*\)(1.7, 2.4, 3.1, 4.7, 6.8, 14.4) are populated. Data for \( E(^{3}\text{He}) = 50, 60 \text{ MeV} \) were analyzed by [1992AD06], and rainbow effects were observed. Differential cross sections for \( E(^{3}\text{He}) = 60 \text{ MeV} \) were measured by [1993MA48,1996RU13]. Measurements and analysis of the \( \alpha \)-particle spectra from the decay of \(^9\text{Be}^*\)(2.43) populated in the inelastic scattering reaction with \( E(^{3}\text{He}) = 40.5 \text{ MeV} \) are reported in [1990BO51]. An optical model description of the elastic scattering is discussed in [1987TR01].

Reaction (b) has been studied in a kinematically complete experiment for \( E(^{3}\text{He}) = 3 \) to 12 MeV [1986LA26] and 11.9 to 24.0 MeV [1987WA25]. See also [1990BO51]. For the earlier work see [1984AJ01].
24. (a) $^9\text{Be}(\alpha,\alpha)^9\text{Be}$

(b) $^9\text{Be}(\alpha,2\alpha)^3\text{He}$, $Q_m = -2.467$

Angular distributions have been studied at many energies in the range $E_\alpha = 5.0$ to 104 MeV [see [1974AJ01,1984AJ01]] and $E_\alpha = 23.1$ MeV ([1984HU1D,1985HU1B]; $\alpha_0$, $\alpha_2$). At $E_\alpha = 35.5$ MeV, states belonging to the $K = \frac{3}{2}^-$ ground-state band are strongly excited $[^9\text{Be}^*(0, 2.43, 6.76, 11.28); \text{it is suggested that the latter has } J^\pi = (\frac{3}{2}^-); \text{see, however, reaction 12}$. The first three states belonging to the $K = \frac{1}{2}^+$ band are also excited $[^9\text{Be}^*(1.68, 3.05, 4.70)]$ ([1982PE03]; coupled channels analysis). A coupled channel folding model analysis for data at $E_\alpha = 65$ MeV is described in [1995RO21]. See also [2000ZH38].

See also the multicluster model calculation of [1993KU21] and the calculations of levels and rotational bands using $(\alpha,\alpha')$ data reported in [1997VO06]. In application-related work backscattering cross sections were measured for $E_\alpha = 6.00–6.52$ MeV [1996QI03], 0–5.3 MeV [1994LE18], 0.15–3.0 MeV [1994LI51]. Related data were compiled and reviewed in [1991LE33,1996ZH36]. For reaction (b) see ([1983ZH09]; 18 MeV); $S_\alpha = 0.96$ [see [1984AJ01]] and ([1987WA25]; $E(3\text{He}) = 12$ to 24 MeV). A measurement of energy-sharing distributions at $E_\alpha = 197$ MeV was reported in [1994CO16]. Cluster knockout at $E_\alpha = 580$ MeV was studied by [1999NA05]. See also $^8\text{Be}$ [1987BU27,1987KO1K, 1984LI1D,1985SR01].

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

The cross section at $E(^6\text{He}) = 8.8–9.3$ MeV was measured by [1991BE49].

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

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

Elastic angular distributions have been measured at $E(^6\text{Li}) = 4, 6$ and 24 MeV and at $E(^7\text{Li}) = 24$ and 34 MeV [see [1979AJ01]] as well as at $E(^6\text{Li}) = 32$ MeV ([1985CO09]; also to $^9\text{Be}^*(2.43)$) and 50 MeV [1988TRZY] and $E(^7\text{Li}) = 78$ MeV ([1986GL1C, 1986GL1D]; also to $^9\text{Be}^*(2.43, 6.76)$). More recently, measurements and analysis of complete angular distributions for elastic scattering and inelastic scattering to $^9\text{Be}^*(2.43) at E_{cm} = 7, 10, 12$ MeV were reported by [1995MU01]. See also the cross section measurements and optical model analysis for $E(^6\text{Li}) = 50$ MeV [1990TR02] and the analyzing power measurements for elastic and inelastic scattering at $E(^6\text{Li}) = 32$ MeV [1993RE08]. Thresholds of non-Rutherford cross sections for ion-beam analysis were studied by [1991BO48]. For the interaction cross section at $E(^6\text{Li}) = 790$ MeV/A see [1985TA18].

For reaction (b), cross section measurements at $E(^7\text{Li}) = 63, 130$ MeV and optical-model analyses are reported in [2000TR01]. The $\alpha$–$^3\text{He}$ decay of $^9\text{Be}$ excited states populated by $E(^7\text{Li}) = 52$ MeV was studied by [1998SO05].
27. $^9\text{Be}(^9\text{Be}, ^9\text{Be})^9\text{Be}$

Elastic angular distributions have been obtained at $E(^9\text{Be}) = 5$ to 26 MeV [see [1979AJ01,1984AJ01]] and at 35 to 50 MeV ([1984OM02]; also to $^9\text{Be}^*$ (2.43)). See also [1985JA09]. For yields and cross sections see [1984OM03,1986CU02,1988LA25]. See also the application-related measurement at $E(^9\text{Be}) = 5.5$ MeV [1988DA05]. In more recent work, elastic scattering measurements at $E(^9\text{Be}) = 40$ MeV were reported by [1992CO05]. It was determined that the angular distribution data of [1984OM02] must be shifted forward by 5° cm. For the interaction cross section at $E(^9\text{Be}) = 790$ MeV/A see [1985TA18].

28. (a) $^9\text{Be}(^{10}\text{B}, ^{10}\text{B})^9\text{Be}$
(b) $^9\text{Be}(^{11}\text{B}, ^{11}\text{B})^9\text{Be}$

Elastic angular distributions have been reported at $E(^{10}\text{B}) = 20.1$ and 30.0 MeV [1983SR01]. For yields and cross section measurements see [1983SR01,1984DA17, 1986CU02]. See also [1983DU13,1984IN03,1986RO12]. Differential cross sections were measured at $E(^{10}\text{B}) = 100$ MeV [1997MU19,2000TR01]. Optical model parameters and values of the asymptotic normalization coefficients (ANC) for $^{10}\text{B} \rightarrow ^9\text{Be} + p$ were deduced.

29. (a) $^9\text{Be}(^{12}\text{C}, ^{12}\text{C})^9\text{Be}$
(b) $^9\text{Be}(^{13}\text{C}, ^{13}\text{C})^9\text{Be}$

Elastic angular distributions have been measured for reaction (a) at $E(^{12}\text{C}) = 12, 15, 18$ and 21 MeV and $E(^9\text{Be}) = 14$ to 76.6 MeV [see [1979AJ01,1984AJ01]] and 158.3 MeV [1984FU10] as well as at $E(^{12}\text{C}) = 65$ MeV ([1985GO1H]; various $^{12}\text{C}$ states). For yield and fusion cross-section measurements see [1983JA09,1985DE22,1984AJ01]. Angular distributions and excitations functions for elastic scattering and inelastic scattering to $^9\text{Be}^* (2.43)$ for $E_{cm} = 10.9$ MeV are reported in [1995CA26]. Reorientation and coupling effects in the $^9\text{Be} + ^{12}\text{C}$ system were studied. See also the measurements and analysis for $E_{cm} = 5.14$–90.46 MeV of [2000RU02].

Elastic angular distributions for reaction (b) are reported for $E(^9\text{Be}) = 14$ to 26 MeV; see [1984AJ01]. Measurements and optical-model analysis for $E(^{13}\text{C}) = 130$ MeV are reported in [2000TR01]. For yield measurements see [1984DA17,1986CU02]. See also the earlier work cited in [1988AJ01].

30. $^9\text{Be}(^{14}\text{N}, ^{14}\text{N})^9\text{Be}$

Elastic angular distributions have been measured at $E(^{14}\text{N}) = 25$ and 27.3 MeV; see [1974AJ01]. For a fusion study see [1984MA28].
31. (a) $^9\text{Be}(^{16}\text{O},^{16}\text{O})^9\text{Be}$  
(b) $^9\text{Be}(^{18}\text{O},^{18}\text{O})^9\text{Be}$

Elastic angular distributions have been reported in the range $E(^{16}\text{O}) = 15$ to $30$ MeV [see [1979AJ01]] and [1988WE17], at $E(^{9}\text{Be}) = 14$, 20 and 26 MeV [see [1984AJ01]], 43 MeV [1985WI18] and 157.7 MeV [1984FU10], as well as at $E(^{18}\text{O}) = 12.1$, 16 and 20 MeV [see [1974AJ01]]. See also the other references cited in [1988AJ01].

32. (a) $^9\text{Be}(^{20}\text{Ne},^{20}\text{Ne})^9\text{Be}$  
(b) $^9\text{Be}(^{24}\text{Mg},^{24}\text{Mg})^9\text{Be}$  
(c) $^9\text{Be}(^{26}\text{Mg},^{26}\text{Mg})^9\text{Be}$  
(d) $^9\text{Be}(^{27}\text{Al},^{27}\text{Al})^9\text{Be}$  
(e) $^9\text{Be}(^{28}\text{Si},^{28}\text{Si})^9\text{Be}$  
(f) $^9\text{Be}(^{39}\text{K},^{39}\text{K})^9\text{Be}$  
(g) $^9\text{Be}(^{40}\text{Ca},^{40}\text{Ca})^9\text{Be}$  
(h) $^9\text{Be}(^{44}\text{Ca},^{44}\text{Ca})^9\text{Be}$

Elastic angular distributions have been measured for many of these reactions: see [1979AJ01], [1984AJ01]. They have been studied on $^{26}\text{Mg}$ and $^{40}\text{Ca}$ at $E(^{9}\text{Be}) = 43$ and 45 MeV, respectively [1985WI18] and on $^{26}\text{Mg}$, $^{27}\text{Al}$ and $^{40}\text{Ca}$ at $E(^{9}\text{Be}) = 158.1$–158.3 MeV [1984FU10]. For pion production in reaction (a) see [1985FR13]. The interaction cross section for $790$ MeV/A $^9\text{Be}$ on $^{27}\text{Al}$ has been measured by [1985TA18]. Breakup measurements involving $^{40}\text{Ca}$ are reported by [1984GR20]. See also the other references cited in [1988AJ01].

33. $^{10}\text{Be}(d,t)^9\text{Be}, \quad Q_m = -0.5550$

Forward angular distributions have been obtained at $E_d = 15.0$ MeV for the tritons to $^9\text{Be}^*(0, 1.7, 2.4, 3.1)$. The ground-state transition is well fitted by $l = 1$. The transition to $^9\text{Be}^*(1.7)$ [$\approx 165 \pm 25$ keV] is consistent with $J^T = \frac{1}{2}^-$, that to $^9\text{Be}^*(2.4)$ is quite well fitted with $l = 3$ [$J^T = \frac{5}{2}^-$], and that to $^9\text{Be}^*(3.1)$ [$\Gamma = 280 \pm 25$ keV] is consistent with $l = 2$. No other narrow states are seen up to $E_x = 5.5$ MeV [1970AU02].

34. $^{10}\text{Be}(\gamma,p)^9\text{Be}, \quad Q_m = -6.5859$

Angular distributions have been measured for protons leading to a number of excited states of $^9\text{Be}^*$ using tagged photons of mean energies $E_\gamma = 57.6$ and 72.9 MeV. The spectrum of states excited is very similar to that from the $^{10}\text{Be}(e,e'p)^9\text{Be}$ and proton pickup reactions from $^{10}\text{B}$. However, the spectroscopic information is limited in that direct knock-out calculations account for only part of the cross sections and meson-exchange current contributions are found to be large [1998DE34].
### Table 9.12
Levels of $^9$Be from $^{10}$Be($e', e'p$)$^9$Be

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$C^2S_{\text{exp}}$</th>
<th>$C^2S_{\text{theor}}$</th>
<th>$J^\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00 ± 0.02</td>
<td>1.000 ± 0.025</td>
<td>1.000</td>
<td>$^3!_2^-$</td>
</tr>
<tr>
<td>2.41 ± 0.02</td>
<td>0.958 ± 0.025</td>
<td>0.964</td>
<td>$^2!_2^-$</td>
</tr>
<tr>
<td>6.67 ± 0.14</td>
<td>0.668 ± 0.028</td>
<td>0.994</td>
<td>$^1!_2^-$</td>
</tr>
<tr>
<td>11.17 ± 0.03</td>
<td>1.299 ± 0.036</td>
<td>1.352</td>
<td>$^1!_2^-$</td>
</tr>
<tr>
<td>14.48 ± 0.09</td>
<td>0.260 ± 0.025</td>
<td>0.412</td>
<td>$^1!_2^-$</td>
</tr>
</tbody>
</table>

* [1993DE1A]. There is evidence for $l=1$ strength at $\approx 17.5$ MeV, for a state at $7.81 \pm 0.18$ MeV (identified with, and suggesting a $^5\!_2^-$ assignment for the 7.94 MeV level in Table 9.2), and for weakly populated states at 5.72 ± 0.26 MeV (identified with the 5.59 MeV level in Table 9.2) and 10.56 ± 0.23 MeV (existence uncertain).

* Normalized to unity for the ground-state transition.

* (6–16)BME interaction of [1965CO25]. The relative spectroscopic factors for the $^2\!_2^-$ levels are sensitive to the details of the effective interaction. For calculations of spectroscopic factors using the (8–16)POT interaction, see [1967CO32].

* $J$ suggested by comparison with theory.

35. $^{10}$Be($e', e'p$)$^9$Be, $Q_m = -6.5859$

Measurements have been performed in parallel kinematics at incident energies of 407.3 and 498.1 MeV such that $E_{cm} = 70$ or 120 MeV for the outgoing proton. The momentum distributions for energy bins centered around the strong peaks in the spectrum are characteristic of p-shell knockout [1998DE23]. The measured excitation energies and relative spectroscopic factors are shown in Table 9.12 [1993DE2A]. In absolute terms, $54 \pm 2\%$ of the individual-particle shell-model sum rule for 0p strength is accounted for up to $E_x = 19$ MeV.

36. $^{10}$Be(n, $d$)$^9$Be, $Q_m = -4.3613$

See [1974AJ01].

37. $^{10}$Be(p, $2p$)$^9$Be, $Q_m = -6.5859$

This reaction shows several peaks corresponding to proton removal from the p shell and the inner s shell. See [1974AJ01,1985BE30,1985DO16].

38. $^{10}$Be(d, $^3$He)$^9$Be, $Q_m = -1.0924$

Angular distributions of the $^3$He groups corresponding to $^9$Be$^*(0, 2.4)$ have been studied at $E_d = 11.8$, 28 and 52 MeV [the latter also to $^9$Be$^*(6.7)$], and at $E_d = 15$ MeV with $S = 0.72$ and 0.82 for $^9$Be$^*(0, 2.4)$; see [1979AJ01]. At $E_d = 52$ MeV, $S = 1.20, 1.23$, and 0.70 for the 0, 2.43, and 6.66 MeV levels; $^9$Be$^*(11.3)$ appears to be strongly populated but is masked by strong transitions from target contaminants [1975SC41]. An analysis for $E_d = 11.8$ MeV and a study of the uniqueness of the asymptotic normalization coefficient method is discussed in [2000FE08].
39. \( ^{10}\text{B}(t, \alpha)^{9}\text{Be} \), \( Q_m = 13.2280 \)

At \( E_t = 12.9 \text{ MeV} \) _α_-groups are observed to the ground state of \( ^9\text{Be} \) and to excited states at \( E_x = 1.75 \pm 0.03, 2.43, 3.02 \pm 0.04 \) (\( \Gamma = 320 \pm 60 \text{ keV} \)), \( 11.27 \pm 0.04 \) (\( \Gamma = 530 \pm 70 \text{ keV} \)), (14.4) [\( \Gamma \approx 800 \text{ keV} \)], 14.39 and 16.67 MeV. The \( T = \frac{3}{2} \) state \( ^{9}\text{Be}^*(14.39) \) is very weakly populated [\( \approx 5\% \) of intensity of \( \alpha_2 \)]. The angular distribution of the \( \alpha_2 \) group shows sharp forward and backward peaking. The \( \alpha_0 \) group is not peaked in the direction: see [1979AJ01]. See also [1984AJ01,1982CI1A].

40. \( ^{10}\text{B}(^{7}\text{Be}, ^{8}\text{B})^{9}\text{Be} \), \( Q_m = -6.4484 \)

This reaction was studied with an 84 MeV \(^7\text{Be}\) radioactive beam [1999AZ02, 2001GA19,2001TR04]. The measured cross section determined the asymptotic normalization coefficients for the virtual transition \(^9\text{B} \to ^7\text{Be} + p\) which may be used to calculate the astrophysical \( S \) factor for \(^7\text{Be}(p, \gamma)^9\text{B}\) at solar energies. See also the calculations and analysis of [1995GA20].

41. \( ^{11}\text{B}(^{3}\text{He}, ^{9}\text{B})^{9}\text{Be} \), \( Q_m = -10.322 \)

At \( E_p = 45 \text{ MeV} \) angular distributions are reported for the \(^3\text{He}\) ions corresponding to \( ^{9}\text{Be}^*(0.24, 11.8, 13.8, 14.39 \{ T = \frac{1}{2} \}, 15.96 \pm 0.04 \{ T = \frac{1}{2} \} \). In addition one or more states may be located at \(^{9}\text{Be}^*(15.13)\). It is suggested that \(^{9}\text{Be}^*(11.8, 13.8, 15.96)\) are the \( J^\pi = \frac{1}{2}^-; T = \frac{1}{2} \) analogs to \(^{9}\text{B}^*(12.06, 14.01, 16.02)\). Angular distributions are also reported at \( E_p = 40 \text{ MeV} \). The intensity of the group to \(^{9}\text{Be}^*(3.1)\) is \( \approx 1\% \) of the ground-state group at that energy: see [1974AJ01]. The excitation energy of the first \( T = \frac{3}{2} \) state is \( E_x = 14392.2 \pm 1.8 \text{ keV} \) [1974KA15], using \( Q_m \). Cross sections for this reaction at \( E_p = 4-11 \text{ MeV} \) were calculated by [1994SH21] with Feshbach–Kerman–Koonin quantum multi-step direct reaction theory.

42. (a) \( ^{11}\text{B}(d, \alpha)^{9}\text{Be} \), \( Q_m = 8.031 \)

(b) \( ^{11}\text{B}(d, n)^{4}\text{He}^{4}\text{He} \), \( Q_m = 6.458 \)

Alpha groups are reported corresponding to \(^{9}\text{Be}^*(0, 1.7, 2.4, 3.1)\). The width of \(^{9}\text{Be}^*(1.7)\) [\( E_x = 1.70 \pm 0.01 \text{ MeV} \)] is \( \Gamma_{cm} = 220 \pm 20 \text{ keV} \). The weighted mean of the values of \( E_x \) of \(^{9}\text{Be}^*(2.4)\), reported in [1974AJ01], is \( 2425 \pm 3 \text{ keV} \). The \( \frac{5}{2}^- \) state is at \( E_x = 3.035 \pm 0.025 \text{ MeV} \); \( \Gamma_{cm} = 257 \pm 25 \text{ keV} \). The ratio \( \Gamma_\gamma / \Gamma \) of \(^{9}\text{Be}^*(1.7) \leq 2.4 \times 10^{-5}\); that for \(^{9}\text{Be}^*(2.4)\) is reported to be \( 1.16 \pm 0.14 \times 10^{-4}\). Since \( \Gamma_\gamma \) is known [see Table 9.3: \( 0.091 \pm 0.010 \text{ eV} \)], \( \Gamma = 0.78 \pm 0.13 \text{ keV} \). See [1974AJ01,1979AJ01] for references.

Angular distributions for \( \alpha_0 \) and \( \alpha_2 \) are reported at \( E_d = 0.39 \) to 3.9 MeV and at 12 MeV [see [1974AJ01,1979AJ01]]. Recent measurements for \( E_{cm} = 57-141 \text{ keV} \) were reported by [1997YA02,1997YA08]. Astrophysical \( S \)-factors were deduced. Reaction (b), at \( E_d = 10.4 \) and 12.0 MeV, proceeds via \(^{9}\text{Be}^*(2.4)\) and to some extent via \(^{9}\text{Be}^*(3.1, 4.7)\) and possibly some higher excited states. The dominant decay of \(^{9}\text{Be}^*(2.4)\) state is to \(^{5}\text{He}_{g.s.} + \alpha\) while \(^{9}\text{Be}^*(3.1, 4.7)\) states decay to \(^{9}\text{Be}_{g.s.} + n\). It should be noted, however, that the peaks
corresponding to $^9\text{Be}^*$\((3.0)\) have a FWHM of $\approx 1$ MeV, which may imply that $^9\text{Be}^*(2.8)$ is involved.

43. $^{12}\text{C}(\gamma, \text{pd})^9\text{Be}$, \[ Q_m = -31.7723 \]

See [1986BU22,1987BU1A,1987VO08,1988BU06]. More recently, the reaction was studied at $E_\gamma = 150–400$ MeV with tagged photons [1999MC06].

44. (a) $^{12}\text{C}(\text{n}, \alpha)^9\text{Be}$, \[ Q_m = -5.7012 \]
(b) $^{12}\text{C}(\text{n}, \alpha)^4\text{He}^4\text{He}$, \[ Q_m = -7.274747 \]

Angular distributions of the $\alpha_0$ group have been measured at $E_\text{n} = 13.9$ to 18.8 MeV [see [1974AJ01]] and at 14.1 MeV [1984HA48]. $^9\text{Be}^*(1.7, 2.4, 3.1, 6.8)$ are also populated. Cross sections and particle-spectra related to neutron detector development have been measured at $E_\text{n} = 4–11$ MeV [1991BR09], 14.1 MeV [2000SA06], 14.6 MeV [1994KO53] and 40, 56 MeV [1994MO41]. See also the calculated cross sections of [1989BR05]. Reaction (b) at $E_\text{n} = 13$ to 18 MeV involves $^9\text{Be}^*(2.4)$. See [1984HA48] for differential cross sections at 14.1 MeV and for partial and total cross sections.

45. $^{12}\text{C}(p, p^3\text{He})^9\text{Be}$, \[ Q_m = -26.2788 \]

See ([1985DE17]; $E_p = 58$ MeV), and the calculations of ([1987ZH10]; $E_p \approx 0.7$ GeV).

46. $^{12}\text{C}(t, ^6\text{Li})^9\text{Be}$, \[ Q_m = -10.4846 \]

Differential cross sections were measured at $E_t = 33$ MeV to $^9\text{Be}_{\text{g.s.}}$. [1989SI02]. Spectroscopic factors for $^3\text{He}$-cluster pickup were deduced.

47. $^{12}\text{C}(\alpha, ^7\text{Be})^9\text{Be}$, \[ Q_m = -24.6927 \]

Cross section measurements at $E_\alpha = 90$ MeV and DWBA analysis are reported in [1991GL03]. See also $^7\text{Be}$ in [2002TI10].

48. (a) $^{12}\text{C}(^7\text{Li}, ^{10}\text{B})^9\text{Be}$, \[ Q_m = -8.4905 \]
(b) $^{12}\text{C}(^{12}\text{C}, ^{15}\text{O})^9\text{Be}$, \[ Q_m = -14.203 \]
(c) $^{12}\text{C}(^{13}\text{C}, ^{16}\text{O})^9\text{Be}$, \[ Q_m = -3.4856 \]
(d) $^{12}\text{C}(^{14}\text{N}, ^{17}\text{F})^9\text{Be}$, \[ Q_m = -10.4359 \]

For reaction (a) see $^{10}\text{B}$. Differential cross sections for reaction (b) were measured at $E(^{12}\text{C}) = 480$ MeV [1988KR11]. For reaction (c) see [1988KR11,1985OS06]. For reaction (d) see ([1986GO1B]; $E(^{14}\text{N}) = 150$ MeV).
49. $^{13}$C$(^7$Li)$^9$Be, $Q_m = -8.1806$

Differential cross sections were measured at $E_t = 33$ MeV to $^9$Be$^*(0, 2.43)$ [1989SI02]. Spectroscopic factors for $\alpha$-cluster pickup were deduced.

50. $^{13}$C$(^3$He, $^7$Be)$^9$Be, $Q_m = -9.0614$

Angular distributions have been obtained at $E(^3$He) = 70 MeV for the transitions to $^9$Be$^*(0, 2.4)$ and $^7$Be$^*(0, 0.43)$. Broad states at $2.9, 4.8 \pm 0.2, 7.3 \pm 0.2$ and $11.9 \pm 0.4$ MeV are also populated: see [1979AJ01].

51. $^{13}$C$(\alpha, ^8$Be)$^9$Be, $Q_m = -10.7393$

See $^8$Be here and $^9$Be in [1979AJ01].

52. $^{14}$N$(^7$Li, $^{12}$C)$^9$Be, $Q_m = 6.4236$

See [1986GO1B]; $E(^{14}$N) = 150 MeV).

53. $^{16}$O$(\alpha, ^{11}$C)$^9$Be, $Q_m = -24.3100$

See [1987KW1B,1987KW01].

54. $^{16}$O$(^{13}$C, $^{20}$Ne)$^9$Be, $Q_m = -5.9177$

See $^{20}$Ne in [1987AJ02]. See also [1985KA1J].

$^9$B

(Figs. 8 and 10)

**General**

References to articles on general properties of $^9$B published since the previous review [1988AJ01] are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for $^9$B located on our website at www.tunl.duke.edu/nucldata/General_Tables/9b.shtml.

The low-lying levels of $^9$B have mainly [441] spatial symmetry and thus large amplitudes for breakup into $\alpha + \alpha + p$. With increasing excitation energy, these states develop large widths making it difficult to identify specific states and the analyses of often rather featureless spectra depend very much on which “known” levels are included in the fit. The relatively narrow states starting, as far as is known, with the $^7_2^-$ level at 11.65 MeV, and including the $T = \frac{1}{2}^-$ states, have mainly [432] spatial symmetry with the $T = \frac{1}{2}^+$ states acquiring their widths through small admixtures of [441] symmetry. States with [432] symmetry and $L = 1$, e.g., the 12.19 MeV level, can have large Gamow–Teller matrix elements.
for $^9C(\beta^+)$ decay. The analogs of two very narrow positive-parity states of $^9Be$ appear to have been identified near 16.7 and 17.5 MeV in $^9B$. See reaction 7(a).

1. (a) $^6Li(^3He, \gamma)^9B$, $Q_m = 16.6023$
   (b) $^6Li(^3He, n)^8B$, $Q_m = -1.9748$, $E_b = 16.6023$
   (c) $^6Li(^3He, p)^8Be$, $Q_m = 16.7874$
   (d) $^6Li(^3He, d)^7Be$, $Q_m = 0.11226$
   (e) $^6Li(^3He, t)^8Be$, $Q_m = -4.307$
   (f) $^6Li(^3He, ^3He)^6Li$
   (g) $^6Li(^3He, \alpha)^5Li$, $Q_m = 14.913$

The 90° yields of $\gamma_0$ and of $\gamma$ to $^9B^*(2.36)$ (reaction (a)) have been measured for $E(^3He) = 0.6$ to 1.2 MeV [as have the 2$\alpha$-particles from the decay of $^8Be^*(16.6)$ (reaction (c))]; they are reported to show a resonance at $E(^3He) = 765 \pm 5$ keV [$^9B^*(17.111)$], attributed to $^9B^*(17.076)$ [$T = \frac{3}{2}^-$]. The total cross section for reaction (b) increases monotonically from threshold to $\approx 7$ mb at 3.8 MeV. It then decreases monotonically from $E(^3He) = 5.5$ to 7.6 MeV and also from 8.9 to 26.5 MeV: see [1979AJ01,1984AJ01], and $^8B$.

Absolute cross sections for protons (reaction (c)) to $^8Be^*(0, 2.9, 16.6, 16.9)$ as well as for the continuum protons have been measured for $E(^3He) = 0.5$ to 1.85 MeV. Reaction rate parameters, $(\sigma v)$, have been calculated for $kT = 0.01$ to 10.0 MeV. Excitation functions for $p_0$ and $p_1$ have been measured for $E(^3He) = 0.9$ to 17 MeV, and polarization measurements are reported at $E(^3He) = 14$ MeV. Resonances are observed at $E(^3He) = 1.6$ and 3.0 MeV [$\Gamma = 0.25$ and 1.5 MeV]: see [1974AJ01,1979AJ01], and $^8Be$. Polarization measurements are also reported at $E(^6Li) = 21$ MeV, and vector analyzing powers for the transition to the ground state of $^8Be$ were measured [1983KO04]. Differential cross sections and analyzing powers were measured for $E(^3He) = 4.6$ MeV [1995BA24]. In the range $E(^3He) = 0.7$ to 2.0 MeV, a resonance in the excitation function for deuterons (reaction (d)) is reported corresponding to $^9B^*(17.6)$. Polarization measurements at $E(^3He) = 33.3$ MeV for the $d_0$ and $d_1$ groups are reported. Excitation functions for $t_0$ (reaction (e)) have been measured for $E(^3He) = 10$ to 16, and 23.3 to 25.4 MeV: see [1974AJ01]. Polarization measurements are reported at $E(^3He) = 33.3$ MeV for the $t_0$ group as well as for the $^3He$ ions to $^4Li$ (0, 2.19) (reaction (f)). The decay of $^9Be$ levels populated by reaction (e) for $E(^3He) = 30.7$–40 MeV was studied in experiments reported in [1987BO03,1988BO03,1989BO42,1992BO25]. The elastic scattering (reaction (f)) has also been studied for $E(^3He) = 0.7$ to 2.0 MeV [see references cited in [1974AJ01,1979AJ01,1984AJ01]]. Differential cross section measurements have been reported at $E(^3He) = 93$ MeV [1994DO32], and 50–72 MeV [1995BU20]. See also the calculations in [1992KA06,1993SI06] and the analyses in [1995MA57,1995MI16]. The $\alpha-\alpha$ coincidences ($^6Li_{\alpha,\alpha}$ decay) (reaction (g)) have been measured for $E(^3He) = 1.4$ to 1.8 MeV: a resonance is observed at $1.57 \pm 0.02$ MeV [$^9B^*(17.63)$], $I = 70 \pm 20$ keV. Polarization measurements of the $\alpha$-particles to $^5Li^*(0, 16.7)$ are reported at $E(^3He) = 33.3$ MeV. See also the measurements at $E(^3He) = 1.5$–3.5 MeV [1988BU04] and at $E(^3He) = 8$–14 MeV [1990AR17]. Reaction amplitudes for resonance scattering were calculated for
Table 9.13
Energy levels of $^9$B

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$J^\pi; T$</th>
<th>$I_{c.m.}$ (keV)</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>$\frac{1}{2}^-$; $\frac{1}{2}^-$</td>
<td>0.54 ± 0.21</td>
<td>p</td>
<td>1, 2, 3, 4, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17</td>
</tr>
<tr>
<td>≈ 1.6$^b$</td>
<td></td>
<td></td>
<td>p, (α)</td>
<td>3, 4, 8, 13</td>
</tr>
<tr>
<td>2.361 ± 5</td>
<td>$\frac{5}{2}^-$; $\frac{1}{2}^+$</td>
<td>81 ± 5</td>
<td>p, α</td>
<td>1, 2, 4, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17</td>
</tr>
<tr>
<td>2.75 ± 300$^c$</td>
<td>$\frac{1}{2}^-$; $\frac{1}{2}^-$</td>
<td>3130 ± 200</td>
<td>p</td>
<td>3, 7, 10</td>
</tr>
<tr>
<td>2.788 ± 30</td>
<td>$\frac{5}{2}^+$; $\frac{1}{2}^-$</td>
<td>550 ± 40</td>
<td>p, α</td>
<td>4, 7, 10, 11, 13, 15, 16</td>
</tr>
<tr>
<td>4.3 ± 200$^d$</td>
<td></td>
<td>1600 ± 200</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>6.97 ± 60</td>
<td>$\frac{7}{2}^-$; $\frac{3}{2}^-$</td>
<td>2000 ± 200</td>
<td>p</td>
<td>4, 7, 11, 14, 15, 16</td>
</tr>
<tr>
<td>11.65 ± 60$^e$</td>
<td>$\frac{\pi}{2}^-$; $\frac{1}{2}^-$</td>
<td>800 ± 50</td>
<td>p</td>
<td>11, 13, 15, 16</td>
</tr>
<tr>
<td>12.19 ± 40$^f$</td>
<td>$\frac{5}{2}^-$; $\frac{1}{2}^-$</td>
<td>450 ± 20</td>
<td>p, α</td>
<td>4, 7, 10, 14</td>
</tr>
<tr>
<td>14.01 ± 70</td>
<td>$\pi = -\frac{1}{2}$; $\frac{1}{2}^+$</td>
<td>390 ± 110</td>
<td>p, α</td>
<td>4, 7, 10, 14</td>
</tr>
<tr>
<td>14.6550 ± 2.5</td>
<td>$\frac{7}{2}^-$; $\frac{5}{2}^-$</td>
<td>0.395 ± 0.042</td>
<td>γ, p</td>
<td>4, 7, 8, 10, 14</td>
</tr>
<tr>
<td>14.7 ± 200$^g$</td>
<td>$\frac{\pi}{2}^-$; $\frac{3}{2}^-$</td>
<td>1350 ± 200</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>15.29 ± 40</td>
<td>$T = \frac{3}{2}$</td>
<td></td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>15.58 ± 40</td>
<td>$T = \frac{5}{2}$</td>
<td></td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>16.024 ± 25</td>
<td>$T = (\frac{3}{2})^+$</td>
<td>180 ± 16</td>
<td></td>
<td>4, 14</td>
</tr>
<tr>
<td>16.711 ± 100$^h$</td>
<td>$\frac{5}{2}^+$; $\frac{3}{2}^+$</td>
<td>7</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>17.076 ± 4</td>
<td>$\frac{1}{2}^-$; $\frac{3}{2}^-$</td>
<td>22 ± 5</td>
<td>(γ, $^3$He)</td>
<td>1, 14</td>
</tr>
<tr>
<td>17.190 ± 25</td>
<td>$\frac{5}{2}^+$; $\frac{1}{2}^-$</td>
<td>120 ± 40</td>
<td>p, d, $^3$He</td>
<td>4, 5, 14</td>
</tr>
<tr>
<td>17.54 ± 100$^i$</td>
<td>$\frac{5}{2}^+$; $\frac{3}{2}^+$</td>
<td>7</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>17.637 ± 10$^j$</td>
<td>$\frac{5}{2}^+$; $\frac{1}{2}^-$</td>
<td>71 ± 8</td>
<td>p, d, $^3$He, α</td>
<td>1, 4, 5, 14</td>
</tr>
</tbody>
</table>

$^a$ See reactions 7 and 8 for additional states and other values.
$^b$ A wide range of excitation energies and widths have been given from searches for the analog of the 1.68 MeV $\frac{1}{2}^+$ state of $^9$Be. See [1987BA54,1992CA31,1995TI06,1996BA22,1999EF01].
$^c$ Analog to $^9$Be$^*$ (2.78). See [1985PU1A,1995TI06,2000GE09].
$^d$ See [1985PU1A]. A level listed at $E_x = 4.8$ MeV in [1988AJ01] was based on [1986AR14,1987KA36].
$^e$ See [1974AJ01,1985PU1A]. Width from [1968KU04].
$^f$ See [1985PU1A,2000GE09,2001BE51].
$^g$ See [1985PU1A].
$^h$ From [1985PU1A]. See [1991DI03].
$^i$ See [1979AJ01,1984AJ01] for references.
$^j$ These two levels may not be distinct.

$E(\alpha)$ = 8–14 MeV by [1996FA05]. For a study of the ($\alpha$, $\alpha$) reaction at 3.5, 4.4 and 5.5 MeV see [1987ZA07]. See [1979AJ01,1984AJ01] for references.

2. $^6$Li($\alpha$, n)$^9$B, $Q_m = -3.9753$

See [1974AJ01].
3. $^6\text{Li}(^6\text{Li}, t)^9\text{B}$, $Q_m = 0.8081$

Angular distributions of the $t_0$ group have been measured for $E(^6\text{Li}) = 4.0$ to 5.5 MeV and at 7.35 and 9.0 MeV. No evidence was observed for a group corresponding to $^9\text{B}^*$ (1.6): see [1974AJ01]. In an experiment reported in [1995TI06], the relative energy spectrum for $^9\text{B} \rightarrow ^8\text{Be} + p$ was measured using $E(^6\text{Li}) = 56$ MeV. The 2.36 MeV $\frac{3}{2}^-$ state is absent from the spectrum because it decays into $^5\text{Li} + \alpha$. The spectrum can be fitted with the 2.79 MeV $\frac{1}{2}^+$ state at an excitation energy of 2.3–3.2 MeV. The best fit occurs for an energy of 2.91 MeV and a width of 3.05 MeV, in good agreement with values deduced from an analysis of $^9\text{Be}(p, n)^9\text{B}$: see reaction 7. The fit can be further improved below 1.5 MeV by adding a small contribution from a $\frac{3}{2}^-$ level. The reaction mechanism for $E(^6\text{Li}) = 2–16$ MeV was studied by [1990LE05].

4. $^7\text{Li}(^3\text{He}, n)^9\text{B}$, $Q_m = 9.3520$

For $^3\text{He}$ incident energies up to 12.5 MeV the only clear peaks at low excitation energy correspond to the $^9\text{B}$ ground state and the unresolved $^9\text{B}^*$ (2.4, 2.8) states. A peak has been reported at $E_x = 4.8 \pm 0.1$ MeV [$\Gamma = 1.0 \pm 0.2$ MeV] in one experiment. At higher excitation, there is evidence for levels with energies (in MeV) and widths [$\Gamma$ (in MeV)] at 12.06 $\pm$ 0.06 [0.8 $\pm$ 0.2], 14.01 $\pm$ 0.07 [0.39 $\pm$ 0.11], 14.67 $\pm$ 0.016 [0.045], 16.024 $\pm$ 0.025 [0.180 $\pm$ 0.016], 17.19 and 17.63 [1965DI03]. $^9\text{B}^*$ (14.66) is the first $T = \frac{3}{2}$ state in $^9\text{B}$. Its decay properties are displayed in Table 9.4 and compared with those of $^9\text{Be}^*$ (14.40): see reaction 9 in $^9\text{Be}$ and [1974AJ01]. Angular distributions have been measured at $E(^3\text{He}) = 1.56$ to 5.27 MeV: see [1974AJ01].

5. (a) $^7\text{Be}(d, n)^8\text{B}$, $Q_m = -2.0871$, $E_0 = 16.4901$
(b) $^7\text{Be}(d, p)^8\text{Be}$, $Q_m = 16.6751$

The cross section for reaction (a) for $E(^7\text{Be}) = 16.9$ MeV is 58 $\pm$ 11 mb [1983HA17, 1985HA40]. The differential cross section was measured at $E_{cm} = 5.8$ MeV [1997LI05] in order to obtain the $^8\text{B} \rightarrow ^7\text{Be} + p$ asymptotic normalization coefficient (ANC), from which the astrophysical $S$ factor for the $^7\text{Be}(p, \gamma)^8\text{B}$ reaction was deduced. The reaction cross section was calculated for $E_{cm} = 5.8, 15.6, 38.9$ MeV [1999FE04]. For $E_d = 0.75$ to 1.70 MeV, resonances in the yields of protons are observed at $E_d = 0.90$ $\pm$ 0.025 MeV (p_0), 1.475 $\pm$ 0.010 MeV (p_1 only) with $I_{cm} = 120 \pm 40$ and 71 $\pm$ 8 keV, respectively [$^9\text{B}^* = 17.19$ and 17.64 MeV]: see [1974AJ01]. See also ([1985CA41]; astrophys.).

6. $^9\text{Be}(\pi^+, \pi^0)^9\text{B}$, $Q_m = 3.5255$

Experiments on isospin splitting in analog giant resonances excited by single pion charge exchange reactions are reviewed in [1994HA41].
Fig. 8. Transitions accounting for 96% of the $^9\text{C}(d)^9\text{B}$ decay are shown. The remaining 4% is spread over several uncertain levels (see Table 9.14). For notation see Fig. 2.
For reaction (a), angular distributions have been reported at many energies in the range \( E_p = 3.5 \) to 49.3 MeV [see [1979AJ01,1984AJ01]] and at 16.44 and 17.57 MeV ([1986MU07]; \( n_0 \)). The width of the ground state is 0.54 ± 0.21 keV; see [1974AJ01].

At \( E_p = 135 \) MeV, excitation energies, widths, and angular distributions have been measured for states up to \( E_x = 17.54 \) MeV [1985PU1A]. Below \( E_x = 5 \) MeV, the dominant excitations are to the ground state and a broad \( \frac{1}{2}^- \) state at \( E_x = 2.75 \pm 0.30 \) MeV [\( \Gamma = 3.13 \pm 0.20 \) MeV]. The 2.36 MeV \( \frac{5}{2}^- \) state, the 2.788 MeV \( \frac{5}{2}^+ \) state, taken at 2.71 ± 0.1 MeV [\( \Gamma = 0.7 \pm 0.1 \) MeV], and a new level at 4.3 ± 0.2 MeV [\( \Gamma = 1.6 \pm 0.2 \) MeV] are also populated. The 0° cross sections for the 0 and 2.75 MeV states are comparable and the extracted \( B(GT) \) values for these states and the \( \frac{5}{2}^- \) level agree well with p-shell predictions [1987RA32,1988MI03]. States at \( E_x = 7.0 \pm 0.1 \) MeV [\( \Gamma = 2.0 \) MeV] and 11.63 ± 0.2 MeV [not broad] are not seen at 0° and have angular distributions consistent with the \( \frac{5}{2}^- \) assignments from single-neutron pickup reaction on \( ^{10}\text{B} \). The angular distributions for states at \( E_x = 12.23 \pm 0.1 \) MeV [\( \Gamma = 0.5 \pm 0.1 \) MeV], 13.96 ± 0.1 MeV [not broad] and 14.60 ± 0.1 MeV [narrow state plus a broad component with \( \Gamma = 0.6 \pm 0.1 \) MeV] are forward peaked with modest \( B(GT) \) values. Cross sections for the 0, 2.36, 12.2, 14.0, 14.6 MeV states and two narrow states at \( E_x = 16.71 \pm 0.1 \) and 17.54 ± 0.1 MeV are compared with shell-model predictions in [1991DI03]. The 16.7 and 17.5 MeV states appear to be the analogs of the 16.67 MeV (\( \frac{5}{2}^- \)) and 17.49 MeV (\( \frac{5}{2}^+ \)) states of \( ^{9}\text{Be} \). There is also evidence at some angles for narrow states at 15.15 ± 0.1 MeV, 15.44 ± 0.1 MeV, and 15.86 ± 0.1 MeV [1985PU1A].

Measurements of neutron polarization for \( E_p = 54 \) MeV were reported in [1988HE08]. See also the cross section measurements at \( E_p = 35 \) MeV of [1987OR02]. For earlier work see [1974AJ01,1984AJ01]. Quasielastic scattering at \( E_p = 300-400 \) MeV was studied by [1994SA43], and differential cross sections for isobaric analog \( \Delta J^\pi = 0^+ \) (Fermi-type) transitions were measured at \( E_p = 35 \) MeV [2000IO17]. See also the analysis and calculations of [1994GA49] for \( E_p = 1 \) GeV, and [1998IO03] for pion production at \( E_p = 800 \) MeV. A summary of monoenergetic neutron sources for \( E_n > 14 \) MeV is presented in [1990BR24]. Application-related measurements are discussed in [1987RA23,1996SH29].

Reaction (b) does not seem to involve states of \( ^9\text{B} \). See also [1982GU1A,1983BY02,1984BA1R,1987RA32,1988BO47,1988HE08] and the application-related work of [1984AL1C,1987VO1F]. For yield and polarization measurements see \( ^{10}\text{B} \).

Angular distributions have been measured for \( E(\text{He}) = 3.0 \) to 25 MeV and at 217 MeV; see [1974AJ01,1979AJ01]. At \( E(\text{He}) = 39.8 \) MeV, \( ^9\text{B}_{g.s.} \) is strongly populated and \( ^9\text{B}^*(2.33, 2.83, 11.62, 12.06, 14.67, (17.19), 17.63) \) are also observed [1969BA06]. At \( E(\text{He}) = 90 \) MeV triton groups are reported to states at \( E_x = 1.16 \pm 0.05 \) MeV [\( \Gamma = 1.3 \pm 0.05 \) MeV], 2.32 ± 0.03, 2.72 ± 0.04 and 4.8 ± 0.03 MeV [1.5 ± 0.3 MeV],
16.7 ± 0.1 MeV [≪ 0.1 MeV], 18.6 ± 0.3 and 20.7 ± 0.5 MeV [1.6 ± 0.3 MeV] [Γ in brackets], in addition to known and possibly unresolved $9^B$ (7.0, 11.7, 12.1, 14.7, 17.64) states [1987KA36]. See also [1983DJZV]. [2001AK09] have fitted $0^\circ$, $2^\circ$, and $3.5^\circ$ spectra at $E(\alpha) = 450$ MeV with levels fixed at excitation energies of 0, 2.361, 2.788, 4.8, and 6.97 MeV together with two levels at 1.80$^{+0.22}_{-0.16}$ and 3.82$^{+0.23}_{-0.22}$ MeV with widths of 600$^{+300}_{-270}$ and 1350$^{+620}_{-360}$ keV; see also [1994AK02] for the excitation of states above $E_x = 10$ MeV at $0^\circ$. Neither [1987KA36] nor [2001AK09] include in their fits the broad $0^+$ at 0 MeV, the level at 2.36 MeV [1990BO51]. The data were analyzed in terms of series expansions of the decay amplitudes in hyperspherical harmonics.

9. (a) $^9$Be($^6$Li, $^6$He)$^9$B, $Q_m = -4.5764$
(b) $^9$Be($^7$Li, $^7$Be)$^9$B, $Q_m = -1.9303$

At $E(\alpha)$ = 32 MeV angular distributions are reported to $^9$B*(0, 2.36) [1985CO09]. Measurements with $E(\alpha)$ = 32 MeV are also reported by [1988BU18]. In addition to $^9$B*(0, 2.36) they report weak levels at $E_x = 1.32 ± 0.08$ MeV, $\Gamma = 0.86 ± 0.26$ MeV and $E_x = 4.60 ± 0.16$ MeV, $\Gamma = 0.68 ± 0.43$ MeV. See also [(1984GL06); $E(\alpha)$ = 93 MeV, $E(\alpha)$ = 78 MeV].

The status of evidence for the mirror state of the $\frac{1}{2}^+$ 1.68 MeV state in $^9$Be was reviewed [1992CA31], and reinvestigated by $^9$Be($^6$Li, $^6$He)$^9$B measurements with $E(\alpha)$ = 32 MeV. They find no evidence for the level. A measurement reported in [1993RE04] with polarized $^6$Li ions at 32 MeV determined polarization observables for $^9$B*(0, 2.36). The results were compared to coupled-channels calculations.

10. $^9$C($\beta^+$$^9$B. $Q_m = 16.4948$

The previous review [1988AJ01] notes that $^9$C $\beta^+$ decay was observed by [1988MI03] to $^9$B*(0, 2.36, 2.8) [$J^\pi = \frac{1}{2}^-, \frac{5}{2}^-, \frac{1}{2}^-$] with branching ratios of $60 ± 10$, $(17 ± 6)$ and $(11 ± 5)$%, respectively. A state at $E_x = 12.1 ± 0.6$ MeV, $\Gamma = 0.4 ± 0.1$ MeV was also observed with the remaining strength going to it. In [2000GE09, 2001BE51], the $\beta$-delayed particle decay of $^8$C has been studied and secondary decays into $^8$B + p and $^7$Li + $\alpha$ have been observed. In [2001BE51], a value of 54.1 ± 1.5% is reported for the ground-state branch and no asymmetry is found with the corresponding transition in $^7$Li($\beta^-$)$^7$Be.

They determine $J^\pi = \frac{1}{2}^-$ for the 12.2 MeV level from a study of angular correlations and measure a large $B(GT)$ value for the transition to the 12.2 MeV level. They observe a transition to the isobaric analog state and obtain new information on the decay of this state. In [2000GE09] a number of $^9$B level energies, branching ratios, and Gamow–Teller strengths were deduced using an $R$-matrix analysis with simplified one-level expressions. Level energies, branching ratios, $B(GT)$ values, and other decay information obtained by combining the results of [2000GE09] and [2001BE51] are presented in Table 9.14 and its footnotes. The data of [2000GE09] have also been analyzed using a multichannel, multilevel $R$-matrix approach and the results are described in [2001BU05]. See reaction 12.
### Table 9.14

Branching ratios in $^9\text{C}(\beta^+\rightarrow\beta^-)$ decay from measurements of $\beta^-$-delayed particle decay

<table>
<thead>
<tr>
<th>$E_x$ in $^9\text{B}$ (MeV)</th>
<th>$J^\pi$</th>
<th>Branching ratio (%)</th>
<th>$B(GT)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$\frac{3}{2}^-$</td>
<td>54.1 ± 1.3$^b$</td>
<td>0.0295 ± 0.0008</td>
</tr>
<tr>
<td>2.34 ± 0.03</td>
<td>$\frac{5}{2}^-$</td>
<td>30.4 ± 5.8$^c$</td>
<td>0.053 ± 0.012</td>
</tr>
<tr>
<td>2.8 ± 0.2</td>
<td>$\frac{3}{2}^-$</td>
<td>5.8 ± 0.6$^d$</td>
<td>0.013 ± 0.002</td>
</tr>
<tr>
<td>12.16 ± 0.10</td>
<td>$\frac{1}{2}^-$</td>
<td>5.9 ± 0.6$^f$</td>
<td>2.16 ± 0.22</td>
</tr>
<tr>
<td>14.0 ± 0.2</td>
<td>$\frac{1}{2}^-$</td>
<td>0.16 ± 0.02$^g$</td>
<td>0.36 ± 0.05</td>
</tr>
<tr>
<td>14.663$^h$</td>
<td>$\frac{3}{2}^-$</td>
<td>0.010</td>
<td>3.1$^h$</td>
</tr>
</tbody>
</table>

$^a$ Except for the transition to the isobaric analog state at 14.66 MeV, the energies and branching ratios are taken from Table VII of [2000GE09] after normalization to the ground-state branch from [2001BE51]. [2000GE09] also list a very weak branch to a narrow, and previously unknown, state at 13.3 MeV and a ≈ 4% background contribution attributed to the tails of higher states. See also [2001BU05].

$^b$ From [2001BE51].

$^c$ From [2000GE09]. The $p_0$ decay branch is 0.5%.

$^d$ From [2000GE09]. The $p_0$ decay branch is 90%. $\Gamma = 2.5$ MeV from the fit to this branch.

$^e$ [2001BE51]. $J^\pi = \frac{3}{2}^-$ from the $\alpha$-$p$ angular distribution for the $\alpha_0$ branch; $E_x = 12.19 ± 0.04$ MeV, $\Gamma = 450 ± 20$ keV; $p_0 9.0 ± 1.0\%$, $p_1 25 ± 7\%$, $\alpha_0 60 ± 7\%$, $\alpha_1 6 ± 4\%$; $B(GT) = 1.92 ± 0.24$.

$^f$ [2000GE09]. $J^\pi$ assumed to be $\frac{1}{2}^-$: $p_0 8.5 ± 1.0\%$, $p_1 18 ± 3\%$, $\alpha 74 ± 8\%$. $\Gamma = 0.45$ MeV from the fit to the $p_0$ branch.

$^g$ From [2000GE09]. Only $p_0$ observed.

$^h$ From [2001BE51]. The summed energy for the decay is measured to be 14940 keV. $\alpha_0 (4.8 ± 0.7) \times 10^{-3}\%$; $\Gamma_{\alpha_0}/\Gamma = 0.46$; $B(F) + B(GT)$ is listed where $B(F) = 3.0$.

In $^9\text{Be}$ and Table 9.8 for the mirror decay $^9\text{Li}(\beta^-)^9\text{Be}$; note the large asymmetry for the decays to the 11.81 MeV level of $^9\text{Be}$ and 12.16 MeV level of $^9\text{B}$.

11. (a) $^{10}\text{B}(p,d)^9\text{B}, \quad Q_m = -6.2118$

(b) $^{10}\text{B}(p,p+n)^9\text{B}, \quad Q_m = -8.4363$

At $E_p = 33.6$ MeV [1968KU04] and 155.6 MeV [1969BA05] deuteron groups are observed to the states shown in Table 9.15. All have angular distributions characteristic of $l_n = 1$. Angular distributions are also reported for $^9\text{B}^*(0, 2.36)$ at $E_p = 18.6$ MeV [1985BE13].

In reaction (b), separation energy spectra and the relative probabilities of knockout of protons and neutrons from the 0s and 0p shells have been measured ([1985BE30, 1985DO16]; $E_p = 1$ GeV).

12. $^{10}\text{B}(d,t)^9\text{B}, \quad Q_m = -2.1791$

Angular distributions have been measured at $E_d = 11.8$ to 28 MeV [see [1974AJ01], [1979AJ01]] and 18 MeV ([1988GO20, 1988GU20]; to $^9\text{B}^*(0, 2.36)$). See also the analysis of cross section data for $E_d = 8$–50 MeV [1995GU22].
Table 9.15
Levels of $^9$B from $^{10}$B(p, d)$^9$B

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$E_x$ (MeV)</th>
<th>$I_{cm}$ (MeV)</th>
<th>$C^2 S_{exp}$</th>
<th>$C^2 S_{theor}$</th>
<th>$J^π$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0.44</td>
<td>0.59</td>
<td>3/2</td>
<td></td>
</tr>
<tr>
<td>2.4 ± 0.1</td>
<td>2.35 ± 0.02</td>
<td>0.60</td>
<td>0.58</td>
<td>5/2</td>
<td></td>
</tr>
<tr>
<td>7.1 ± 0.2</td>
<td>7.1 ± 0.2</td>
<td>2.15 ± 0.15</td>
<td>0.52</td>
<td>7/2</td>
<td></td>
</tr>
<tr>
<td>11.5 ± 0.2</td>
<td>11.75 ± 0.1</td>
<td>0.80 ± 0.05</td>
<td>1.12</td>
<td>9/2</td>
<td></td>
</tr>
<tr>
<td>14.9 ± 0.3</td>
<td>14.6 ± 0.2</td>
<td>1.35 ± 0.2</td>
<td>0.32</td>
<td>11/2</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ [1969BA05]: $E_p = 155.6$ MeV.
$^b$ [1968KR02]: $E_p = 33.6$ MeV.
$^c$ (6–16)2BME interaction of [1965CO25]. The relative spectroscopic factors for the $7/2^-$ levels are sensitive to the details of the effective interaction [caoutohor D.J.M.]. For the (8–16)2POT interaction, see [1967CO32]. [1968KR02] make a graphical comparison of relative experimental and theoretical spectroscopic factors; see also [1991AB04].
$^d$ $J$ suggested by comparison with theory.

13. (a) $^{10}$B($^3$He, α)$^9$B, $Q_m = 12.1413$
   (b) $^{10}$B($^3$He, α)$^9$Be, $Q_m = 12.3264$
   (c) $^{10}$B($^3$He, 2α)$^8$Li, $Q_m = 10.452$

Alpha-particle spectra show the excitation of $^9$B*(0, 2.4, 2.8, 11.8): see [1966LA04]. Measurements by [1968KR02] determine $E_x = 2.361 ± 0.005$ and $2.788 ± 0.030$ MeV [$Γ = 81 ± 5$ and $548 ± 40$ keV, respectively]; see Table 9.11 in [1966LA04] for other values. There is some evidence for a state with $E_x ≈ 1.6$ MeV, $Γ ≈ 0.7$ MeV, but it is not conclusive. No evidence is found for any narrow levels in $^9$B with $Γ ≤ 100$ keV and $4 < E_x < 7$ MeV; the upper limit to the intensity of the corresponding α-group is 1% of the intensity of the group to $^9$B*(2.4). Angular distributions have been determined at $E(3$He$) = 5.5$ and 33.7 MeV [see 974AJ01].

In reaction (b), a study of the decays of $^9$B*(2.4, 2.8) shows that $^9$B*(2.4) decays < 0.5% by proton emission to $^8$Be$^{g.s.}$ [it decays to $^8$Li$^{g.s.}$ by α-emission] while the second state, $E_x = 2.71 ± 0.03$ MeV [$Γ = 0.71 ± 0.06$ MeV], decays almost 100% by that channel [1966WI08]. No evidence is found for excited states of $^9$B with $3.5 < E_x < 9.5$ MeV which decay by proton emission to $^8$Be$^{g.s.}$ [1968KR02]. In a kinematically complete experiment (reaction (c)) at $E(3$He$) = 2.3$ and 5.0 MeV, a state is reported at $4.9 ± 0.2$ MeV with a width of $1.5 ± 0.3$ MeV [1986AR14]. Likewise, from reactions (b) and (c) a state is reported at $1.8 ± 0.2$ MeV with a width of $0.9 ± 0.3$ MeV [1988AR05].

14. $^{11}$B(p, t)$^9$B, $Q_m = −11.409$

At $E_p = 45$ MeV angular distributions have been obtained for the triton groups to $^9$B*(0, 2.36, 12.06, 14.01, 14.66, 16.02). In addition the spectra show some indication of the groups corresponding to $^9$B*(7.0, 17.19, 17.64). $T = 1/2^-$ states are reported at $E_x = 15.29 ± 0.04$ and $15.58 ± 0.04$ MeV [1971HA10]. The first two $T = 1/2^-$ states have been ob-
served at \(E_x = 14.6550 \pm 0.0025\) [1974KA15] and \(17.076 \pm 0.004\) MeV [\(I^* = 22 \pm 5\) keV] [1974BE66].

15. (a) \(^{12}\)C(p, \(\alpha\))\(^9\)B, \(Q_m = -7.5516\)
(b) \(^{12}\)C(p, p)\(^4\)He\(^4\)He\(^4\)He, \(Q_m = -7.274747\)
(c) \(^{12}\)C(p, pt)\(^9\)B, \(Q_m = -27.3655\)

Angular distributions have been measured at \(E_p = 14.0\) to 54.1 MeV [see [1974AJ01]]. At \(E_p = 54.1\) MeV peaks are observed at 0, 2.32 \(\pm 0.04\), 6.97 \(\pm 0.06\), and 11.46 \(\pm 0.25\) MeV [1971MA2C]. The angular distribution for the 6.97 MeV state is similar to other \(J = \frac{7}{2}\) transitions [1972MA21]. At \(E_p = 42.8\) MeV angular distributions for \(^9\)B\(^\ast\)(0, 2.36, 6.98) involve \(l = 1, 3\) and 3, respectively [1983PE07]. A broad state at 2.9 \(\pm 0.2\) MeV has also been reported: see [1974AJ01]. Angular distributions involving the \(\alpha_0\) and \(\alpha^*\) groups [to \(^4\)He\(^\ast\)(20.1), \(0^+\)] to \(^9\)B\(_{g.s.}\) have been studied at \(E_p = 42\) MeV: see [1984AJ01]. For reaction (c) see ([1985DE17]; \(E_p = 58\) MeV). See also [1984AJ01,1988AJ01].

16. (a) \(^{12}\)C(t, \(^6\)He)\(^9\)B, \(Q_m = -15.0610\)
(b) \(^{12}\)C(\(3\)He, \(^6\)Li)\(^9\)B, \(Q_m = -11.5713\)

Differential cross sections were measured for reaction (a) at \(E_t = 38\) MeV and for reaction (b) at \(E(\text{\(3\)He}) = 33\) MeV by [1989SI02]. Spectroscopic factors for cluster pickup were extracted. A reanalysis of the data for reaction (a) is presented in [1992CL04]. Spectroscopic factors are compared with shell model and microscopic calculations. In other work on reaction (b) angular distributions were studied at \(E(\text{\(3\)He}) = 30.0\) and 40.7 MeV [see [1974AJ01]] and at \(E(\text{\(3\)He}) = 33.4\) MeV ([1986CL1B]; to \(^9\)B\(^\ast\)(0, 2.36), and cross sections for \(^9\)B\(^\ast\)(0, 2.36, 2.78, 6.97, 11.7) were measured by [1993MA48]. Spectroscopic factors for \(^3\)H pickup were extracted and compared with shell-model predictions. See also the analysis in [1995MA57].

17. \(^{12}\)C(\(\alpha\), \(^7\)Li)\(^9\)B, \(Q_m = -24.8986\)

Angular distributions have been measured at \(E_\alpha = 49.0\) and 80.1 MeV [1984GO03]. See also [1984AJ01]. Differential cross sections were measured at \(E_\alpha = 90\) MeV [1991GL03].

\(^9\)C
(Figs. 9 and 10)

General

References to articles on general properties of \(^9\)C published since the previous review [1988AJ01] are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for \(^9\)C located on our website at www.tunl.duke.edu/nucldata/General_Tables/9c.shtml.
Table 9.16
Energy levels of $^9$C $^{a,b}$

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$J^\pi; T$</th>
<th>$\tau_{1/2}$ or $\Gamma$</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>$\frac{3}{2}^-$; $\frac{3}{2}$</td>
<td>$\tau_{1/2} = 126.5 \pm 0.9$ ms</td>
<td>$\beta^+$</td>
<td>1, 4, 6 $^a$</td>
</tr>
<tr>
<td>2.218 ± 11</td>
<td>$\frac{1}{2}^-$</td>
<td>$\Gamma = 100 \pm 20$ keV</td>
<td></td>
<td>6</td>
</tr>
</tbody>
</table>

$a$ See also [1974AJ01,1979AJ01].

$b$ Evidence for additional levels in $^9$C is presented in reaction 6.

Ground state properties

$\mu = -3.3914 \pm 0.0005 \mu_N$ [1996MA38]. See also [1988HU08].

The sum of the magnetic moments of $^9$Li and $^9$C leads to $\langle \sigma \rangle = 1.44$, an anomalously high value that remains unexplained [1988HU08,1996MA38].

The r.m.s. matter radius of $^9$C is 2.42 $\pm$ 0.03 fm has been deduced from interaction cross sections on Be, C, and Al at $E \approx 730$ MeV/A [1996OZ01] [see also for derived proton, charge and neutron matter r.m.s. radii]. Interaction cross sections have also been measured on C, Al, Sn, and Pb at $E \approx 285$ MeV/A [1997BL08]. See also reaction 7.

1. $^9$C($\beta^+$)$^9$B, $Q_m = 16.4948$

The half-life of $^9$C is 126.5 $\pm$ 0.9 ms: see [1974AJ01]. New information on the decay scheme is given in [2000GE09,2001BE51] and the data of [2000GE09] has been the subject of a separate $R$-matrix fit [2001BU05]. The decay is complex; see reaction 10 in $^9$B.

2. $^2$H($^8$B, $^9$C)n, $Q_m = -0.9246$

The cross section has been determined at $E \approx 14.4$ MeV/A and used to determine the asymptotic normalization coefficient for $^9$C $\rightarrow$ $^8$B + p and $S_{18} = 45 \pm 13$ eV b ($E_{cm} = 1$–100 keV) for the $^8$B(p, $\gamma$)$^9$C reaction [2001BE45].

3. $^8$B(p, $\gamma$)$^9$C, $Q_m = 1.3000$

Cross section data from one-proton removal reactions with $^9$C [see reaction 7] have been used to determine the asymptotic normalization coefficient for $^9$C $\rightarrow$ $^8$B + p and $S_{18}(0)$ for the $^8$B(p, $\gamma$)$^9$C reaction; $S_{18}(0) = 46 \pm 6$ eV b [2002TR14] and $S_{18}(0) = 49 \pm 4$ eV b [2003EN05] [see reaction 2 and [2003MO12]; theor.]. The $^8$B(p, $\gamma$)$^9$C reaction has also been studied by Coulomb dissociation in inverse kinematics [2003MO23].

4. $^9$Be($\pi^+$, $\pi^-$)$^9$C, $Q_m = -17.5629$

See [1984AJ01,1986SE04]. The total reaction cross section for $E_{\pi^+} = 180$ and 240 MeV is measured and analyzed in [1989GR06].

5. $^{10}$B($^7$Li, $^8$He)$^9$C, $Q_m = -33.550$

The ground state of $^9$C has been observed in the angular range 0° to 12° at $E(^7$Li) = 350 MeV [2001CA37].
Fig. 9. Energy levels of $^9$C. For notation see Fig. 2.

6. $^{12}$C($^3$He, $^6$He)$^9$C, $Q_m = -31.5744$

At $E(^3$He) = 74.1 MeV $^6$He groups are observed to the ground state and to a state at $E_x = 2218 \pm 11$ keV, $\Gamma = 100 \pm 20$ keV: see [1984AJ01].
At $E(3\text{He}) = 76.6$ MeV a new $^9\text{C}$ level at $E_x = 3.3 \pm 0.05$ MeV is claimed in addition to $^9\text{C}^*(0, 2,2)$. There is evidence for a broad level at $E_x \approx 4.3$ MeV that could be the analog of the 4.3 MeV level of $^9\text{Li}$ and is expected to have a width of $\approx 2.6$ MeV: see [1991GO13].

7. (a) C, Al, Si, Sn, Pb($^9\text{C}, ^8\text{B} + p$)  
(b) C, Al, Si, Sn, Pb($^9\text{C}, ^7\text{Be} + 2p$)

One-proton and two-proton removal cross sections have been measured on C, Al, Sn, and Pb targets at $E \approx 285$ MeV/\text{A} [1997BL08], on a C target at $E \approx 78.3$ MeV/\text{A} [2003EN05], and on a Si target at $E = 20–70$ MeV/\text{A} [2004WA06]. Eikonal theory is used in [2003EN05,2004WA06] to extract quenching factors ($\approx 0.82$) which renormalize theoretical p-shell spectroscopic factors to reproduce the measured one-nucleon removal cross sections. See also reaction 3.

$^9\text{N}$  
(not illustrated)

Not observed: see [1988AJ01]. Mass excesses of 46.56 and 46.40 MeV have been estimated from two different mass formulae [2000PO32]. $^9\text{N}$ would then be proton unbound by $\approx 4$ MeV. However, mass formulae neither take into account the fact that the last occupied orbit(s) may change near the drip lines nor the fact that an extended low-$l$ orbit leads to a lowered Coulomb energy. The suggested s-wave ground-state of $^9\text{He}$ and a Coulomb energy estimated from the $^{11}\text{N}$ ground state imply that $^9\text{N}$ should be proton unbound by $\approx 1.8$ MeV, high enough above the Coulomb barrier that the “state” should be too broad to observe. The analog of one of the narrow excited states of $^9\text{He}$ could remain relatively narrow in $^9\text{N}$.

$A = 10$

General

References to articles on general properties of $A = 10$ nuclei published since the previous review [1988AJ01] are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for $A = 10$ located on our website at www.tunl.duke.edu/nucldata/General_Tables/10.shtml.

$^{10}\text{n}$  
(not illustrated)

$^{10}\text{n}$ has not been observed: see [1979AJ01]. See also ([1986AB10]; theor.).
Fig. 10. Isobar diagram, $A = 9$. 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 $^9$Be: here $M$ represents the atomic mass excess in MeV. Levels which are presumed to be isospin multiplets are connected by dashed lines.
Table 9.17
Mirror states \((T = \frac{1}{2})\) in \(A = 9\) nuclei

<table>
<thead>
<tr>
<th>(^9\text{Be})</th>
<th>(^9\text{B})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_x) (MeV)</td>
<td>(J^\pi)</td>
</tr>
<tr>
<td>0</td>
<td>(\frac{1}{2}^-)</td>
</tr>
<tr>
<td>1.684</td>
<td>(\frac{1}{2}^+)</td>
</tr>
<tr>
<td>2.429</td>
<td>(\frac{1}{2}^-)</td>
</tr>
<tr>
<td>2.78</td>
<td>(\frac{1}{2}^-)</td>
</tr>
<tr>
<td>3.049</td>
<td>(\frac{1}{2}^+)</td>
</tr>
<tr>
<td>4.704</td>
<td>(\frac{3}{2}^+)</td>
</tr>
<tr>
<td>5.59</td>
<td>(\frac{3}{2}^-)</td>
</tr>
<tr>
<td>6.38</td>
<td>(\frac{7}{2}^-)</td>
</tr>
<tr>
<td>6.76</td>
<td>(\frac{5}{2}^+)</td>
</tr>
<tr>
<td>7.94</td>
<td>(\frac{7}{2}^-)</td>
</tr>
<tr>
<td>11.283</td>
<td>(\frac{5}{2}^-)</td>
</tr>
<tr>
<td>11.81</td>
<td>(\frac{5}{2}^-)</td>
</tr>
<tr>
<td>13.79</td>
<td>(\pi = -)</td>
</tr>
<tr>
<td>15.97</td>
<td></td>
</tr>
<tr>
<td>16.67</td>
<td>(\frac{3}{2}^+)</td>
</tr>
<tr>
<td>17.493</td>
<td>(\frac{7}{2}^-)</td>
</tr>
</tbody>
</table>

a As taken from Tables 9.2 and 9.13.
b Defined as \(E_x(^9\text{B}) - E_x(^9\text{Be})\).
c See footnote b to Table 9.13.
d See footnote b to Table 9.2.

Table 9.18
Isospin quadruplet states \((T = \frac{3}{2})\) in \(A = 9\) nuclei

<table>
<thead>
<tr>
<th>(^9\text{Li})</th>
<th>(^9\text{Be})</th>
<th>(^9\text{B})</th>
<th>(^9\text{C})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_x) (MeV)</td>
<td>(J^\pi)</td>
<td>(E_x) (MeV)</td>
<td>(J^\pi)</td>
</tr>
<tr>
<td>0</td>
<td>(\frac{1}{2}^-)</td>
<td>14.392</td>
<td>(\frac{3}{2}^-)</td>
</tr>
<tr>
<td>2.691</td>
<td>(\frac{1}{2}^-)</td>
<td>16.975</td>
<td>(\frac{5}{2}^-)</td>
</tr>
<tr>
<td>4.296</td>
<td>(\frac{3}{2}^-)</td>
<td>18.65</td>
<td>(\frac{5}{2}^-)</td>
</tr>
<tr>
<td>5.38</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a As taken from Tables 9.1, 9.2, 9.13 and 9.16.

\(^{10}\text{He}\)
(Figs. 11 and 17)

General

References to articles on general properties of \(^{10}\text{He}\) published since the previous review [1988AJ01] are grouped into categories and listed, along with brief de-
**10^He**

Table 10.1
Energy levels of 10^He^a

<table>
<thead>
<tr>
<th>E_x (MeV)</th>
<th>J^π; T</th>
<th>Γ_cm (MeV)</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>(0^+); 3</td>
<td>0.3 ± 0.2</td>
<td>n</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>3.24 ± 0.20</td>
<td>(2^+); 3</td>
<td>1.0 ± 0.3</td>
<td>n</td>
<td>3</td>
</tr>
<tr>
<td>6.80 ± 0.07</td>
<td>(3^−); 3</td>
<td>0.6 ± 0.3</td>
<td>n</td>
<td>3</td>
</tr>
</tbody>
</table>

^a Based on data reviewed in this evaluation.

Table 10.2
10^He level parameters from 10^Be(14^C, 14^O)10^He^a

<table>
<thead>
<tr>
<th>J^π; T</th>
<th>E_R (MeV)</th>
<th>E_x (MeV)</th>
<th>Γ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0^+); 3</td>
<td>1.07 ± 0.07</td>
<td>0</td>
<td>0.3 ± 0.2</td>
</tr>
<tr>
<td>(2^+); 3</td>
<td>4.31 ± 0.20</td>
<td>3.24 ± 0.20</td>
<td>1.0 ± 0.3</td>
</tr>
<tr>
<td>(3^−); 3</td>
<td>7.87 ± 0.06</td>
<td>6.80 ± 0.07</td>
<td>0.6 ± 0.3</td>
</tr>
</tbody>
</table>

^a From Table I of [1994OS04].

^b 8^He + 2n decay energy.

1. 1^H(11^Li, 2p)10^He, \( Q_m = -15.302 \)

10^He has been observed in quasifree proton-knockout reaction with 83 MeV/A 11^Li incident on targets of CH_2 [1997KO07]. The preliminary value determined for the decay energy for 10^He \( \rightarrow 8^He + 2n \) is 1.7 ± 0.3(stat.) ± 0.3(syst.) MeV.

2. 2^H(11^Li, 3^He)10^He, \( Q_m = -9.808 \)

Reaction products from 61 MeV/A 11^Li incident on targets of CD_2 and C were studied in experiments described in [1994KO16, 1995KO27]. The transfer reaction 2^H(11^Li, 3^He)10^He as well as the final state interaction of particles 8^He + n + n emitted in fragmentation were considered. Invariant-mass measurements for 8^He + n + n coincidences were used. Evidence was obtained for a 10^He resonance at 1.2 ± 0.3 MeV above the 8^He + n + n threshold with a width \( \Gamma \leq 1.2 \) MeV.

3. 10^Be(14^C, 14^O)10^He, \( Q_m = -41.191 \)

The double charge-exchange reaction 10^Be(14^C, 14^O)10^He was studied at \( E_{lab} = 334.4 \) MeV [1994OS04, 1995BO10, 1999BO26]. See also [1995OSZX, 1995VO05, 1996OS1A, 1998BO1M]. The measured \( Q \)-value for the 10^He ground state resonance is \( -41.19 \pm 0.07 \) MeV which corresponds to a mass excess of 48.81 ± 0.07 MeV. This is also the value adopted in [2003AU03]. 10^He is then particle unstable against 2n emission by 1.07 ± 0.07 MeV. The measured width of the ground state resonance is \( \Gamma = \)
Excited states are reported at $E_x = 3.24 \pm 0.20 \text{ MeV}$, $\Gamma = 1.0 \pm 0.3 \text{ MeV}$ and $E_x = 6.80 \pm 0.07 \text{ MeV}$, $\Gamma = 0.6 \pm 0.3 \text{ MeV}$. Widths of the two excited-state resonances are described using $R$-matrix calculations by [1994OS04]. See Table 10.2.
General References to articles on general properties of $^{10}$Li published since the previous review [1988AJ01] are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for $^{10}$Li located on our website at www.tunl.duke.edu/nucldata/General_Tables/10li.shtml.

$^{10}$Li ground-state mass The mass excess of $^{10}$Li adopted by [2003AU03] is $33051 \pm 15$ keV. This indicates that this nucleus is neutron unbound by $25 \pm 15$ keV. The width of this state is $230 \pm 60$ keV [2003AU03]. The general consensus for the $^{10}$Li ground state configuration is that a broad s-wave neutron resonance couples with the $\frac{1}{2}^-$ $^9$Li ground state to give either $1^-$ or $2^-$ resonance; see reaction 7. This state has been referred to as a virtual resonance in the n + $^9$Li system with an energy < 50 keV, based on scattering length considerations [2002GA12].

Although most experimental effort has focused on resonances near the threshold energy, the situation at higher excitation energies is better understood. Two resonances near $E_{\text{res}} = 250$ keV and 500 keV (above the $^9$Li + n threshold) have been observed under various experimental conditions. In addition, the work of Bohlen et al. (e.g., [1999BO26]) has resulted in the observation of several higher-lying $^{10}$Li resonances. Table 10.3 shows a summary of observed resonances reported for $^{10}$Li. Energies in Table 10.3 are given relative to the $^9$Li + n threshold energy.

1. (a) $^1$H($^{11}$Li, p + n)$^8$LiX
   (b) $^1$H($^{11}$Li, p + n)$^9$LiX

   The separation-energy distribution for 83 MeV/A $^{11}$Li incident on a CH$_2$ target was measured by [1997KO07]. Two states in $^{10}$Li at $E_{\text{res}} = 5.2$ MeV and 0.4 MeV were observed in reactions (a) and (b), respectively. ($E_{\text{res}}$ is the resonance energy relative to the $^9$Li + n threshold). s-wave properties of the $^9$Li + n potential were studied [2002MA77] by calculation of the break-up reactions of a $^{11}$Li beam.

2. $^2$H($^9$Li, p)$^{10}$Li, $Q_m = -2.250$

   The structure of $^{10}$Li was investigated in a kinematically complete experiment using the $^9$Li(d, p)$^{10}$Li reaction in inverse kinematics at $E(^9$Li) = 20 MeV/A [2003SA07]. The resulting $Q$-value spectrum was best fit with a single resonance at $E_{\text{res}} = 0.35 \pm 0.11$ MeV or two resonances located at $E_{\text{res}} = 0.77 \pm 0.24$ MeV and $E_{\text{res}} \geq 0.2$ MeV.

3. $^9$Be($^9$Be, $^8$B)$^{10}$Li, $Q_m = -33.277$

   In an experiment at $E(^9$Be) = 40.1 \pm 0.1$ MeV/A the measured energy spectrum of $^8$B particles was best fit with a single p-wave resonance at $E_{\text{res}} = 0.50 \pm 0.06$ MeV, $\Gamma = 400 \pm 60$ keV [1999CA48]. An excess strength at threshold was observed but that strength
Table 10.3
Summary of observed resonances reported for $^{10}\text{Li}$. Resonances are grouped to reflect different levels in $^{10}\text{Li}$.

<table>
<thead>
<tr>
<th>$E_{\text{res}}$ (MeV)</th>
<th>$I_{\text{res}}$ (MeV)</th>
<th>Reaction</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\leq 0.05$</td>
<td></td>
<td>$^{\text{n}}\text{Be}(^{11}\text{Be}, ^{3}\text{Li} + n)X$</td>
<td>[1995ZI03]</td>
</tr>
<tr>
<td>$\leq 0.05$</td>
<td></td>
<td>$^{9}\text{Be}(^{10}\text{O}, ^{9}\text{Li} + n)X$</td>
<td>[1999TH01]</td>
</tr>
<tr>
<td>$\leq 0.05$</td>
<td></td>
<td>$^{9}\text{Be}(^{11}\text{Be}, X)^{10}\text{Li}$</td>
<td>[2001CH31]</td>
</tr>
<tr>
<td>$\leq 0.05$</td>
<td></td>
<td>$^{9}\text{Be}(^{11}\text{Be}, X)^{10}\text{Li}$</td>
<td>[2001CH46]</td>
</tr>
<tr>
<td>$&lt; 0.1$</td>
<td>$&lt; 0.23$</td>
<td>$^{11}\text{B}(^{7}\text{Li}, ^8\text{B})^{10}\text{Li}$</td>
<td>[1994YO01]</td>
</tr>
<tr>
<td>$0.15 \pm 0.15$</td>
<td>$0.4 \pm 0.1$</td>
<td>$^{11}\text{B}(\pi^-, p)^{10}\text{Li}$</td>
<td>[1998GO30]</td>
</tr>
<tr>
<td>$&lt; 0.15$</td>
<td></td>
<td>$^{9}\text{Be}(^{10}\text{Li}, ^{11}\text{Be})X$</td>
<td>[1993KR09]</td>
</tr>
<tr>
<td>$0.24 \pm 0.04$</td>
<td>$0.10 \pm 0.07$</td>
<td>$^{10}\text{Be}(^{12}\text{C}, ^{12}\text{N})^{10}\text{Li}$</td>
<td>[1999BO26]</td>
</tr>
<tr>
<td>$(0.35 \pm 0.11)\text{d}$</td>
<td>$&lt; 0.32$</td>
<td>$^{2}\text{H}(^{9}\text{Li}, p)^{10}\text{Li}$</td>
<td>[2003SA07]</td>
</tr>
<tr>
<td>$0.4$</td>
<td></td>
<td>$^{14}\text{C}(\pi^-, dd)^{10}\text{Li}$</td>
<td>[1998GO30]</td>
</tr>
<tr>
<td>$(0.40 \pm 0.05)\text{f}$</td>
<td>$0.15 \pm 0.07$</td>
<td>$^{9}\text{Be}(^{13}\text{C}, ^{12}\text{N})^{10}\text{Li}$</td>
<td>[1993BO03]</td>
</tr>
<tr>
<td>$0.50 \pm 0.06$</td>
<td>$0.4 \pm 0.06$</td>
<td>$^{9}\text{Be}(^{11}\text{Be}, ^{6}\text{B})^{10}\text{Li}$</td>
<td>[1999CA48]</td>
</tr>
<tr>
<td>$0.53 \pm 0.06$</td>
<td>$0.35 \pm 0.08$</td>
<td>$^{9}\text{Be}(^{13}\text{C}, ^{12}\text{N})^{10}\text{Li}$</td>
<td>[1999BO26]</td>
</tr>
<tr>
<td>$0.538 \pm 0.062$</td>
<td>$0.358 \pm 0.023$</td>
<td>$^{11}\text{B}(^{7}\text{Li}, ^{8}\text{B})^{10}\text{Li}$</td>
<td>[1994YO01]</td>
</tr>
<tr>
<td>$0.62 \pm 0.10$</td>
<td>$0.6 \pm 0.1$</td>
<td>$^{9}\text{Be}(^{9}\text{Be}, ^{8}\text{B})^{10}\text{Li}$</td>
<td>[1999TH01]</td>
</tr>
<tr>
<td>$0.7 \pm 0.2$</td>
<td>$0.1 \pm 0.1$</td>
<td>$^{11}\text{B}(\pi^-, p)^{10}\text{Li}$</td>
<td>[1998GO30]</td>
</tr>
<tr>
<td>$(0.8 \pm 0.25)\text{f}$</td>
<td>$1.2 \pm 0.3$</td>
<td>$^{9}\text{Be}(^{11}\text{Be}, ^{8}\text{B})^{10}\text{Li}$</td>
<td>[1975WI26]</td>
</tr>
<tr>
<td>$(0.8 \pm 0.06)\text{f}$</td>
<td>$0.3 \pm 0.1$</td>
<td>$^{9}\text{Be}(^{13}\text{C}, ^{12}\text{N})^{10}\text{Li}$</td>
<td>[1993BO03]</td>
</tr>
<tr>
<td>$1.40 \pm 0.08$</td>
<td>$0.20 \pm 0.07$</td>
<td>$^{10}\text{Be}(^{12}\text{C}, ^{12}\text{N})^{10}\text{Li}$</td>
<td>[1999BO26]</td>
</tr>
<tr>
<td>$\approx 1.6$</td>
<td></td>
<td>$^{9}\text{Be}(^{13}\text{C}, ^{12}\text{N})^{10}\text{Li}$</td>
<td>[1999BO26]</td>
</tr>
<tr>
<td>$2.35 \pm 0.10$</td>
<td>$1.2 \pm 0.4$</td>
<td>$^{h}\text{Be}(^{10}\text{O}, ^{9}\text{Li})X$</td>
<td>[1999BO26]</td>
</tr>
<tr>
<td>$2.5$</td>
<td></td>
<td>$^{n}\text{Be}(^{10}\text{O}, ^{9}\text{Li})X$</td>
<td>[1993KR09]</td>
</tr>
<tr>
<td>$2.85 \pm 0.07$</td>
<td>$0.3 \pm 0.2$</td>
<td>$^{9}\text{Be}(^{13}\text{C}, ^{12}\text{N})^{10}\text{Li}$</td>
<td>[1999BO26]</td>
</tr>
<tr>
<td>$4.19 \pm 0.10$</td>
<td>$0.12 \pm 0.08$</td>
<td>$^{10}\text{Be}(^{12}\text{C}, ^{12}\text{N})^{10}\text{Li}$</td>
<td>[1999BO26]</td>
</tr>
<tr>
<td>$4.64 \pm 0.10$</td>
<td>$0.2 \pm 0.1$</td>
<td>$^{10}\text{Be}(^{12}\text{C}, ^{12}\text{N})^{10}\text{Li}$</td>
<td>[1999BO26]</td>
</tr>
<tr>
<td>$5.2$</td>
<td>$\approx 0.4$</td>
<td>$^{14}\text{C}(\pi^-, d + d)^{10}\text{Li}$</td>
<td>[1998GO30]</td>
</tr>
</tbody>
</table>

(continued on next page)
Table 10.3 (continued)

<table>
<thead>
<tr>
<th>$E_{\text{res}}$ (MeV)</th>
<th>$\Gamma_{\text{res}}$ (MeV)</th>
<th>Reaction</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.7 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td>$^9\text{Be}(^{13}\text{C}, ^{12}\text{N})^{10}\text{Li}$</td>
<td>[1999BO26]</td>
</tr>
</tbody>
</table>

$a$ Relative to $^9\text{Li} + n$ threshold.

$b$ An $s$-wave resonance at $E_{\text{res}} = 0.21 \pm 0.05$ MeV, $\Gamma_{\text{lab}} = 0.12 \pm 0.1$ MeV is reported in [1997ZI04].

$c$ Audi and Wapstra deduce $\Delta m = 33050 \pm 15$ keV which corresponds to a $^{10}\text{Li}{_{\text{g.s.}}}$ at $E_{\text{res}} = 25 \pm 15$ keV [$J^\pi = (1^-, 2^-)$] [2003AU03].

d It is unclear with which level the observed 0.35 MeV resonance should be grouped.

e A weighted average of [1994YO01,1998GO30,1999BO26,1999CA48] yields $E_{\text{res}} = 0.50 \pm 0.03$ MeV and $\Gamma_{\text{lab}} = 0.36 \pm 0.02$ MeV.

f Not reported in the $^9\text{Be}(^{13}\text{C}, ^{12}\text{N})^{10}\text{Li}$ work of [1999BO26].

g Not reported in the $^9\text{Be}(^{8}\text{Be}, ^{10}\text{Li})^{10}\text{Li}$ work of [1999CA48].

h Not shown in any spectra in [1997BO10] or [1999BO26].

could not be definitely attributed to a $^{10}\text{Li}$ level. No higher states were observed. This work reported in [1999CA48] also included a review of previous measurements of $^{10}\text{Li}$.

In early work [1975WI26] cited in [1988AJ01] $^{10}\text{Li}$ was observed for $E(^{9}\text{Be}) = 121$ MeV with a differential cross section (cm) $\approx 30$ mb/sr at $\theta = 14^\circ$ (lab). The observed group corresponds to $E_{\text{res}} = 0.80 \pm 0.25$ MeV, $\Gamma = 1.2 \pm 0.3$ MeV. However, these levels were not observed in [1999CA48].

4. $^9\text{Be}(^{11}\text{Be}, X)^{10}\text{Li}$

An experimental study [2001CH46] of the reaction products of 46 MeV/A $^{11}\text{Be}$ on $^9\text{Be}$ found that only 7 ± 3% of the $^9\text{Li}$ residues are in coincidence with the 2.7 MeV $\gamma$ rays corresponding to the $^9\text{Li}$ first excited state. This implies that the low-energy neutrons from the decay of $^{10}\text{Li}$ represent a direct $l = 0$ transition to the $^9\text{Li}$ ground state. The authors of [2001CH46] present arguments that this result indicates that the valence neutron corresponding to $^{10}\text{Li}{_{\text{g.s.}}}$ is in a $\frac{1}{2}^+$ intruder state from the sd shell rather than the $\frac{1}{2}^-$ state that might be expected to correspond to a single neutron hole in the p-shell. See also [2001CH31].

5. $^9\text{Be}(^{13}\text{C}, ^{12}\text{N})^{10}\text{Li}, \quad Q_m = -35.916$

This reaction at $E_{\text{lab}} = 336$ MeV was used in a study of $^{10}\text{Li}$ [1993BO03] in which levels at $E_{\text{res}} = 0.4, 0.8,$ and 4.5 MeV were reported. Later work by [1998BO38,1999BO26] did not report these levels. This reaction was also used at $E_{\text{lab}} = 336.4$ MeV along with $^{10}\text{Be}(^{12}\text{C}, ^{12}\text{N})^{10}\text{Li}$ (reaction 8: $E_{\text{lab}} = 357.0$ MeV) and $^9\text{Be}(^{15}\text{N}, ^{14}\text{O})^{10}\text{Li}$ (reaction 6: $E_{\text{lab}} = 240$ MeV) to study $^{10}\text{Li}$ [1998BO38,1999BO26]. The $(^{12}\text{C}, ^{12}\text{N})$ reaction shows a distinct selectivity for unnatural parity states, whereas natural parity states in $^{10}\text{Li}$ are more strongly populated by $^9\text{Be}(^{13}\text{C}, ^{12}\text{N})^{10}\text{Li}$. A summary discussion and analysis of the results of these experiments is given in [1999BO26], and the parameters for eight levels are presented. See Table 10.4 here. See also [1997BO10].
Fig. 12. Energy levels of $^{10}\text{Li}$. For notation see Fig. 2.
Table 10.4

<table>
<thead>
<tr>
<th>$E_{\text{res}}$ (MeV)</th>
<th>$\Gamma_{\text{lab}}$ (MeV)</th>
<th>$J^\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.24 ± 0.04</td>
<td>0.10 ± 0.07</td>
<td>(1+)</td>
</tr>
<tr>
<td>0.53 ± 0.06</td>
<td>0.35 ± 0.08</td>
<td>(2+)</td>
</tr>
<tr>
<td>1.40 ± 0.08</td>
<td>0.20 ± 0.07</td>
<td>(2− + 1+)</td>
</tr>
<tr>
<td>2.35 ± 0.10</td>
<td>1.2 ± 0.4</td>
<td>(1+, 3+)</td>
</tr>
<tr>
<td>2.85 ± 0.07</td>
<td>0.3 ± 0.2</td>
<td>(1−, 2+)</td>
</tr>
<tr>
<td>4.19 ± 0.10</td>
<td>0.12 ± 0.08</td>
<td></td>
</tr>
<tr>
<td>4.64 ± 0.10</td>
<td>0.2 ± 0.1</td>
<td>(3−, 2+)</td>
</tr>
<tr>
<td>5.7 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ From Table 1 of [1999BO26]. See also [1997BO10,1998BO38].

$^b$ Resonance energy relative to $^9\text{Li} + n$ threshold.

$^c$ Probable spin/parity based on natural or unnatural parity selectivity [1999BO26].

6. $^9\text{Be}(^{15}\text{N}, ^{14}\text{O})^{10}\text{Li}$, $Q_m = -29.609$

This reaction was used [1998BO38] at $E_{\text{lab}} = 240$ MeV along with $^9\text{Be}(^{13}\text{C}, ^{12}\text{N})^{10}\text{Li}$ (reaction 5: $E_{\text{lab}} = 336.4$ MeV) and $^{10}\text{Be}(^{12}\text{C}, ^{12}\text{N})^{10}\text{Li}$ (reaction 8: $E_{\text{lab}} = 357$ MeV) in a study of $^{10}\text{Li}$. See also [1999BO26] and Table 10.4 here.

7. $^9\text{Be}(^{18}\text{O}, ^9\text{Li} + n)X$.

In an experiment performed with 80 MeV/A $^{18}\text{O}$ on $^9\text{Be}$ [1999TH01], the decay structure of $^{10}\text{Li}$ was studied using the method of sequential neutron decay spectroscopy (SNDS). Evidence for low-lying s-wave strength was observed which supports arguments that $^{10}\text{Li}$ should have a ground state in which the $p_{3/2}$ proton is coupled to the $s_{1/2}$ neutron to form a $1^−$ or $2^−$ state.

8. $^{10}\text{Be}(^{12}\text{C}, ^{12}\text{N})^{10}\text{Li}$, $Q_m = -37.782$

This reaction was studied at $E_{\text{lab}} = 357$ MeV along with $^9\text{Be}(^{13}\text{C}, ^{12}\text{N})^{10}\text{Li}$ (reaction 5: $E_{\text{lab}} = 336.4$ MeV) to determine the structure of $^{10}\text{Li}$ [1997BO10,1998BO38,1999BO26]. See also reaction 6. The $^{10}\text{Be}(^{12}\text{C}, ^{12}\text{N})^{10}\text{Li}$ reaction shows a distinct selectivity for unnatural-parity states. $^{10}\text{Li}$ states at $E_{\text{res}} = 0.24, 1.40, 4.19, \text{ and } 4.64$ MeV are identified in reaction 8. Parameters for these states and four others are presented in a summary table in [1999BO26] and in Table 10.4 here.

9. $^{11}\text{Be}(d, ^3\text{He})^{10}\text{Li}$, $Q_m = -14.672$

This reaction was studied in inverse kinematics with $^{11}\text{Be}$ at 35 MeV/A incident on a deuterium target [2000FO17].

10. $^{11}\text{B}(\pi^-, p)^{10}\text{Li}$, $Q_m = 107.898$

Inclusive spectra of protons, deuterons and tritons from the absorption of stopped pions in $^{11}\text{B}$ were measured by [1990AM05]. They reported observation of the $^{10}\text{Li}$ ground state at a $^9\text{Li} + n$ resonance energy, $E_{\text{res}} = 0.15 \pm 0.15$ MeV with a width $\Gamma_{\text{res}} < 0.4$ MeV.
In more recent work [1998GO30], stopped pions were used for $^{11}$B($\pi^-$,p)$^{10}$Li along with $^{14}$C($\pi^-$,d)d (reaction 15). Missing-mass spectra were measured. An analysis of $^{11}$B($\pi^-$,p) in terms of a one-peak description gave a resonance energy and width $E_{\text{res}} = 0.48 \pm 0.10$ MeV, $\Gamma_{\text{res}} = 0.50 \pm 0.10$ MeV. An appreciably better description in terms of two peaks gave $E_{\text{res}} = 0.1 \pm 0.1$ MeV, $\Gamma_{\text{res}} = 0.4 \pm 0.1$ MeV and $E_{\text{res}} = 0.7 \pm 0.2$ MeV, $\Gamma_{\text{res}} = 0.1 \pm 0.1$ MeV. It is suggested that the lower of these two states is the $^{10}$Li $g$s with unnatural parity. These results are compared with other available data in $^{10}$Li. For results of their analysis of $^{14}$C($\pi^-$,d)d (reaction 15).

11. $^{11}$B($^7$Li,$^8$B)$^{10}$Li, $Q_m = -32.397$

An experiment at $E(7\text{Li}) = 18.8$ MeV/A was reported by [1994YO01]. A broad state in the 5° reaction products was best fit by a single $p_{1/2}$ resonance at $E_{\text{res}} = 538 \pm 62$ keV with a width $\Gamma_{\text{lab}} = 358 \pm 23$ keV. However, two p-wave states separated by no more than 160 keV could not be ruled out as the components of the dominant peak in the spectrum. In addition the data show weak evidence for a narrow s- or p-wave resonance that is unbound to neutron decay by less than 100 keV ($\Gamma \approx 230$ keV).

12. (a) $^{nat}$C($^{11}$Li,$^9$Li+n)X
(b) $^{nat}$C($^{11}$Be,$^9$Li+n)X

Reaction (a) and (b) were studied at 280 and 460 MeV/A, respectively, by [1995ZI03]. Analysis of the momentum distributions led to the conclusion that $^{10}$Li$_{g.s.}$ is a virtual state in n+$^9$Li with a scattering length $a_s < -20$ fm and excitation energy $\lesssim 50$ keV. A study [1997ZI1F,1997ZI04] of $^{11}$Li on carbon (reaction (a)) and Pb (reaction 16) utilized invariant-mass spectroscopy. Resonance-like structures were observed with $E_{\text{res}} = 0.21 \pm 0.05$ MeV, $\Gamma_{\text{res}} = 0.12 \pm 0.05$ MeV; $E_{\text{res}} = 0.62 \pm 0.10$ MeV, $\Gamma_{\text{res}} = 0.6 \pm 0.1$ MeV; $E_{\text{res}} \approx 1.6$ MeV. The relative intensities of the first two structures are 0.26 ± 0.10 and 0.74 ± 0.10, respectively. The low-energy behavior of the lowest resonance is only reproduced for $l = 0$, indicating a low-lying s-wave scattering state, but the authors caution that the parameterization of the apparent peak that leads to $E_{\text{res}} = 0.21$ MeV is not ideal for fitting a low-lying s-wave scattering state.

13. $^{nat}$C($^{18}$O,$^9$Li+n)X

A study of the neutron decay of $^{10}$Li produced by 80 MeV/A $^{18}$O incident on a carbon target was reported by [1993KR09]. Neutrons and $^9$Li nuclei were detected in coincidence in a collinear geometry. Analysis of the relative velocity spectrum indicated a $^{10}$Li state which the authors conclude is consistent with the $^{10}$Li ground state at $E_{\text{res}} = 0.15 \pm 0.15$ MeV above the $^9$Li+n threshold reported by [1990AM05]. The authors explored the possibility that if $^9$Li$^*$($2.7$) plays a role in the breakup, then their observation would be consistent with a $^{10}$Li state at $E_x = 2.5$ MeV. However the work of [2001CH46] indicates that $^9$Li$^*$($2.7$) plays a minor role in the reaction (see reaction 4).
10 Li, 10 Be


14. 13 C(14 C, 17 F)10 Li, \( Q_m = -28.858 \)

This reaction was studied at \( E_{\text{lab}} = 337 \text{ MeV} \) along with 9 Be(13 C, 12 N)10 Li (reaction 5; \( E_{\text{lab}} = 336 \text{ MeV} \)) by [1993BO03]. Only one broad peak was observed in the (14 C, 17 F) spectrum at 3.8°–7.0°. Analysis of the peak failed to give a unique solution, but it supported the identification of levels reported in the (13 C, 12 N) spectrum in [1993BO03]. See, however, the later work reported by the same authors (discussed under reaction 5) which did not confirm these levels.

15. 14 C(\( \pi^- \), d + d)10 Li, \( Q_m = 83.268 \)

The reaction, along with 11 B(\( \pi^- \), p) (reaction 10), was studied with stopped pions [1998GO30]. The (\( \pi^- \), d + d) reaction indicated a 10 Li state with \( E_{\text{res}} = 0.40 \pm 0.10 \text{ MeV} \), \( \Gamma_{\text{res}} = 0.30 \pm 0.07 \text{ MeV} \) and conformed with the results of 11 B(\( \pi^- \), p) (see reaction 10) and the results of [1993BO03] and [1994YO01]. The (\( \pi^- \), d + d) reaction also indicates a state with \( E_{\text{res}} = 5.2 \pm 0.2 \text{ MeV} \), \( \Gamma_{\text{res}} \approx 0.4 \text{ MeV} \) [1998GO30].

16. nat Pb(11 Li, 9 Li + n)X

See reaction 12 and [1997ZI1F, 1997ZI04].

### 10 Be

(Figs. 13 and 16)

**General**

References to articles on general properties of 10 Be published since the previous review [1988AJ01] are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for 10 Be located on our website at: www.tunl.duke.edu/nucldata/General_Tables/10be.shtml.

The interaction nuclear radius of 10 Be is 2.46±0.03 fm [1985TA18], \( E = 790 \text{ MeV/A} \); see also for derived nuclear matter, charge and neutron matter r.m.s. radii.

\[
B(\text{E2}) \uparrow \text{ for } ^{10}\text{Be}^* (3.37) = 52 \pm 6 \, e^2 \text{ fm}^4 \ [1987\text{RA01}];
\]

\[
B(\text{E2}) \downarrow \text{ for } ^{10}\text{Be}^* (3.37) = 10.5 \pm 1.0 \, e^2 \text{ fm}^4.
\]

**10 Be atomic excitations** Isotope shifts for various \( ^1 S \) and \( ^1 D \) Rydberg series atomic excitations in 9 Be and 10 Be were measured in [1988WE09].

1. \( ^{10}\text{Be}(\beta^-)^{10}\text{Be}, \ Q_m = 0.5560 \)

The half-life of 10 Be is (1.51 ± 0.04) × 10⁶ years; this is the weighted average of 1.51 ± 0.06 Ma [1987HO1P], 1.53 ± 5% Ma [1993MI26] and 1.48 ± 5% Ma [1993MI26].
Table 10.5
Energy levels of $^{10}$Be

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$J^p$; $T$</th>
<th>$\tau$ or $T_{1/2}$ (keV)</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s. 0$^+$; 1</td>
<td>$\tau_{1/2} = (1.51 \pm 0.04) \times 10^6$ y</td>
<td>$\beta^-$</td>
<td>1, 3, 4, 6, 7, 9, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 41, 42, 43, 44, 46, 47, 50, 52, 53, 55</td>
<td></td>
</tr>
<tr>
<td>3.36803 ± 0.03 2$^+$; 1</td>
<td>$\tau_m = 180 \pm 17$ fs</td>
<td>$\gamma$</td>
<td>3, 4, 5, 6, 7, 9, 13, 14, 15, 17, 18, 19, 20, 21, 22, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 41, 42, 43, 44, 46, 47, 50, 51, 52, 55</td>
<td></td>
</tr>
<tr>
<td>5.95839 ± 0.05 2$^+$; 1</td>
<td>$\tau_m &lt; 80$ fs</td>
<td>$\gamma$ (3), 6, 9, 14, 15, 17, 18, 21, 22, 25, 26, 27, 28, 30, 31, 34, 42, 44, 46, 47, 50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.9599 ± 0.6 1$^-$; 1</td>
<td></td>
<td>$\gamma$ (3), 6, 14, 15, 17, 18, 19, 21, 26, 27, 30, (31), 34, 42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.1793 ± 0.7 0$^+$; 1</td>
<td>$\tau_m = 1.1^{+0.4}_{-0.3}$ ps</td>
<td>$\pi$, $\gamma$ (3), 6, 14, 30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.2633 ± 5.0 2$^+$; 1</td>
<td></td>
<td>$\gamma$ (3), 6, 14, 15, 19, 21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.371 ± 1 3$^+$; 1</td>
<td>$I^* = 15.7 \pm 0.5$ keV</td>
<td>$n$, $\gamma$ (3), 6, 7, 9, 10, 13, 14, 15, 17, 18, 27, 47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.542 ± 1 2$^+$; 1</td>
<td>6.3 ± 0.8</td>
<td>$n$, $\alpha$ (3), 6, 7, 10, 14, 15, 17, 26, 27, 42, 46, 47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.27 (4$^-$); 1</td>
<td>150 ± 20</td>
<td>$n$ 6, 7, 10, (13), 14, 15, 18, 21, 26, 27, (30), (31), 34, 42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.56 ± 20$^c$ 2$^+$; 1</td>
<td>141 ± 10$^e,f$</td>
<td>$n$, $\alpha$ 6, 7, 10, (13), 14, 15, 17, 18, 26, 27, 28, (30), 34, 42, 44, 46, 47, 54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.15 ± 20 3$^-$</td>
<td>296 ± 15$^f$</td>
<td>$\alpha$ 3, 7, 17, 54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.57 ± 30 1$^+$; 1</td>
<td></td>
<td>$n$, $\alpha$ 6, 7, 10, 14, 47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.23 ± 50 2$^+$; 1</td>
<td>200 ± 80$^f$</td>
<td>$\alpha$ (3), 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.76 ± 20 (4$^+$)</td>
<td>121 ± 10</td>
<td>$\alpha$ 6, 7, 13, 14, 15, 17, 18, 42, 47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.93 ± 100 (5$^-$)$^g$</td>
<td>200 ± 80$^f$</td>
<td>$\alpha$ 7, (21), 45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.05 ± 100</td>
<td>200 ± 130$^f$</td>
<td>$\alpha$ 7, (45)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.80 ± 50</td>
<td>330 ± 150$^f$</td>
<td>$\alpha$ 7, 18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.68 ± 100</td>
<td>310 ± 140$^f$</td>
<td>$\alpha$ 7, 45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.3 ± 200 (6$^-$)$^g$</td>
<td>800 ± 200$^b$</td>
<td>(18), (21), 47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.12 ± 200 (2$^-$)</td>
<td>150</td>
<td>(4), 6, 45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.79</td>
<td>112 ± 35</td>
<td>$\gamma$, n, t, $\alpha$ 4, 6, 7, (11)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18.15 ± 50 (0$^-$)</td>
<td>90 ± 30$^f$</td>
<td>t 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18.55</td>
<td>310$^f$</td>
<td>n, t 4, 6, 7, 11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(19.8)</td>
<td></td>
<td>$\beta$ 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.8 ± 100</td>
<td></td>
<td>$\alpha$ 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21.216 ± 23 (2$^-$; 2)</td>
<td>sharp</td>
<td>n, p, t 4, 11</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(continued on next page)
### Table 10.5 (continued)

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)$^b$</th>
<th>$J^\pi; T$ or $T_{cm}$ (keV)</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.8 ± 100</td>
<td>$\approx 200^d$</td>
<td>p, (d)</td>
<td>7</td>
</tr>
<tr>
<td>22.4 ± 100</td>
<td>$\approx 250^d$</td>
<td>(n), p, t</td>
<td>7, (11)</td>
</tr>
<tr>
<td>23.0 ± 100</td>
<td>p</td>
<td>(4), 7</td>
<td>7</td>
</tr>
<tr>
<td>23.35 ± 50</td>
<td>(n), p, d, (t), $\alpha$</td>
<td>7, (11)</td>
<td></td>
</tr>
<tr>
<td>23.65 ± 50</td>
<td>p, (t), $\alpha$</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>24.0 ± 100</td>
<td>$\approx 150^d$</td>
<td>d, (t), $\alpha$</td>
<td>7, 33</td>
</tr>
<tr>
<td>24.25 ± 50</td>
<td>$\approx 200^d$</td>
<td>(p), d, t, $\alpha$</td>
<td>7</td>
</tr>
<tr>
<td>24.6 ± 100</td>
<td>$\approx 150^d$</td>
<td>p, d</td>
<td>7</td>
</tr>
<tr>
<td>24.8 ± 100</td>
<td>$\approx 100^d$</td>
<td>p, d</td>
<td>7</td>
</tr>
<tr>
<td>25.05 ± 100</td>
<td>$\approx 150^d$</td>
<td>d, $\alpha$</td>
<td>7</td>
</tr>
<tr>
<td>25.6 ± 100</td>
<td>$\approx 300^f$</td>
<td>d</td>
<td>7</td>
</tr>
<tr>
<td>25.95 ± 50</td>
<td>$\approx 100^f$</td>
<td>d, (t)</td>
<td>7</td>
</tr>
<tr>
<td>26.3 ± 100</td>
<td>p, d, $\alpha$</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>26.8 ± 100</td>
<td>p, d, $\alpha$</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>27.2 ± 200</td>
<td>p, d, t, $\alpha$</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ See also Table 10.12.
$^b$ See reactions 4, 45 and 47 for evidence of other levels.
$^c$ A $J^\pi = 3^+$ state is predicted near 9 MeV, however, evidence is ambiguous: see reaction 28.
$^d$ Previously reported at 9.4 MeV.
$^e$ 141 ± 10 keV from $^3\text{Li}(^3\text{Li}, \alpha)$; other value 291 ± 20 keV from $^9\text{Be}(d, p)$.
$^f$ Not corrected for experimental system resolution and therefore upper limits.
$^g$ From systematics in reaction 21.
$^h$ From [2001BO35]: $^{12}\text{C}(^{15}\text{N}, ^{17}\text{F})$.

The log $ft = 13.396 \pm 0.012$. For the earlier work see [1974AJ01]. See also [1992WA02, 1990HO28, 1998MA36].

2. $^4\text{He}(^6\text{He}, ^6\text{He})^4\text{He}$, $E_b = 7.4133$

At $E(^6\text{He}) = 151$ MeV, angular distributions were measured to investigate two-neutron exchange and the cluster configurations that dominate in the reaction. The data are consistent with a significant spatial correlation for the exchanged neutrons [1998TE03]. Measurements at lower energies, $E_{cm} = 11.6$ MeV and 15.9 MeV, indicate that a simple dineutron exchange is not dominant and give evidence that the structure of $^6\text{He}$ is more complex than an alpha-plus-dineutron model [1999RA15]. See also [2000BB06].

3. (a) $^6\text{Li}(^6\text{He}, ^{10}\text{Be} + d)$
(b) $^6\text{Li}(^6\text{He}, ^6\text{He} + \alpha)^2\text{H}$, $Q_m = -1.4738$

Molecular cluster states in $^{10}\text{Be}$ were studied by bombarding $^6\text{Li}$ targets with $E(^6\text{He}) = 17$ MeV projectiles and detecting the $^{10}\text{Be} + d$ and $^6\text{He} + ^4\text{He}$ reaction products [1999MI39]. In reaction (a) reconstruction of the missing energy indicates that $^{10}\text{Be}^*(0, 3.37)$ participate in the reaction as well as unresolved states at 6 MeV and 7.5 MeV. In reaction (b) the 10.2 MeV level is observed, and due to its apparent cluster nature it is suggested that this state could be the $4^+$ member in the rotational band (6.18 $[0^+]$).
Fig. 13. Energy levels of $^{10}$Be. For notation see Fig. 2.
for $E_{7.54} \approx 10^{+9} \, \text{Be}$ the yield of neutrons (reaction (b) to $9 \, \text{Be}$) for particular transitions are shown in Fig. 13 since it is clear that they have been observed although the lack of displayed in Table 10.2 of [1984AJ01] is not shown here because it has not been published. However, those published uncertainties make their inclusion in this table inadvisable.

Electromagnetic transition strengths in $10 \, \text{Be}$

<table>
<thead>
<tr>
<th>$E_\gamma$ (MeV)</th>
<th>$J^\pi \rightarrow J^\pi$</th>
<th>Branch (%)</th>
<th>$\Gamma_\gamma$ (eV)</th>
<th>Mult.</th>
<th>$\Gamma_\gamma/\Gamma_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.368 $\rightarrow$ 0</td>
<td>$2^+ \rightarrow 0^+$</td>
<td>100</td>
<td>$(3.66 \pm 0.35) \times 10^{-3}$</td>
<td>E2</td>
<td>8.00 $\pm$ 0.76</td>
</tr>
<tr>
<td>6.179 $\rightarrow$ 3.368</td>
<td>$0^+ \rightarrow 2^+$</td>
<td>76 $\pm$ 2</td>
<td>$(4.5 \pm 1.7) \times 10^{-4a}$</td>
<td>E2</td>
<td>2.5 $\pm$ 0.9</td>
</tr>
<tr>
<td></td>
<td>$\rightarrow 5.960$</td>
<td>$1^- \rightarrow 24 \pm 2$</td>
<td>$(1.44 \pm 0.53) \times 10^{-4b}$</td>
<td>E1</td>
<td>$(4.3 \pm 1.6) \times 10^{-2}$</td>
</tr>
<tr>
<td>7.371 $\rightarrow$ 3.368</td>
<td>$3^- \rightarrow 2^+$</td>
<td>85 $\pm$ 8</td>
<td>$0.62 \pm 0.06c$</td>
<td>E1</td>
<td>$(3.1 \pm 0.3) \times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td>$\rightarrow 5.958$</td>
<td>$3^- \rightarrow 2^+$</td>
<td>15 $\pm$ 11</td>
<td>$0.11 \pm 0.08c$</td>
<td>E1</td>
</tr>
</tbody>
</table>

- $\Gamma_\gamma$ from lifetimes and branching ratios. See also $9 \, \text{Be}(d, p)/10 \, \text{Be}$ [reaction 14] and Table 10.12.
- $a$ Assumed maximum of asymmetrical uncertainty.
- $b$ From $9 \, \text{Be}(n, \gamma)/10 \, \text{Be}$ [1994KI09].

Neutron-capture $\gamma$-rays in $10 \, \text{Be}$

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)$^b$</th>
<th>Transition</th>
<th>$E_\chi$ (keV)$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6809.585 $\pm$ 0.033</td>
<td>capt. $\rightarrow$ g.s.</td>
<td>6812.038 $\pm$ 0.029</td>
</tr>
<tr>
<td>5955.9 $\pm$ 0.5$^a$</td>
<td>5.96$^c$ $\rightarrow$ g.s.</td>
<td>5958.387 $\pm$ 0.051</td>
</tr>
<tr>
<td>3443.374 $\pm$ 0.030</td>
<td>capt. $\rightarrow$ 3.37</td>
<td></td>
</tr>
<tr>
<td>3367.415 $\pm$ 0.030</td>
<td>3.37 $\rightarrow$ g.s.</td>
<td>3368.029 $\pm$ 0.029</td>
</tr>
<tr>
<td>2589.999 $\pm$ 0.060</td>
<td>5.96$^c$ $\rightarrow$ 3.37</td>
<td></td>
</tr>
<tr>
<td>853.605 $\pm$ 0.060</td>
<td>capt. $\rightarrow$ 5.96$^c$</td>
<td></td>
</tr>
</tbody>
</table>

- $a$ See also Table 10.2 in [1974AJ01,1979AJ01].
- $b$ [1983KE11]. 12 eV has been added in quadrature to the uncertainties. See [1988AJ01]. Some of the work displayed in Table 10.2 of [1984AJ01] is not shown here because it has not been published. However, those particular transitions are shown in Fig. 13 since it is clear that they have been observed although the lack of published uncertainties make their inclusion in this table inadvisable.
- $c$ This is the $2^+$ member of the doublet at $E_\chi = 5.96$ MeV.

The yield of $\gamma_0$ and $\gamma_1$ has been studied for $E_\gamma = 0.4$ to 1.1 MeV $[10 \, \text{Be}^* (17.79)]$ is said to be involved); see [1984AJ01]. The neutron yield exhibits a weak structure at $E_\gamma = 0.24$ MeV and broad resonances at $E_\gamma \approx 0.77 \, \text{MeV}$ $[\Gamma_{\text{lab}} = 160 \pm 50 \, \text{keV}]$ and 1.74 MeV; see [1966LA04]$[10 \, \text{Be}^* (17.79, 18.47)]$. The total cross section for reaction (c), the yield of neutrons (reaction (b) to $9 \, \text{Be}^* (14.39)$), and the yield of $\gamma$-rays from $7 \, \text{Li}^* (0.48)$ (reaction (d)) all show a sharp anomaly at $E_\gamma = 5.685 \, \text{MeV}$: $J^\pi = 2^-$; $T = 2$ is suggested for a state at $E_\chi = 21.22 \, \text{MeV}$. The total cross section for $\alpha_0$ (reaction (e)) and the all-neutrons yield do not show this structure: see [1984AJ01,1988AJ01]. An additional anomaly in the proton yield is reported at $E_\gamma = 8.5 \, \text{MeV}$ $[10 \, \text{Be}^* (23.2)]$ [see [1987AB15]]. For
Table 10.8
Levels of $^{10}\text{Be}$ from $^7\text{Li}(\alpha,p)^{10}\text{Be}$

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$J^π$</th>
<th>$Γ_{\text{cm}}$ (keV)</th>
<th>$L$</th>
<th>$S_{\text{rel}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$0^+$</td>
<td>1</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>3.37</td>
<td>$2^+$</td>
<td>3</td>
<td>0.067</td>
<td></td>
</tr>
<tr>
<td>5.96</td>
<td>$2^+, 1^-$</td>
<td>doublet</td>
<td>1.37</td>
<td>24.06</td>
</tr>
<tr>
<td>6.18</td>
<td>$0^+$</td>
<td>1</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>6.26</td>
<td>$2^-$</td>
<td>2</td>
<td>0.53</td>
<td></td>
</tr>
<tr>
<td>7.37</td>
<td>$3^-$</td>
<td>2</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td>7.54</td>
<td>$2^+$</td>
<td>3</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>9.27</td>
<td>$(4^+)$</td>
<td>2</td>
<td>0.84</td>
<td></td>
</tr>
<tr>
<td>9.64±0.10</td>
<td>$(2^+)$</td>
<td>3</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>10.57</td>
<td>$≥1$</td>
<td>0, 1</td>
<td>0.08, 0.035</td>
<td></td>
</tr>
<tr>
<td>11.76</td>
<td>$(4^+)$</td>
<td>3</td>
<td>0.049</td>
<td></td>
</tr>
<tr>
<td>17.12±0.20</td>
<td>$(2^-)$</td>
<td>$≈150$</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>17.79</td>
<td>$(2^-)\text{b}$</td>
<td>170</td>
<td>2</td>
<td>1.0</td>
</tr>
<tr>
<td>18.55</td>
<td>$(2^-)\text{b}$</td>
<td>380</td>
<td>2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

a See Table II in [1994HA16].
b By analogy with $^{10}\text{B}$ states.
c In some cases, the shell model calculations of Kurath and Millener [1975KU01] suggest different $L$-values and/or different $2N+L$ values from those used in the DWBA calculations of [1994HA16].

reaction (c) a reanalysis of the proton yields indicate two states at $E_x = 21.216±0.023$ and 23.138±0.140 MeV with $Γ_{\text{cm}} = 80±30$ and 440±178 keV, respectively [1990GU36]. For reaction (e) the angular distributions of $α_0$ and $α_1$ products were measured at $E_t = 151$ and 272 keV, and the analysis suggests possible evidence for a $2^+$ resonance, $^{10}\text{Be}^+(17.3)$, at $E_{\text{res}} = 117±3$ keV with $Γ_{\text{lab}} = 253±1$ keV [1987AB09]. Differential cross sections and $S$-factors are reported by [1983CE1A] for $E_t = 70$ to 110 keV for $^6\text{He}^+(0, 1.80)$. The zero-energy $S$-factor for $^6\text{He}^+(1.80)$ is $14±2.5$ MeV b. The relevance to a Li-seeded tritium plasma is discussed by [1983CE1A]. See also ([1985CA41]; astrophys.).

5. $^7\text{Li}(^3\text{He},\pi^+)^{10}\text{Be}, \quad Q_m = -122.3379$

Cross sections have been measured to $^{10}\text{Be}^+(3.37, 6.2[u], 7.4[u] [u=unresolved])$ at $E(^3\text{He}) = 235$ MeV. The ground-state group is not seen: its intensity at $θ_{\text{lab}} = 20°$ is $≤0.1$ of that to $^{10}\text{Be}^+(3.37)$ [1984BI08].

6. $^7\text{Li}(\alpha,p)^{10}\text{Be}, \quad Q_m = -2.5629$

Angular distributions were measured at $E_\alpha = 65$ MeV [1994HA16]. Observed states are shown in Table 10.8. For $^{10}\text{Be}^+(11.76)$ the angular distribution is consistent with $L = 3$ which supports a $J^π = 4^+$ assignment. It is suggested that the 11.76 MeV state is the $4^+$ member of the ground-state $K^π = 0^+$ rotational band (g.s. $[0^+]$, 3.37 $[2^+]$, 11.76 $[4^+]$ [ $J^π$ in brackets]).
7. (a) $^7\text{Li}(7\text{Li}, p + ^9\text{Li})^4\text{He}$, $Q_m = -4.8526$
(b) $^7\text{Li}(7\text{Li}, d + ^8\text{Li})^4\text{He}$, $Q_m = -6.69185$
(c) $^7\text{Li}(7\text{Li}, t + ^7\text{Li})^4\text{He}$, $Q_m = -2.46691$
(d) $^7\text{Li}(7\text{Li}, \alpha)^{10}\text{Be}$, $Q_m = 14.7840$
(e) $^7\text{Li}(7\text{Li}, \alpha + ^6\text{He})^4\text{He}$, $Q_m = 7.3707$
(f) $^7\text{Li}(7\text{Li}, \alpha + ^9\text{Be})n$, $Q_m = 7.9718$

Resonant particle decay spectroscopy measurements have been reported for reactions (a), (b), (c), (e), (f): see Table 10.9 for an overview of experimental conditions. These measurements are particularly well-suited for spectroscopic studies of levels that decay to excited states of the component isotopes, i.e., $\alpha + ^6\text{He}^*(1.8)$. Values of $\Gamma_r/\Gamma = (3.5 \pm 1.2) \times 10^{-3}$ and $0.16 \pm 0.04$ for $^{10}\text{Be}^*(7.542, 9.6)$, respectively, are determined by [2002LI15]. See also [2004AR01] for a cluster model analysis.

New evidence suggests that the previously accepted level energy at 9.4 MeV corresponds to the level presently observed at 9.6 MeV [1996SO17, 2001MI39, 2002LI15]. [1997CU03, 2001CU06] measured $E_x = 9.56 \pm 0.02$ MeV and determined $\Gamma_{cm} = 141 \pm 10$ keV and $J^\pi = 2^+$. Assuming that the $^{10}\text{Be}^*(9.56)$ state is $2^+$ suggests that it is probably a member of the $K^\pi = 1^+$ band and the $3^- 10.15$ MeV level is probably in the $K^\pi = (1^-, 2^-)$ band [2001CU06, 2002LI15]. See also [2004MI07] and Fig. 8 in [2002LI15].

The work of [1996SO17] reported a new level that decays by $\alpha$-emission at $E_x = 10.2$ MeV with $\Gamma < 400$ keV. The level energy is identified as $E_x = 10.15 \pm 0.02$ MeV by [2001CU06] who also determined $\Gamma_{cm} = 296 \pm 15$ keV and, based on $\alpha + ^6\text{He}$ decay angular correlations, $J^\pi = 3^-$. This is in contrast with a $J = 4$ spin value that was suggested by [1996SO17]. The 10.2 MeV level appears to have a small $\Gamma_{n}$; it is neither observed in fast neutron capture nor in the $^9\text{Be} + n$ decay channel.

A natural parity state at 11.23 ± 0.05 MeV with $\Gamma_{cm} = 200 \pm 80$ keV is identified by [2001CU06] along with inconclusive evidence for states at 13.1, 13.9 and 14.7 MeV. [2002LI15] observed a new state at 18.15 ± 0.05 MeV with $\Gamma = 100 \pm 30$ keV; based on reaction systematics they deduce $J^\pi = 0^-$. See Table 10.10 for other states observed in [2003FL02].

For reaction (d), angular distributions of $\alpha_1$ and $\alpha_{2+3+4+5}$ were reported in [1969CA1A]. Groups corresponding to $^{10}\text{Be}^*(0, 3.4, 6.0, 7.4, 9.4, 10.7, 11.9, 17.9)$ and possibly $^{10}\text{Be}^*(18.8)$ were reported in [1971GL1A]. See [1974AJ01].

8. $^9\text{Li}(p, \alpha)^6\text{He}$, $Q_m = 12.2233$, $E_b = 19.6366$

A calculation estimating the impact of $^9\text{Li}(p, \alpha)^6\text{He} \rightarrow ^6\text{Li}$ and other reactions on the production of primordial $^6\text{Li}$ in Big Bang nucleosynthesis is given in [1997NO04].

9. $^9\text{Be}(n, \gamma)^{10}\text{Be}$, $Q_m = 6.8122$

The thermal capture cross section is $8.49 \pm 0.34$ mb [1986CO14]. Reported $\gamma$-ray transitions are displayed in Table 10.7 [1983KE11]. Partial cross sections involving $^{10}\text{Be}^*(0, 3.37, 5.96)$ are listed in [1987LY01]. See also the references cited in [1988AJ01].
Retardation of E1 strength was found in a measurement of the capture γ-rays from $^9$Be + n using $E_n = 622$ keV neutrons to populate the $J^z = 3^-$ D-wave resonance at $^{10}$Be$^*$ (7.372) [1994K109]; $\Gamma_n = 17.5$ keV. Capture to the $J^z = 2^+$ states at $^{10}$Be$^*$ (3.368, 5.958) was observed, and $\Gamma_y = 0.62 \pm 0.06$ and 0.11 ± 0.08 eV were deduced, respectively. Simple capture models indicate that capture to the 3368 keV state is appreciably hindered, which is explained by assuming a strong coupling between the d-state single particle neutron motion and the E1 giant resonance.

### Table 10.9

<table>
<thead>
<tr>
<th>$E(\text{Li})$ (MeV)</th>
<th>$I_{cm}$ (MeV)</th>
<th>Decay</th>
<th>$E_x$ (MeV)</th>
<th>$I_{cm}$ (keV)</th>
<th>Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>9.27, 9.64, 10.2, 10.57</td>
<td>$^7\text{Li}, \alpha + ^6\text{He}$, ($^7\text{Li}, \alpha + ^9\text{Be}$)</td>
<td>34, 50.9</td>
<td>9.56, 10.15, 10.6, 11.23, 11.8, (13.1), (13.9), (14.7), 17.8</td>
<td>($^7\text{Li}, \alpha + ^6\text{He}$)</td>
</tr>
<tr>
<td>34</td>
<td>7.542, 8, 30, 52</td>
<td>$^7\text{Li}, \alpha$, ($^7\text{Li}, 2\alpha$), ($^7\text{Li}, \alpha + ^6\text{He}$)</td>
<td>34, 50.9</td>
<td>see Table 10.10</td>
<td>($^7\text{Li}, \alpha + ^6\text{He}$), ($^7\text{Li}, \alpha + ^9\text{Be}$), (13.1), (13.9), (14.7), 17.8</td>
</tr>
</tbody>
</table>

### Table 10.10

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$I_{cm}$ (keV)</th>
<th>Decay</th>
<th>$E_x$ (MeV)</th>
<th>$I_{cm}$ (keV)</th>
<th>Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.542$^b$</td>
<td>21.8 ± 0.1</td>
<td>α</td>
<td>21.6 ± 0.1</td>
<td>$^7\text{Li}, \alpha + ^6\text{He}$, ($^7\text{Li}, \alpha + ^9\text{Be}$)</td>
<td></td>
</tr>
<tr>
<td>9.56 ± 0.02$^c$</td>
<td>22.4 ± 0.1</td>
<td>α</td>
<td>23.0 ± 0.1</td>
<td>($^7\text{Li}, \alpha + ^6\text{He}$)</td>
<td></td>
</tr>
<tr>
<td>10.15 ± 0.02d</td>
<td>23.0 ± 0.1</td>
<td>α</td>
<td>23.35 ± 0.05</td>
<td>($^7\text{Li}, \alpha + ^6\text{He}$)</td>
<td></td>
</tr>
<tr>
<td>10.57</td>
<td>200 ± 80$^d$</td>
<td>α</td>
<td>23.65 ± 0.05</td>
<td>($^7\text{Li}, \alpha + ^6\text{He}$)</td>
<td></td>
</tr>
<tr>
<td>11.23 ± 0.05</td>
<td>24.0 ± 0.1</td>
<td>α</td>
<td>24.0 ± 0.1</td>
<td>($^7\text{Li}, \alpha + ^6\text{He}$)</td>
<td></td>
</tr>
<tr>
<td>11.76</td>
<td>200 ± 80$^d$</td>
<td>α</td>
<td>24.25 ± 0.05</td>
<td>($^7\text{Li}, \alpha + ^6\text{He}$)</td>
<td></td>
</tr>
<tr>
<td>11.93 ± 0.1</td>
<td>290 ± 130$^d$</td>
<td>α</td>
<td>24.6 ± 0.1</td>
<td>($^7\text{Li}, \alpha + ^6\text{He}$)</td>
<td></td>
</tr>
<tr>
<td>13.05 ± 0.1</td>
<td>330 ± 150$^d$</td>
<td>α</td>
<td>24.8 ± 0.1</td>
<td>($^7\text{Li}, \alpha + ^6\text{He}$)</td>
<td></td>
</tr>
<tr>
<td>13.85 ± 0.1</td>
<td>310 ± 140$^d$</td>
<td>α</td>
<td>25.05 ± 0.1</td>
<td>($^7\text{Li}, \alpha + ^6\text{He}$)</td>
<td></td>
</tr>
<tr>
<td>17.79</td>
<td>400 ± 100$^d$</td>
<td>α</td>
<td>25.6 ± 0.1</td>
<td>($^7\text{Li}, \alpha + ^6\text{He}$)</td>
<td></td>
</tr>
<tr>
<td>18.15 ± 0.05$^e$</td>
<td>90 ± 30</td>
<td>t_1</td>
<td>25.95 ± 0.05</td>
<td>($^7\text{Li}, \alpha + ^6\text{He}$)</td>
<td></td>
</tr>
<tr>
<td>18.55</td>
<td>310</td>
<td>t_1</td>
<td>26.3 ± 0.1</td>
<td>($^7\text{Li}, \alpha + ^6\text{He}$)</td>
<td></td>
</tr>
<tr>
<td>(19.8)</td>
<td>26.8 ± 0.1</td>
<td>α</td>
<td>27.2 ± 0.2</td>
<td>($^7\text{Li}, \alpha + ^6\text{He}$)</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ [2003FL02, 2003FL02, 2003FL02, 2003FL02].

$^b$ $\Gamma_n = 22 ± 8$ eV [2002LI15].

$^c$ $J^z = 2^*$, $\Gamma_n = 23 ± 6$ keV [2002LI15].

$^d$ $J^z = 3^-$ [2001CU06].

$^e$ $J^z = (0^-)$ [2002LI15].

$^f$ Not corrected for experimental system resolution and therefore upper limits [2003FL02].
The scattering amplitude (bound) $a = 7.778 \pm 0.003$ fm, $\sigma_{\text{free}} = 6.151 \pm 0.005$ b [1981MUZQ]. The difference in the spin-dependent scattering lengths, $b^+ - b^-$ is $+0.24 \pm 0.07$ [1987GL06]. See also [1987LY01]. Total cross section measurements have been reported for $E_n = 0.002$ eV to 2.6 GeV/c [see [1979AJ01,1984AJ01]] and at 24 keV [1983AI01], 7 to 15 MeV ([1983DA22]; also reaction cross sections) and 10.96, 13.89 and 16.89 MeV ([1985TE01]; for $n_0$ and $n_2$).

Observe resonances are displayed in Table 10.11. Analysis of polarization and differential cross section data leads to the $J^\pi = 3^-$, $2^+$ assignments for $^{10}\text{Be}^*$ (7.37, 7.55), respectively. Below $E_n = 0.5$ MeV the scattering cross section reflects the effect of bound $1^-$ and $2^-$ states, presumably $^{10}\text{Be}^*$ (5.960, 6.26). There is also indication of interference with s-wave background and with a broad $l = 1$, $J^\pi = 3^+$ state. The structure at $E_n = 2.73$ MeV is ascribed to two levels: a broad state at about 2.85 MeV with $J^\pi = (2^+)$, and a narrow one at $E_n = 2.73$ MeV, $\Gamma^\text{cm} \approx 100$ keV, with a probable assignment of $J^\pi = 4^-$. The $4^-$ assignment results from a study of the polarization of the $n_0$ group at $E_n = 2.60$ to 2.77 MeV. A rapid variation of the polarization over this interval is observed, and the data are consistent with $4^-$ ($l = 2$) for $^{10}\text{Be}^*$ (9.27). A weak dip at $E_n \approx 4.3$ MeV is ascribed to a level with $J \geq 1$. See [1974AJ01] for references. The analyzing power has been measured for $E_n = 1.6$ to 15 MeV [see [1984AJ01]] and at $E_n = 9$ to 17 MeV ([1984BY03]; $n_0, n_2$).

The non-elastic and the $(n, 2n)$ cross sections rise rapidly to $\approx 0.6$ b ($\approx 0.5$ b for (n,2n)) at $E_n \approx 3.5$ MeV and then stay approximately constant to $E_n = 15$ MeV; see [1979AJ01,1984AJ01]. For total $\gamma$-ray production cross sections for $E_n = 2$ to 25 MeV, see [1986GO1L]. See also references cited in [1988AJ01].

Cross sections have been measured at $E_n = 14.1$–14.9 MeV for reaction (a), and at 16.3–18.8 MeV for reaction (b); see [1979AJ01]. For reaction (c), measurements have been reported at $E_n = 13.3$–15.0 (t), at 22.5 MeV (see [1979AJ01]), and at 14.6 MeV

### Table 10.11

Resonances in $^9\text{Be}(n, n)^9\text{Be}^m$

<table>
<thead>
<tr>
<th>$E_{\text{res}}$ (MeV ± keV)</th>
<th>$^{10}\text{Be}^*$ (MeV)</th>
<th>$\Gamma^\text{cm}$ (keV)</th>
<th>$J^\pi$</th>
<th>$l$</th>
<th>$a^{2b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6220 ± 0.8</td>
<td>7.371</td>
<td>15.7 ± 0.5</td>
<td>3$^-$</td>
<td>2</td>
<td>0.075</td>
</tr>
<tr>
<td>0.8118 ± 0.7</td>
<td>7.542</td>
<td>6.3 ± 0.8</td>
<td>2$^+$</td>
<td>1</td>
<td>0.0028</td>
</tr>
<tr>
<td>2.73</td>
<td>9.27</td>
<td>$\approx 100$</td>
<td>(4$^-$)</td>
<td>(2)</td>
<td></td>
</tr>
<tr>
<td>(2.85)</td>
<td>9.4</td>
<td>$\approx 400$</td>
<td>(2$^+$)</td>
<td>(1)</td>
<td></td>
</tr>
<tr>
<td>4.3</td>
<td>10.7</td>
<td>$\geq 1$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**a** For references see Table 10.3 in [1979AJ01].

**b** $R = 5.6$ fm.
10\text{Be}


[1987ZA01]. A measurement of the $^9\text{Be}(n, \gamma)^7\text{Li}$ inclusive cross sections that encompassed $E_n = 12$–200 MeV observed peaks corresponding to $^{10}\text{Be}^*(17.79, 18.55, 21.22, 22.26, (24.0))$ [2002NE02]. For the 18.55 and 24.0 MeV states, the peaks were observed at 18.76 and 23.4 MeV, respectively.

12. $^9\text{Be}(n, \alpha)^4\text{He}$, $Q_m = -0.6011$, $E_b = 6.8122$

The cross section for production of $^4\text{He}$ shows a smooth rise to a broad maximum of 104 ± 7 mb at 3.0 MeV, followed by a gradual decrease to 70 mb at 4.4 MeV. From $E_n = 3.9$ to 8.6 MeV, the cross section decreases smoothly from 100 mb to 32 mb. Excitation functions have been measured for $\alpha_0$ and $\alpha_1$ for $E_n = 12.2$ to 18.0 MeV: see [1979AJ01] for references.

13. (a) $^9\text{Be}(p, \pi^+)^{10}\text{Be}$, $Q_m = -133.5403$
(b) $^9\text{Be}(p, K^+)$

Angular distributions for reaction (a) have been studied at $E_p = 185$ to 800 MeV [see [1984AJ01]] and at $E_p = 650$ MeV ([1986HO23]; to $^{10}\text{Be}^*(0, 3.37)$). States at $E_x = 6.07 \pm 0.13, 7.39 \pm 0.13, 9.31 \pm 0.24, 11.76$ MeV have also been populated. $\alpha_0$ measurements involving $^{10}\text{Be}^*(0, 3.37)$ are reported at $E_p = 200$ to 250 MeV [see [1984AJ01]] and at 650 MeV [1986HO23].

For reaction (b), the $K^+$ production cross sections were measured for $E_p = 835$–990 MeV [1988KO36]. Calculations for one- and two-step $K^+$ production for $E_p = 0.8$–3 GeV are given in [2000PA15].

14. $^9\text{Be}(d, p)^{10}\text{Be}$, $Q_m = 4.5877$

Angular distributions of proton groups have been studied at many energies in the range $E_d = 0.06$ to 17.3 MeV and at 698 MeV [see [1979AJ01,1984AJ01,1988AJ01] and [1997YA02]], as well as at $E_d = 2.0$ to 2.8 MeV ([1984AN16,1984DE46]; $p_0$, $p_1$; also VAP) and $E_d = 12.5$ MeV ([1987VA13]; $p_0$, $p_1$). The angular distributions show $I_n = 1$ transfer for $^{10}\text{Be}^*(0, 3.37, 5.958, 7.54)$, $I_n = 0$ transfer for $^{10}\text{Be}^*(5.960, 6.26)$, $I_n = 2$ transfer for $^{10}\text{Be}^*(7.37)$. $^{10}\text{Be}^*(6.18, 9.27, 9.6)$ are also populated, as are two states at $E_x = 10.57 \pm 0.03$ and 11.76 ± 0.02 MeV. The state reported by [1974AN27] at 9.4 MeV is most likely the 9.6 MeV $2^+$ state based on its separation from the 9.27 MeV state [2001CU06]. $^{10}\text{Be}^*(9.27, 9.6, 11.76)$ have $\Gamma_{c.m.} = 150 \pm 20, 291 \pm 20$ and 121 ± 10 keV, respectively. See [1979AJ01] for references. See also [1989SZ02,1995LY03,1998LE27, 2000GE16].

Angular distributions and excitation functions for $^9\text{Be}(d, p_0)$ and $(d, p_1)$ were measured for the energy range $E_{cm} = 57$–139 keV [1997YA02,1997YA08]. Astrophysical $S(E)$-factors were deduced and the spectroscopic factor $S = 0.92$ was deduced for $^9\text{Be}(d, p_0)$.
[2000GE16] analyzed $\sigma(E)$ and $S(E)$ for $E = 0.085$–11 MeV and evaluated the impact of this reaction for forming heavier B, C and N nuclei in nucleosynthesis.

At $E_d = 1.0$ MeV, $p + \gamma$ coincidences were measured. In this experiment $E_x = 3368.4 \pm 0.43$ keV was measured, which confirms $E_x = 3368.03 \pm 0.03$ keV [Table 10.5] for $^{10}\text{Be}^*(3.3)$ [1999BU26]: see reaction 55.
Radiative transitions in $^9\text{Be}(d,p)^{10}\text{Be}$

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>Transition</th>
<th>$\Delta J^\pi$</th>
<th>Mult.</th>
<th>Branch (%)</th>
<th>$\tau_\gamma$ (ps)</th>
<th>$I_\gamma^*$ (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3368.0 ± 0.2</td>
<td>3.37 → g.s.</td>
<td>$2^+ \rightarrow 0^+$</td>
<td>E2</td>
<td>100</td>
<td>0.189 ± 0.020</td>
<td>3.48 ± 0.37</td>
</tr>
<tr>
<td>5958.3 ± 0.3</td>
<td>5.96 → 3.37</td>
<td>$2^+ \rightarrow 2^+$</td>
<td>M1 $\geq$ 90</td>
<td>&lt; 0.08</td>
<td>0.160 ± 0.030</td>
<td>4.11 ± 0.78</td>
</tr>
<tr>
<td>5959.9 ± 0.6</td>
<td>5.96 → g.s.</td>
<td>$2^+ \rightarrow 0^+$</td>
<td>E2</td>
<td>&lt; 10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6179.3 ± 0.7</td>
<td>6.18 → 5.96</td>
<td>$0^+ \rightarrow 1^-$</td>
<td>E1</td>
<td>83$^{+10}_{-6}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6263.3 ± 5</td>
<td>6.26 → 5.96</td>
<td>$2^+ \rightarrow 1^-$</td>
<td>M1 $\leq$ 1</td>
<td>1.1$^{+0.4}_{-0.3}$</td>
<td>0.14 ± 0.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.26 → g.s.</td>
<td>$0^+ \rightarrow 0^+$</td>
<td>E0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ See Table 10.4 in [1979AJ01] for references. However, note that there are several typographical errors in the $^{10}\text{Be}^*$ (6.18) decay.

At $E_\gamma = 15.3$ MeV the $p_0$ and $p_1 + \gamma_1$ double-differential cross sections were measured and evaluated with coupled-channel calculations which suggest that multistep processes are important in the reaction mechanism [2001ZE09].

Attempts to understand the $\gamma$-decay of $^{10}\text{Be}^*$ (5.96) and its population in $^9\text{Be}(n,\gamma)^{10}\text{Be}$ led to the discovery that it consisted of two states separated by 1.6 ± 0.5 keV. The lower of the two has $J^\pi = 2^+$ and decays primarily by a cascade transition via $^{10}\text{Be}^*$ (3.37) [it is the state fed directly in the $^9\text{Be}(n,\gamma)$ decay]; the higher state has $J^\pi = 1^-$ and decays mainly to the $^{10}\text{Be}_{g.s.}$. Angular distributions measured with the $\gamma$-ray detector located normal to the reaction plane lead to $l_\theta$ values consistent with the assignments of $2^+$ and $1^-$ for $^{10}\text{Be}^*$ (5.9584, 5.9599) obtained from the character of the $\gamma$-decay. $^{10}\text{Be}^*$ (6.18) decays primarily to $^{10}\text{Be}^*$ (3.37): $E_\gamma = 219.4 ± 0.3$ keV for the 6.18 → 5.96 transition. See Table 10.12 for a listing of the information on radiative transitions obtained in this reaction and lifetime measurements. For $(p,\gamma)$ correlations through $^{10}\text{Be}^*$ (3.37) see [1987VA13] and references in [1974AJ01]. For polarization measurements see $^{11}$B in [1990AJ01].

15. $^9\text{Be}(\alpha, ^3\text{He})^{10}\text{Be}$, $Q_m = -13.7654$

Angular distributions have been studied at $E_\alpha = 65$ MeV to $^{10}\text{Be}^*$ (0, 3.37, 5.96, 6.26, 7.37, 7.54, 9.33[u], 11.88). DWBA analyses of these lead to spectroscopic factors [1980HA33] which are in poor agreement with those reported in other reactions: see [1984AJ01].

Cluster model analyses of the reaction [1996VO03,1997VO06,1997VO17] explain the levels between 5.95 and 6.26 MeV as $2\alpha$--$2n$-cluster states, by analogy with cluster states in $^9\text{Be}$. The analysis further suggests that states at 5.960, 6.263, 7.371, 9.27 and 11.76 MeV (with $J^\pi = 1^-, 2^-, 3^-, 4^-$ and $5^-$, respectively) comprise the $K^\pi = 1^-$ rotational band.
Table 10.13

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$J^\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00 ± 0.06</td>
<td>0$^+$</td>
</tr>
<tr>
<td>3.31 ± 0.06</td>
<td>2$^+$</td>
</tr>
<tr>
<td>5.91 ± 0.06</td>
<td>2$^+$, 1$^-$</td>
</tr>
<tr>
<td>7.31 ± 0.07</td>
<td>3$^-$</td>
</tr>
<tr>
<td>9.20 ± 0.06</td>
<td>4$^-$</td>
</tr>
<tr>
<td>9.58 ± 0.06</td>
<td>4$^-$</td>
</tr>
<tr>
<td>11.79 ± 0.06</td>
<td>4$^-$</td>
</tr>
<tr>
<td>13.78 ± 0.06</td>
<td>4$^-$</td>
</tr>
<tr>
<td>15.25 ± 0.06</td>
<td>4$^-$</td>
</tr>
</tbody>
</table>

$^a$ W.N. Catford, private communication.

16. $^9$Be($^6$He,$^5$He)$^{10}$Be, $Q_m = 4.946$

At $E(^6$He) = 25 MeV/A, 1- and 2-neutron transfer cross sections were measured in a study of n–n correlations for neutrons in $^6$He [2003GE05]. The reaction was dominated by 1-neutron transfer.

17. (a) $^9$Be($^7$Li,$^6$Li)$^{10}$Be, $Q_m = -0.4381$

(b) $^9$Be($^7$Li,$\alpha + ^6$He)$^6$Li, $Q_m = -7.8514$

(c) $^9$Be($^8$Li,$^7$Li)$^{10}$Be, $Q_m = 4.7799$

Angular distributions have been measured at $E(^7$Li) = 34 MeV (reactions (a) and (b)) to $^{10}$Be$_{g.s.}$, $S = 2.07$, and $^{10}$Be$^*$($3.4$), $S = 0.42$ ($p_{1/2}$), 0.38 ($p_{3/2}$): see [1979AJ01]. At $E(^7$Li) = 52 MeV, states are reported at $^{10}$Be$^*$($0$, 3.37, $\approx 6$ (multiplet), 7.5 (doublet), 9.6, 10.2, 11.8) [2001MI39]. At $E(^8$Li) = 11 MeV [1998KO17] and 14.3 MeV [1989BE28, 1993BE22] angular distributions for $^{10}$Be$^*$($0$, 3.37) have been measured. A DWBA analysis of the $E(^8$Li) = 14.3 MeV data yields spectroscopic factors of $S_{g.s.} = 4.0$ and $S_{3.37} = 0.2$ ($p_{1/2}$). At $E(^8$Be) = 20 MeV an angular distribution involving $^8$Be$_{g.s.}$ + $^{10}$Be$_{g.s.}$ has been measured: transitions to excited states of $^{10}$Be are very weak [1985JA09].

18. $^9$Be($^9$Be,$^8$Be)$^{10}$Be, $Q_m = 5.1468$

At $E(^8$Be) = 20 MeV an angular distribution involving $^8$Be$_{g.s.}$ and $^{10}$Be$_{g.s.}$ was measured: transitions to excited states are weak [1985JA09]. At $E(^9$Be) = 48 MeV, excited states of $^{10}$Be were populated [2003AS04]: see Table 10.13. The excitation energy of $^{10}$Be states was deduced from the measured energy of the $^8$Be recoil, which was detected as two $\alpha$ particles. The $\alpha$-particle energy spectra were analyzed in a CCBA model analysis to justify their interpretation of spin values.

19. $^9$Be($^{11}$Be,$^{10}$Be)$^{10}$Be, $Q_m = 6.308$

The $^{10}$Be core excitations in the $^{11}$Be ground state were determined by measuring $^{10}$Be fragments in coincidence with $\gamma$-rays in $^9$Be($^{11}$Be,$^{10}$Be + $\gamma$)X at 60 MeV/A. The $\gamma$-rays
corresponding to $^{10}$Be$^\ast$(3.37, 5.96, 6.26) were observed in 6.1%, 6.6% and 9.1% of the events, respectively. This indicates a small 0d admixture to the $^{11}$Be ground state which is dominated by a 1s single-particle component [2000AU02]. In a different experiment at $E(^{11}\text{Be}) = 46 \text{ MeV}/A$, $\gamma$-ray plus $^{10}\text{Be}$ coincidences were observed. The $\gamma$-rays corresponding to transitions between 6.263 $\rightarrow$ 3.368 MeV, 5.96 $\rightarrow$ 0 MeV and 3.368 $\rightarrow$ 0 MeV were observed [2001CH46], though in this case excitation energies were not resolved in the charged particle spectra. See [1992WA22,2000PA53] for calculations of spectroscopic factors. Also see [1995KE02,1996ES01,1999TO07].

20. $^{9}\text{Be}(^{11}\text{B},^{10}\text{B})^{10}\text{Be}$, $Q_m = -4.642$

Differential cross sections for $^{9}\text{Be}(^{11}\text{B},^{10}\text{B})^{10}\text{Be}$ were measured at $E(^{11}\text{B}) = 45 \text{ MeV}$ for the angular range $\theta_{\text{lab}} = 10$$^{\circ}$$^{165}\circ$ [2003KY01]. The quasisymmetric distributions involving $^{10}\text{Be}^\ast$(0, 3.368) and $^{10}\text{Be}^\ast$(0.078, 1.74, 2.154, 3.587) were analyzed in a coupled-reaction-channels method. Spectroscopic amplitudes are discussed for all possible 1- and 2-step processes. Analysis indicates that the reaction proceeds primarily by one-step proton- or neutron transfer.

21. $^{9}\text{Be}(^{14}\text{N},^{13}\text{N})^{10}\text{Be}$, $Q_m = -3.7412$

At $E(^{14}\text{N}) = 217.9 \text{ MeV}$, $^{10}\text{Be}^\ast$(0, 3.37, 5.960, 6.25, 7.37, 9.27, 11.8, 15.34) states are reported with $J^\pi = 0^+, 2^+, 1^-(+2^+), 2^-, 3^-, 4^-, (5^-), (6^-)$, respectively [2003BO24, 2003BO38]. The data are interpreted by assuming that the levels are $\alpha$-cluster molecular states with the binding energy provided by the excess neutrons. In this analysis, the members of the $K^\pi = 1^+$ rotational band are described by the formula, $E_x \approx 0.25 (J(J+1)-1 \times 2) + 5.96 \text{ MeV}$. See also [2003HO30].

22. (a) $^{10}\text{Be}(p,p')^{10}\text{Be}$
(b) $^{10}\text{Be}(d,d)^{10}\text{Be}$

Angular distributions of the $p_0$ and $p_1$ groups have been measured at $E_p = 12.0$ to 16.0 MeV. The reaction was measured in inverse kinematics by scattering 59.2 MeV $^{10}\text{Be}$ projectiles from protons [2000IW02] and measuring the $^{10}\text{Be}$ recoils and associated de-excitation $\gamma$-rays. Scattering reactions involving $^{10}\text{Be}^\ast$(0, 3.77, 5.96) were observed. For the first excited state, a deformation length of $\delta = 1.80 \pm 0.25 \text{ fm}$, $\beta^2 = 0.635 \pm 0.042$ and $(M_n/M_p)/(N/Z) = 0.51 \pm 0.12$ are deduced. For the 5.96 MeV level, the branching ratio for decay via the 3.368 MeV state is 14$\pm$6% of the branch for decay directly to the ground state. For reaction (b), elastically scattered deuterons have been studied at $E_d = 12.0$ and 15.0 MeV; see [1974AJ01].

23. $^{10}\text{Be}(^{11}\text{Be},^{11}\text{Be})^{10}\text{Be}$

Theoretical analysis of elastic and inelastic $^{11}\text{Be}$ scattering suggest enhancement of the fusion process due to strong multi-step processes in the inelastic and transfer transitions of the active neutron. In some cases, a neck formation is suggested that is analogous to a “covalent bond” for $^{10}\text{Be}$–n–$^{10}\text{Be}$ [1995IM01].
24. (a) $^{10}\text{Be}(\gamma, \pi^+) ^{10}\text{Be}$, $Q_m = -140.1262$
(b) $^{10}\text{Be}(e, e' \pi^+) ^{10}\text{Be}$, $Q_m = -140.1262$

Differential cross sections have been measured to $^{10}\text{Be}^*$ at 0, 3.37, 5.96 MeV and at $E_\gamma = 183$ MeV [1984AJ01] and 320 MeV [1994SA02], indicates that core polarization non-local effects due to off-shell dynamics must be accounted for rigorously to obtain agreement with data. See also [1990BE49] for calculations at $E_\gamma \approx 200$ MeV and [1990ER03] for $E_\gamma = 180–320$ MeV.

25. $^{10}\text{Be}(\mu^-, \nu) ^{10}\text{Be}$, $Q_m = 105.1024$

Partial capture rates leading to the $2^+$ states $^{10}\text{Be}^*(3.37, 5.96)$ have been reported: see [1984AJ01]. A review of muon capture rates [1998MU17], discusses a renormalization of the nuclear vector and axial vector strengths.

26. $^{10}\text{Be}(\pi^-, \gamma) ^{10}\text{Be}$, $Q_m = 139.0142$

The photon spectrum from stopped pions is dominated by peaks corresponding to $^{10}\text{Be}^*(0, 3.4, 6.0, 7.5, 9.4)$. Branching ratios have been obtained: those to $^{10}\text{Be}^*(0, 3.4)$ are $(2.02 \pm 0.17)\%$ and $(4.65 \pm 0.30)\%$, respectively [absolute branching ratio per stopped pion] [1986PE05]. See [1979AJ01] for the earlier work. Also see [1998NA01].

27. (a) $^{10}\text{Be}(n, p) ^{10}\text{Be}$, $Q_m = 0.2264$
(b) $^{10}\text{Be}(d, 2p) ^{10}\text{Be}$, $Q_m = -1.9982$

The cross section for reaction (a) at thermal neutron energies is $\sigma = 6.4 \pm 0.5$ mb, which is one order of magnitude lower than that of the (n,t) channel [1987LA16]. At $E_n = 96$ MeV, the $^{10}\text{Be}$ excitation spectra was evaluated by carrying out a multipole decomposition up to $E_x = 35$ MeV [2001RI02] to deduce the Gamow–Teller strength distribution; while low-lying states were unresolved, the high excitation spectra was dominated by a broad $L = 1$ peak that was centered at $E_x = 22$ MeV. Also see [1974AJ01] and $^{11}\text{B}$ in [1990AJ01]. For reaction (b) at $E_d = 55$ MeV, states are reported at $^{10}\text{Be}^*(0, 3.37, 5.96, 7.37, 7.54, 9.27)[u], 9.4[u]) [u = unresolved] [1979ST15], and angular distributions are given for the $J^\pi = 0^+ \ ^{10}\text{Be}_{g.s.}$ and the $J^\pi = 2^+ \ ^{10}\text{Be}'$ at 3.37, 5.96 and 9.4 MeV.

28. $^{10}\text{Be}(t, ^3\text{He}) ^{10}\text{Be}$, $Q_m = -0.5374$

At $E_t = 381$ MeV, states were observed at 0, 3.37, 5.96 and 9.4 MeV with some strength at 12–13.25 MeV [1997DA28,1998DA05]. A proportionality between the 0-degree ($^3\text{He}$) cross section and the Gamow–Teller strength deduced from $\beta$-decay measurements is discussed. The 3.37, 5.96 and 9.4 MeV states are identified as spin-flip Gamow–Teller excitations ($\Delta S = 1, \Delta T = 1$). $J^\pi = 3^+$ is suggested for the 9.4 MeV state, though $2^+$ or $4^+$ cannot be ruled out. Shell model predictions indicate $J^\pi = 3^+$ Isobaric Analog States
(IAS) in $^{10}\text{Be}$, $^{10}\text{B}$ and $^{10}\text{C}$ at approximately 9, 11 and 8 MeV, respectively [1993WA06, 2001MI29]. However, the uncertainty in $J^\pi$ and lack of observation of these states in $^{10}\text{B}$ and $^{10}\text{C}$ prevents an acceptance of this suggested $J^\pi = 3^+$ state as a new level at the present time; we associate this level with the 9.56 MeV, $J^\pi = 2^+$ level in Table 10.5. The $2^+$ states at 3.37 and 5.96 MeV are Gamow–Teller excitations and the IAS of the 3.37 and 5.3 MeV states in $^{10}\text{C}$. The values $B(GT^-) = 0.68 \pm 0.02$ from $^{10}\text{B}(p, n)^{10}\text{C}^*$ (5.38) and $B(GT^+) = 0.95 \pm 0.13$ from $^{10}\text{B}(t, ^3\text{He})^{10}\text{Be}^*(5.96)$ may indicate that the nuclear structure of $^{10}\text{Be}$ and $^{10}\text{C}$ differs because of the presence of the Coulomb force, giving rise to isospin symmetry violation.

29. $^{10}\text{Be}(^7\text{Li}, ^7\text{Be})^{10}\text{Be}^*$, $Q_m = -1.4182$

At $E(^7\text{Li}) = 39$ MeV, $^{10}\text{Be}^*(0, 3.37, 5.96)$ states were observed [1988ET02]. At this energy sequential processes are blocked, due to isospin mixing, and the one-step mechanism is most important. Also see [1989ET03].

30. $^{11}\text{Li}(\beta^-)^{11}\text{Be} \rightarrow ^{10}\text{Be} + n$, $Q_m = 20.1190$

New constraints on the $^{11}\text{Li}$ $\beta$-decay branch that feeds the $^{11}\text{Be}$ ground state indicate that the $^{11}\text{Li}$ $\beta$-delayed single neutron emission probability is $P_{1n} = 87.6 \pm 0.8\%$ [1997BO01].

The $\beta$-delayed neutrons following $^{11}\text{Li}$ decay were measured by [1997MO35]; results of their observations are presented in Table 10.14. A different technique, utilizing a $\beta$-neutron-$\gamma$-ray triple coincidence was employed by [1997AO01,1997AO04]; see Table 10.15. While the overall shape of the neutron energy spectra measured by [1997MO35] and [1997AO01,1997AO04] are in excellent agreement, the analysis of their data leads to different interpretations and conflicting results. The measurements of [1997AO01, 1997AO04] reported involvement of a new $^{11}\text{Be}$ state at $E_x = 8.03$ MeV; this new state is implied by both an $\approx 1.5$ MeV neutron in coincidence with the 2590 keV $^{10}\text{Be}^*(5.96 \rightarrow 3.36)$ $\gamma$-ray, and an $\approx 3.6$ MeV neutron in coincidence with the 3368 keV $^{10}\text{Be}^*(3.36 \rightarrow 0)$ $\gamma$-ray. However, the interpretation of $\beta$–n coincidences by [1997MO35] included low-energy neutrons from the unobserved $^{11}\text{Be}^*(3.87, 3.96) \rightarrow ^{10}\text{Be}^*(3.36) + n$ and $^{11}\text{Be}^*(6.51, 6.70, 7.03) \rightarrow ^{10}\text{Be}^*(\approx 6) + n$ decay branches into the analysis, and with their inferred branching ratios it was not necessary to introduce a new state at 8.03 MeV.

To address the question of a possible level in $^{11}\text{Be}$ at $E_x = 8.03$ MeV, [2003FY01] developed a procedure to evaluate Doppler broadening in isotropic $\gamma$-ray decay that occurs, for example, following $\beta$-delayed neutron decay. A model was developed that indicates a well-defined $\gamma$-ray spectrum shape that depends on recoil velocity after decay, the level lifetime, and recoil energy-losses/stopping powers in the target. The 2590 keV $\gamma$-ray from $^{10}\text{Be}^*(5.958)$ decay was evaluated, and the observed Doppler broadening was consistent with population of this level via neutron-decay from a $^{11}\text{Be}$ level around $E_x = 8.6$–9.1 MeV. This interpretation favors the analysis of [1997AO01,1997AO04].

For earlier work see [1984AJ01,1988AJ01] where population of complex decay branches are reported.
Table 10.14

$^{10}$Be levels observed following $^{11}$Li $\beta$-delayed neutron decay in a $\beta$–n coincidence measurement [1997MO35]

<table>
<thead>
<tr>
<th>Decay to $^{11}$Be$^*$ (MeV)</th>
<th>Branching ratio (%)</th>
<th>$B$(GT)</th>
<th>$^{11}$Be n-decay to $^{10}$Be$^*$ (MeV)</th>
<th>Branching ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.5 ± 6.0</td>
<td>0.0084 ± 0.0009</td>
<td>0</td>
<td>33.3</td>
</tr>
<tr>
<td>0.32</td>
<td>7.8 ± 0.8</td>
<td></td>
<td>0.045 ± 0.003</td>
<td>16.4</td>
</tr>
<tr>
<td>2.643</td>
<td>33.3 ± 2.0</td>
<td></td>
<td>3.368</td>
<td>b</td>
</tr>
<tr>
<td>3.866</td>
<td>(16.4 + x) ± 1.0$^b$</td>
<td>0.021 ± 0.03</td>
<td>0.050 ± 0.005</td>
<td>10</td>
</tr>
<tr>
<td>3.955</td>
<td>≈ 6.4 + y$^b$</td>
<td></td>
<td>5.958, 6.179</td>
<td>≈ 9</td>
</tr>
<tr>
<td>5.15</td>
<td>4.9 ± 0.5</td>
<td></td>
<td>2n-decay to $^9$Be$^d$</td>
<td>2.8</td>
</tr>
<tr>
<td>5.849</td>
<td>10 ± 1</td>
<td></td>
<td>6.179</td>
<td>1.0</td>
</tr>
<tr>
<td>6.51–7.03</td>
<td>≈ 4</td>
<td></td>
<td>9.403</td>
<td>2.5</td>
</tr>
<tr>
<td>≈ 10.6</td>
<td>6.3 ± 0.7</td>
<td></td>
<td>1.6 n-decay to $^8$Be$^e$</td>
<td></td>
</tr>
<tr>
<td>18.1</td>
<td>≈ 0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*a* Branching ratios relative to 100 $^{11}$Li decays.

$^{11}$Li decays following the branches $^{11}$Li → $^{11}$Be$^*$ (3.866, 3.955) → $^{10}$Be$^*$ (3.368) produce very low energy neutrons and lead to an additional ≈ 7.5% (= x + y) of unobserved strength that should be shared by decays to $^{11}$Be$^*$ (3.866, 3.955).

$c$ $^{11}$Li decays following the branches $^{11}$Li → $^{11}$Be$^*$ (6.51–7.03) → $^{10}$Be$^*$ (5.958, 6.179) produce very low energy neutrons and lead to ≈ 9% of unobserved strength that should be shared by decays to $^{11}$Be$^*$ (6.51–7.03).

$d$ $P_{2n} = 4.2 ± 0.4\%$ [1997BO01].

c $P_{3n} = 1.9 ± 0.2\%$ [1997BO01].

Table 10.15

$^{10}$Be levels observed following $^{11}$Li $\beta$-delayed neutron decay in a triple coincidence ($\beta$–n–$\gamma$) measurement [1997AO01,1997AO04]

<table>
<thead>
<tr>
<th>Decay to $^{11}$Be$^*$ (MeV)</th>
<th>$J^\pi$ Branching ratio (%)</th>
<th>$\log f t$</th>
<th>$^{11}$Be$^<em>$ n-decay to $^{10}$Be$^</em>$</th>
<th>$E_x$ (MeV)</th>
<th>$J^\pi$ Branching ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.32</td>
<td>$\frac{1}{2}^-$</td>
<td>7.6 ± 0.8</td>
<td>5.67 ± 0.04</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>2.69</td>
<td>$\frac{3}{2}^-$</td>
<td>26 ± 5</td>
<td>4.87 ± 0.08</td>
<td>0</td>
<td>0$^+$</td>
</tr>
<tr>
<td>3.96</td>
<td>$\frac{3}{2}^a$</td>
<td>21 ± 4</td>
<td>4.81 ± 0.08</td>
<td>3.368</td>
<td>2$^+$</td>
</tr>
<tr>
<td>5.24</td>
<td>$\frac{5}{2}^-$</td>
<td>8.1 ± 1.6</td>
<td>5.05 ± 0.08</td>
<td>3.368</td>
<td>2$^+$</td>
</tr>
<tr>
<td>8.03 ± 0.05</td>
<td>$\frac{1}{2}, \frac{3}{2}^-</td>
<td>13 ± 3</td>
<td>4.43 ± 0.08</td>
<td>0</td>
<td>0$^+$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.368</td>
<td>2$^+$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.958</td>
<td>2$^+$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.179</td>
<td>0$^+$</td>
</tr>
</tbody>
</table>

$a$ Branching ratios relative to 100 $^{11}$Li decays.

$b$ One coauthor (D.J.M.) suggests $J^\pi = \frac{5}{2}^-$. 
Angular distributions were measured for $E(^{11}\text{Be}) = 35$ MeV/A [2000FO17, 2001WI05]. The $^{10}\text{Be}_{g.s.}$, 3.4 MeV and unresolved states near 6 MeV were observed. The spectroscopic factors for the $^{10}\text{Be}^*(3.37)$ state inferred from standard DWBA and coupled-channels analysis differ by roughly a factor of 1.7. A “best estimate” for describing the $^{11}\text{Be}$ ground-state wave function includes a 16% core excitation of the $^{10}\text{Be}^*(3.34)$ state $[2^+ \otimes d]$. Also see [1999TI04,2000YI02]. For calculations at $E(^{11}\text{Be}) = 800$ MeV see [1998CA18].

Structure is observed in the summed proton spectrum corresponding to $Q = -10.9 \pm 0.35, -14.7 \pm 0.4, -21.1 \pm 0.4, -35 \pm 1$ MeV: see [1974AJ01]. See also [1994SH21] for a quasiquantum multi-step reaction model.

Fusion evaporation products from $^{11}\text{B} + ^7\text{Li}$ were measured at $E_d = 11.8$ and 22 MeV to $^{10}\text{Be}_{g.s.}$ [see [1974AJ01]] and at 52 MeV to $^{10}\text{Be}^*(0, 3.37, 5.96, 9.6)$: $S = 0.65, 2.03, 0.13, 1.19$ (normalized to the theoretical value for the ground state); $\pi = +$ for $^{10}\text{Be}^*(9.6)$: see [1979AJ01].

Photo-breakup reactions on $^{12}\text{C}$ have been reported for $E_\gamma = 80–700$ MeV (see Table 10.16). Two-nucleon photoemission shows promise as a means to study short-range nucleon–nucleon correlations, however it is necessary to understand the reaction mechanism and final state interactions. Between the Giant Dipole Resonance and the $\Delta$-resonance, $\gamma$-ray absorption is primarily on clusters or pairs of nucleons which are emitted.
Table 10.16
Summary of two-proton photo- and electro-breakup measurements on $^{12}\text{C}$

<table>
<thead>
<tr>
<th>$E_\gamma$ (MeV)</th>
<th>Refs.</th>
<th>$E_e$ (MeV)</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>120–400</td>
<td>[1996MA02]</td>
<td>510</td>
<td>[1995Z001]</td>
</tr>
<tr>
<td>200–500</td>
<td>[1995CR04]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>250–600</td>
<td>[1998HA01]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>[1987KA13]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

after photon absorption. Above the $\Delta$ resonance ($E_\Delta \approx 300$ MeV) $\gamma$-rays may interact with a single nucleon to form a $\Delta$, which then either decays into a nucleon plus pion, or the $\Delta$ may interact with another nucleon leading to emission of a pair of nucleons. The missing-mass spectra show strong peaks corresponding to $(1p)^2$ and $(1p1s)$ proton pair removal, while the $(1s)^2$ peak is weak and broad which makes that contribution difficult to identify. Ejectile energy correlations appear to indicate that final state interactions play a role at low missing mass, however at high missing mass the energy appears to be divided between the two protons and hence final state interactions are not relevant. Polarization observables were measured by [2001PO19] and asymmetries were observed to be smaller than expected. See also [1994RY02,1996RY04,1998RY01,1999IR01].

38. $^{12}\text{C}(e, e'2p)^{10}\text{Be}$, $Q_m = -27.1846$

Electro-production of proton pairs on $^{12}\text{C}$ targets has been reported for electron energies ranging from $E = 0.1$–14.5 GeV: see Table 10.16. The $^{10}\text{Be}_{g.s.}$ is observed, but low-lying resonances are not resolved. Above $E_\Delta = 25$ MeV, peaks corresponding to $(1p)^2$, $(1p1s)$ and $(1s)^2$ proton pair removal are observed. As in ($\gamma$, 2p) reactions [see reaction 37], two-nucleon emission induced by virtual photons also shows promise as a means to study short-range nucleon–nucleon correlations; however the reaction mechanism and final state interactions must be understood. See also [1996RY04,1997RY01,2003AN15].

39. $^{12}\text{C}(\pi^-, n + p)^{10}\text{Be}$, $Q_m = 111.6032$

The reaction mechanism for the absorption of stopped pions on $\alpha$, np and pp clusters in $^{12}\text{C}$ is discussed in [1987GA11].

40. $^{12}\text{C}(n, ^3\text{He})^{10}\text{Be}$, $Q_m = -19.4666$

At $E_n = 40$–56 MeV, the pulse shape response for discriminating various final-state channels resulting from $n + ^{12}\text{C}$ interactions in NE213 and BC401a liquid scintillator was measured by [1994MO41]. See also [1989BR05] for calculated cross sections at $E_n = 15$–60 MeV.
41. 12C(6He, 10Be + 2α)

At $E(6\text{He}) = 18$ MeV, this reaction was studied by detecting the triple coincidence $(10\text{Be} + 2\alpha)$ [2004MI05]. The kinematical reconstruction indicates that $^{10}\text{Be}^*(0, 3.37)$ and the multiplet near $E_x \approx 6$ MeV participate in this reaction.

42. 12C(6Li, 8B) 10Be, $Q_m = -21.4414$

At $E(6\text{Li}) = 80$ MeV, $^{10}\text{Be}^*(0, 3.37, 5.96, 7.54, 9.4; J^\pi$ probably $2^+), 11.8$) are populated and the angular distribution to $^{10}\text{Be}_{gs}$ has been measured: see [1976WE09, 1977WE03].

43. 12C(9Be, 11C) 10Be, $Q_m = -11.9094$

The $^{10}\text{Be}^*(0, 3.368)$ states, and higher lying unresolved states were observed at $E(9\text{Be}) = 40.1$ MeV [1999CA48].

44. 12C(11B, 13N) 10Be, $Q_m = -9.284$

At $E(11\text{B}) = 190$ MeV, the $J^\pi = 0^+$ $^{10}\text{Be}_{gs}$, and $J^\pi = 2^+$ excited states at $^{10}\text{Be}^*(3.36, 5.95, 9.4)$ excited states are observed [1998BE63].

45. 12C(12Be, α + 6He) 14C, $Q_m = 2.037$

Excited states in $^{10}\text{Be}$ were reconstructed from the $\alpha + 6\text{He}$ relative energy spectra at $E(12\text{Be}) = 378$ MeV [2001FR02]. Tentative evidence was found for states at $E_x = 13.2, 14.8$ and 16.1 MeV, while other known levels were observed at 11.9 and 17.2 MeV.

46. 12C(12C, α + 6He) 14C, $Q_m = -20.6141$

At $E(12\text{C}) = 357$ MeV, the $^{10}\text{Be}^*(0, 3.37, 5.96, 7.54, 9.4)$ levels were populated [1996ST29]. The $J^\pi = 0^+$ $^{10}\text{Be}_{gs}$ ground state is strongly populated and appears to result from a two-proton transfer which tends to leave the neutron configuration undisturbed.

47. 12C(15N, 17F) 10Be, $Q_m = -14.4567$

At $E(15\text{N}) = 318.5$ MeV, known $^{10}\text{Be}$ levels at 0, 3.37, 5.96, 7.37 and 9.5 MeV were observed [2001BO35]. Additional measurements by [2001BO35] at $E(15\text{N}) = 240$ MeV observed known levels at 3.37, 5.96, 7.37 [u] + 7.54 [u], 9.27 [u] + 9.55, 10.5, 11.8 MeV [u = unresolved] and new levels at 13.6 ± 0.1, 15.3 ± 0.2, 16.9 ± 0.2 MeV with $\Gamma$ = 200 ± 50 keV, 0.8 ± 0.2 MeV and 1.4 ± 0.3 MeV, respectively.

48. 13C(π+, 3p) 10Be, $Q_m = 108.2216$

The mechanism for $\pi^+$ absorption on 2 and 3 nucleon clusters in targets ranging from Li to C was studied using pions at $E_{\pi^+} = 50, 100, 140$ and 180 MeV [1992RA11].
Table 10.17
10 Be levels from 13 C(t, 6 Li)10 Be [1989SI02]

<table>
<thead>
<tr>
<th>Ex (MeV)</th>
<th>Jπ</th>
<th>L</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0+</td>
<td>1</td>
<td>0.16</td>
</tr>
<tr>
<td>3.36</td>
<td>2+</td>
<td>3a</td>
<td>3.1</td>
</tr>
<tr>
<td>5.96</td>
<td>4+b</td>
<td>3a</td>
<td>4.1</td>
</tr>
</tbody>
</table>

a [1975KU01] suggest L = 1 should be dominant.
b Levels at Ex = 5.96 MeV are known to have Jπ = 2+ and 1−. See Table 10.5.

49. 13 C(p, d + 2p)10 Be, Qm = −29.9064

See 12 C in [1990AJ01].

50. 13 C(t, 6 Li)10 Be, Qm = −8.6187

Angular distributions were measured at E(3H) = 38 MeV [1989SI02]. 10 Be∗(0, 3.36, 5.96) levels were observed and a DWBA analysis was used to extract spectroscopic factors shown in Table 10.17. The results indicate that more strength goes to the 10 Be excited states than shell model calculations predict.

51. 14 C(14 C, 18 O)10 Be, Qm = −5.79

See [1985KO04].

52. 14 C(18 O, 22 Ne)10 Be, Qm = −2.34

At E(18 O) = 102 MeV, a study of α-unbound states in 22 Ne indicated that 10 Be∗(0, 3.37) participate in the reaction [2002CU04].

53. (a) 12 C, N, O, Mg, Al, Si, Mn, Fe, Ni, Au(p, 10 Be)X
(b) C, 14 N, 16 O(n, 10 Be)X

Astrophysical production of 10 Be has been evaluated by measuring formation cross sections for protons incident on 16 O and 28 Si at E_p = 30–500 MeV [1997SI29], on 12 C at E_p = 40–500 MeV [2002KI19] and on O, Mg, Al, Si, Mn, Fe and Ni targets at E_p = 100 MeV–2.6 GeV [1990DI13,1990DI06,1993BO41]. The results of [1997SI29] suggest “a soft solar proton spectrum with relatively few high energy protons over the last few million years”, when compared with 10 Be concentrations found in lunar rocks. See [1997BA2M,1997GR1H,1997MU1D,1997ZO1C] for surveys of terrestrial 10 Be concentrations, and see [2000NA34] for a model estimating 14 N, 16 O(p, 10 Be) and (n, 10 Be) cross sections for E_p = 10 MeV–10 GeV and for discussion of various atmospheric transport models for distributing 10 Be.

Spallation cross sections for E_p = 50–250 MeV protons on 16 O were measured and were compared with Monte Carlo predictions from MCNPX [1999CH50]; these data are
relevant, for example, for estimating secondary radiation induced in proton therapy treatments. The target mass dependence of the cross sections for formation of $^{10}\text{Be}$ from $E_p = 12$ GeV proton induced spallation reactions on Al through Au targets was measured by [1993SH27]. Overall, $^{10}\text{Be}$ production cross sections are found to increase with increasing target mass.

For reaction (b), the $^{10}\text{Be}$ production cross sections for neutron induced reactions on C, N and O targets were measured at $E_n = 14.6$ MeV by [2000SU23]. See also [2000NA34].

54. (a) $^{12}\text{C}(^{10}\text{Be}, X)$
(b) $^{28}\text{Si}(^{10}\text{Be}, X)$

At $E(^{10}\text{Be}) \approx 30$ MeV/A, the $^{10}\text{Be} + ^{12}\text{C}$ reaction was observed to populate various exit channels [2004AH02,2004AS02]. States at $E_x = 9.6 \pm 0.1$ and $10.2 \pm 0.1$ MeV were observed in the $^6\text{He} + \alpha$ breakup channel. Cross sections were given for breakup channels populating $^8\text{Be}^*(0, 3.0)$ and $^9\text{Be}^*(2.43)$, and other cross section were given for the (n, p) charge exchange reaction and proton pickup reaction that populate $^{10}\text{B}$ and $^{11}\text{B}$, respectively.

For reaction (b), fragmentation of $^{10}\text{Be}$ was measured on Si targets for $E(^{10}\text{Be}) = 20$–60 MeV/A [1996WA27] and $E(^{10}\text{Be}) = 30$–60 MeV/A [2001WA40]. The total reaction cross section was found to be near 1.55 b in this energy region, and $R_{\text{r.m.s.}}(^{10}\text{Be}) \approx 2.38$ fm is deduced from the cross section data.

55. $^{252}\text{Cf}$ ternary cold fission

The de-excitation of $^{10}\text{Be}^*$ nuclei formed in the ternary cold fission of $^{252}\text{Cf} \rightarrow ^{146}\text{Ba} + ^{96}\text{Sr} + ^{10}\text{Be}^*(3.37)$ yields $\gamma$-rays that are roughly 6 keV lower in energy [1998RA16] than expected from the accepted excitation energy of $E_x = 3368.03 \pm 0.03$ keV. The absence of Doppler broadening suggests that the $^{10}\text{Be}$ is formed and decays while in the potential well of the heavier Ba and Sr nuclei [1998RA16]. A theoretical analysis of the reaction explains the observation as an anharmonic perturbation, which shifts the excitation energy lower [2000MI07].

$^{10}\text{B}$ (Figs. 14, 15 and 17)

General

References to articles on general properties of $^{10}\text{B}$ published since the previous review [1988AJ01] are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for $^{10}\text{B}$ located on our website at: www.tunl.duke.edu/nucldata/General_Tables/10b.shtml.

$\mu = +1.80064475 \pm 0.0000057 \mu_N$ see [1989RA17];

$Q = +84.72 \pm 0.56$ mb see [1978LEZA, 1989RA17].
Mass of $^{10}\text{B}$  The mass excess adopted by [2003AU03] is 12050.7 ± 0.4 keV.

Isotopic abundance  (19.9 ± 0.2)% [1984DE1A].

$^{10}\text{B}^*(0.72)$: $\mu = +0.63 \pm 0.12 \mu_N$ see [1978LEZA,1989RA17].

$B(\text{E2})_\downarrow$ for $^{10}\text{B}^*(0.72) = 4.18 \pm 0.02 \text{ e}^2 \text{fm}^4$ [1983VE03].

Electromagnetic transitions

Detailed information on electromagnetic transition strengths in $^{10}\text{B}$ is displayed in Tables 10.19 and 10.20. Table 10.19 relates to levels below the proton threshold and draws on Table 10.21 for the lifetimes of bound levels and on Table 10.22 for radiative widths from the $^6\text{Li}(\alpha, \gamma)^{10}\text{B}$ reaction. With the exception of the 5.11 MeV $2^-$ level with one nucleon in the sd shell and the 5.18 MeV $1^+$ level with two nucleons in the sd shell, the remaining levels in Table 10.19 have been established as being dominantly p-shell in character. Furthermore, analysis of the empirical p-shell wave functions which best fit the electromagnetic data shows that the p-shell states all have mainly [42] spatial symmetry and that $L$ and $K_L$ (to distinguish the two D states) are rather good quantum numbers [1979KU05]. Table 10.20 relates to levels above the proton threshold studied mainly via the $^9\text{Be}(p, \gamma)^{10}\text{B}$ reaction. The region contains a number of overlapping resonances including a number of isospin-mixed s-wave resonances involving the analogs of the 5.96 MeV $1^-$ and 6.26 MeV $2^-$ levels of $^{10}\text{Be}$. The lowest negative-parity states also have mainly [42] spatial symmetry and in addition (51) SU(3) symmetry. Thus, the $1^-$ and $2^-; T = 1$ states above are mainly $^1\text{P}$ and $^1\text{D}$ in character while for the $T = 0$ states the dominant components are as follows: $^3\text{P}$ for the 5.11 MeV $2^-$ state, $^3\text{D}$ for the 6.13 MeV $3^-$ state, $^3\text{F}$ for the 6.56 MeV $4^-$ state, and $^3\text{P}$ for the 6.88 MeV $1^-$ state.

1. $^6\text{Li}(\alpha, \gamma)^{10}\text{B}$, \quad $Q_m = 4.4610$

Observed resonances are displayed in Table 10.22. For a discussion of isovector parity-mixing between the 5.11 MeV and 5.16 MeV levels of $^{10}\text{B}$ see [1984NA07] in which thick-target yields were measured with a $^6\text{Li}$ polarized target to obtain a parity-mixing parameter. In later work [1989BA24] strengths and mixing ratios of $\gamma$-transitions from these two levels were measured. However, it is clear that for the transitions to the 1.740 MeV level contributions from the double-escape peaks of stronger transitions to the 0.718 MeV level were not properly accounted for. For the $2^+; 1 \rightarrow 0^+$ transition, the published 4% branch disagrees with the limit of < 0.5% in Table 10.19 and would correspond to a $B(\text{E2})$ of 140 W.u. Similarly, the branch of 10.9% for the $2^-; 0 \rightarrow 0^+$; 1 transition corresponds to a $B(\text{M2})$ of 130 W.u. The mixing ratios from 3-point angular distributions also appear unreliable. Total transition strengths of $\omega\gamma_{cm} = 0.046 \pm 0.004 \text{ eV}$ and 0.385 ± 0.020 eV were determined for the $2^-$ and $2^+$ resonances, respectively, which are in good agreement with the values in Table 10.22. For a preliminary report involving a target of laser-polarized $^6\text{Li}$ atoms see [1987MU13]. See also the astrophysics-related work in [1996RE16,1997NO04].
2. (a) $^6\text{Li}(\alpha, n)^9\text{B}$, $Q_m = -3.9753$, $E_b = 4.4610$
(b) $^6\text{Li}(\alpha, p)^9\text{Be}$, $Q_m = -2.1249$
(c) $^6\text{Li}(\alpha, d)^8\text{Be}$, $Q_m = -1.5657$

The excitation functions for neutrons [from threshold to $E_{\alpha} = 15.5$ MeV] and for deuterons [$E_{\alpha} = 9.5$ to 25 MeV; $d_0$, $d_1$ over most of range] do not show resonance structure: see [1974AJ01,1979AJ01]. Reaction-mechanism studies of $(\alpha, p)$ and $(\alpha, d)$ at $E_{\alpha} = 26.7$ MeV are reported in [1990LI37,1989LI24], respectively. A calculation of the $(\alpha, d)$ cross section at $E_{\alpha} \leq 24$ MeV is described in [1994FU07].

3. (a) $^6\text{Li}(\alpha, \alpha)^6\text{Li}$, $E_b = 4.461008$
(b) $^6\text{Li}(\alpha, 2\alpha)^2\text{H}$, $Q_m = -1.473844$

Excitation functions of $\alpha_0$ and $\alpha_1$ have been reported for $E_{\alpha} \leq 18.0$ MeV and 9.5 to 12.5 MeV, respectively: see [1974AJ01]. Reported anomalies are displayed in Table 10.23. Elastic scattering and VAP measurements are reported for $E(^6\text{Li}) = 15.1$ to 22.7 MeV [see [1984AJ01]] and at $E(^6\text{Li}) = 19.8$ MeV ([1986CA1F]; also TAP). Differential cross section measurements at $E_{\alpha} = 50$ MeV are reported by [1992SA01,1996BU06]. Theoretical work reported since the previous review include: studies of target-clustering influence on exchange effects [1988LE06]; knock-out exchange contributions in RGM [1989LE07]; a description of a double-folding model potential [1993SI09]; calculations with a multi-configuration RGM [1995FU11]; a study of continuum-continuum coupling for $^6\text{Li} \rightarrow \alpha + d$ breakup data [1995KA07]; a folding-potential analysis for $E_{\alpha} = 3$–50.5 MeV [1995SA12]; and a study of coupling effects of resonant and continuum states for $^6\text{Li}(\alpha, \alpha)$ at $E_{\alpha} = 40$ MeV [1996SI13]. Small anomalies have been reported in reaction (b) corresponding to $^{10}\text{B}^*$(8.67, 9.65, 10.32, 11.65): see [1984AJ01]. See, however, Table 10.18. See also $^6\text{Li}$ in [1988AJ01,2002TI10,1987BU27], ([1986ST1E]; applications) and ([1986YA15,1988LE06]; theor.).

4. $^6\text{Li}(^6\text{Li}, d)^{10}\text{B}$, $Q_m = 2.9872$

Angular distributions of deuteron groups have been determined at $E(^6\text{Li}) = 2.4$ to 9.0 MeV ($d_0$, $d_1$, $d_3$) and 7.35 and 9.0 MeV ($d_4$, $d_5$). The $d_2$ groups corresponding to the isospin-forbidden reaction $^6\text{Li}(^6\text{Li}, d_2)^{10}\text{B}$ ($0^+$; 1) were observed weakly in early work (see [1974AJ01]) and $^{12}\text{C}$ in [1980AJ01]. More recent angular distribution measurements [1993WI13] at $E(^6\text{Li}) = 3$–8 MeV deduced the isospin-breaking matrix element.

A reaction-mechanism study of $^6\text{Li}(^6\text{Li}, d)^{10}\text{B}$ for $E_{cm} = 7.2$–13.3 MeV is described in [1987AR13].

5. $^7\text{Li}(^3\text{He}, \gamma)^{10}\text{B}$, $Q_m = 17.7883$

Capture $\gamma$-rays have been observed for $E(^3\text{He}) = 0.8$ to 6.0 MeV. The $\gamma_0$ and $\gamma_5$ yields [to $^{10}\text{B}^*(0, 4.77)$] show resonances at $E(^3\text{He}) = 1.1$ and 2.2 MeV [$E_{res} = 0.92$ and 2.1 MeV], the $\gamma_1$ and $\gamma_4$ yields [to $^{10}\text{B}^*(0.72, 3.59)$] at 1.4 MeV and the $\gamma_4$ yield at 3.4 MeV: see Table 10.10 in [1979AJ01]. Both the 1.1 and 2.2 MeV resonances
Table 10.18
Energy levels of $^{10}\text{B}$

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$J^\pi$; $\Gamma$</th>
<th>$\tau_m$ or $\Gamma_m$ (keV)</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>$3^+;0$</td>
<td>stable$^b$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.71835 ± 0.04</td>
<td>$1^+;0$</td>
<td>$\tau_m = 1.020 \pm 0.005$ ns$^c$</td>
<td>$\gamma$</td>
<td>1, 4, 5, 10, 12, 17, 18, 19, 20, 21, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 44, 45, 46, 47, 51, 52, 53, 54, 55, 56, 58, 59</td>
</tr>
<tr>
<td>1.74015 ± 0.17</td>
<td>$0^+;1$</td>
<td>7 ± 3 fs</td>
<td>$\gamma$</td>
<td>1, 4, 10, 12, 17, 18, 19, 20, 24, 25, 26, 27, 30, 42, 43, 44, 45, 46, 47, 51, 52, 56</td>
</tr>
<tr>
<td>2.154 ± 0.5</td>
<td>$1^+;0$</td>
<td>2.13 ± 0.20 ps</td>
<td>$\gamma$</td>
<td>1, 4, 12, 17, 18, 19, 20, 24, 25, 26, 27, 28, 30, 31, 36, 44, 45, 46, 47, 50, 51, 52, 53, 54, 55</td>
</tr>
<tr>
<td>3.5871 ± 0.5</td>
<td>$2^+;0$</td>
<td>153 ± 12 fs</td>
<td>$\gamma$</td>
<td>1, 4, 5, 12, 17, 18, 19, 24, 25, 26, 27, 28, 30, 31, 43, 44, 46, 51, 52, 53, 55, 58</td>
</tr>
<tr>
<td>4.774 ± 0.5</td>
<td>$3^+;0$</td>
<td>$\Gamma = 7.8 \pm 1.2$ eV$^d$</td>
<td>$\gamma, \alpha$</td>
<td>1, 4, 5, 11, 17, 18, 19, 24, 25, 26, 27, 28, 30, 31, 46, 51, 52, 53, 58, 60</td>
</tr>
<tr>
<td>5.1103 ± 0.6</td>
<td>$2^-;0$</td>
<td>0.98 ± 0.07 keV</td>
<td>$\gamma, \alpha$</td>
<td>1, 11, 12, 17, 18, 24, 25, 27, 31, 46, 52</td>
</tr>
<tr>
<td>5.1639 ± 0.6</td>
<td>$2^+;1$</td>
<td>1.8 ± 0.4 eV$^d$</td>
<td>$\gamma, \alpha$</td>
<td>1, 12, 17, 18, 24, 25, 27, 28, 43, 46, 51</td>
</tr>
<tr>
<td>5.18 ± 0.10</td>
<td>$1^+;0$</td>
<td>110 ± 10 keV</td>
<td>$\gamma, \alpha$</td>
<td>1, 3, 11, 12, 17, 18, 28, 31, 46</td>
</tr>
<tr>
<td>5.9195 ± 0.6</td>
<td>$2^+;0$</td>
<td>5.82 ± 0.06$^e$</td>
<td>$\gamma, \alpha$</td>
<td>1, 3, 11, 12, 17, 18, 19, 24, 27, 28, 30, 31, 46, 51, 52, 53</td>
</tr>
<tr>
<td>6.0250 ± 0.6</td>
<td>$4^+;0$</td>
<td>0.054 ± 0.22$^e$</td>
<td>$\gamma, \alpha$</td>
<td>1, 3, 11, 17, 18, 19, 24, 25, 26, 27, 28, 30, 31, 44, 46, 52, 53, 56, 58</td>
</tr>
<tr>
<td>6.1272 ± 0.7</td>
<td>$3^-;0$</td>
<td>1.52 ± 0.08$^e$</td>
<td>$\alpha$</td>
<td>3, 11, 17, 18, 19, 24, 25, 27, 28, 30, 44, 46, 52</td>
</tr>
<tr>
<td>6.560 ± 1.0$^f$</td>
<td>$4^-;0$</td>
<td>25.1 ± 1.1</td>
<td>$\alpha$</td>
<td>3, 11, 17, 18, 19, 24, 25, 27, 28, 30, 31, 44, 46, 51, 52, 60</td>
</tr>
<tr>
<td>6.873 ± 5</td>
<td>$1^-;0 + 1$</td>
<td>120 ± 5</td>
<td>$\gamma, p, d, \alpha$</td>
<td>1, 11, 12, 14, 16, 17</td>
</tr>
<tr>
<td>7.002 ± 6</td>
<td>(3+$^h$);0$^d$</td>
<td>100 ± 10</td>
<td>$p, d, \alpha$</td>
<td>3, 11, 16, 17, 19, 25, 27, 28, 30, 46, 52, 58</td>
</tr>
</tbody>
</table>

(continued on next page)
### Table 10.18 (continued)

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$J^π; T$</th>
<th>$τ_{m}$ or $Γ_{cm}$ (keV)</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.430 ± 10</td>
<td>1−; 1 + 0h</td>
<td>100 ± 10</td>
<td>$γ$, p, d, α</td>
<td>1, 12, 14, 16</td>
</tr>
<tr>
<td>7.469 ± 6h,i</td>
<td>2+; 1i</td>
<td>65 ± 10</td>
<td>$γ$, p</td>
<td>12, 14, 17, 19, 24, 46, 51, 56</td>
</tr>
<tr>
<td>7.480 ± 4h,i</td>
<td>2−; 0 + 1i</td>
<td>80 ± 8</td>
<td>$γ$, p, d, α</td>
<td>12, 14, 16, 19, 28</td>
</tr>
<tr>
<td>7.5599 ± 0.6</td>
<td>0+; 1</td>
<td>2.65 ± 0.18</td>
<td>$γ$, p</td>
<td>12, 14, 17, 46</td>
</tr>
<tr>
<td>(7.67 ± 30)</td>
<td>(1+; 0)</td>
<td>250 ± 20</td>
<td>p, (d), α</td>
<td>14, 16, 25</td>
</tr>
<tr>
<td>7.75 ± 30h</td>
<td>2−; 0 + 1i</td>
<td>210 ± 60h</td>
<td>$γ$, p, d, α</td>
<td>12, 14, 16, 17, 19, 25, 46</td>
</tr>
<tr>
<td>7.96 ± 70h</td>
<td>T = 0</td>
<td>285 ± 91</td>
<td>$α$, 6Li(3+)</td>
<td>11</td>
</tr>
<tr>
<td>8.07</td>
<td>2+; (0)</td>
<td>800 ± 200</td>
<td>p, d, α</td>
<td>14, 16, 17, 24, 25</td>
</tr>
<tr>
<td>8.68h²</td>
<td>(3+); 0k</td>
<td>p</td>
<td></td>
<td>16, 58</td>
</tr>
<tr>
<td>8.899 ± 6</td>
<td>3+; 1</td>
<td>84 ± 7</td>
<td>n, p, α</td>
<td>13, 14, 16, 17, 19, 24, 25, 51</td>
</tr>
<tr>
<td>8.894 ± 2</td>
<td>2+; 1</td>
<td>40 ± 1</td>
<td>p, α</td>
<td>14, 16, 19, 24, 25, 51</td>
</tr>
<tr>
<td>9.58 ± 60h</td>
<td>T = 0</td>
<td>257 ± 64</td>
<td>$α$, 6Li(3+)</td>
<td>11</td>
</tr>
<tr>
<td>10.84 ± 10</td>
<td>(2+, 3+, 4+)</td>
<td>300 ± 100</td>
<td>$γ$, n, p</td>
<td>12, 13, 14, 16, 24, 25, 46</td>
</tr>
<tr>
<td>11.52 ± 35</td>
<td></td>
<td>500 ± 100</td>
<td>($γ$), α</td>
<td>16, 24, 25, 44, 46</td>
</tr>
<tr>
<td>12.56 ± 30</td>
<td>(0+, 1+, 2+)</td>
<td>100 ± 30</td>
<td>$γ$, p</td>
<td>12, 24, 46</td>
</tr>
<tr>
<td>13.49 ± 5</td>
<td>(0+, 1+, 2+)</td>
<td>300 ± 50</td>
<td>$γ$, p</td>
<td>12, 24, 46</td>
</tr>
<tr>
<td>14.4 ± 100</td>
<td></td>
<td>800 ± 200</td>
<td>$γ$, p, α</td>
<td>3, 12, 44, 46</td>
</tr>
<tr>
<td>(18.2 ± 200)</td>
<td>(1500 ± 300)</td>
<td></td>
<td></td>
<td>46</td>
</tr>
<tr>
<td>18.43</td>
<td>2−; 1</td>
<td>340</td>
<td>$γ$, 3He</td>
<td>5, 7</td>
</tr>
<tr>
<td>18.80</td>
<td>2+</td>
<td>&lt; 600</td>
<td>$γ$, 3He, α</td>
<td>5, 9</td>
</tr>
<tr>
<td>19.29</td>
<td>2−; 1</td>
<td>190 ± 20</td>
<td>$γ$, n, p, 3He, α</td>
<td>5, 6, 7, 9</td>
</tr>
<tr>
<td>20.1 ± 100</td>
<td>1−; 1</td>
<td>broad</td>
<td>$γ$, n, p, t, 3He, α</td>
<td>5, 6, 7, 8, 9, 23</td>
</tr>
<tr>
<td>(21.1)</td>
<td></td>
<td>$γ$, 3He</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>23.1 ± 100</td>
<td></td>
<td>broad</td>
<td>$γ$, n</td>
<td>23</td>
</tr>
</tbody>
</table>

a See footnotes on level parameters changed since [1988AJ01]. See also Tables 10.19, 10.20, 10.21 and 10.24.

b $\mu = 1.80064475 ± 0.00000057 \mu N$, $Q = 84.72 ± 0.56$ mb.

c $\mu = +0.63 ± 0.12 \mu N$.

d See Table 10.22.

e See Table 10.23.

f See [1971YO05].

g See [1971YO05,1979OE01].

h See Table 10.24 and reaction 12.

i From [1969MO29]; see reaction 14 and Table 10.25.

j New levels since [1988AJ01].

k Energy and tentative spin assignment from [1979OE01]. If this is the same level as seen in reaction 16, the width is ≈ 220 keV (see Table 10.26) and decay modes of p, d, α are likely.

$[^{10}B^*(18.4, 19.3)]$ appear to result from s-wave capture; the subsequent decay is to two 3+ states $[^{10}B^*(0, 4.77)]$. Therefore the most likely assignment is $J^π = 2^−$; $T = 1$ for both [there appears to be no decay of these states via $α_2$ to $^6Li^+(3.56)$ which has $J^π = 0^+$; $T = 1$; see reaction 9]. The assignment for $[^{10}B^*(18.8)]$ [1.4 MeV resonance] is $1^+$ or $2^+$ but there appears to be $α_2$ decay and therefore $J^π = 2^+$. $[^{10}B^*(20.1)]$ [3.4 MeV resonance] has an isotropic angular distribution of $γ_2$ and therefore $J^π = 1^−$, $2^−$. The $γ_2$ group resonates at this energy which eliminates $2^−$. See [1974AJ01] for references.
Fig. 14. Energy levels of $^{10}$B. For $\gamma$ transitions see Fig. 15, and Tables 10.19 and 10.20. For notation see Fig. 2.
Fig. 15. $\gamma$ transitions for $^{10}\text{B}$. See Tables 10.19 and 10.20. For notation see Fig. 2.
Table 10.19
Electromagnetic transition strengths for levels below the proton threshold in $^{10}$B

<table>
<thead>
<tr>
<th>$E_i$ → $E_f$ (MeV)</th>
<th>$J_i^p$; $T_i$</th>
<th>$J_f^p$; $T_f$</th>
<th>Branch (%)</th>
<th>Mixing ratio ($\delta$, (E2/M1))</th>
<th>$\Gamma_\gamma$ (eV)</th>
<th>Mult.</th>
<th>$\Gamma_\gamma/\Gamma_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.718 → 0^a</td>
<td>1^+; 0 → 3^+; 0</td>
<td>100</td>
<td>(6.453 ± 0.032) × 10^{-7}</td>
<td>E2</td>
<td>3.240 ± 0.016</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.740 → 0.718^a</td>
<td>0^+; 1 → 1^+; 0</td>
<td>100</td>
<td>0.094 ± 0.040</td>
<td>M1</td>
<td>4.2 ± 1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.154 → 0^a,b,c</td>
<td>1^+; 0 → 3^+; 0</td>
<td>21.1 ± 1.6</td>
<td>(6.52 ± 0.79) × 10^{-5}</td>
<td>E2</td>
<td>1.33 ± 0.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>→ 0.718</td>
<td>→ 1^+; 0</td>
<td>27.3 ± 0.9</td>
<td>(5.6 ± 1.6) × 10^{-6}</td>
<td>M1</td>
<td>(9.1 ± 2.7) × 10^{-5}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.587 → 0a,b,c,d</td>
<td>2^+; 0 → 3^+; 0</td>
<td>19 ± 3</td>
<td>(5.19 ± 0.16) × 10^{-4}</td>
<td>E2</td>
<td>12.2 ± 1.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>→ 0.718</td>
<td>→ 1^+; 0</td>
<td>67 ± 3</td>
<td>(2.5 ± 1.5) × 10^{-4}</td>
<td>M1</td>
<td>0.107 ± 0.011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>→ 2.154</td>
<td>→ 1^+; 0</td>
<td>14 ± 2</td>
<td>(5.7 ± 1.7) × 10^{-4}</td>
<td>M1</td>
<td>(2.6 ± 1.5) × 10^{-4}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.774 → 0e,f,j</td>
<td>3^+; 0 → 3^+; 0</td>
<td>0.5 ± 0.1</td>
<td>&lt; 2.5 × 10^{-4}</td>
<td>E2</td>
<td>&lt; 5 × 10^{-4}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>→ 0.718</td>
<td>→ 1^+; 0</td>
<td>99.5 ± 0.1</td>
<td>(2.85 ± 0.27) × 10^{-3}</td>
<td>E2</td>
<td>13.9 ± 1.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>→ 5.110 → 0e,g,h</td>
<td>2^+; 0 → 3^+; 0</td>
<td>64 ± 7</td>
<td>(7.6 ± 3.4) × 10^{-5}</td>
<td>E2</td>
<td>11.9 ± 5.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.164 → 0e,i</td>
<td>2^+; 1 → 3^+; 0</td>
<td>4.4 ± 0.4</td>
<td>(5.3 ± 0.9) × 10^{-4}</td>
<td>E2</td>
<td>&lt; 4.8 × 10^{-5}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>→ 0.718</td>
<td>→ 1^+; 0</td>
<td>22.6 ± 0.6</td>
<td>(9.0 ± 2.0) × 10^{-5}</td>
<td>E2</td>
<td>&lt; 4.2 × 10^{-2}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>→ 1.740</td>
<td>→ 0^+; 1</td>
<td>5 ± 5</td>
<td>(1.79 ± 0.15) × 10^{-2}</td>
<td>E2</td>
<td>15.4 ± 1.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.587 → 0e,i</td>
<td>2^+; 0 → 2^+; 0</td>
<td>7.8 ± 0.3</td>
<td>(1.8 ± 1.8) × 10^{-3}</td>
<td>M2</td>
<td>&lt; 120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>→ 0.718</td>
<td>→ 1^+; 0</td>
<td>22.6 ± 0.6</td>
<td>(2.1 ± 0.4) × 10^{-2}</td>
<td>E2</td>
<td>(3.7 ± 1.1) × 10^{-4}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>→ 1.740</td>
<td>→ 0^+; 1</td>
<td>5 ± 5</td>
<td>(1.0 ± 0.3) × 10^{-2}</td>
<td>E1</td>
<td>(5.0 ± 1.0) × 10^{-4}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>→ 2.154</td>
<td>→ 1^+; 0</td>
<td>65.3 ± 0.9</td>
<td>(6.6 ± 1.8) × 10^{-2}</td>
<td>E1</td>
<td>(2.3 ± 0.6) × 10^{-2}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>→ 3.587</td>
<td>→ 2^+; 0</td>
<td>7.8 ± 0.3</td>
<td>(9.4 ± 8.2) × 10^{-4}</td>
<td>E2</td>
<td>&lt; 0.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(continued on next page)
Table 10.19 (continued)

<table>
<thead>
<tr>
<th>$E_i \rightarrow E_f$ (MeV)</th>
<th>$J_i^T ; T_i \rightarrow J_f^T ; T_f$</th>
<th>Branch (%)</th>
<th>Mixing ratio ($\delta$) (E2/M1)</th>
<th>$\Gamma_\gamma$ (eV)</th>
<th>Mult.</th>
<th>$\Gamma_\gamma / \Gamma_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.180 $\rightarrow$ 1.740</td>
<td>$1^+; 0 \rightarrow 0^+; 1$</td>
<td>$\approx 100$</td>
<td></td>
<td>$0.06 \pm 0.02$</td>
<td>M1</td>
<td>$(7.0 \pm 3.5) \times 10^{-2}$</td>
</tr>
<tr>
<td>5.920 $\rightarrow$ 0$^+$</td>
<td>$2^+; 0 \rightarrow 3^+; 0$</td>
<td>82 $\pm$ 5</td>
<td></td>
<td>$0.112 \pm 0.022$</td>
<td>M1</td>
<td>$(2.6 \pm 0.5) \times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td>$\rightarrow 0.718$</td>
<td></td>
<td></td>
<td>$0.025 \pm 0.007$</td>
<td>M1</td>
<td>$(8.6 \pm 2.4) \times 10^{-3}$</td>
</tr>
<tr>
<td>6.025 $\rightarrow$ 0$^+$</td>
<td>$4^+; 0 \rightarrow 3^+; 0$</td>
<td>100</td>
<td>$-(3.16 \pm 0.12)$</td>
<td>$(1.04 \pm 0.16) \times 10^{-2}$</td>
<td>M1</td>
<td>$(2.3 \pm 0.4) \times 10^{-3}$</td>
</tr>
</tbody>
</table>

$\Gamma_\gamma$ from lifetime in Table 10.21.

b Branches are averages from [1969YO01].

c Mixing ratios from [1968WA15]. Note that the inverse of $\delta$ was determined for the 3.587 $\rightarrow$ 0.718 transition and that there is an ambiguity for the 2.154 $\rightarrow$ 0.718 transition. The solution with the larger E2 value is more consistent with the value from the perturbed Cohen and Kurath wave functions [1968WA15] and is used here to obtain the M1 and E2 strengths.

c Branches from [1969YO01] and [1969GA06] are in agreement.

d $\Gamma_\gamma$ from Table 10.22.

f Branches from [1966AL06].

g Branches from [1966FO05].

h $M2 < 120$ W.u. for all branches.

i Branches and mixing ratios from [1979KE08]. Limit on branch to 1.74 MeV level from [1967PA01, 1968WA15, 1982RI04]. $\Gamma_\gamma$ is a sensitive function of $\Gamma_\alpha / \Gamma$ (see footnote e of Table 10.22).

j Without a mixing ratio, only upper limits can be given on the M1 and E2 strengths for the ground-state transition.
Table 10.20
Electromagnetic transition strengths for levels above the proton threshold in \(^{10}\text{B}^4\)

<table>
<thead>
<tr>
<th>(E_i \rightarrow E_f) (MeV)</th>
<th>(J_{fi}^\pi; T_{fi} \rightarrow J_{f}^\pi; T_{f})</th>
<th>Branch (%)</th>
<th>(\omega_{\text{Gam}}) (eV)</th>
<th>(\Gamma^*_\gamma) (eV)</th>
<th>Mult.</th>
<th>(\Gamma_\gamma / \Gamma_W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.870^b \rightarrow 0</td>
<td>(1^-; 0^+ \rightarrow 3^+; 0)</td>
<td>&lt; 4.6</td>
<td>&lt; 0.09</td>
<td></td>
<td>M2</td>
<td>&lt; 84</td>
</tr>
<tr>
<td>\rightarrow 0.718</td>
<td>(1^-; 0^+ \rightarrow 1^+; 0)</td>
<td>20 ± 2</td>
<td>0.31 ± 0.08</td>
<td>E1</td>
<td>(4.2 ± 1.1) \times 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>\rightarrow 1.740</td>
<td>(0^+; 1 \rightarrow 0^+; 1)</td>
<td>53 ± 2</td>
<td>0.82 ± 0.20</td>
<td>E1</td>
<td>(1.9 ± 0.5) \times 10^{-2}</td>
<td></td>
</tr>
<tr>
<td>\rightarrow 2.154</td>
<td>(1^+; 0 \rightarrow 1^+; 0)</td>
<td>13 ± 1</td>
<td>0.20 ± 0.5</td>
<td>E1</td>
<td>(6.0 ± 1.5) \times 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>\rightarrow 5.110</td>
<td>(2^+; 0 \rightarrow 2^+; 0)</td>
<td>4 ± 1</td>
<td>0.062 ± 0.022</td>
<td>M1</td>
<td>0.54 ± 0.19</td>
<td></td>
</tr>
<tr>
<td>\rightarrow 8.516</td>
<td>(2^+; 1 \rightarrow 2^+; 1)</td>
<td>3 ± 1</td>
<td>0.046 ± 0.019</td>
<td>E1</td>
<td>(2.9 ± 1.2) \times 10^{-2}</td>
<td></td>
</tr>
<tr>
<td>\rightarrow 5.920</td>
<td>(2^+; 0 \rightarrow 2^+; 0)</td>
<td>3.5 ± 1.0</td>
<td>0.054 ± 0.021</td>
<td>E1</td>
<td>0.20 ± 0.08</td>
<td></td>
</tr>
<tr>
<td>7.43^d \rightarrow 0.718</td>
<td>(1^-; 1^+ \rightarrow 1^-; 0)</td>
<td>46</td>
<td>0.58 ± 0.13</td>
<td>E1</td>
<td>(2.3 ± 0.5) \times 10^{-2}</td>
<td></td>
</tr>
<tr>
<td>\rightarrow 1.740</td>
<td>(0^+; 1 \rightarrow 0^+; 1)</td>
<td>&lt; 5</td>
<td>&lt; 0.06</td>
<td>E1</td>
<td>&lt; 4.0 \times 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>\rightarrow 2.154</td>
<td>(1^+; 0 \rightarrow 2^+; 0)</td>
<td>22</td>
<td>0.27 ± 0.08</td>
<td>E1</td>
<td>(2.2 ± 0.7) \times 10^{-2}</td>
<td></td>
</tr>
<tr>
<td>\rightarrow 5.110</td>
<td>(2^+; 0 \rightarrow 2^+; 0)</td>
<td>32</td>
<td>0.4 ± 0.1(^e)</td>
<td>M1</td>
<td>5.8 ± 1.5</td>
<td></td>
</tr>
<tr>
<td>7.43^d \rightarrow 0</td>
<td>(2^+; 1 \rightarrow 3^+; 0)</td>
<td>(^f)</td>
<td>7.3 ± 0.5</td>
<td>M1</td>
<td>1.34 ± 0.08</td>
<td></td>
</tr>
<tr>
<td>7.48^f \rightarrow 0</td>
<td>(2^-; 1 \rightarrow 3^+; 0)</td>
<td>(^f)</td>
<td>2.8 ± 1.4</td>
<td>E1</td>
<td>(3.8 ± 1.9) \times 10^{-2}</td>
<td></td>
</tr>
<tr>
<td>\rightarrow 2.154</td>
<td>(1^-; 0 \rightarrow 1^-; 0)</td>
<td>1.9</td>
<td>0.20 ± 0.07</td>
<td>M1</td>
<td>0.10 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>7.56^f \rightarrow 0.718</td>
<td>(0^+; 1 \rightarrow 1^-; 0)</td>
<td>77 ± 5</td>
<td>4.8 ± 0.6</td>
<td>M1</td>
<td>0.72 ± 0.09</td>
<td></td>
</tr>
<tr>
<td>\rightarrow 2.154</td>
<td>(1^-; 0 \rightarrow 1^-; 0)</td>
<td>9 ± 2</td>
<td>0.57 ± 0.14</td>
<td>M1</td>
<td>0.17 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>\rightarrow 5.180</td>
<td>(1^-; 0 \rightarrow 1^-; 0)</td>
<td>14 ± 2</td>
<td>0.87 ± 0.15</td>
<td>M1</td>
<td>3.1 ± 0.6</td>
<td></td>
</tr>
<tr>
<td>7.73^b \rightarrow 0</td>
<td>(2^-; 1 \rightarrow 3^+; 0)</td>
<td>77</td>
<td>2.7 ± 0.7</td>
<td>E1</td>
<td>(2.9 ± 0.8) \times 10^{-2}</td>
<td></td>
</tr>
<tr>
<td>\rightarrow 0.718</td>
<td>(1^-; 0 \rightarrow 1^-; 0)</td>
<td>11</td>
<td>0.40 ± 0.18</td>
<td>E1</td>
<td>(5.8 ± 2.6) \times 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>\rightarrow 2.154</td>
<td>(1^-; 0 \rightarrow 1^-; 0)</td>
<td>3.7</td>
<td>0.13 ± 0.07</td>
<td>E1</td>
<td>(3.8 ± 2.0) \times 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>\rightarrow 3.587</td>
<td>(2^-; 0 \rightarrow 2^+; 0)</td>
<td>3.4</td>
<td>0.12 ± 0.07</td>
<td>E1</td>
<td>(8.3 ± 4.8) \times 10^{-3}</td>
<td></td>
</tr>
</tbody>
</table>

(continued on next page)
Table 10.20 (continued)

<table>
<thead>
<tr>
<th>$E_i$ → $E_f$ (MeV)</th>
<th>$J_i^T$ → $J_f^T$</th>
<th>Branch (%)</th>
<th>$\omega \gamma_{\text{cm}}$ (eV)</th>
<th>$\Gamma \gamma$ (eV)</th>
<th>Mult.</th>
<th>$\Gamma \gamma / \Gamma_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>→ 5.110</td>
<td>→ 2$^-$; 0</td>
<td>4.8</td>
<td>0.17 $\pm$ 0.09</td>
<td>0.27 $\pm$ 0.14</td>
<td>M1</td>
<td>0.70 $\pm$ 0.35</td>
</tr>
</tbody>
</table>

---

The $\omega \gamma_{\text{cm}}$ values for individual transitions are for the $^9$Be(p, $\gamma$)$^{10}$B reaction [1964HO02] and the corresponding $\gamma$-ray branches are given without errors. Otherwise the total $\omega \gamma_{\text{cm}}$ or $\Gamma \gamma$ value is given in a footnote and the branches are given with errors.

- $\Gamma_{\gamma_{\text{cm}}} = 120 \pm 5$ keV, $\Gamma_p/\Gamma = 0.38 \pm 0.10$ eV, $\Gamma_p/\Gamma = 0.48 \pm 0.11$ eV from [1975AU02]. $\Gamma_p/\Gamma = 0.23 \pm 0.04$, $\Gamma_p/\Gamma = 0.33 \pm 0.02$ from [1997ZA06].
- $\Gamma_p = 1.54 \pm 0.40$ eV is an equally weighted average from (p, $\gamma$) and ($\alpha$, $\gamma$). The three major branches and the non-observation of a ground-state branch are in agreement with earlier work [1979AJ01].
- $\approx 20\%$ isospin mixed [1956WI16]. See discussion of reaction 12.
- $\Gamma_{\gamma_{\text{cm}}} = 140 \pm 30$ keV, $\Gamma_p/\Gamma = 0.7$ [1964HO02]. Note, however, $\Gamma_p/\Gamma = 0.38 \pm 0.06$ in Table 10.25.
- Some of this strength could be due to the 7.48 MeV doublet [1964HO02].
- The doublet analyzed as a single state gives $\Gamma_{\gamma_{\text{cm}}} = 72 \pm 4$ keV and a ground-state branch of 96.8\% with $\omega \gamma_{\text{cm}} = 10.1 \pm 1.3$ eV [1964HO02]. Small branches with $\omega \gamma_{\text{cm}} = 0.13 \pm 0.04$ eV and $\omega \gamma_{\text{cm}} = 0.20 \pm 0.07$ eV to the 0.718 and 2.154 MeV 1$^+$ states could be due to either or both members of the doublet. Analysis of elastic proton scattering shows a doublet of 2$^+$ ($E_\gamma = 7.469$ MeV, $\Gamma_{\gamma_{\text{cm}}} = 65 \pm 10$ keV, $\Gamma_p/\Gamma = 1$) and 2$^-$ ($E_\gamma = 7.480$ MeV, $\Gamma_{\gamma_{\text{cm}}} = 80 \pm 8$ keV, $\Gamma_p/\Gamma = 0.90 \pm 0.05$) levels [1969MO29]. $\Gamma_p = 1.17 \pm 0.07$ eV for M1 excitation in (e, $e'$) and $\Gamma_p/\Gamma = 1$ gives $\omega \gamma_{\text{cm}} = 7.3 \pm 0.5$ eV for the 2$^+$; 1 level.
- Branches are averages of [1961SP04,1964HO02]. $\Gamma_{\gamma_{\text{cm}}} = 2.65 \pm 0.18$ keV [1972HA63]. Using $\sigma(p, \gamma) = 920 \pm 84$ mb [1964HO02] gives $\omega \gamma_{\text{cm}} = 0.82 \pm 0.10$ eV.
- This is averaged with $\omega \gamma_{\text{cm}} = 0.73 \pm 0.11$ eV [1995ZA04] to give $\omega \gamma_{\text{cm}} = 0.78 \pm 0.08$ eV.
- $\Gamma_{\gamma_{\text{cm}}} = 210 \pm 60$ keV [1964HO02]. The transition strengths are for $\Gamma_p/\Gamma = 1.0$ instead of $\Gamma_p/\Gamma = 0.7$ [1964HO02]. Analysis of elastic proton scattering gives $E_\gamma = 7.79$ MeV, $\Gamma_{\gamma_{\text{cm}}} = 265 \pm 30$ keV, $\Gamma_p/\Gamma = 0.90 \pm 0.05$ [1969MO29].
- The 7.48 MeV and 7.75 MeV 2$^-$ levels may form an isospin mixed pair because both possess strong ground-state E1 transitions and only one 2$^-$; $T = 1$ level, corresponding to the analog of the 6.26 MeV level of $^{10}$Be, is expected.
6. $^7\text{Li}(^3\text{He}, n)^9\text{B}$, $Q_m = 9.3520$, $E_h = 17.7883$

The excitation curve is smooth up to $E(^3\text{He}) = 1.8$ MeV and the $n_0$ yield shows resonance behavior at $E(^3\text{He}) = 2.2$ and $3.25$ MeV, $\Gamma_{\text{lab}} = 270 \pm 30$ and $500 \pm 100$ keV. No other resonances are observed up to $E(^3\text{He}) = 5.5$ MeV. See Table 10.10 in [1979AJ01], ([1986AB10]; theor.) and [1974AJ01].

7. $^7\text{Li}(^3\text{He}, p)^9\text{Be}$, $Q_m = 11.2025$, $E_h = 17.7883$

The yield of protons has been measured for \(E(^3\text{He}) = 0.60\) to $4.8$ MeV: there is some indication of weak maxima at $1.1, 2.3$ and $3.3$ MeV. Measurements of $A_y$ for the ground-state group at $E(^3\text{He}) = 14$ MeV [1983LE17,1983RO22] and $33$ MeV [1983LE17] have been reported. Measurements of differential cross sections and analyzing powers were reported at $E(^3\text{He}) = 4.6$ MeV [1995BA24]. The polarization at $E(^3\text{He}) = 14$ MeV was measured by [1984ME11,1984TR03]. $P = A$ in this and in the inverse reaction [see reaction 4 in $^{12}\text{C}$ in [1985AJ01] for some additional comments]. Proton yields as a function of angle were measured for $E(^3\text{He}) = 93$ MeV by [1994DO32]. Astrophysics-related measurements at $E_{\text{cm}} = 0.5\text{–}2$ MeV [1990RA16] and $E(^3\text{He}) = 160, 170$ keV [2002YA06] have been reported. Astrophysical $S$-factors were deduced. A theoretical study of the reaction mechanism and astrophysical implications are described in [1993YA01]. Calculations for the reaction and the inverse reaction to deduce time-reversal-invariance violation amplitude features were reported in [1988KH11]. For earlier references see [1984AJ01]. See also ([1986AB10]; theor.).

8. (a) $^7\text{Li}(^3\text{He}, d)^8\text{Be}$, $Q_m = 11.2025$, $E_h = 17.7883$
(b) $^7\text{Li}(^3\text{He}, t)^7\text{Be}$, $Q_m = -0.88081$
(c) $^7\text{Li}(^3\text{He}, ^3\text{He})^7\text{Li}$

Yields of deuterons have been measured for $E(^3\text{He}) = 1.0$ to $2.5$ MeV (d0) and yields of tritons are reported for $2.0$ to $4.2$ MeV (t0): a broad peak is reported at $E(^3\text{He}) \approx 3.5$ MeV in the t0 yield. See [1979AJ01] for references. Polarization measurements are reported at $E(^3\text{He}) = 33.3$ MeV for the deuteron groups to $^8\text{Be}^*(16.63, 17.64, 18.15)$ and for the triton and $^3\text{He}$ groups to $^7\text{Be}^*(0, 0.43)$ and $^7\text{Li}^*(0, 0.48, 4.63)$: see [1984AJ01]. Measurements of the yields for deuterons, alphas, tritons and $^3\text{He}$ as a function of angle at $E(^3\text{He}) = 93$ MeV are described in [1994DO32]. A compilation and analysis of cross section data for studying evidence for clusters in $^7\text{Li}$ is presented in [1995MI16].

9. $^7\text{Li}(^3\text{He}, \alpha)^6\text{Li}$, $Q_m = 13.32732$, $E_h = 17.7883$

Excitation functions have been measured for $E(^3\text{He}) = 1.3$ to $18.0$ MeV: see [1974AJ01]. The $\alpha_0$ group (at $8^\circ$) shows a broad maximum at $\approx 2$ MeV, a minimum at $3$ MeV, followed by a steep rise which flattens off between $E(^3\text{He}) = 4.5$ and $5.5$ MeV. Integrated $\alpha_0$ and $\alpha_1$ yields rise monotonically to $4$ MeV and then tend to decrease. Angular distributions give evidence of the resonances at $E(^3\text{He}) = 1.4$ and $2.1$ MeV seen in $^7\text{Li}(^3\text{He}, \gamma)^{10}\text{B}$: $J^\pi = 2^+$ or $1^-$; $T = (1)$ for both [see, however, reaction 5]: $\Gamma_{\alpha}$ is small.
10B

Table 10.21

Lifetimes of bound states of 10B

<table>
<thead>
<tr>
<th>10B* (MeV)</th>
<th>( \tau_m )</th>
<th>Reactions</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.72</td>
<td>1.020 ± 0.005 ns</td>
<td>(^{10}\text{B}(p, p'))</td>
<td>[1983VE03]a</td>
</tr>
<tr>
<td>1.74</td>
<td>7 ± 3 fs</td>
<td>6Li((\alpha, \gamma))</td>
<td>[1979KE08]</td>
</tr>
<tr>
<td>2.15</td>
<td>2.30 ± 0.26 ps</td>
<td>mean</td>
<td>[1979AJ01]b</td>
</tr>
<tr>
<td>1.9 ± 0.3 ps</td>
<td>6Li((\alpha, \gamma))</td>
<td>[1979KE08]</td>
<td></td>
</tr>
<tr>
<td>2.13 ± 0.20 ps</td>
<td>mean</td>
<td>all values</td>
<td></td>
</tr>
<tr>
<td>3.59</td>
<td>153 ± 13 fs</td>
<td>mean</td>
<td>[1979AJ01]</td>
</tr>
<tr>
<td>150 ± 30 fs</td>
<td>6Li((\alpha, \gamma))</td>
<td>[1979KE08]</td>
<td></td>
</tr>
<tr>
<td>153 ± 12 fs</td>
<td>mean</td>
<td>all values</td>
<td></td>
</tr>
</tbody>
</table>

a See also Table 10.20 of [1966LA04].
b Table 10.9 in [1979AJ01].

Table 10.22

Levels of 10B from 6Li(\(\alpha, \gamma\))10B\(^*\)

<table>
<thead>
<tr>
<th>(E_x) (MeV)</th>
<th>(J^\pi)</th>
<th>(\Gamma_m)</th>
<th>(\omega\gamma) (eV)</th>
<th>(\Gamma_\gamma) (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.774(^c)</td>
<td>(3^+; 0)</td>
<td>7.8 ± 1.2 eV</td>
<td>(4.20 ± 0.36) × 10(^{-2})</td>
<td>(1.80 ± 0.15) × 10(^{-2})</td>
</tr>
<tr>
<td>5.112(^d)</td>
<td>(2^+; 0)</td>
<td>0.98 ± 0.07 keV</td>
<td>0.055 ± 0.010</td>
<td>0.033 ± 0.006</td>
</tr>
<tr>
<td>5.164(^e)</td>
<td>(2^+; 1)</td>
<td>1.8 ± 0.4 eV</td>
<td>0.40 ± 0.04</td>
<td>1.50 ± 0.40</td>
</tr>
<tr>
<td>5.180(^f)</td>
<td>(1^+; 0)</td>
<td>200 ± 30 keV</td>
<td>0.06 ± 0.03</td>
<td>0.06 ± 0.03</td>
</tr>
<tr>
<td>5.920(^g)</td>
<td>(2^+; 0)</td>
<td>6 ± 1 keV</td>
<td>0.228 ± 0.038</td>
<td>0.135 ± 0.023</td>
</tr>
<tr>
<td>6.024(^h)</td>
<td>(4^+; 0)</td>
<td>0.342 ± 0.048</td>
<td>0.114 ± 0.016</td>
<td></td>
</tr>
<tr>
<td>6.873(^i)</td>
<td>(1^-; 0 + 1)</td>
<td>120 ± 5 keV</td>
<td>0.48 ± 0.11</td>
<td>1.44 ± 0.34</td>
</tr>
<tr>
<td>7.440(^j)</td>
<td>(2^+; 0)</td>
<td>90 ± 10 keV</td>
<td>0.29 ± 0.13</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) \(E_x\) from adopted level energies: see Table 10.8 in [1988AJ01] for resonance energies and measured branching ratios. The measured branching ratios also appear in Table 10.19. Values of \(\omega\gamma\) from [1966AL06, 1966FO05] have been multiplied by 0.6 to convert them to the cm system [1979SP01].
\(^b\) \(\omega\gamma\) and \(\Gamma_\gamma\) represent the sum for all transitions from a given level.
\(^c\) Average of \(\omega\gamma\) = 0.041 ± 0.004 [1985NE05] and \(\omega\gamma\) = 0.046 ± 0.008 [1966AL06]; \(\Gamma_m = \Gamma_\alpha = 7.8 ± 1.2\ eV [1981HE05].\)
\(^d\) \(\Gamma_m = \Gamma_\alpha = 0.98 ± 0.07\ keV [1984NA07].\)
\(^e\) \(\omega\gamma\) = 0.041 ± 0.004 [1985NE05] and \(\omega\gamma\) = 0.046 ± 0.008 [1966AL06]; \(\Gamma_m = \Gamma_\alpha = 7.8 ± 1.2\ eV [1981HE05].\)
\(^f\) \(\omega\gamma\) = 0.041 ± 0.004 [1985NE05] and \(\omega\gamma\) = 0.046 ± 0.008 [1966AL06]; \(\Gamma_m = \Gamma_\alpha = 7.8 ± 1.2\ eV [1981HE05].\)
\(^g\) \(\omega\gamma\) = 0.041 ± 0.004 [1985NE05] and \(\omega\gamma\) = 0.046 ± 0.008 [1966AL06]; \(\Gamma_m = \Gamma_\alpha = 7.8 ± 1.2\ eV [1981HE05].\)
\(^h\) \(\omega\gamma\) = 0.041 ± 0.004 [1985NE05] and \(\omega\gamma\) = 0.046 ± 0.008 [1966AL06]; \(\Gamma_m = \Gamma_\alpha = 7.8 ± 1.2\ eV [1981HE05].\)
\(^i\) \(\omega\gamma\) = 0.041 ± 0.004 [1985NE05] and \(\omega\gamma\) = 0.046 ± 0.008 [1966AL06]; \(\Gamma_m = \Gamma_\alpha = 7.8 ± 1.2\ eV [1981HE05].\)
\(^j\) \(\omega\gamma\) = 0.041 ± 0.004 [1985NE05] and \(\omega\gamma\) = 0.046 ± 0.008 [1966AL06]; \(\Gamma_m = \Gamma_\alpha = 7.8 ± 1.2\ eV [1981HE05].\)
Table 10.23

\begin{tabular}{|c|c|c|c|c|}
\hline
$E_\alpha$ (MeV) & $E_x$ (MeV) & $\Gamma_{cm}$ (keV) & $J^\pi$ & $T$ \\
\hline
1.210 ± 30 & 5.19 & 105 & 1$^+; 0$ & \\
2.440$^b$ & 5.920 & 5.82 ± 0.06 & 2$^+; 0$ & \\
2.6060 ± 1.5 & 6.024 & 0.054 ± 0.024 & 4$^+; 0$ & \\
2.7855 ± 1.5$^c$ & 6.132 & 1.52 ± 0.08 & 3$^+; 0$ & \\
3.4985 ± 1.6 & 6.560 & 25.1 ± 1.1 & (4$^-, 2^-$); 0 & \\
4.250 ± 15 & 7.011 & 110 ± 15 & (2)$^+; 0$ & \\
\hline
\end{tabular}

$^a$ For references see Table 10.8 in [1979AJ01] and Table 10.9 in [1974AJ01].
$^b$ [1981HE05].
$^c$ [1981HE05]: $\Gamma_\alpha = 1.47 ± 0.07$ keV, $\Gamma_3 = 0.048 ± 0.030$.

Table 10.24

\begin{tabular}{|c|c|c|c|c|}
\hline
$E_\alpha$ (MeV) & $E_x$ (MeV) & $\Gamma_{cm}$ (keV) & $J^\pi$ & $T_\gamma$ \\
\hline
0.319$^b$ & 6.873 ± 5 & 120 ± 5 & 1$^-; 0^+; 1$ & 0.14 ± 0.04 \\
0.938 ± 10$^c$ & 7.430 & 140 ± 30 & 1$^-; 1^+; 0$ & 1.25 ± 0.18 \\
0.992 ± 2$^d$ & 7.478 & 82 ± 4 & 2$^+; 1$ & 1.04 ± 1.3 \\
1.0832 ± 0.4$^d$ & 7.5599 & 2.65 ± 0.18$^e$ & 0$^+; 1$ & 0.78 ± 0.08$^e$ \\
1.290 ± 40$^e$ & 7.75 & 210 ± 60 & 2$^-; 1^+; 0$ & 3.52 ± 0.74 \\
\hline
\end{tabular}

$^a$ See Table 10.20 for decay schemes.
$^b$ [1975AU02].
$^c$ [1964HO02].
$^d$ [1964BO13].
$^e$ See Table 10.20.

The $\alpha_2$ yield [to $^6$Li$(3.56), J^\pi = 0^+; T = 1$] shows some structure at $E(3$He) = 1.4 MeV and a broad maximum at $\approx 3.3$ MeV; see Table 10.10 in [1979AJ01]. Polarization measurements are reported at $E(3$He) = 33.3 MeV to $^6$Li$^*(0, 2.19, 3.56)$: see [1984AJ01]. See also [1983AN1D, 1984PA1E, 1994DO32].

10. $^7$Li$(\alpha, n)^{10}$B, \ $Q_m = -2.7893$

Angular distributions are reported at $E_\alpha = 28$ and 32 MeV for the $n_0$, $n_1$ and $n_2$ groups [1985GU1E]. See [1979AJ01, 1984AJ01] for the earlier work. Neutron spectra and photon yields from $^7$Li$(\alpha, n)$ neutron sources for $E_\alpha = 5.5$–5.8 MeV were measured by [1999VL02].

11. (a) $^7$Li$(^{12}$C, $\alpha + ^6$Li)$^9$Be, \ $Q_m = -12.9515$

(b) $^7$Li$(^{12}$C, $d + ^8$Be)$^9$Be, \ $Q_m = -14.5172$

(c) $^7$Li$(^{12}$C, $p + ^9$Be)$^9$Be, \ $Q_m = -15.0764$

The breakup of $^{10}$B was studied [2001LE05] in an experiment with 76 MeV $^{12}$C incident on Li$_3$O. Breakup of $^{10}$B into $\alpha + ^6$Li, $\alpha + ^6$Li$^*(3^+)$, $^8$Be + d and $^9$Be + p was observed. Evidence was obtained for two new $^{10}$B states at $E_x = 7.96 ± 0.07$ MeV,
Parameters of the observed resonances are listed in Table 10.24. An angle-integrated excitation function has been measured over the energy range $E_p = 75$ to 1800 keV [1995ZA04]. This establishes the absolute $(p, \gamma)$ cross sections for this region with considerably more certainty than existed at the time of the previous review [1988AJ01]. Table 10.24 lists six resonances in this energy region with 5 rather broad resonances and a narrow $J^\pi = 0^+; T = 1$ resonance ($\Gamma_{cm} = 2.65$ keV) at $E_p = 1038$ keV. The excitation function is dominated by three broad unresolved resonances at $E_p = 938$, 980, and 992 keV. The existence of the 938 keV resonance has been established from analyses of the excitation functions for $\gamma$-ray transitions to specific final states. However, the $2^+$ and $2^-$ levels near 990 keV have similar widths and dominant ground-state radiative transitions and thus cannot be distinguished from consideration of the $(p, \gamma)$ data alone. The $\gamma$ transitions from this reaction are given in Table 10.20 and the information obtained is summarized in the following discussion.

The $E_p = 330$ keV resonance ($E_x = 6.87$ MeV) is ascribed to s-wave protons because of its comparatively large proton width [see $^9$Be(p, p)] and because of the isotropy of the $\gamma$ radiation. The strong E1 transitions to both $T = 0$ and $T = 1$ final states in Table 10.20 indicate considerable isospin mixing [1956WI16] because only $T = 0 \leftrightarrow T = 1$ isovector E1 transitions are possible in $^{10}$B. The transition to the 1.74 MeV level implies $J^\pi = 1^-$ and its relative strength, together with the existence of substantial deuteron and alpha widths, indicates a dominance of $T = 0$ for the 6.87 MeV state.

Most of the data in Table 10.20 comes from an analysis of the excitation functions for $\gamma$-ray transitions to specific final states [1964HO02]. The $E_p = 938$ keV resonance was originally given a tentative $J^\pi = 2^+; T = 0$ assignment. The $1^-$ assignment was made for a resonance in elastic proton scattering at $E_p = 945 \pm 10$ keV with a width $\Gamma_{cm} = 130 \pm 10$ keV and the suggestion was made that this level is the missing isospin-mixed partner of the 6.87 MeV level [1969MO29]. An estimate of the isospin mixing was made in [1969RO12]. See also the appendix in [2001BA47]. The relative E1 strengths for the transitions to the $1^+; 0$ levels at 0.72 and 2.15 MeV imply $T = 1$ isospin admixtures of 15% and 21%, respectively, and the strength of the 7.43 $\rightarrow$ 1.74 E1 transition expected for this level of admixture is just below the observed upper limit. The strong M1 transition to the $2^-$; 0 level at 5.11 MeV, expected to be mainly $^1P \rightarrow ^3P$, implies an isospin admixture of $\approx 8.5\%$ but this should be treated as a lower limit because some of the 7.43 $\rightarrow$ 5.11 strength may be due to one or both of the two levels near 7.48 MeV [1964HO02]. However, it does appear from Fig. 6 of [1975AU02] that the transition is mainly from the 7.43 MeV level. The $T = 1$ component of the $1^- doublet corresponds to the 5.96 MeV level of $^{10}$Be shifted downwards by $\approx 400$ keV with respect to p-shell levels on account of the smaller Coulomb energy shift for (sd) orbits. The 0.93 MeV resonance is also observed in the $^9$Be(p, d) and $^9$Be(p, $\alpha$) reactions via the $T = 0$ component in the wave function [1956WE37]. The $\alpha$ width which results from the isospin mixing is sufficient to account for the strength of the 7.43 $\rightarrow$ 0.72 transition observed via the $^6$Li($\alpha, \gamma$) reaction and calls into question the existence of a $2^-; 0$ level at 7.43 MeV proposed by [1975AU02].
The prominent $E_p = 992$ keV resonance was originally assigned as $2^{-} 1$ largely on account of the apparent $s$-wave formation and the strength of the ground-state transition [1964HO02]. However, earlier elastic proton scattering data had indicated the existence of a $p$-wave $2^{+}$ state near 980 keV and an $s$-wave $2^{-}$ state near 998 keV [1956MO90]. See also [1969MO29]. Then, low-energy electron scattering [see $^{10}$B(e, e$'$)] revealed a very strong $M1$ transition to a state at this energy [1965SP04] which can account for over 70% of the $(p, \gamma)$ cross section. This state was identified with the second $2^{+}$ 1 level predicted by shell model calculations with similar spatial structure to the $^{10}$B ground state. The analog in $^{10}$Be is at 5.96 MeV and is populated as a strong Gamow–Teller transition in charge-exchange reactions on $^{10}$B [see reaction 28 in $^{10}$Be].

Subtraction of the $M1$ strength associated with the $2^{+} 1$ level leaves substantial ground-state transition strength for the $2^{-}$ level, indicating a $T = 1$ component. The $s$-wave resonance at $E_p = 1290 \pm 30$ keV also has a strong ground-state transition and was assigned as $2^{-} 1$ [1964HO02]. Thus, there appears to be a doublet of isospin-mixed $2^{-}$ levels with the $T = 1$ component corresponding to the 6.26 MeV level of $^{10}$Be.

The narrow $E_p = 1083$ keV level is formed by $p$-wave protons and has $J^\pi = 0^{+}$ (see reaction 14 [$^{9}$Be(p, p)] and reaction 16 [$^{9}$Be(p, $\alpha$)]). The isotropy of the $\gamma$ rays supports this assignment. The strong $M1$ transitions to the $J^\pi = 1^{+}$; $T = 0$ levels at 0.72, 2.15, and 5.18 MeV [Table 10.22] indicate $T = 1$. The analog is at 6.18 MeV in $^{10}$Be. The width of the 5.18 MeV level of $^{10}$B observed in the decay is $100 \pm 10$ keV [1975AU02]. The 7.56 MeV $0^{+}$ 1 and 5.18 MeV $1^{+}$ 0 levels are the lowest $(sd)^2$, or $2h\omega$, levels in $^{10}$B. The strong $M1$ transition between them is consistent with these assignments.

Since the previous review [1988AJ01] several measurements and analyses have been done for low proton energies. Branching ratios and angular distributions for capture to $^{10}$B states at $E_x = 0, 0.718, 1.740$ and 2.154 MeV were measured for proton energies $E_p = 40–180$ keV [1992CE02]. Astrophysical $S$-factors were deduced. Measurements of an angle integrated $S$-factor for $E_p = 75–1800$ keV were reported by [1995ZA04]. The spectrum is dominated by three broad peaks and the analysis included interference effects with the direct-capture process. The best fit was obtained for $J^{\pi}$ values of $1^{-}, 2^{-}$, and $2^{-}$ and the resulting resonance energies were $E_p$(lab) = $380 \pm 30, 989 \pm 2$ and $1405 \pm 20$ keV. The widths were $T_{lab} = 330 \pm 30, 90 \pm 3$ and $430 \pm 30$ keV, respectively. The low-energy $S$-factor is about one third of that obtained by [1992CE02]. A measurement by [1998WU05] with 100 keV polarized protons on a thick $^{9}$Be target determined analyzing powers for capture to the $^{10}$B ground state and the first three excited states. Astrophysical $S$-factors were deduced using a direct-capture-plus-resonance model. These data were used in an evaluation of thermonuclear proton-capture rates by [2000NE09]. Polarized protons at $E_p = 280–0$ keV were used [1999GA21] to measure the analyzing power for the ground state transition. Comparison of the results to calculations showed that the analyzing power could be reproduced only by the interference of direct capture with the tail of a $2^{+}$ resonance that was taken to be at 7.478 MeV (the 7.469 MeV state in Table 10.18). Although these results indicate that the resonance strength in the $(p, \gamma)$ channel near 7.48 MeV is predominantly $2^{+}$, the data do not rule out a small contribution from an additional state.

Existing data on $^{9}$Be(p, $\gamma$)$^{10}$B were reanalyzed within the framework of an $R$-matrix method by [1999SA39]. Parameters of resonances at $E_p$(cm) = 296, 890, 972 and 1196 keV were determined and compared (see Table II of [1999SA39]) with parame-
terms given in [1988AJ01,1995ZA04,1998WU05]. Data for proton energies up to \(E_p = 1800\) keV and \(\gamma\)-transitions to the four lowest \(^{10}\text{B}\) states were fitted using \(R\)-matrix formulæ by [2002BA09]. A good fit was obtained with two \(^1\)\(^-\) levels, two \(^2\)\(^-\) levels, one \(^0\)\(^+\) level and one \(^2\)\(^+\) level. Level parameters derived from these fits using different combinations of input data are presented in Tables 5, 6, and 8 of [2002BA09]. In related work since [1988AJ01], asymptotic normalization coefficients obtained from peripheral transfer reactions such as \(^{10}\text{B}(^{7}\text{Be},^{8}\text{B})^{9}\text{Be}\) at low energies have been used to determine \(^9\text{Be} (p, \gamma)^{10}\text{B}\) \(S\)-factors [1999SA39]. Extracted asymptotic normalization coefficients used for determining stellar reaction rates for \(^9\text{Be} (p, \gamma)^{10}\text{B}\) are discussed in [2003KR14]. See also the astrophysics-related work [1996RE16,1997NO04,2000IC01].

For further information concerning \(^9\text{Be} (p, \gamma)^{10}\text{B}\) experiments for \(E_p > 1330\) keV, refer to [1988AJ01].

13. \(^9\text{Be} (p, n)^{9}\text{B}\), \(Q_m = -1.8504\), \(E_b = 6.5859\)

As noted in [1988AJ01], “Resonances in the neutron yield occur at \(E_p = 2562 \pm 6, 4720 \pm 10\) and, possibly, at 3500 keV with \(I_{\gamma n} = 84 \pm 7, \approx 500\) and \(\approx 700\) keV. These three resonances correspond to \(^{10}\text{B}^*(8.890, 10.83, 9.7)\); see Table 10.13 in [1974AJ01]. Cross section measurements for the \((p, n)\) and \((p, n_0)\) reactions have been obtained by ([1983BY01]; \(E_p = 8.15\) to 15.68 MeV) [see also for a review of earlier work]. They indicate possible structure in \(^{10}\text{B}\) near 13–14 MeV [1983BY01].”

“The \(E_p = 2.56\) MeV resonance is considerably broader than that observed at the same energy in \(^{9}\text{Be} (p, \alpha)\) and \(^9\text{Be} (p, \gamma)\) and the two resonances are believed to be distinct. The shape of the resonance and the magnitude of the cross section can be accounted for with \(J^\pi = 3^-\) or \(3^+\); the former assignment is in better accord with \(^{10}\text{Be}^*(7.37)\). For \(J^\pi = 3^-\), \(\theta_n^2 = 0.135, \theta_p^2 = 0.115 (R = 4.47\) fm); see [1974AJ01].”

“The analyzing power for \(n_0\) has been measured for \(E_p = 2.7\) to 17 MeV [1980MA33, 1983BY02, 1986MU07] as has the polarization in the range \(E_p = 2.7\) to 10 MeV [1983BY02]. See [1983BY02, 1986MU07] for discussions of the \(\sigma(\theta), A_\gamma(\theta)\) and \(P(\theta)\) measurements. Polarization measurements have also been reported at \(E_p = 3.9\) to 15.1 MeV and 800 MeV: [see [1984AJ01]] and at 53.5, 53.9 and 71.0 MeV [1988HE08] \([K_y, K_z]\).”

A summary of monoenergetic neutron beam sources for \(E_n > 14\) MeV is presented in [1990BR24]. See also the measurements at \(E_p = 300, 400\) MeV reported in [1994SA43]. Neutron spectra were measured for \(E_p = 20–40\) MeV [1996SH29] and for \(E_p = 3–5\) MeV [2001HO13]. See also the measurements of \(\sigma(E_n)\) for \(E_p = 35\) MeV [1987OR02] and the thick-target yield measurements of [1987RA23]. This reaction was used by [1987RA32] at \(E_p = 135\) MeV to deduce Gamow–Teller transitions \(B(\text{GT})\) and the quenching factor. Measurements of \(\sigma(\theta)\) at \(E_p = 35\) MeV were used to study the isovector part of optical potentials through analog transitions. Calculations of \(\sigma(\theta, E_n)\) for \(E_p = 1\) GeV are described in [1994GA49]. See also the analysis for \(E_p = 800\) MeV to study pion-production medium effects [1998IO03]. See also \(^9\text{B}\) and references cited in [1988AJ01].
14. (a) \( ^{9}\text{Be}(p, p)^{9}\text{Be} \), \( E_b = 6.5859 \)
(b) \( ^{9}\text{Be}(p, p+n)^{9}\text{Be} \), \( Q_m = -1.6654 \)
(c) \( ^{9}\text{Be}(p, p+\alpha)^{5}\text{He} \), \( Q_m = -2.467 \)

The elastic scattering resonances up to \( E_x = 8 \) MeV shown in Table 10.25 come from [1956MO90,1969MO29]. Below \( E_p = 0.7 \) MeV only s-waves are present exhibiting a resonance at \( E_p = 330 \) keV with \( J^\pi = 1^- \). Apart from the tentative \( 1^+ \) assignment at \( E_p = 1200 \) keV, which was introduced to satisfy a need for resonant p-wave formation [1969MO29], there is good agreement between the results of [1956MO90] and [1969MO29]. The analysis requires a large d-wave admixture with the s-wave protons forming the \( E_p = 1340 \) keV resonance [1969MO29].

Between \( E_p = 0.8 \) and 1.6 MeV polarization and cross section measurements are well fitted by a phase-shift analysis using only \( 3S_1, 5S_2, 5P_1 \), and \( 5P_2 \) phases [1973RO24]. However, the spin assignments of \( 1^+ \) for a state at \( E_x = 7.48 \) MeV and \( 1^- \) for a state at \( E_x = 7.82 \) MeV to fit this data are in disagreement with the assignments in Table 10.25 and with other data. In particular, these assignments leave no state near 7.48 MeV to explain the strong M1 transition observed in electron scattering and no state near 7.8 MeV to explain the strong radiative transition to the ground state [2001BA47].

The \( 2^+ \) state at 8.07 MeV has been observed via inelastic electron scattering and given the same spin-parity assignment. It has also been observed via inelastic pion scattering.

The next prominent elastic scattering resonance occurs at \( E_p = 2.56 \) MeV (\( E_x = 8.89 \) MeV) and has a width of \( \approx 100 \) keV. The analogs of the 7.37 MeV \( 3^- \) and 7.54 MeV \( 2^+ \) levels of \(^{10}\text{Be}\) are known to be nearly degenerate at 8.89 MeV in \(^{10}\text{B}\). The \( 3^- \) level (\( I^\pi \approx 85 \) keV) dominates in the \(^{9}\text{Be}(p, p)\) and \(^{9}\text{Be}(p, n)\) reactions while the \( 2^+ \) level (\( I^\pi \approx 40 \) keV) dominates the \(^{9}\text{Be}(p, \alpha \gamma)^{9}\text{Li} \) cross section [1977KI04]. In fits to elastic scattering in this region [1983AL10], including polarization data [1976MA58], a number of other relatively narrow states have been introduced between 8.4 and 9.1 MeV. The data of [1983AL10] extends to \( E_p = 5 \) MeV and three more levels have been proposed. The highest at \( E_p = 4.72 \) MeV (\( E_x = 10.83 \) MeV) occurs at an energy where resonances have been observed in a number of other reaction channels. The assignment of \( J^\pi = 2^+: T = 1 \) is consistent with that obtained for a resonance observed in the \(^{9}\text{Be}(p, p_0), ^{9}\text{Be}(p, p_2), \) and \(^{9}\text{Be}(p, \alpha_2) \) reactions [1974YA1C].

15. (a) \( ^{9}\text{Be}(p, t)^{7}\text{Be} \), \( Q_m = -12.0833, E_b = 6.5859 \)
(b) \( ^{9}\text{Be}(p, \alpha^2\text{He})^{7}\text{Li} \), \( Q_m = -11.2025 \)

Polarization measurements (reaction (b)) are reported at \( E_p = 23.06 \) MeV: see [1984AJ01]. For a study at \( E_p = 190 \) and 300 MeV see [1987GR11]. See also [1985SE15].

16. (a) \( ^{9}\text{Be}(p, d)^{8}\text{Be} \), \( Q_m = 0.5592, E_b = 6.5859 \)
(b) \( ^{9}\text{Be}(p, \alpha)^{6}\text{Li} \), \( Q_m = 2.1249 \)

Proton-induced reactions on \(^{9}\text{Be}\) are of considerable interest in regard to primordial and stellar nucleosynthesis. Subsequent to the previous compilation [1988AJ01], there have been two studies of the reactions (a) and (b) at low proton energies [1997ZA06,
Table 10.25
Resonances in $^9$Be(p, p)$^9$Be

<table>
<thead>
<tr>
<th>$E_p$ (keV)</th>
<th>$E_x$ (MeV)</th>
<th>$\Gamma_{cm}$ (keV)</th>
<th>$J^\pi$</th>
<th>$\Gamma_p/\Gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>330$^a$</td>
<td>6.88</td>
<td>65 ± 10</td>
<td>1$^-$</td>
<td>0.30</td>
</tr>
<tr>
<td>945 ± 10$^b$</td>
<td>7.437</td>
<td>130 ± 10</td>
<td>1$^-$</td>
<td>0.38 ± 0.06</td>
</tr>
<tr>
<td>980 ± 6$^b$</td>
<td>7.469</td>
<td>65 ± 10</td>
<td>2$^+$</td>
<td>1.0</td>
</tr>
<tr>
<td>1084 ± 2$^b$</td>
<td>7.564</td>
<td>80 ± 8</td>
<td>2$^-$</td>
<td>0.90 ± 0.05</td>
</tr>
<tr>
<td>(1200 ± 30)$^b$</td>
<td>(7.67)</td>
<td>3.3</td>
<td>0$^+$</td>
<td>1.0</td>
</tr>
<tr>
<td>(1340 ± 30)$^b$</td>
<td>7.795</td>
<td>250 ± 20</td>
<td>(1$^+$)</td>
<td>0.30 ± 0.10</td>
</tr>
<tr>
<td>1650 ± 200$^b$</td>
<td>8.07</td>
<td>≈ 800</td>
<td>2$^+$</td>
<td>0.06–0.2</td>
</tr>
<tr>
<td>2550 ± 5$^c$</td>
<td>8.880</td>
<td>105 ± 5</td>
<td>3$^+$</td>
<td>0.85</td>
</tr>
<tr>
<td>2563 ± 5$^c$</td>
<td>8.892</td>
<td>36 ± 4</td>
<td>2$^+$</td>
<td>0.35</td>
</tr>
<tr>
<td>4720 ± 100$^d$</td>
<td>10.83</td>
<td>400 ± 100</td>
<td>2$^+$</td>
<td>0.4</td>
</tr>
</tbody>
</table>

$^a$ From [1956MO90] where it is noted that $\Gamma_{cm}$ cannot be determined accurately from the $^9$Be(p, p) data alone and that $\Gamma_p/\Gamma$ is accurate only to within a factor of two. In [1969MO29], the following values for widths are taken from other reactions: $\Gamma_{cm} = 145$ keV, $\Gamma_p = 40$ keV, $\Gamma_\alpha = 50$ keV, and $\Gamma_\gamma = 55$ keV.

$^b$ [1969MO29].

$^c$ [1983AL10]. See also [1956MA55,1977KI04].

$^d$ [1983AL10]. See [1974YA1C].

1998BR10]. Excitation functions and angular distributions for $E_p = 16$ to 390 keV have been measured by [1997ZA06]. Both polarized and unpolarized protons have been used by [1998BR10] to measure angular distributions and analyzing powers for $E_p = 77$ to 321 keV. Earlier measurements [1973SI1B] provided excitation functions for $E_p = 30$ to 700 keV and angular distributions for $E_p = 110$ to 600 keV. The prominent feature in the excitation functions for both reactions, expressed as values of the astrophysical $S$ factors, is a peak at $E_p \approx 310$ keV attributed to the 6.87 MeV $1^-$ level of $^{10}$B. The analyses of both [1997ZA06] and [1998BR10] indicate substantial direct reaction contributions to the $^{9}$Be(p, $d$)$^{8}$Be cross section at energies below the $E_p \approx 310$ keV resonance.

The low-energy data and attempts to fit it are summarized by [2001BA47] where an $R$-matrix fit of almost all the data is performed for $E_p \lesssim 700$ keV. The discussion in [2001BA47] includes arguments questioning some of the $^{10}$B $J^\pi$ assignments of [1988AJ01]. In particular, it is argued in Appendix A of [2001BA47] that the dominant $T = 1$ isospin-mixed partner of the 6.87 MeV $1^-$; 0 + 1 level exists near $E_x = 7.44$ MeV (see reaction 12 and Table 10.20) where a resonance is seen in reactions (a) and (b) [1956WE37].

Table 10.26 shows resonances observed in early measurements of excitation functions for deuterons and $\alpha$-particles. Up to $E_p = 2.3$ MeV, the information is taken from a multi-level $R$-matrix analysis of the $p, d_0, a_0, \alpha_1$, and $\gamma$ channels by [1969CO1J] [see also [1964HO02,1969MO29]] omitting only the nearly pure $T = 1$ states at 7.47 MeV ($2^+$) and 7.56 MeV ($0^+$). [1969CO1J] give reduced widths and radiative widths for all these states. The separation of the $3^-/2^+$; $T = 1$ doublet at $E_p = 2.56$ MeV comes from an $R$-matrix analysis of the $(\alpha_2\gamma)$ and $p_0$ yields by [1977KI04]. The higher resonances appear on a background of direct reaction contributions and, given the assignment of both $\alpha_2$ and
Table 10.26
Resonances in $^9\text{Be}(p, d)^8\text{Be}$ and $^9\text{Be}(p, \alpha)^6\text{Li}$

<table>
<thead>
<tr>
<th>$E_p$ (MeV)</th>
<th>$E_x$ (MeV)</th>
<th>$I'_{2m}$ (keV)</th>
<th>$J^\pi; T$</th>
<th>Decay channels</th>
<th>$I'_{p}/I'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.330</td>
<td>6.880</td>
<td>135</td>
<td>$1^-; 0 + 1$</td>
<td>$d_0, \alpha_0$</td>
<td>0.27</td>
</tr>
<tr>
<td>0.375$^b$</td>
<td>6.924</td>
<td>110</td>
<td>$1^+; 0$</td>
<td>$d_0, \alpha_0$</td>
<td>$\approx 0.015$</td>
</tr>
<tr>
<td>0.450$^c$</td>
<td>6.992</td>
<td>90</td>
<td>$3^+; 0$</td>
<td>$d_0, \alpha_0$</td>
<td>$\approx 0.017$</td>
</tr>
<tr>
<td>0.650</td>
<td>7.171</td>
<td>430</td>
<td>$2^-; 0$</td>
<td>$d_0, \alpha_0$</td>
<td>0.10</td>
</tr>
<tr>
<td>0.955</td>
<td>7.447</td>
<td>130</td>
<td>$1^-; 1 + 0$</td>
<td>$d_0, \alpha_0$</td>
<td>0.38</td>
</tr>
<tr>
<td>0.992</td>
<td>7.480</td>
<td>80</td>
<td>$2^-; 0 + 1$</td>
<td>$d_0, \alpha_0$</td>
<td>0.90</td>
</tr>
<tr>
<td>1.20</td>
<td>7.66</td>
<td>250</td>
<td>$1^+; 0$</td>
<td>$d_0, \alpha_0$</td>
<td>0.30</td>
</tr>
<tr>
<td>1.30</td>
<td>7.76</td>
<td>245</td>
<td>$2^-; 0$</td>
<td>$d_0, \alpha_0$</td>
<td>0.90</td>
</tr>
<tr>
<td>1.65–1.80</td>
<td>8.07–8.21</td>
<td>$\approx 1000$</td>
<td>$2^+; 0$</td>
<td>$d_0, \alpha_0, \alpha_1$</td>
<td></td>
</tr>
<tr>
<td>2.30$^d$</td>
<td>8.66</td>
<td>$\approx 300$</td>
<td>$(2^-, 3^-)$</td>
<td>small</td>
<td></td>
</tr>
<tr>
<td>2.561$^e$</td>
<td>8.89</td>
<td>$100 \pm 20$</td>
<td>$3^-; 1$</td>
<td>$\alpha_2$</td>
<td>0.06–0.3</td>
</tr>
<tr>
<td>2.566$^e$</td>
<td>8.89</td>
<td>$40 \pm 1$</td>
<td>$2^+; 1$</td>
<td>$\alpha_2$</td>
<td></td>
</tr>
<tr>
<td>4.5$^f,g$</td>
<td>10.6</td>
<td>200$^g$</td>
<td>$\alpha_0, \alpha_2$</td>
<td>$\alpha_2$</td>
<td></td>
</tr>
<tr>
<td>4.78</td>
<td>10.8</td>
<td>300</td>
<td>$2^+; 1$</td>
<td>$\alpha_1, \alpha_2$</td>
<td></td>
</tr>
<tr>
<td>5.58</td>
<td>11.5</td>
<td>500</td>
<td>$\alpha_1, \alpha_2$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ For references and for a listing of other reported resonances and additional information see Table 10.14 in [1979AJ01]. The information up to $E_p = 2.3$ MeV is taken from a multi-level R-matrix analysis of the p, d, $\alpha_0, \alpha_1$, and $\gamma$ channels by [1969CO1J]. See also [1964HO02,1969MO29].

$^b$ Level appears only in the analysis of [1969CO1J].

$^c$ Other analyses have given $1^+, 2^+$, or $3^- [1979AJ01].$ See also [2001BA47].

$^d$ See also [1956WE37] for (p, d) and [1965MO1C] for (p, $\alpha$).

$^e$ From an R-matrix analysis of the ($\alpha_2\gamma$) and p0 yields [1977KI04].

$^f$ [1969MO29].

$^g$ [1974YA1C].

$\alpha_0$ or $\alpha_1$ decays in the same or different experiments [1959MA20,1974YA1C], it is not clear whether the resonances are due to isospin-mixed or unresolved states.

The existence of a 3.5 MeV resonance ($E_x = 9.7$ MeV) included in the previous compilation [1988AJ01] and assigned $T = 1$ was based on a small bump in the $^9\text{Be}(p, \alpha\gamma)^6\text{Li}$ cross section between the 2.56 MeV and 4.5 MeV resonances [1959MA20]. However, there is no known analog state in $^{10}\text{Be}$ and no resonance structure is observed in the $^9\text{Be}(n, \alpha)^6\text{He}$ spectrum [1957ST95].

Other measurements at higher energies include those at $E_p = 50$ MeV [1989GU08], $E_p = 25, 30$ MeV [1992PE12], $E_p = 2.475$ MeV ([1994LE08]; applications), $E_p = 40$ MeV [1997FA17], and $E_p = 60$ MeV [1987KA25]. For earlier measurements see [1988AJ01]. Polarization measurements have been made in the range $E_p = 0.30$ to 15 MeV and at 185 MeV [see [1974AJ01,1979AJ01]] at $E_p = 60$ MeV ([1987KA25]; $\Lambda_1$; inclusive deuteron spectra).

17. $^{9}\text{Be}(d,n)^{10}\text{B}$, $Q_m = 4.3613$

Neutron groups are observed corresponding to the $^{10}\text{B}$ states listed in Table 10.27. Angular distributions have been measured for $E_d = 0.5$ to 16 MeV [see [1974AJ01, 1979AJ01]], at 8 MeV ([1986BA40]: n_0 $\rightarrow$ n_5, n_6+7+8; also at 4 MeV to the latter) and at 18 MeV ([1987KAZL]: n_0, n_1) and at 5.5, 1.0, 1.5 and 2.0 MeV ([1995VU01]; n_0, n_6). At 25 MeV differential cross sections were measured and analyzed for levels below 6.57 MeV [1992MI03]. Spectroscopic factors were deduced and compared with previous data and with coupled-reaction-channel calculations. See Tables 2 and 3 of [1992MI03]. Observed $\gamma$-transitions are listed in Table 10.16 of [1979AJ01]. See Tables 10.19, 10.20 and 10.21 here for the parameters of radiative transitions and for $\tau_m$. Measurements of neutron angular distributions for $E_d = 15, 18$ MeV were analyzed [1988KA30] in the framework of the peripheral model of direct reactions. Neutron yields and differential cross sections at $E_d = 40$ MeV were measured by [1987SC11]. See also the neutron measurements at $E_d = 2.6–7$ MeV [1993ME10], $E_d = 21$ MeV [1994CO26], $E_d = 20.2$ MeV [1998BE31], $E_d = 5–10$ MeV [1998OL04], $E_d = 0.5–1.54$ MeV [1999AB38], and $E_d = 9.8$ MeV [1999JO03]. Application-related yields and spectra were measured at $E_d = 1.5, 1.95, 2.5$ and 5 MeV by [2002COZZ]. At low energies ($E_d = 24–111$ keV), cross sections were measured and astrophysical $S$ factors were deduced by [2001HO23]. An analysis of differential cross sections for $E_d = 7–15$ MeV was used to deduce optical model parameters and asymptotic normalization coefficients [2000FE08]. $^{10}\text{B}$ level information resulting from $^{9}\text{Be}(d,n)$ experiments prior to [1988AJ01] was summarized in [1988AJ01]. See also $^{11}\text{B}$ in [1985AJ01] and references cited in [1988AJ01]. Angular distributions of neutrons from $^{9}\text{Be}(d,n)$ at $E(9\text{Be}) = 3–7$ MeV were measured by [2002MA20].

18. $^{9}\text{Be}(^3\text{He},d)^{10}\text{B}$, $Q_m = 1.0924$

Deuteron groups have been observed to a number of states of $^{10}\text{B}$: see Table 10.27. Prior to the previous review [1988AJ01] angular distributions had been reported at $E(3\text{He}) = 10–33.3$ MeV [see [1974AJ01,1979AJ01,1984AJ01]]. More recently, differential cross sections were measured and analyzed at $E(3\text{He}) = 32.5$ MeV [1993AR14], 22.3–34 MeV [1996AR07], and 42 MeV [1998AR15]. Nuclear vertex constants and spectroscopic factors were deduced for the population of $^{10}\text{B}$ levels at $E_x = 0.0, 0.72, 1.74, 2.15, 3.59, 5.2, 5.92, 6.13, 6.56, 7.00, 7.5, 7.82, 8.9$ and spectroscopic factors were derived. The angular distributions to $^{10}\text{B}^*$(4.77, 6.03) could not be fitted by either DWBA or coupled channel analyses. In general coupled-channels calculations give a better fit to the 65 MeV data than does DWBA [1980HA33]. Comparisons with other one-proton stripping reactions [(d, n) and ($^3\text{He},d$)] are discussed in [1980HA33] as well as in [1997VO06].
Table 10.27
Levels of $^{10}\text{B}$ from $^{9}\text{Be}(d,n)$ and $^{9}\text{Be}(^{3}\text{He},d)^{a}$

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)$^{a}$</th>
<th>$^{9}\text{Be}(d,n)^{b}$</th>
<th>$^{9}\text{Be}(^{3}\text{He},d)^{c}$</th>
<th>$J^\pi; T^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$l_p$</td>
<td>$S_{rel}$</td>
<td>$l_p$</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1.00</td>
<td>1</td>
</tr>
<tr>
<td>0.72</td>
<td>1</td>
<td>1.97</td>
<td>1</td>
</tr>
<tr>
<td>1.74</td>
<td>1</td>
<td>1.36</td>
<td>1</td>
</tr>
<tr>
<td>2.15</td>
<td>1</td>
<td>0.41</td>
<td>1</td>
</tr>
<tr>
<td>3.59</td>
<td>1</td>
<td>0.10</td>
<td>1</td>
</tr>
<tr>
<td>4.77</td>
<td>(≥ 2)</td>
<td>(3)$^{d}$</td>
<td>1</td>
</tr>
<tr>
<td>5.11</td>
<td>0</td>
<td>0.14</td>
<td>0 + 2</td>
</tr>
<tr>
<td>5.16</td>
<td>1</td>
<td>0.43</td>
<td>1</td>
</tr>
<tr>
<td>5.18</td>
<td>1</td>
<td>0.49</td>
<td>1</td>
</tr>
<tr>
<td>6.03</td>
<td>(3)$^{d}$</td>
<td>(3)$^{d}$</td>
<td>(3)$^{d}$</td>
</tr>
<tr>
<td>6.13</td>
<td>(2)</td>
<td>(2)$^{e}$</td>
<td>(2)$^{e}$</td>
</tr>
<tr>
<td>6.56</td>
<td>(3)</td>
<td>(2)$^{e}$</td>
<td>(2)$^{e}$</td>
</tr>
<tr>
<td>6.89 ± 15</td>
<td>(1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.00 ± 15</td>
<td>(1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.48 ± 15</td>
<td>f</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.56 ± 25</td>
<td>f</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.85 ± 50</td>
<td>f</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.07 ± 50</td>
<td>f</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.12 ± 50</td>
<td>f</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^{a}$ Values without uncertainties are from Table 10.18; others are from Table 10.15 in [1979AJ01]. See that table for additional information and for references. See also [1984AJ01], and see the discussions under $^{9}\text{Be}(d,n)$ and $^{9}\text{Be}(^{3}\text{He},d)$ in this review.

$^{b}$ $S_{rel}$ from experiment at $E_d = 12.0–16.0$ MeV.

$^{c}$ $E(^{3}\text{He}) = 18$ MeV; DWBA analysis; values shown are those obtained with one of the two optical-model potentials used in the analysis. For earlier $(^{3}\text{He},d)$ results see Table 10.17 in [1979AJ01].

$^{d}$ Angular distribution poorly fitted by DWBA.

$^{e}$ See [1980BL02] for a discussion of these two states, including a comparison with the (d,n) data: $l_p = 2$ is slightly preferred to $l_p = 1$ on the basis of the observed strengths. Neither $l_p = 2$ nor 1 gives a good DWBA fit.

$^{f}$ State observed in (d,n) reaction; $l_p$ not determined.

$^{g}$ Group shown corresponds to unresolved states in $^{10}\text{B}$.

20. (a) $^{9}\text{Be}(^{7}\text{Li},^{6}\text{He})^{10}\text{B}$, $Q_m = -3.3904$

(b) $^{9}\text{Be}(^{10}\text{B},^{10}\text{B})^{9}\text{Be}$

(c) $^{9}\text{Be}(^{11}\text{B},^{10}\text{B})^{10}\text{Be}$, $Q_m = -4.642$

(d) $^{9}\text{Be}(^{12}\text{C},^{11}\text{B})^{10}\text{B}$, $Q_m = -9.371$

At $E(^{7}\text{Li}) = 34$ MeV angular distributions have been obtained for the $^{6}\text{He}$ ions to the first four states of $^{10}\text{B}$. Absolute values of the spectroscopic factors are $S = 0.88, 1.38$ (p$_{1/2}$ or p$_{3/2}$), 1.40, and 0.46 (p$_{1/2}$), 0.54 (p$_{3/2}$) for $^{10}\text{B}^*(0, 0.74, 1.74, 2.15)$ (FRDWBA analysis); see [1979AJ01]. See also [1988AL1G]. At $E(^{7}\text{Li}) = 14.13$ MeV a measurement of secondary beam production yields was reported by [1991BE49].
Cross sections have been measured for reaction (b) at $E(\text{^10B}) = 100 \text{ MeV}$ to obtain asymptotic normalization coefficients (ANC’s) [1997MU19,1998MU09,2001KR12]. Astrophysical $S$-factors for $^9\text{Be}(p,\gamma)^{10}\text{B}$ were deduced. In work described in [2000FE08] ANC’s were deduced from a set of proton transfer reactions at different energies to study the uniqueness of the ANC method.

For reaction (c), angular distributions were measured at $E_{\text{lab}}(^{11}\text{B}) = 45 \text{ MeV}$ [2003KY01] optical parameters for the $^{10}\text{B} + ^{10}\text{Be}$ interaction.

For reaction (d) angular distributions were measured at $E(^{12}\text{C}) = 65 \text{ MeV}$ for transitions to $^{10}\text{B}$ levels at 0.0, 0.72, 1.74 and 2.15 MeV [2000RU05]. Data were analyzed within the coupled reaction channel (CRC) method. It was found that two-step processes are important for all transitions.

21. $^{10}\text{Be}(\beta^-)^{10}\text{B}$, $Q_m = 0.5560$

See $^{10}\text{Be}$.

22. $^{10}\text{Be}(p,n)^{10}\text{B}$, $Q_m = -0.2264$

The yield of the $n_1$ group has been studied for $E_p = 0.9$ to 2.0 MeV: see $^{11}\text{B}$ in [1990AJ01,1986TE1A]. An analysis of data for $E = 0.95–1.9 \text{ MeV}$ and application of dispersion theory of reaction excitation functions at two-particle channel thresholds was reported in [1988DU06].

23. (a) $^{10}\text{B}(\gamma,n)^9\text{B}$, $Q_m = -8.4363$
(b) $^{10}\text{B}(\gamma,p)^8\text{Be}$, $Q_m = -6.5859$
(c) $^{10}\text{B}(\gamma,p+n)^8\text{Be}$, $Q_m = -8.2513$
(d) $^{10}\text{B}(\gamma,\pi^+)^{10}\text{Be}$, $Q_m = -140.1262$

Absolute measurements have been made of the $^{10}\text{B}(\gamma,n)$ cross section from threshold to 35 MeV with quasimonochromatic photons; the integrated cross section is 0.54 in units of the classical dipole sum $(60NZ/A \text{ MeV mb})$. The $(\gamma,2n)$ and $(\gamma,2np)$ cross section is zero, within statistics, for $E_{\gamma} = 16$ to 35 MeV: see [1979AJ01,1988DI02]. The giant resonance is broad with the major structure contained in two peaks at $E_{\chi} = 20.1 \pm 0.1$ and $23.1 \pm 0.1 \text{ MeV}$ ($\sigma_{\text{max}} \approx 5.5 \text{ mb}$ for each of the two maxima): see [1979AJ01]. [1987AH02] [and H. H. Thies, private communication] using $bs$ report two broad [$\Gamma \approx 2 \text{ MeV}$] maxima at 20.2 and 23.0 MeV [$\pm 0.05 \text{ MeV}$] ($\sigma = 5.0$ and 6.0 mb, respectively; $\pm 10\%$) and a minor structure at $E_{\chi} = 17.0 \text{ MeV}$. For reaction (b), differential cross section measurements were reported at $E_{\gamma} = 66–103 \text{ MeV}$ [1988SU14] and at 57.6 and 72.9 MeV [1998DE13]. See also the knock-out mechanism analysis described in [1997JO07].

For reaction (c) see [1988SU14]. For a DWIA study of reaction (d) for $E_{\gamma} = 164 \text{ MeV}$, see the analysis reported in [1994SA44]. See also $^9\text{Be}$, and the earlier references cited in [1988AJ01].
24. (a) $^{10}$B(e, e)$^{10}$B
   (b) $^{10}$B(e, e$\pi^+$)$^{10}$Be, $Q_m = -140.1262$
   (c) $^{10}$B(e, e$n$)$^{9}$B, $Q_m = -8.4363$
   (d) $^{10}$B(e, e$p$)$^{9}$Be, $Q_m = -6.5859$

Inelastic electron groups for which extensive form-factor measurements are available are displayed in Table 10.28. Transverse form factors in the momentum-transfer range $q = 2.0$–3.8 fm$^{-1}$ were measured for $^{10}$B*(0, 1.74, 5.16) by [1988HI02]. Measurements spanning the range $q = 0.48$–2.58 fm$^{-1}$ were made by [1995CI02] to determine longitudinal and transverse form factors for $^{10}$B levels up to $E_x = 6.7$ MeV with the exception of the broad $E_x = 5.18$ MeV level. The experimental form factors are compared with the results of extensive shell-model calculations [1995CI02]. Similar shell-model calculations of transverse scattering form factors for the 0, 1.74, and 5.16 MeV levels are reported in [1994BO04].

In [1995CI02], analyses that determined the r.m.s. radius of the ground-state charge distribution to be $2.58 \pm 0.05 \pm 0.05$ fm are described. This value is consistent with the tabulated value of $2.45 \pm 0.12$ fm [1987DE43]. In an appendix, $B$(E2) values derived from the longitudinal form factors [1995CI02,1966SP02,1976FA13,1979AN08] are given for the 0.72, 2.15, 3.59, 5.92, and 6.03 MeV levels. The $B$(E2) value for the 4.77 MeV level is known to be very small and the longitudinal form factor appears to be dominated by the C0 multipole. The results of an analysis by the same method [by coauthor D.J.M.; see [2004MIZX]] are listed in Table 10.28, together with similar analyses for other states for which the form factors appear to be dominated by a single multipole. The effects of including electron distortion, not taken into account in the transition strengths reported in the previous tabulation [1988AJ01], are significant.

The previous tabulation also included information on states at 8.07 and 8.9 MeV from [1979AN08] and at 10.79 and 11.56 MeV from [1976FA13]. The C2 strength reported for the 8.07 MeV level, analyzed as a 2$^+$ level, was such that the level should have been very strongly populated by inelastic pion scattering and this is not the case [1988ZE01]. For the 8.9 MeV excitation, the contributions from the 2$^+$; 1 and 3$^-$; 1 members of the doublet near this energy cannot be separated. In the 11 MeV region, there is evidence for considerable M1 strength [1976FA13].

For reaction (b) see $^{10}$Be. For reactions (c) and (d) see [1984AJ01,1997JO07]. See also the earlier references cited in [1988AJ01].

25. $^{10}$B($\pi$, $\pi'$)$^{10}$B

The inelastic scattering of 162 MeV pions has been studied [1988ZE01] over the angular range 35° to 100° in the laboratory system and the data were analyzed with a model that incorporates shell-model wave functions into a distorted-wave impulse approximation formalism. Reduced transition probabilities were obtained for low-lying states. Higher states, or groups of unresolved states, at 7.0, 7.8, 8.07, 8.9, 9.7, 10.7, 11.5, and 12.8 MeV were studied.
Table 10.28
Transition strengths and radiative widths from $^{10}\text{B}(e,e')^\mu$

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$J^\pi$; $T$</th>
<th>Malt.</th>
<th>$B(\lambda\gamma)$ e(^2) fm(^2)</th>
<th>$B(\lambda\gamma)$ (W.u.)</th>
<th>$\Gamma_{\gamma}$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.72</td>
<td>1(^+_\tau); 0</td>
<td>C2</td>
<td>1.71 ± 0.14</td>
<td>3.12 ± 0.26</td>
<td>(6.1 ± 0.5) × 10(^{-7})</td>
</tr>
<tr>
<td>1.74</td>
<td>0(^+_\tau); 1</td>
<td>M3</td>
<td>7.00 ± 0.20(^b)</td>
<td>125 ± 4</td>
<td>(8.90 ± 0.26) × 10(^{-10})</td>
</tr>
<tr>
<td>2.15</td>
<td>1(^+_\tau); 0</td>
<td>C2</td>
<td>0.41 ± 0.05</td>
<td>0.75 ± 0.08</td>
<td>(3.6 ± 0.4) × 10(^{-5})</td>
</tr>
<tr>
<td>3.59</td>
<td>2(^+); 0</td>
<td>C2</td>
<td>0.62 ± 0.05</td>
<td>0.67 ± 0.05</td>
<td>(4.1 ± 0.3) × 10(^{-4})</td>
</tr>
<tr>
<td>5.16(^c)</td>
<td>2(^+); 1</td>
<td>M3</td>
<td>19.4 ± 1.3</td>
<td>69.2 ± 4.6</td>
<td>(1.00 ± 0.07) × 10(^{-6})</td>
</tr>
<tr>
<td>5.92</td>
<td>2(^+); 0</td>
<td>C2</td>
<td>0.15 ± 0.05</td>
<td>0.16 ± 0.06</td>
<td>(1.2 ± 0.4) × 10(^{-3})</td>
</tr>
<tr>
<td>6.03</td>
<td>4(^+); 0</td>
<td>C2</td>
<td>18.7 ± 0.7</td>
<td>11.4 ± 0.4</td>
<td>(9.3 ± 0.4) × 10(^{-2})</td>
</tr>
<tr>
<td>6.13</td>
<td>3(^-); 0</td>
<td>C3(^d)</td>
<td>33.0 ± 3.8</td>
<td>5.6 ± 0.7</td>
<td>(4.0 ± 0.5) × 10(^{-6})</td>
</tr>
<tr>
<td>6.56</td>
<td>4(^-); 0</td>
<td>C3(^e)</td>
<td>21.7 ± 3.1</td>
<td>2.8 ± 0.4</td>
<td>(3.3 ± 0.5) × 10(^{-6})</td>
</tr>
<tr>
<td>7.48(^f)</td>
<td>2(^+); 1</td>
<td>M1</td>
<td>0.018 ± 0.002</td>
<td>1.27 ± 0.14</td>
<td>11.0 ± 1.2</td>
</tr>
</tbody>
</table>

\(^a\) From [2004MIZX], analysis using polynomial times Gaussian fits to data from [1966SP02, 1976FA13, 1979AN08, 1995CI02]. Distortion effects are taken into account by using $q_{eff} = q(1 + 2.75/E_0)$ where $E_0$ is the incident electron energy in MeV [1995CI02].

\(^b\) From a full DWBA analysis (R.S. Hicks, private communication).

\(^c\) Assumed to correspond to $2^+$ state at 5.16 MeV. $F_2$ at $q_{eff} = 1.32$ fm\(^{-1}\) for the transition to the $2^+$ state at 5.110 MeV is an order of magnitude smaller than $F_2$ for the 5.164 MeV level [1995CI02]. A small M1 contribution at low $q$ has been subtracted.

\(^d\) Shell-model calculations predict a dominant C3 contribution and a smaller C1 contribution [1995CI02].

\(^e\) Shell-model calculations predict a dominant C3 contribution [1995CI02].

\(^f\) Using the low-$q$ data from [1966SP02, 1976FA13]. In this evaluation, we have adopted a $2^+$ assignment for the 7.48 MeV state. However, see Tables 10.18 and 10.20 for a nearby $2^+$ level.

26. $^{10}\text{B}(n,n)^{10}\text{B}$

Angular distributions have been studied for $E_n = 1.5$ to 14.1 MeV [see [1974AJ01, 1979AJ01]] and at 3.02 to 12.01 MeV ([1986SA1U, 1987SA1H]; $n_1 \rightarrow n_5$), 8 to 14 MeV ([1983DA22]; $n_0$) and 9.96 to 16.94 MeV ([1986MU1D]; $n_0$). Measurements were made by [1990SA24] for $E_n$ from 3.02 MeV up to 12.01 MeV. See also the experimental study of [1988RE09] and the optical model analysis of [1996CH33]. See also $^{11}\text{B}$ in [1985AJ01, 1990AJ01] and [1984TO02].

27. (a) $^{10}\text{B}(p,p)^{10}\text{B}$

(b) $^{10}\text{B}(p,2p)^7\text{Be}$, $Q_m = -6.5859$

Angular distributions have been measured for a number of energies between $E_p = 3.0$ and 800 MeV [see [1974AJ01, 1979AJ01, 1984AJ01]] and at 10 to 17 MeV ([1986MU1D]; $p_0$). Differential cross sections have been measured [2001CH78] from $E_p = 0.5$–3.3 MeV in $5^\circ$ steps from $100^\circ$–170$^\circ$. Cross sections and polarization observables for 200 MeV polarized protons were measured by ([1992BA76]; $p_0$, $p_1$). See also the $E_p = 200$ MeV measurements and analyses reported in [1991LE22]. Microscopic model analyses are reported for $E_p = 25$, 30, 40 MeV by [2000DE61] and for $E_p = 200$ MeV by [1997DO01]. Table 10.29 displays the states observed in this reaction. Inelastic scattering data were used to deduce the deformation parameters, $\beta_L$. The $\gamma$-ray results are shown in Tables 10.19 and 10.20. See also [1979AJ01]. For $\tau_m$ see Table 10.21 [1983VE03].
Table 10.29

$^{10}$B levels from $^{10}$B(p, p), $^{10}$B(d, d) and $^{10}$B($^{3}$He, $^{3}$He)$^{a}$

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)$^{b}$</th>
<th>$I_{cm}$ (keV)</th>
<th>L</th>
<th>$\beta_{L}$$^{b,c}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7183 ± 0.4$^{d,e,f}$</td>
<td>2</td>
<td>0.67 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>1.7402$^{g}$</td>
<td>(3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1541 ± 0.5$^{d}$</td>
<td>2</td>
<td>0.49 ± 0.04</td>
<td></td>
</tr>
<tr>
<td>3.5870 ± 0.5$^{d}$</td>
<td>2</td>
<td>0.45 ± 0.04</td>
<td></td>
</tr>
<tr>
<td>4.7740 ± 0.5$^{h}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.1103 ± 0.6</td>
<td>3</td>
<td>0.45 ± 0.04</td>
<td></td>
</tr>
<tr>
<td>5.1639 ± 0.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.18 ± 10$^{b,j}$</td>
<td>110 ± 10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.9195 ± 0.6$^{d}$</td>
<td>&lt; 5</td>
<td>0.28 ± 0.03</td>
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<tr>
<td>6.0250 ± 0.6$^{d}$</td>
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<td>0.95 ± 0.04</td>
</tr>
<tr>
<td>6.1272 ± 0.7$^{d}$</td>
<td>&lt; 5</td>
<td>3</td>
<td>0.58 ± 0.03</td>
</tr>
<tr>
<td>6.55 ± 10$^{d}$</td>
<td>25 ± 5</td>
<td>3</td>
<td>0.46 ± 0.04$^{l}$</td>
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<tr>
<td>7.00 ± 10$^{d}$</td>
<td>95 ± 10</td>
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<tr>
<td>7.48 ± 10</td>
<td>90 ± 15</td>
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</tr>
</tbody>
</table>

$^{a}$ For references and a more complete presentation see Table 10.19 in [1979AJ01].

$^{b}$ From (p, p) and (p, $p'$).

$^{c}$ See results obtained from ($^{3}$He, $^{3}$He$'$) in Table 10.19 of [1979AJ01].

$^{d}$ Also observed in (d, d) and ($^{3}$He, $^{3}$He$'$).

$^{e}$ $E_A = 718.35 ± 0.04$ (from $E_{\gamma}$).

$^{f}$ $E_A = 718.5 ± 0.2$ and 1740.0 ± 0.6 keV (from $E_{\gamma}$).

$^{g}$ Also observed in ($^{3}$He, $^{3}$He$'$).

$^{h}$ Also observed in (d, d).

$^{i}$ Not reported in (p, p) at $E_p = 10$ MeV.

$^{j}$ Assumes $J^T = 4^-$: $\beta_L = 0.59 ± 0.03$ if $J^T = 2^-$.

Axions may cause e$^+$ e$^-$ pairs in competition with $\gamma$-ray emission in an isoscalar M1 transition: a search for axions was undertaken in the case of the 3.59 → g.s. [2$^+ → 3^+$] transition. It was negative [1986DE25]. A beam dump experiment and other attempts to observe axions are discussed in [1987HA1O]. For reaction (b) at $E_p = 1$ GeV see [1985BE30, 1985DO16] and [1974AJ01]. See also [1988KRZY], ([1985KI1B,1988KOZL]; applied) and 11C in [1985AJ01,1990AJ01].

28. $^{10}$B(d, d)$^{10}$B

Angular distributions have been reported at $E_d = 4$ to 28 MeV: see [1974AJ01, 1979AJ01]. Observed deuteron groups are displayed in Table 10.29. The very low intensity of the group to $^{10}$B$^*(1.74)$ and the absence of the group to $^{10}$B$^*(5.16)$ is good evidence of their $T = 1$ character: see [1974AJ01]. See also the cross section measurements at $E_d = 13.6$ MeV reported in [1991BE42].

29. $^{10}$B(t, t)$^{10}$B

Angular distributions of elastically scattered tritons have been measured at $E_t = 1.5$ to 3.3 MeV: see [1974AJ01].
30. $^{10}\text{B}(^{3}\text{He}, ^{3}\text{He})^{10}\text{B}$

Angular distributions have been measured at $E(^{3}\text{He}) = 4$ to 46.1 MeV [see [1974AJ01, 1979AJ01, 1984AJ01]] and at 2.10 and 2.98 MeV ([1987BA34]; elastic). $L = 2$ gives a good fit of the distributions of $^{3}\text{He}$ ions to $^{10}\text{B}^*(0.72, 2.15, 3.59, 6.03)$: derived $\beta_L$ are shown in Table 10.19 of [1979AJ01]. See also Table 10.29 here, $^{13}\text{N}$ in [1986AJ01] and see the Strong-Absorption Model analysis for $E(^{3}\text{He}) = 41$ MeV reported in [1987RA36].

31. (a) $^{10}\text{B}(\alpha, \alpha)^{10}\text{B}$
(b) $^{10}\text{B}(\alpha, 2\alpha)^{6}\text{Li}$, $Q_m = -4.4610$

Angular distributions have been measured for $E_\alpha = 5$ to 56 MeV [see [1974AJ01, 1979AJ01, 1984AJ01]] and at 91.8 MeV ([1985JVI12]; $\alpha_0$). Measurements of cross sections relative to Rutherford scattering at large angles for $E_\alpha = 1$–3.3 MeV were reported by [1992MC03]. Data for $E_\alpha = 1.5$–10 MeV were compiled and reviewed for depth-profiling applications in [1991LE33]. Reaction (b) has been studied at $E_\alpha = 24$ and 700 MeV: see [1979AJ01, 1984AJ01]. See also ([1983GO27, 1985SH1D]; theor.).

32. (a) $^{10}\text{B}(^{6}\text{Li}, ^{6}\text{Li})^{10}\text{B}$
(b) $^{10}\text{B}(^{7}\text{Li}, ^{7}\text{Li})^{10}\text{B}$

Elastic-scattering angular distributions have been studied at $E(^{6}\text{Li}) = 5.8$ and 30 MeV: see [1979AJ01]. A model for calculating departures from Rutherford backscattering for Lithium targets is described in [1991BO48]. For reaction (b), elastic scattering angular distributions were studied at $E(^{7}\text{Li}) = 24$ MeV: see [1979AJ01]. Differential cross section measurements at $E(^{7}\text{Li}) = 39$ MeV were reported in [1988ET02].

33. (a) $^{10}\text{B}(^{7}\text{Be}, ^{7}\text{Be})^{10}\text{B}$
(b) $^{10}\text{B}(^{8}\text{Be}, ^{8}\text{Be})^{10}\text{B}$

Elastic scattering differential cross section measurements at $E(^{7}\text{Be}) = 84$ MeV have been reported [1999AZ02, 2001AZ01, 2001GA19, 2001TR04]. The results were used along with $^{10}\text{B}(^{7}\text{Be}, ^{8}\text{B})$ data to deduce asymptotic normalization coefficients for the virtual transitions $^{8}\text{B} \rightarrow ^{7}\text{Be} + p$ and to calculate the astrophysical $S$ factor and direct-capture rates for $^{7}\text{Be}(p, \gamma)^{8}\text{B}$. See also the analysis in [2002GA11].

For reaction (b), the elastic angular distributions have been measured at $E(^{10}\text{B}) = 20.1$ and 30.0 MeV [1983SR01]. For yield and cross section measurements see [1983SR01, 1986CU02]. See also the calculations of [1984IN03, 1986RO12].

34. (a) $^{10}\text{B}(^{10}\text{B}, ^{10}\text{B})^{10}\text{B}$
(b) $^{10}\text{B}(^{11}\text{B}, ^{11}\text{B})^{10}\text{B}$

Elastic angular distributions (reaction (a)) have been studied at $E(^{10}\text{B}) = 8$, 13 and 21 MeV (see the references cited in [1979AJ01]) and at $E(^{10}\text{B}) = 4$–15 MeV [1975DI08]. These data were used by [2000RU05] to study the energy dependence of optical model parameters. For reaction (b) see the references cited in [1988AJ01]. See also [2000RU05].
35. (a) $^{10}$B($^{12}$C,$^{12}$C)$^{10}$B
(b) $^{10}$B($^{13}$C,$^{13}$C)$^{10}$B

Elastic angular distributions have been measured at $E(^{10}$B) = 18 and 100 MeV for reaction (a) [see [1979AJ01]] and at 18–46 MeV [see [1984AJ01]] and 42.5, 62.3 and 80.9 MeV for reaction (b) [1985MA10]. For yield, cross section and fusion experiments see [1983DA20,1983MA53,1985MA10,1988MA07,1984AJ01]. For other references on these reactions, see [1988AJ01].

36. $^{10}$B($^{14}$N,$^{14}$N)$^{10}$B

Angular distributions have been reported at $E(^{10}$B) = 100 MeV and $E(^{14}$N) = 73.9 and 93.6 MeV [1979AJ01,1984AJ01], and at 38.1, 42.0 and 50 MeV [1988TA13]. For fusion cross section studies see [1983DE26,2001DI12] and the references cited in [1979AJ01, 1984AJ01,1988AJ01].

37. (a) $^{10}$B($^{16}$O,$^{16}$O)$^{10}$B
(b) $^{10}$B($^{17}$O,$^{17}$O)$^{10}$B
(c) $^{10}$B($^{18}$O,$^{18}$O)$^{10}$B

Elastic angular distributions (for reaction (a)) have been studied at $E(^{10}$B) = 33.7 to 100 MeV and at $E(^{16}$O) = 15–32.5 MeV [1979AJ01,1984AJ01], at $E_{cm}$ = 14.77, 16.15 and 18.65 MeV [1988KO10], and for reactions (a), (b) and (c) at $E(^{16}$O) = 16–64 MeV [1994AN05]. For elastic cross sections for reaction (c) at $E(^{16}$O) = 20, 24 and 30.5 MeV, see [1974AJ01]. For a study of the time scales for binary processes for the $^{16}$O$+^{10}$B system at $E_{cm}$ = 17–25 MeV see [2002SU17]. See also [2001DE50]. For yield and fusion cross section measurements see [1993AN08,1993AN15,1994AN05] and earlier references cited in [1988AJ01].

38. (a) $^{10}$B($^{19}$F,$^{19}$F)$^{10}$B
(b) $^{10}$B($^{20}$Ne,$^{20}$Ne)$^{10}$B

The elastic scattering has been investigated for $E(^{19}$F) = 20 and 24 MeV for reaction (a) and $E(^{10}$B) = 65.9 MeV for reaction (b); see [1974AJ01,1984AJ01].

39. (a) $^{10}$B($^{24}$Mg,$^{24}$Mg)$^{10}$B
(b) $^{10}$B($^{25}$Mg,$^{25}$Mg)$^{10}$B

The elastic scattering for both reactions has been studied at $E(^{10}$B) = 87.4 MeV: see [1984AJ01]. The elastic scattering for reaction (b) has been measured at $E(^{10}$B) = 34 MeV by [1985WI18].
40. (a) $^{10}\text{B}(^{27}\text{Al},^{27}\text{Al})^{10}\text{B}$  
(b) $^{10}\text{B}(^{28}\text{Si},^{28}\text{Si})^{10}\text{B}$  
(c) $^{10}\text{B}(^{30}\text{Si},^{30}\text{Si})^{10}\text{B}$

The elastic scattering for all three reactions has been studied at $E(^{10}\text{B}) = 41.6$ and $\approx 50$ MeV [and also at 33.7 MeV for reaction (b)]; see [1984AJ01]. See also [1984TE1A].

41. (a) $^{10}\text{B}(^{39}\text{K},^{39}\text{K})^{10}\text{B}$  
(b) $^{10}\text{B}(^{40}\text{Ca},^{40}\text{Ca})^{10}\text{B}$

The elastic scattering has been studied at $E(^{10}\text{B}) = 44$ MeV for reaction (a) [1985WI18] and at 46.6 MeV for reaction (b): see [1984AJ01].

42. $^{10}\text{C}(\beta^+,^{10}\text{B})$, $Q_m = 3.6480$

The half-life of $^{10}\text{C}$ is 19.290 ± 0.012 sec [1990BA02]; the decay is to $^{10}\text{B}^*(0.72, 1.74)$ with branching ratios of (98.53 ± 0.02)% [1979AJ01] and (1.4645 ± 0.0019)% [world average [1999FU04]], see [1991KR19,1991NA01,1995SA16,1999FU04] for measurements since [1988AJ01]; an upper limit for decay to $^{10}\text{B}^*(2.15)$, $\leq 8 \times 10^{-4}$%, is given in [1979AJ01]. The excitation energies of $^{10}\text{B}^*$ are 718.380 ± 0.011 keV and 1740.05 ± 0.04 keV, respectively, which were determined from de-excitation $\gamma$-rays with $E_\gamma = 718.353 \pm 0.010$ keV and 1021.646 ± 0.014 keV [1988BA55,1989BA28]. See [2003SU04] for discussion of $B$(GT) values.

The $0^+ \rightarrow 0^+$ super-allowed $\beta$-decay branch for $^{10}\text{C}$ decay to $^{10}\text{B}^*(1.74)$ is important for determining the $V_{ud}$ matrix element and for testing the unitarity of the Cabibbo–Kobayashi–Maskawa matrix. The $V_{ud}$ matrix element is determined by $f t$-values; for $^{10}\text{C}$, this depends on the $^{10}\text{C}^*(0, [0^+]) \rightarrow ^{10}\text{B}^*(1.74, [0^+])$ branching ratio, 1.4645 ± 0.0019 [J$^\pi$ in brackets], the $^{10}\text{C}$ half-life [1990BA02], and the decay energy to the $^{10}\text{B}^*(1.74)$ state, 1907.86 ± 0.12 keV [1998BA83]. The experimental $f t$ value is 3037 ± 8, which yields $\log ft = 3.4825 \pm 0.0014$. Various corrections to the $f t$-values, to account for nuclear structure and isospin effects, are discussed in [1991RA09,1992BA22,1993CH06,1994BA65,1996SA09,1998TOZQ,2000BA52,2000HAZU]. After correction, the $f t$ value is $\approx 3068.9 \pm 8.5$ (99FU04), which by itself satisfies the unitarity test of the CKM matrix. However, higher precision measurements are desirable since the satisfaction of CKM unitarity, based on all $0^+ \rightarrow 0^+$ decays, continues to be debated in the literature [2002HA47,2002TO19,2002WI09,2003WI01].

43. $^{11}\text{B}(\gamma, n)^{10}\text{B}$, $Q_m = -11.454$

The intensities of the transitions to $^{10}\text{B}^*(3.59, 5.16)$ [$T = 0$ and 1, respectively] depend on the region of the giant dipole resonance in $^{11}\text{B}$ from which the decay takes place: it is suggested that the lower-energy region consists mainly of $T = \frac{1}{2}$ states and the higher-energy region of $T = \frac{3}{2}$ states: see $^{11}\text{B}$ in [1980AJ01]. See also $^{11}\text{B}$ in [1985AJ01,1990AJ01,1984AL22].
44. (a) $^{11}\text{B}(p, d)^{10}\text{B}$, $Q_m = -9.230$
(b) $^{11}\text{B}(p, p + n)^{10}\text{B}$, $Q_m = -11.454$

Angular distributions of deuteron groups have been measured at several energies in the range $E_p = 17.7$ to 154.8 MeV [see [1979AJ01]] and at 18.6 MeV ([1985BE13]; d$_0$, d$_1$). The population of the first five states of $^{10}\text{B}$ and of $^{10}\text{B}^*$ (5.2, 6.0, 6.56, 7.5, 11.4 ± 0.2, 14.1 ± 0.2) is reported. Data at $E_p = 33$ MeV was used [1991AB04] in a test of Cohen-Kurath wave functions and intermediate coupling. For reaction (b) see ([1985BE30, 1985BO1B]; 1 GeV). Cross sections $\sigma(E)$ for both reactions (a) and (b) are calculated in a “quasiquantum multistep direct reaction” theory described in [1994SH21]. See also references cited in [1988AJ01].

45. $^{11}\text{B}(d, t)^{10}\text{B}$, $Q_m = -5.197$

Angular distributions have been measured at $E_d = 11.8$ MeV ($t_0 \rightarrow t_3$; $l = 1$) [see [1974AJ01]] and at 18 MeV [1987GU1F,1988GU1D]. A combined DWBA and dispersion-theory analysis of cross section data is described in [1995GU22]. Vertex constants and spectroscopic factors were deduced.

46. (a) $^{11}\text{B}^{(3}\text{He, } \alpha)^{10}\text{B}$, $Q_m = 9.124$
(b) $^{11}\text{B}^{(3}\text{He, } 2\alpha)^{6}\text{Li}$, $Q_m = 4.663$

Reported levels are displayed in Table 10.30. Angular distributions have been measured at a number of energies between $E(3\text{He}) = 1.0$ and 33 MeV [see [1974AJ01]] and at 23.4 MeV ([1987VA1I]; $\alpha_0$, $\alpha_1$). For the decay of observed states see Tables 10.19 and 10.20.

The $\alpha-\alpha$ angular correlations (reaction (b)) have been measured for the transitions via $^{10}\text{B}^*(5.92, 6.03, 6.13, 6.56, 7.00)$. The results are consistent with $J^\pi = 2^+$ and $4^+$ for $^{10}\text{B}^*(5.92, 6.03)$ and require $J^\pi = 3^-$ for $^{10}\text{B}^*(6.13)$. There is substantial interference between levels of opposite parity for the $\alpha$-particles due to $^{10}\text{B}^*(6.56, 7.00)$. The data are fitted by $J^\pi = 3^+$ for $^{10}\text{B}^*(7.00)$ and $(3, 4)^-$ for $^{10}\text{B}^*(6.56)$. The $(^6\text{Li}(\alpha, \alpha)$ results then require $J^\pi = 4^-$. See, however, reaction 16, and see [1974AJ01] for the references. See also ([1988GO1E]; theor.).

47. $^{11}\text{B}^{(7}\text{Li, } ^8\text{Li})^{10}\text{B}$, $Q_m = -9.422$

Angular distributions have been measured at $E(7\text{Li}) = 34$ MeV involving $^{10}\text{B}^*(0.0, 0.72, 1.74, 2.15)$ and $^8\text{Li}_{e.s.}$ (as well as $^8\text{Li}^*(0.98)$ in the case of the $^{10}\text{B}_{e.s.}$ transition) [1987CO16].

48. (a) $^{12}\text{C}(\gamma, d)^{10}\text{B}$, $Q_m = -25.1864$
(b) $^{12}\text{C}(\gamma, p + n)^{10}\text{B}$, $Q_m = -27.4110$

For reaction (a) see [1986SH1M] and $^{12}\text{C}$ in [1990AJ01]. Reaction (b) was studied at $E_\gamma = 189-427$ MeV [1987KA13], 83–133 MeV [1988DA16], 80–159 MeV [1993HA12],
Table 10.30

$^8$B levels from $^{11}$B($^3$He, $^\alpha$) $^{10}$Ba

<table>
<thead>
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<th>$E_x$ (MeV ± keV)</th>
<th>$I_{cm}$ (keV)</th>
<th>$l$</th>
<th>$S_{rel}$</th>
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<tr>
<td>(18.2 ± 200)</td>
<td>(1500 ± 300)</td>
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</table>

a See Table 10.21 in [1979AJ01] for references.


49. $^{12}$C(n, t) $^{10}$B, $Q_m = -18.9292$

Cross section measurements at $E_n = 40–56$ keV for determining efficiency of neutron detectors were reported in [1994MO41]. Calculated cross sections are tabulated in [1998BR05]. See also ([1985FR07,1987FR16]; $E_n = 319$ to 545 MeV) and [1986DO12].

50. $^{12}$C($\pi^\pm, \pi^\pm$) $^{10}$B, $Q_m = -25.1864$

At $E_{\pi^+} = 180$ MeV and $E_{\pi^-} = 220$ MeV, $^{10}$B$^+(0.72, 2.15)$ are populated; see [1984AJ01]. At $E_{\pi^+} = 150$ MeV momentum distributions of pions to unresolved states of $^{10}$B are reported by [1987HU13].
(a) $^{12}\text{C}(p, ^3\text{He})^{10}\text{B}$, $Q_m = -19.6929$

(b) $^{12}\text{C}(p, p + d)^{10}\text{B}$, $Q_m = -25.1864$

Angular distributions of $^3\text{He}$ ions have been measured for $E_p = 39.8, 51.9$ and $185$ MeV: see [1979AJ01]. $^{10}\text{B}^*(0, 0.72, 1.74, 2.15, 3.59, 4.77, 5.16, 5.92, 6.56, 7.50, 8.90)$ are populated. A calculation of $^3\text{He}$ and $\alpha$-particle multiplicities is described in [1987GA08]. For reaction (b) see [1985DE17]; $E_p = 58$ MeV; $^{10}\text{B}^*(0.72, 1.74)$ and [1984AJ01]. Calculations of cross sections for $E_p = 58$ MeV and 0.7 GeV are described in [1990LO18] and [1987ZH10], respectively. See also the references cited in [1988AJ01].

52. $^{12}\text{C}(d, \alpha)^{10}\text{B}$, $Q_m = -1.3400$

Alpha groups have been observed to most of the known states of $^{10}\text{B}$ below $E_x = 7.1$ MeV: see Table 10.23 in [1974AJ01]. Angular distributions have been measured for $E_d = 5.0$ to 40 MeV: see [1979AJ01]. Single-particle $S$-values are 1.5, 0.5, 0.1, 0.1 and 0.3, respectively, for $^{10}\text{B}^*(0, 0.72, 2.15, 3.59, 4.77)$. A study of the $m_s = 0$ yield at $E_d = 14.5$ MeV ($\theta = 0^\circ$) leads to assignments of $3^+, 2^-$ and $(3^+, 4^-)$ for $^{10}\text{B}^*(4.77, 5.11, 6.56)$. The population of the isospin-forbidden group to $^{10}\text{B}^*(1.74)$ [$\alpha_2$] has been studied with $E_d$ up to 30 MeV: see $^{14}\text{N}$ in [1986AJ01]. See also [1984LO1A].

53. $^{12}\text{C}(\alpha, ^6\text{Li})^{10}\text{B}$, $Q_m = -23.7126$

Angular distributions have been reported at $E_\alpha = 42$ and 46 MeV: see [1979AJ01]. At $E_\alpha = 65$ MeV, an investigation of the $^6\text{Li}$ breakup shows that $^{10}\text{B}^*(0, 0.72, 2.16, 3.57, 4.77, 5.2, 5.9, 6.0)$ are involved: see [1984AJ01]. See also the cross section measurements at $E_\alpha = 33.8$ MeV [1987GA20] and at $E_\alpha = 90$ MeV [1991GL03].

54. $^{12}\text{C}(^7\text{Li}, ^6\text{Be})^{10}\text{B}$, $Q_m = -8.4905$

At $E(^7\text{Li}) = 78$ MeV angular distributions have been measured to $^{10}\text{B}^*(0, 2.15)$ [1986GL1C].

55. (a) $^{12}\text{C}(^{12}\text{C}, ^{14}\text{N})^{10}\text{B}$, $Q_m = -14.9141$

(b) $^{12}\text{C}(^{14}\text{N}, ^{16}\text{O})^{10}\text{B}$, $Q_m = -4.4503$

Angular distributions (reaction (a)) involving $^{10}\text{B}^*(0, 0.7)$ have been studied at $E(^{12}\text{C}) = 49.0$ to 75.5 and 93.8 MeV. Angular distributions (reaction (b)) involving $^{10}\text{B}^*(0, 0.72, 2.15, 3.59)$ have been measured at $E(^{14}\text{N}) = 53$ MeV and 78.8 MeV (not to $^{10}\text{B}^*(3.59)$): see [1979AJ01,1984AJ01] for references. See also [1986AR04,1986CR1A, 1986MO1D].

56. $^{13}\text{C}(p, \alpha)^{10}\text{B}$, $Q_m = -4.0616$

Differential cross sections were measured [1988AB11] at $E_p = 18–45$ MeV. Measurements at $E_p = 30.95$ MeV were reported by [1988BA30]. Known p-shell levels at 0,
$^{10}\text{B, }^{10}\text{C}$

0.72, 1.74, 2.15, 3.59, 4.77, 5.16, 5.92, 6.03 and 7.47 MeV were excited [1988AB11, 1988BA30]. Analyses in both these studies used DWBA direct pickup calculations using a triton cluster form factor and the shell model calculations of [1975KU01]. Spectroscopic factors were deduced. For earlier work at $E_p = 5.8\text{–}18$ MeV and 43.7 and 50.5 MeV see [1979AJ01]. See also references cited in [1988AJ01].

57. $^{14}\text{N}(p, p + \alpha)^{10}\text{B}, \quad Q_m = -11.6122$

See ([1986VD1C]; $E_p = 50$ MeV). See also ([1986GO28]; theor.).

58. $^{14}\text{N}(d, ^6\text{Li})^{10}\text{B}, \quad Q_m = -10.1384$

At $E_d = 80$ MeV angular distributions are reported to $^{10}\text{B}^+(0, 0.72, 2.15, 3.59, 4.8, 6.04, 7.05, 8.68)$: see [1979OE01].

59. $^{16}\text{O}(^9\text{Be}, ^{15}\text{N})^{10}\text{B}, \quad Q_m = -5.5415$

See [1985WI18].

60. (a) $^{\text{n}}\text{Ag}(^{14}\text{N}, \alpha + ^6\text{Li})X$

(b) $^{\text{n}}\text{Ag}(^{14}\text{N}, p + ^9\text{Be})X$

The breakup of $^{10}\text{B}$ was studied [1989NA03, 1992NA01] in an experiment with an $E/A = 35$ MeV $^{14}\text{N}$ beam incident on $^{\text{n}}\text{Ag}$. In the breakup of $^{10}\text{B}$ into $\alpha + ^6\text{Li}$ the 4.77 MeV $3^+$ and 6.56 MeV $4^-$ states were observed together with unresolved groups of states near 5.1, 6.0, and 7.0 MeV. In the $^9\text{Be} + p$ channel peaks centered near 6.9, 7.5, and 8.9 MeV were observed. Similar results have been obtained for an $^{36}\text{Ar}$ beam incident on $^{197}\text{Au}$ [1992ZH08].

$^{10}\text{C}$

(Figs. 16 and 17)

General

References to articles on general properties of $^{10}\text{C}$ published since the previous review [1988AJ01] are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for $^{10}\text{C}$ located on our website at: www.tunl.duke.edu/nuclidata/General_Tables/10c.shtml.

Mass of $^{10}\text{C}$  The threshold energy for the $^{10}\text{B}(p, n)^{10}\text{C}$ reaction is 4877.03 ± 0.13 keV: then $Q_0 = -4430.30 \pm 0.12$ keV [1998BA83]. Using the [2003AU03] masses for $^{10}\text{B}$, $p$ and $n$, the atomic mass excess is then 15698.8 ± 0.4 keV. However, we adopt the [2003AU03] value: 15698.6 ± 0.4 keV. See also unpublished work on $^{12}\text{C}(p, t)^{10}\text{C}$ that is quoted in [1984AJ01].
Table 10.31
Energy levels of $^{10}\text{C}$

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$J^\pi$</th>
<th>$\tau$ or $\Gamma_{cm}$ (keV)</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>g.s.</td>
<td>$0^+; 1$</td>
<td>$\tau_{1/2} = 19.290 \pm 0.012$ sec</td>
<td>$\beta^+$</td>
<td>1, 2, 3, 6, 8, 9, 11, 12</td>
</tr>
<tr>
<td>3.3536 ± 0.7</td>
<td>$2^+$</td>
<td>$\tau_m = 155 \pm 25$ fs</td>
<td>$\gamma$</td>
<td>2, 4, 6, 8, 9, 11, 12</td>
</tr>
<tr>
<td>5.22 ± 40</td>
<td>$a$</td>
<td>$\Gamma = 225 \pm 45$ keV</td>
<td></td>
<td>6, 8, 9, 11</td>
</tr>
<tr>
<td>5.38 ± 70</td>
<td>$a$</td>
<td>$300 \pm 60$</td>
<td></td>
<td>6, 8, 9, 11</td>
</tr>
<tr>
<td>6.580 ± 20</td>
<td>$(2^+)$</td>
<td>$190 \pm 35$</td>
<td></td>
<td>6, 8, 9, 11</td>
</tr>
<tr>
<td>≈ 9</td>
<td></td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>≈ 10</td>
<td></td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>≈ 16.5</td>
<td></td>
<td></td>
<td></td>
<td>8</td>
</tr>
</tbody>
</table>

- One of these two states is presumably a $2^+$ state.
- Presumed analog of $^{10}\text{B}^*$ (18.80) [1993WA06].
- See reaction 8 for possible evidence of other states.

Table 10.32
Electromagnetic transition strengths in $^{10}\text{C}$

<table>
<thead>
<tr>
<th>$E_x \rightarrow E_f$ (MeV)</th>
<th>$J^\pi_x \rightarrow J^\pi_f$</th>
<th>Branch (%)</th>
<th>$\Gamma_\gamma$ (eV)$^a$</th>
<th>Mult.</th>
<th>$\Gamma_\gamma/\Gamma_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.354 → 0</td>
<td>$2^+ \rightarrow 0^+$</td>
<td>100</td>
<td>$(4.25 \pm 0.69) \times 10^{-3}$</td>
<td>E2</td>
<td>9.5 ± 1.5</td>
</tr>
</tbody>
</table>

- $\Gamma_\gamma$ from lifetime.

$B(E2)\uparrow$ for $^{10}\text{C}^*(3.35) = 62 \pm 10$ e$^2$ fm$^4$;

$B(E2)\downarrow$ for $^{10}\text{C}^*(3.35) = 12.4 \pm 2.0$ e$^2$ fm$^4$ [1968FI09].

1. $^{10}\text{C}(\beta^+)^{10}\text{B}$, $Q_m = 3.6480$

The half-life of $^{10}\text{C}$ is 19.290 ± 0.012 sec [1990BA02], which is the average of 19282 ± 20 ms [1974AZ01], 19270 ± 80 ms [1963BA52], 19300 ± 41 ms [1990BA02] and 19294 ± 16 ms [1990BA02]. The nucleus $^{10}\text{C}$ decays to $^{10}\text{B}^*$ (0.7, 1.7): the branching ratios are (98.53 ± 0.02)% [1979AJ01] and (1.4645 ± 0.0019)% [1999FU04], respectively. See also the discussion of reaction 42 in $^{10}\text{B}$.

By measuring the relative polarization of positrons emitted from $^{10}\text{C}$ $\beta$-decay (pure GT) and $^{14}\text{O}$ (pure Fermi), ratio = 0.9996 ± 0.0036 [1988GI02,1990CA41,1991CA12], constraints on the scalar and tensor admixtures to the dominant vector and axial vector currents were determined as, $|C_s/C_A| = 0.001 ± 0.009$.

2. $^1\text{H}(^{10}\text{C}, 10\text{C} + p)$

Elastic and inelastic scattering cross sections for $^{10}\text{C}^*(0, 3.35)$ were measured at $E_x(^{10}\text{C}) = 45.3$ MeV/A [2003JO09]. The data is best fit with $|M_s|/|M_p| = 0.71$ which gives $|M_s| = 5.51 ± 0.07$ fm$^2$ when compared with the known value $|M_p| = 7.87 ± 0.64$ fm$^2$, which is derived from $B(E2) = 62 ± 10$ e$^2$ fm$^4$. 
Fig. 16. Energy levels of $^{10}$C. For notation see Fig. 2.
3. $^{6}\text{Li}(\alpha, \pi^{-})^{10}\text{C}$, \(Q_m = -138.7572\)

The \(\pi^{-}\) production rates for various projectile and target combinations, including $^{6}\text{Li} + ^{4}\text{He}$, were measured at 4.5 GeV/c per nucleon in [1993CH35]. In general the observed \(\pi^{-}\) production cross section falls off exponentially with increasing \(\pi^{-}\) energy. In some cases the angular distributions show a slight dependence on target and projectile mass.

4. $^{7}\text{Li}(^{3}\text{He}, \pi^{-})^{10}\text{C}$, \(Q_m = -125.4299\)

At \(E(^{3}\text{He}) = 235\) MeV $^{10}\text{C}^*(3.35)$ is populated [1984BI08]. \(\pi^{-}\) production in this reaction has also been studied by [1984BR22] at \(E(^{3}\text{He}) = 910\) MeV.

5. $^{7}\text{Li}(^{7}\text{Li}, 4n)^{10}\text{C}$, \(Q_m = -18.1683\)

Tetraneutron ($n^4$) production has been studied in this and in other reactions involving $^{10}\text{Ca}$ at \(E(^{7}\text{Li}) = 82\) MeV [1987ALZG]: it was not observed. However, evidence that is consistent with the existence of $n^4$ is observed in the breakup of $^{14}\text{Be}$ [2002MA21].

6. $^{9}\text{Be}(p, \pi^-)^{10}\text{C}$, \(Q_m = -136.6323\)

Angular distributions of \(\pi^{-}\) groups have been measured at \(E_p = 185\) MeV (to $^{10}\text{C}^*(0, 3.35, 5.28, 6.63)$), at 200 MeV (g.s.), at 800 MeV (to $^{10}\text{C}^*(0, 3.35, 5.3, 6.6)$) [see [1984AJ01]] and at \(E_p = 650\) MeV ([1986HO23]; $^{10}\text{C}^*(0, 3.35)$; also \(A_y\)). \(A_y\) measurements have also been reported at \(E_p = 200\) to 250 MeV: see [1984AJ01]. At \(E_p = 800\) MeV, the angular distributions of produced pions were measured for Be and C targets [1988BA58]; they observed \(\sigma(0^\circ)/\sigma(20^\circ) \approx 6\).

7. (a) $^{10}\text{B}(\pi^+, \pi^0)^{10}\text{C}$, \(Q_m = 0.9456\)
(b) $^{10}\text{B}(\pi^+, \eta)^{10}\text{C}$, \(Q_m = -411.3778\)

In [1987SI18], calculations of polarization observables for $^{10}\text{B}(\pi^+, \pi^0)$ at 70 MeV and $^{10}\text{B}(\pi^+, \eta)$ at 460 MeV suggest that new measurements could provide insight into the single-charge-exchange reaction mechanism.

8. $^{10}\text{B}(p, n)^{10}\text{C}$, \(Q_m = -4.4304\)
\(Q_0 = -4430.30 \pm 0.12\) keV [1998BA83].

Level parameters for $^{10}\text{C}^*(3.35)$ are \(E_x = 3352.7 \pm 1.5\) keV, \(\tau_m = 155 \pm 25\) fs, \(\Gamma_x = 4.25 \pm 0.69\) meV. [See [1969P A09] and other references cited in [1974AJ01].] Angular distributions have been measured for the $n_0$ and $n_1$ groups and for the neutrons to $^{10}\text{C}^*(5.2 \pm 0.3)$ at \(E_p = 30\) and 50 MeV [see [1974AJ01,1979AJ01]] and for the $n_0$ and $n_1$ groups at \(E_p = 14.0, 14.3\) and 14.6 MeV [1985SC08] and 15.8 and 18.6 MeV [1985GU1C].

At \(E_p = 186\) MeV, angular distributions of neutrons were measured for \(\theta = 0^\circ - 50^\circ\) [1993WA06]. Levels were observed at 0 \([0^+], 3.35 \{2^+\}, 5.3 \{2^+\}, 6.6, \approx 9, \approx 10, \text{ and}\)}
16.5 MeV \([2^+]) \([J^\pi]\) in brackets. For \(E_x = 3.35\) MeV, \(B(GT) = 0.03\) and for 5.3 MeV, \(B(GT) = 0.68 \pm 0.02\). A multipole decomposition analysis suggests additional states at 17.2 and 20.2 with \(J^\pi = 2^-\) or \(1^-\), respectively. Higher-lying resonances that were excited with \(E_p = 186\) MeV protons, the Giant-Dipole Resonance \((\Delta L = 1, \Delta S = 0)\) and the Giant Spin Dipole Resonance \((\Delta L = 1, \Delta S = 1)\), are discussed in [1994RA23, 1994WA22,1995YA12]. In their analysis a broad peak from quasifree scattering, was estimated phenomenologically and subtracted from the excitation spectrum; a multipole decomposition analysis of the remaining structure indicated a prominent \(\Delta L = 1\) resonance around \(E_x = 17–20\) MeV with a possible mixture of \(2^-\), \(1^-\) and \(2^+\) states (analogous to \(^{10}\)B*(18.43, 18.8, 19.3, 20.1) and a small peak at \(E_x = 24\) MeV (possible analog of the \(^{10}\)B GDR). Data from \(E_p = 1\) GeV were analyzed to develop a formalism for charge-exchange processes involving pion and \(\Delta\)-isobar excitations [1994GA49].

The threshold value for \(^{10}\)B(p, n) was measured by [1989BA28]; a subsequent analysis of that data, by [1998BA83], rigorously evaluated the proton beam energy spread (740 eV), non-uniform energy losses for all protons, and energy losses induced by ionizing target atoms prior to capture. The threshold value was determined to be \(E_{\text{thres.}} = 4877.30 \pm 0.13\) keV, which yields \(Q_0 = 4430.30 \pm 0.12\) keV for \(^{10}\)B(p, n).

At \(E_p = 7\) and 9 MeV, thick target neutron and \(\gamma\)-ray yields and relative ratios are measured for a compilation of proton-induced radiations that provide elemental analysis [1987RA23]. Neutron production rates were measured for \(E_{\text{cm}} = 5.9\) MeV [1988CHZN]. The \(^{10}\)B(p, n) cross section was measured at \(E_p = 4.8–30\) MeV to evaluate the feasibility of producing isotopically enriched \(^{10}\)CO2 for use in PET imaging [2000AL06].

9. \(^{10}\)B(\(^3\)He, t)\(^{10}\)C, \(Q_m = -3.6666\)

Angular distributions have been measured at \(E(\(^3\)He) = 14\) MeV and 217 MeV; see [1979AJ01]. The latter \([to \(^{10}\)C*(0, 3.35, 5.6)]\) have been compared with microscopic calculations using a central + tensor interaction \([J^\pi = 0^+, 2^+, 2^+\), respectively\]. Structures have been reported at \(E_x = 5.22 \pm 0.04\) \([\Gamma = 225 \pm 45\) keV\], 5.38 \(\pm 0.07\) \([300 \pm 60\) keV\] and 6.580 \(\pm 0.020\) MeV [190 \(\pm 35\) keV].

10. \(^{12}\)C(\(\mu^+, X\))\(^{10}\)C

The production of radioactive isotopes from 100 and 190 GeV muons incident on a \(^{12}\)C target was measured by [2000HA33] to estimate the \(\mu\)-induced backgrounds in large volume scintillator detector experiments.

11. \(^{12}\)C(p, t)\(^{10}\)C, \(Q_m = -23.3595\)

Angular distributions have been reported at \(E_p = 30.0\) to 54.1 MeV and at 80 MeV [see [1974AJ01,1979AJ01,1984AJ01]]. \(L = 0, 2\) and 2 \(to \(^{10}\)C*(0, 3.35, 5.28)\) thus leading to \(0^+, 2^+\) and \(2^+\) respectively, for these states [but note that the “5.28 MeV” state is certainly unresolved]; see reaction 9 and Table 10.31. \(^{10}\)C*(6.6) is also populated. Two measurements of the excitation energy of \(^{10}\)C*(3.4) are 3353.5 \(\pm 1.0\) keV and 3354.3 \(\pm 1.1\) keV; see [1984AJ01] [based on \(Q_m\)]. See also ([1987KW01]; theor.).
12. $^{13}\text{C}(^{3}\text{He}, ^{6}\text{He})^{10}\text{C}$, $Q_m = -15.2376$

At $E(^{3}\text{He}) = 70.3$ MeV the angular distributions of the $^{6}\text{He}$ ions corresponding to the population of $^{10}\text{C}^*(0, 3.35)$ have been measured. The group to $^{10}\text{C}^*(3.35)$ is much more intense than the ground-state group: see [1979AJ01].

13. $^{16}\text{O}(p, X)^{10}\text{C}$

Spallation reaction rates for incident protons on $^{16}\text{O}$ and $^{12}\text{C}$ targets with $E_p \approx 50–250$ MeV were calculated by [1999CH50] using the GNASH code. These reaction rates are important for estimating the secondary radiation induced in medical proton therapy treatment.

14. $^{9}\text{Be}$, $^{nat}\text{C}$, $^{27}\text{Al}(^{10}\text{C}, X)$

Total interaction cross sections of $E(^{10}\text{C}) = 730$ MeV/A projectiles were measured on $^{9}\text{Be}$, $^{nat}\text{C}$ and $^{27}\text{Al}$ targets [1996OZ01]. The deduced cross sections, $\sigma = 752 \pm 13$, 795 ± 12 and 1171 ± 20 mb, respectively, indicate $R_{\text{r.m.s.}}(^{10}\text{C}) = 2.27 \pm 0.03$ fm.

**10N**

(not illustrated)

*General*

References to articles on general properties of $^{10}\text{N}$ published since the previous review [1988AJ01] are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for $^{10}\text{N}$ located on our website at www.tunl.duke.edu/nucldata/General_Tables/10n.shtml.

The first evidence for a state in $^{10}\text{N}$ has been observed in the $^{10}\text{B}(^{14}\text{N}, ^{14}\text{B})^{10}\text{N}$ reaction at $E(^{14}\text{N}) = 30$ MeV/A [2002LE16]. The resonance is $2.64 \pm 0.4$ MeV above the $^{9}\text{C} + p$ threshold and the width is $\Gamma = 2.3 \pm 1.6$ MeV. Large $L = 2$ two-nucleon transfer amplitudes calculated for $^{10}\text{B} + 2p \rightarrow ^{12}\text{N}_{g.s.}$ and $^{12}\text{N}_{g.s.} \rightarrow ^{10}\text{N}(1^+)$ suggest that the observed state is the analog of the 0.24 MeV $1^+$ state of $^{10}\text{Li}$. Furthermore, the energy of the observed state is consistent with a p-shell Coulomb energy shift. The virtual s-wave state near threshold in $^{9}\text{Li} + n$ (see $^{10}\text{Li}$) implies a broad s-wave state about 1.8 MeV above the $^{9}\text{C} + p$ threshold in $^{10}\text{N}$ (see the discussion of $^{9}\text{N}$).

**10O, 10F, 10Ne**

(not illustrated)

Not observed: see [1979AJ01]. See also [1988AJ01].
Fig. 17. Caption on next page.
Fig. 17. Isobar diagram, $A = 10$. 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 $^{10}{\text{B}}$: here $M$ represents the atomic mass excess in MeV. Levels which are presumed to be isospin multiplets are connected by dashed lines.

Table 10.33

<table>
<thead>
<tr>
<th>$^{10}$Be</th>
<th>$^{10}$B</th>
<th>$^{10}$C</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_x$ (MeV)</td>
<td>$J^\pi$; $T = 1$</td>
<td>$E_x$ (MeV)</td>
</tr>
<tr>
<td>0</td>
<td>0$^+$</td>
<td>1.74015</td>
</tr>
<tr>
<td>3.36803</td>
<td>2$^-$</td>
<td>5.1639</td>
</tr>
<tr>
<td>5.9599$^d$</td>
<td>1$^-$</td>
<td>6.873</td>
</tr>
<tr>
<td>5.9599$^d$</td>
<td>1$^+$</td>
<td>7.430</td>
</tr>
<tr>
<td>5.95839</td>
<td>2$^+$</td>
<td>7.469</td>
</tr>
<tr>
<td>6.2633$^d$</td>
<td>2$^-$</td>
<td>7.480</td>
</tr>
<tr>
<td>6.1793</td>
<td>0$^+$</td>
<td>7.5999</td>
</tr>
<tr>
<td>6.2633$^d$</td>
<td>2$^-$</td>
<td>7.75</td>
</tr>
<tr>
<td>7.371</td>
<td>3$^+$</td>
<td>8.889</td>
</tr>
<tr>
<td>7.542</td>
<td>2$^+$</td>
<td>8.894</td>
</tr>
</tbody>
</table>

$^a$ As taken from Tables 10.5, 10.18 and 10.31.

$^b$ Defined as $E_x(^{10}{\text{B}}) - E_x(^{10}{\text{Be}}) - 1.74015$.

$^c$ Defined as $E_x(^{10}{\text{C}}) - E_x(^{10}{\text{Be}})$.

$^d$ Two entries for the same $^{10}$Be level.

$^e$ See footnote $^a$ in Table 10.31 and [1997DA28].

Errata

Errata will be provided online at our website at www.tunl.duke.edu/nucldata/Errata/Errata.shtml.

References


$^2$ Closed 31 March 2004.

$^3$ References are arranged and designated by the year of publication followed by the first two letters of the first-mentioned author’s name and then by two additional characters. Most of the references appear in the National Nuclear Data Center files (Nuclear Science References Database) and have NSR key numbers. Otherwise, TUNL key numbers were assigned with the last two characters of the form 1A, 1B, etc. In response to many requests for more informative citations, we have, when possible, included up to ten authors per paper and added the authors’ initials.

$^4$ The Reference key for conference reports follows the body of the reference citations. For citations marked with $^\dagger$ please refer to the Reference key for a complete citation of the conference proceeding.

† For references marked with † please refer to the Reference key (below) for a complete citation of the publication.


[1986BE1Q] Belozerov, et al., [Dubna 86], p. 93.


[1992GO27] V.V. Komarov, A.M. Popova, F.I. Karmanov, V.L. Shablov, O.F. Nemets, Yu.N. Pavlenko, V.M. Pu-


[1992KO26] V.V. Komarov, A.M. Popova, F.I. Karmanov, V.L. Shablov, O.F. Nemets, Yu.N. Pavlenko, V.M. Pu-


[1992KO26] V.V. Komarov, A.M. Popova, F.I. Karmanov, V.L. Shablov, O.F. Nemets, Yu.N. Pavlenko, V.M. Pu-


Reference key5


5 Abstracts to contributed papers presented at various conferences, meetings, etc., are referred to by the following key. The list is alphabetical by name; some names may be repeated for different publication years.


